Reduction of workers’ hand-arm vibration exposure through optimal machine design: AHP methodology applied to a case study

Manuscript Details

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Title	REDUCTION OF WORKERS' HAND-ARM VIBRATION EXPOSURE THROUGH OPTIMAL MACHINE DESIGN: AHP METHODOLOGY APPLIED TO A CASE STUDY
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Abstract

The exposure of workers to mechanical vibrations represents a significant risk in many industrial sectors, due to the widespread presence of vibrating machines, and its assessment and reduction are actually considered a priority in the whole of the European context. The present work has a dual objective: (i) as a preliminary step, to analyse the state of the art in the field of vibratory machines and their design or selection, focusing on hand-arm vibrations; (ii) to propose a new instrument for systematic analysis that may be used by manufacturers of vibratory hand-held machines when choosing optimal technical solutions to minime vibration emissions. A general review of fixed and portable vibratory machines from different productive areas is given initially; existing methods and technical solutions for reducing their emissions at source are consequently detailed, based on International regulations, scientific literature, technical standards and guidelines. A framework based on an Analytic Hierarchy Process (AHP) multi-criteria analysis is then defined and proposed as a possible instrument for choosing anti-vibration solutions while designing hand-held machines. Finally, such procedure is applied to the real case study of an Italian company producing brush-cutters.

Keywords	Occupational Health and Safety; vibratory machines; vibration reduction; hand-held machines; AHP multi-criteria analysis; brush-cutters
Taxonomy	Analytical Hierarchy Process, Cost Benefit Analysis, Machine Dynamics, Forestry Safety
Manuscript region of origin	Europe

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Submission Files Included in this PDF

File Name [File Type]

rev2_Cover_letter.docx [Cover Letter]

rev2_Response.docx [Response to Reviewers (without Author Details)]

rev2_Highlights.docx [Highlights]

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DIPARTIMENTO INNOVAZIONI
TECNOLOGICHE E SICUREZZA
DEGLI IMPIANTI PRODOTTI
E INSEDIAMENTI ANTROPICI

Prof. N. Paltrinieri
Associated Editor of
Safety Science
Norwegian University of Science & Technology NTNU, Norway

Parma, Italy, 26 July 2019

Dear Prof. Paltrinieri,

Thank you again for inviting us to resubmit our paper.
We have modified the manuscript according to the suggestions made by the reviewer.
The use of English language in the main text and in the abstract has been checked and corrected by a professional native language reader.
We hope the paper will be now suitable for publication in Safety Science.
Please find enclosed an electronic copy of the revised manuscript, actually re-entitled:

"REDUCTION OF WORKERS' HAND-HARM VIBRATION EXPOSURE THROUGH OPTIMAL MACHINE DESIGN: AHP METHODOLOGY APPLIED TO A CASE STUDY"

Point-by-point answers to all comments raised by the reviewer are also included.

We wish to take this opportunity to send to You our best regards.
Looking forward to hearing from You soon,
Yours sincerely

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RESPONSE TO REVIEWER # 1

The authors thank the reviewer for his/her positive comment about the first revision of the paper and for the useful additional observations.
Responses are given just below the original comments.
Please note that, all along the manuscript, the modified or added parts (including corrections to English language) are highlighted in yellow.

Comment 1

Sections 2 and 3.
I understand that the authors use these two sections as the theoretical basis of the evaluation instrument (AHP technique). I also consider that these two sections play an interesting informative role (didactic). However, the extension of these sections is about 13 pages, and consequently, this extension is somewhat high for a scientific paper. Therefore, I recommend that the authors try to apply a synthesis effort on these two sections, in order to reduce somewhat this extension, by using summary tables and removing some information that can be considered "alternative". As an example of this, I suggest eliminating all aspects related to WBV vibrations, since this paper focuses on HAV vibrations.
Answer
According to your comment, we have tried to reduce the extension of Sections 2 and 3 and we were finally able to obtain a global reduction of almost 6 pages.
In particular, following your suggestion, we have eliminated all aspects directly related to WBV (excluding some minimal citations where necessary) and, for example, Par. 2.1 (focused on vibration assessment) has been turned into an introductive part of Section 2 and it actually refers only to HAV vibrations. Consequently, the general subdivision into paragraphs of Section 2 has been modified.
The abstract has been modified, too, by adding a specific reference to HAV, as well as Introduction and Conclusions.
We have kept the specific paragraphs concerning fixed machines - since they can present HAV problems (even if less frequently than WBV) - but we have tried anyway to give more importance to hand-held machines all along the manuscript, in view of the final case study analysis.
In addition, we have deleted all information that we have considered as not fundamental for the main scope of the paper. For example, the paragraph that was dedicated to UNI CEN/TR 15350:2013 has been reduced and incorporated into Par.3.2.1 (“Use of data provided by manufacturers”).
Finally, we have chosen to keep unchanged the list of anti-vibration technical solutions (*a-f*) presented in Par.3.1.2, since it gives fundamental technical details about the AHP alternatives that are used in the framework presented in Section 4.

Comment 2

Keywords.

Taken as a reference Directive 2002/44/EC, is more correct to use "Occupational Health and Safety" that only "occupational safety".

Answer

The keyword has been modified as suggested.

Comment 3

Discussion and analysis of the results section.

A more critical discussion of the results is necessary, where, in addition, the authors cite other works linked to the OHS where the AHP technique has been used. The limitations indicated by the authors, particularly the WBV vibrations, really is a criterion for exclusion from the study. The limitations could indicate limitations of the AHP technique, as well as the statistical representativeness of the results. For example: (i) The authors indicate that "Ergonomics is considered more important than noise of vibrations". This criterion is very debatable, especially considering legal aspects (Directive 90/269 / CEE vs. Directive 2002/44 / EC and Directive 2003/10 / EC); (ii) The authors indicate that "exhaust gas is considered here only in terms of environmental impact". This is also very problematic since occupational exposure to chemical contaminants also has its own directives (Directive 98/24 / EC and Directive 2004/37 / EC). These two and similar aspects require more discussion and/or justification.

Answer

According to your comment, we have significantly modified Section 6, also introducing the concept of statistical representativeness of the results and adding the citations of two dedicated references. The specific topics that you have indicated (ergonomics and gas emissions) have been described in a different way, with (we hope) an adequate discussion. In addition, some other brief comments to the results have been added. Finally, the wrong concept of “limitation“ related to WBV analysis has been deleted, as you suggested.

Comment 4

Conclusions section:

(i) The authors indicate that "In particular, the validity, consistence and robustness ...". In this regard, the authors must clarify (also in other parts of the manuscript, including the abstract) that the methodology has not been validated in strict terms. The methodology "only" has been applied to a real study, whose results have no validity or statistical representativeness

Answer

In all the manuscript, as well as in the abstract, the concept of “validation” of the proposed methodology has been replaced by the concept of its “application”, as required. The concepts of “robustness” and “consistence” - where deemed necessary - have been kept, but it has been specified that they refer specifically to the numerical AHP analysis (and subsequent sensitivity analysis) for the considered case study.

(ii) It would be very valuable for the authors to improve the conclusions section considering the specific results of the case study.

<u>Answer</u>

We agree, thank you, we have reported the main results of the case study in the conclusions.

<u>Comment 5</u>

Other aspects:

(i) Emak SpA company: the authors must name this company always in the same way (including uppercase and lowercase).

<u>Answer</u>

According to your comment, the company is now named as “Emak S.p.A.” whenever it appears in the manuscript.

(ii) It is important to reduce the aspects referred to Emak SpA company in order that the paper is not used as a direct and explicitly advertising means of this company. This circumstance can have a negative impact on the credibility of the paper.

<u>Answer</u>

In Section 5 (introductive general part and Par.5.1) we have modified some paragraphs, particularly trying to eliminate every possible “advertising tone” in favour of Emak SpA. The descriptions of some of the technical solutions applied by the company have been consequently reduced, where they have been evaluated as not fundamental for the scope of the paper.

(iii) The European harmonized standards listed in Table 1 should be included in the references.

<u>Answer</u>

In Table 1, the citations of 26 European harmonized standards have been added (we have selected the ones that are strictly related to the reported “examples of involved machines”). Consequently, these standards have been added also to the final list of references, whose numbering has been updated accordingly.

(iv) The percentage of workers exposed to HAV vibrations in Europe should be quantified by citation.

<u>Answer</u>

At the beginning of Section 2, after clarifying the concept of HAV vibrations, we have inserted additional information about the involved number of workers. In particular, it has been specified that - in absence of an official European document clearly distinguishing the exposure percentages for WBV and HAV - we have decided to cite single national experiences (scientific researches, public studies, etc.) that could give an idea of the importance that the HAV theme has in some of the European countries. Two dedicated additional references have been added, consequently.

(v) Define the criteria and interval of low vibrations HAV (regarding exposure limit values and action values according to Directive 2002/44/EC).

<u>Answer</u>

In revision1 of the paper, the vibratory limit/action values imposed by Directive 2002/44/EC (and consequent national decrees) are given at the beginning of Section 2, in terms of A(8). The employer has to check the workers' exposure and to take action accordingly. From HIS point of view, desired "low vibrations" are when such limit/action values are not exceeded.
The role of manufacturer is different, since the Machinery Directive only say that " machinery must be designed and constructed in such a way that risks resulting from vibrations produced by the machinery are reduced to the lowest level, taking account of technical progress and the availability of means of reducing vibration, in particular at source. The level of vibration emission may be assessed with reference to comparative emission data for similar machinery." The Directive only fixes the vibratory threshold beyond which it is necessary to indicate the exact vibration emission values in the machine Instructions, together with their uncertainty (see Par.3.2.1.).
This means that the manufacturer (from HIS point of view) does not have exact limit/action values to respect, but has anyway to try to reduce as much as possible vibrations, by looking at the state of the art and at the available technologies, also because, in this way, he acquires a better position on the market, compared to his competitors.
Emak S.p.A. has confirmed us this concept, underlining that even the EN ISO 11806-1:2011 standard, regarding safety of brush-cutters, does not talk about exact vibratory limits; it only says that vibration reduction shall be an integral part of the design process and suggests, consequently, (i) to follow the technical rules and guidelines given by CR 1030-1 and (ii) to take information about comparative data on vibration levels from ISO/TR22521 (for hand-held forestry machinery) – as Emak S.p.A. typically does.
Emak S.p.A. has refused to furnish us its own vibratory criteria (that is, which vibratory values they try to obtain on their machines as optimal target), since this is part of their marketing strategy (with consequent privacy problems) and it can also vary with time.
Finally, we think – according to your observation - that in our manuscript some general expressions as "products with reduced vibrations" or "low vibration hand-held machine", need some kind of clarification in the text, following the concepts what we have just detailed. Consequently, we have added some lines of explication just before Par.3.1 and also at the beginning of Par. 5.2.

(vi) It is advisable that the authors use an English Language Editing service.
<u>Answer</u>
According to your request, the use of English language in the main text and in the abstract has been checked and corrected by a professional native language reader.

Highlights

- Fixed and portable vibratory machines are listed by typology and application sector
- An overview of solutions to reduce vibration risk in such machines is shown
- An AHP-based framework for designing low-vibration hand-held machines is presented
- The proposed framework is applied to a case study of company producing brush-cutters
- The best solution for reducing vibrations is to insert anti-vibration systems

Abstract

The exposure of workers to mechanical vibrations represents a significant risk in many industrial sectors, due to the widespread presence of vibrating machines, and its assessment and reduction are actually considered a priority in the whole of the European context.
The present work has a dual objective: (i) as a preliminary step, to analyse the state of the art in the field of vibratory machines and their design or selection, focusing on hand-arm vibrations; (ii) to propose a new instrument for systematic analysis that may be used by manufacturers of vibratory hand-held machines when choosing optimal technical solutions to minime vibration emissions.
A general review of fixed and portable vibratory machines from different productive areas is given initially; existing methods and technical solutions for reducing their emissions *at source* are consequently detailed, based on International regulations, scientific literature, technical standards and guidelines. A framework based on an Analytic Hierarchy Process (AHP) multi-criteria analysis is then defined and proposed as a possible instrument for choosing anti-vibration solutions while designing hand-held machines. Finally, such procedure is applied to the real case study of an Italian company producing brush-cutters.

Keywords:

Occupational Health and Safety; vibratory machines; vibration reduction; hand-held machines; AHP multi-criteria analysis; brush-cutters.

REDUCTION OF WORKERS' HAND-ARM VIBRATION EXPOSURE THROUGH OPTIMAL MACHINE DESIGN: AHP METHODOLOGY APPLIED TO A CASE STUDY

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REDUCTION OF WORKERS' HAND-ARM VIBRATION EXPOSURE THROUGH OPTIMAL MACHINE DESIGN: AHP METHODOLOGY APPLIED TO A CASE STUDY

1 Introduction

According to the Sixth European Working Conditions Survey (6th EWCS) [Eurofound, 2017], almost 20% of workers in the 28 EU Member States (EU28) are exposed to vibrations produced by tools or machines for at least a quarter of the working time. The sectors mainly involved are construction, industry and agriculture, as shown in Figure 1.

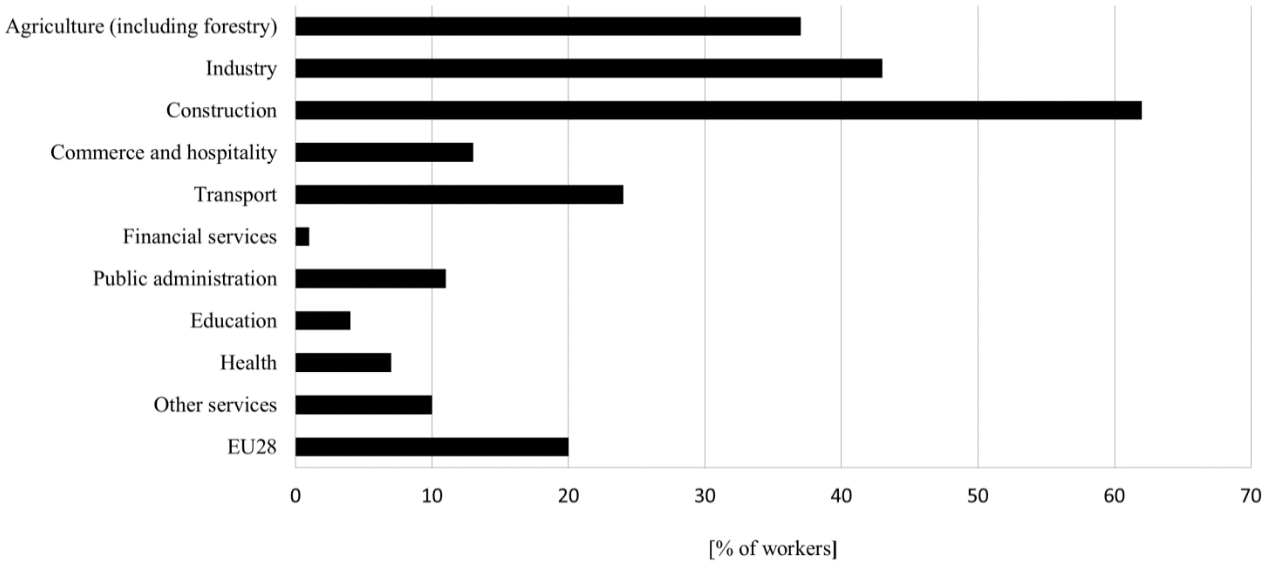

Figure 1. Comparison of exposure to vibrations between European (EU28) workers in different job sectors [Eurofound, 2017].

Vibrations can be generated by the operation of the machinery itself (rotating or reciprocating masses, gas pulsation, aerodynamic phenomena), by the impact of hand-held machinery on hard materials, or by interaction between the machinery and its environment (e.g. movement of mobile machinery over rough ground).

Several professional diseases have been proved to be correlated to vibration exposure, on hand-arm as well as whole-body systems [Griffin, 1990]. Directive 2006/42/EC, i.e. the so-called "Machinery Directive" [European Parliament and Council, 2006], implemented in Italy by Legislative Decree n.17 of 27 January 2010 [Italian Government, 2010], requires machine producers to minimize the risk resulting from vibrations, ultimately encouraging them to seek good technical solutions in the field in order to reduce vibration emission. For certain categories of machinery, it also lays down that information on vibrational emissions is reported in the Instructions.

Indeed, the exposure to vibrations appears in both the "physical stress" sheets (even in combination with other issues such as manual material handling, excessive exertion and impact, working posture, highly repetitive tasks, individual capacity), and the "discomfort" sheets in the "Guidance on the application of the essential health and safety requirements on ergonomics set out in section 1.1.6 of Annex I to the Machinery Directive 2006/42/EC" [European Commission, 2010].

At the same time, Directive 2002/44/EC [European Parliament and Council, 2002] (currently implemented in Italy by Legislative Decree n. 81 of 9 April 2008, also known as "Consolidated Act on health and safety at work" and subsequent further decrees [Italian Government, 2008]) requires employers to apply technical as well as organisational solutions for minimization of vibration exposure of workers. For this purpose, they should choose machines (and safety components) accurately and take into account the additional contingent factors (e.g. duration of use, posture, additional loads, …) that can render the real *exposure* different from the initial *emission*. Using personal protective equipment is often not enough: priority must be given to interventions *at source*.

Methods for systematic introduction of safety concepts in design were developed and reviewed in the past by several researchers [Rausand and Bouwer Utne, 2009; Anderson, 2005; Fadier and De la Garza, 2007; Gauthier and Charron, 2002], who also advised on the importance of incorporating ergonomic factors in the design process. Other investigators proposed methodologies to compare the suitability and desirability of candidate alternative safety devices, to be used by the designer during the design phase and by users too (e.g. safeguards [Caputo et al., 2013]). In this sense, the role of the international standards available and technical reports when performing a correct evaluation of data provided by producers or databases has also been recently analysed in literature [Brocal et al., 2018].

The main objective of the present work is to propose a new evaluation instrument that could be easily used by manufacturers to face up to the design of vibratory hand-held machines through a dedicated systematic procedure, based on specific analysis steps and evaluation criteria, and able to balance the need for a reduced vibration emission with other typical business goals. Most of the solutions currently adopted to reduce vibrations in machines are in fact internally chosen by companies on the basis of experience and common sense only, under the pressure of competition on the market, without following a scientific methodology.

An additional goal is to give a review of the state of the art in the field of vibratory machines and their optimal design (or selection) in terms of vibrational emissions, based on International regulations, scientific literature, technical standards and guidelines. Such initial analysis is fundamental in order to correctly and consciously carry out the subsequent procedure for realizing the above-mentioned evaluation instrument.

These objectives are achieved in the manuscript as follows.

Firstly, the existing fixed and hand-held machines producing the most vibrations in the European context, are described in Chapter 2 through a general analysis covering different productive areas and focusing on hand-arm vibrations. Secondly, general methods and solutions for reducing their vibratory emission at source and the consequent exposure are detailed in Chapter 3. Attention has been focused on hand-held machines as well as fixed industrial machines in order to define a complete scenario for the above-mentioned concept of "interventions *at source*" for reducing vibrations (that is extensively applicable in both cases), even if the final evaluation instrument

proposed refers to the case of portable machines only. The analysis of vibratory transport systems and vehicles, instead, is not an objective of this research, since the authors believe these require a dedicated study, due to the high number of transport typologies and their specific vibration frequency range.
Based on this information, the methodology adopted to obtain the above-mentioned evaluation instrument is then described in Chapter 4, where a specific multi-criteria approach, namely the Analytic Hierarchy Process method, is used. Consequently, a framework for the design of hand-held machines with reduced vibration emission is presented and is finally applied, in Chapter 5, to a real industrial case study in the field of outdoor hand-held equipment for gardening and forestry activities, i.e. the design of brush-cutters.

2 Hand-arm vibrations risk assessment

The current European and Italian regulations on risks connected with exposure of workers to vibrations makes a distinction between "hand-arm vibrations" (HAV), transmitted to the human hand-arm system, and "whole-body vibrations" (WBV), transmitted to the whole body [European Parliament and Council, 2002].
This paper focuses on machines that can present occupational issues of HAV, which entail health-and-safety-related risks in terms of vascular, bone, joint, neurological and/or muscular disorders.
Unfortunately, the above-mentioned "Sixth European Working Conditions Survey (6th EWCS)" does not distinguish between WBV and HAV in terms of percentage of exposed workers. The extent of the specific problem of hand-arm vibrations can however be estimated by referring to recent studies concerning single European countries. For example, Swedish scientific research [Vihlborg et al., 2017] presents data from a national statistics report, attesting that 14% of all employed men (and 3% of women) in Sweden are exposed to vibrations from hand-held machines for at least 25% of their working time. In the United Kingdom, over 7,000 new claims for Hand-Arm Vibration Syndrome (that is, a disease due to HAV exposure with vascular, neurologic and musculoskeletal features) have been reported between 2008 and 2017 [UK Department for Work and Pensions, 2018].
In Italy, according to Directive 2002/44/EC, specific vibration thresholds exist to avoid excessive exposure [Italian Government, 2008]. When the so-called "*exposure action values*" (2.5 m/s^2 standardised to an eight-hour reference period for HAV) are exceeded, the employer must establish and implement a programme of technical and/or organisational measures intended to minimise the exposure to mechanical vibrations and related risks. If even the so-called "*exposure limit values*" (5 m/s^2 standardised to an eight-hour reference period for HAV) are exceeded despite the measures taken by the employer to comply with regulations, the employer must take immediate action to rapidly reduce exposure below such limit (for example, by reducing exposition time).
The daily exposure value, standardised to an eight-hour reference period, is generally called "*A(8)*". In case of HAV, it is calculated starting from the square root *ahv* of the sum of the squares of the root-mean-square values of the frequency-weighted accelerations on three orthogonal axes (ahw_x, ahw_y, ahw_z), by applying a factor equal to the square root of T/T_0, where T and T_0 are the total daily duration of exposure and the reference 8-hour duration, respectively. The related

weighting curves are set by specific international standards, in particular UNI EN ISO 5349-1:2004 [UNI, 2004] for HAV, updated by UNI ISO/TR 18570:2018 [UNI, 2018] for the specific case of vascular hand-arm vibration risks (vibration white finger) only. Such standards highlight that the frequency range where HAV exposure can occur is typically 8-1000Hz.

Within the main productive contexts where vibration exposure is significant (agriculture, industry, construction), several extremely different sectors can be identified. Exposure to vibrations is in fact cited as possible risk for workers by many of the so-called "European harmonized standards", covering a wide variety of work activities.

2.1 Harmonized standards related to vibration risk

Harmonized standards for product safety, in particular the ones adopted by the European Committee for Standardization (CEN) and by the European Committee for Electrotechnical standardization (Cenelec), help designers to understand and apply the Health and Safety requirements for the machines of interest correctly. They are valid for all the UE States; in Italy, they are generally adopted as "UNI EN" standards. The application of harmonized standards is not mandatory, but it guarantees the conformity with the Product Directives if such standards are published in the Official Journal of the European Union.

The International Organization for Standardization (ISO) provides other kinds of standards, which represent a worldwide valid reference and can subsequently be adopted in Europe as "EN ISO" standards.

Although technical standards are not laws, they become mandatory regulations if referred to in National legislative decrees.

Manufacturers are responsible for carrying out the conformity assessment, drawing up the technical file, issuing the EU declaration of conformity and affixing the CE marking on a product, complying with national laws and possibly applying harmonized standards [HSE, 2011a].

Among harmonized standards, several deal with vibration exposure risk (see "EU Commission communication about titles and references of the harmonized standards fulfilling Machinery Directive" [European Commission, 2018]).

Table 1 shows a list of the machinery sectors mainly involved (i.e., only if expressly cited as possible sources of exposure to dangerous vibrations by the CEN/TC harmonized standards). Some categories have been marked with an asterisk to underline that one or more cases of work accidents linked to machine non-conformity to Directive 2006/42/EC for vibration exposure have also appeared in the *9th Report 2017 on Italian market surveillance* for such machines, recently published by the Italian National Institute for Insurance against Accidents at Work (INAIL) [INAIL, 2017].

CEN/TC code	Sector denomination and examples of machines involved
143	Machine tools (stationary grinding machines [CEN, 2015a], etc.)
144*	Tractors and machinery for agriculture and forestry (hand-held powered brush-cutters and grass-trimmers [CEN, 2011a], etc.)
146	Packaging machines (form, fill and seal machines [CEN, 2009a] , etc.)
148	Continuous handling equipment and systems (pneumatic handling of bulk materials [CEN, 2010a], etc.)
150	Industrial trucks (forklifts [CEN, 2008], etc.)
151	Construction equipment and building material machines (machines for the manufacture of

	constructional products from concrete and calcium-silicate such as block making machines [CEN, 2010b]; concrete compactors and smoothing machines [CEN, 2011b]; earth-moving machinery [CEN, 2018a], etc.)
153	Machinery intended for use with foodstuffs and feed (pasta processing plants such as dryers and coolers [CEN, 2013], etc.)
183	Waste management (rear loaded refuse collection vehicles [CEN, 2015b], etc.)
186	Industrial thermo-processing (industrial furnaces and industrial heating equipment used in metallurgical and metal working plants, ceramic manufacturing plants [CEN, 2009b], etc.)
192	Fire and rescue service equipment (vehicle mounted hydraulic platforms [CEN, 2010c], etc.)
196	Mining machinery and equipment (continuous loaders, underground dozers [CEN, 2018b], etc.)
201	Leather and imitation leather goods and footwear manufacturing machinery (hand guided cutting and punching machines [CEN, 2009c] , etc.)
202	Foundry machinery (sand lump crusher, knock-out equipment [CEN, 2010d], etc.)
255*	Hand-held power tools (fastener driving tools [CEN, 2018c]; percussive drills, hammers and breakers [CEN, 2011c]; polishers and rotary, orbital and random orbital sanders [CEN, 2009d]; grinders [CEN, 2012]; saws, polishing and filing machines with reciprocating action, and small saws with oscillating or rotating action [CEN, 2019]; etc.)
256	Railway applications (track-portable machines and trolleys for construction and maintenance [CEN, 2011d], etc.)
271	Surface treatment equipment (machinery for the supply and circulation of coating materials under pressure [CEN, 2010e], etc.)
274	Aircraft ground support equipment (container/pallet loaders, baggage and equipment tractors [CEN, 2009e], etc.)
310	Advanced automation technologies and their applications (industrial robots [CEN, 2011e], etc.)
322	Equipment for making and shaping of metals (electric arc furnaces for production of steel [CEN, 2010f], hydraulically powered open die hot forging presses for the forging of steel and non-ferrous metals [CEN, 2010g], etc.)

Table 1. Sectors affected by the risk of operator exposure to vibrations, according to CEN/TC harmonized standards.
** presence of recent cases of non-conformities to Directive 2006/42/EC [INAIL, 2017].*

Vibrating machines can be classified into three groups, depending on how vibrations are transmitted to humans, namely:

(i) fixed machines - vibrations can be transmitted to operators through the floor or industrial platforms (WBV) or, sometimes, through hands (HAV);
(ii) hand-held or hand-guided machines - vibrations are transmitted to operators through hands (HAV);
(iii) vehicles and mobile machinery - operators are typically subjected to vibrations through the seat while driving (WBV).

Case (i) and (ii) will be further detailed in the next paragraphs of this paper since they can pose a hand-arm vibration hazard. The present study does not take into account, instead, case (iii) or vibration exposure due to proximity to heavy/rail transport or to specific construction and road works.

2.2 Vibratory fixed machines

Table 2 shows the most common industrial fixed machines which are characterized by the presence of vibrations for different application sectors (and therefore potential exposure of operators, e.g. if located in manoeuvring and control positions). Such list is based on:

(i) an analysis of the European industrial market, carried out by exploring the websites of several companies and the product categories that are presented there;
(ii) the INAIL "Sector risk profiles" database [INAIL, 2013], an operational tool which addresses business risk assessment and collects information on risk in different sectors, at each stage of the production cycle, as observed directly in groups of Italian companies;
(iii) identification of machine typologies presenting vibratory phenomena through the analysis of the content of the CEN/TC harmonized standards complying with machinery Directive [European Commission, 2018].

In many cases the vibration is desired and is an essential component of the machine's functionality. Despite the many sectors involved, it should be noted that some types of machinery (e.g. vibrating feeders and screens) are present in many different areas; it may therefore be hypothesized that common criteria can be identified for the design/selection of machine components for vibration risk reduction purposes.

Machine typology	Application sectors	Machine details and related activities
Fixed vibrators for concrete compaction	Construction	Two typologies: i) external, rigidly anchored to the formworks ii) vibrating tables with circular vibratory motion
Hammer mills	Construction	Grinding of aggregates and debris from demolition
	Ceramics	Grinding for production of cotto tiles
Vibrating grids	Foundry	Shake-out machines
Vibratory crushers	Foundry	Comminution of resin-bonded lumbs and core break pieces
Machines for metal processing	Engineering industry	Forging presses Presses for thin sheet moulding (car bodies, kitchen tops, etc.) Machine tools (also including pedestal grinders, etc.)
	Foundry	Microfusion (injection presses)
	Steelworks	Presses, lamination plants
	Paper mills	Presses
Vibrating screens and sieves	Food	Elimination of water and separation of foreign objects (e.g.: olives industry)
	Ceramics	Preparation of doughs, glazes, tiles
	Small metallic components	Separation from swarfs
	Steelworks	Mineral screening (harsh conditions, at very high temperatures)
	Foundry	Classification of foundry sand
	Recycling	Recovery of various types of materials or particle sizes Separation of liquid parts from solid parts
	Similar machines are present in other sectors such as: food, chemical industry, pharmaceutics, mining and stone processing, wood, energy production, waste incineration	
Vibratory linear feeders (hoppers or tapes)	Food	Filling machines for bulk solid products (legumes, olives, etc.) Vibrating bottoms for silos (to facilitate product release) Short pasta production lines (shaker pre-dryer)
	Foundry	Vibrating loaders for feeding melting furnace
	Similar machines are present in other sectors such as: pharmaceutics, packaging, small metallic components, steelworks	
Vibratory conveyors (tapes or flat surfaces)	Food	Transport and draining of vegetables (es: salad) and fruits Conveying and drying systems for salt and milk powder
	Steelworks	Transport of ferrous scrap
	Chemical industry	Transport of chemical powders

	Similar machines are present in other sectors, e.g. wood, foundry, mining and stone processing, energy production, pharmaceutics, ceramics	
Vibratory bowl feeders	Small components (metals, plastics)	Conveying and feeding small spare parts in automatic assembly systems
	Pharmaceutics	Conveying and feeding tablets
Vibratory spiral elevators (vertical transport with thermal treatment)	Plastics and rubber processing	Cooling of plastic granules after extrusion and screening Rubber treatment after polymerization
	Steelworks	Cooling of the metallic scrap after treatment in furnace
	Food	Thermal treatment of foodstuffs
Vibratory machines for packaging	Food	Vibrating tapes for packaging of loose products (rice etc.)
Pneumatic transport plant	Textile industry	Spinning of carded yarn
	Similar transport systems are present in other sectors such as: mining, pharmaceutics, chemical industry, agriculture, energy production, foundry	
Mobile platforms	Slaughter industry	Platforms for operator access to specific activities areas
Machinery for circulation of coating materials	Surface coating	Colour mixing machinery Atomizing and spray equipment
Collaborative robots	Assembly lines (automotive, etc.)	Assistance of human co-workers
Ingot moulds	Steelworks	Oscillating system of ingot moulds, in cases where they are possibly still used for steel casting
Vibratory finishing machines (with abrasive components)	Galvanic industry Processing of (even precious) metals	Surface finishing Elimination of metal burrs

Table 2. Most common vibratory fixed machines typologies and application sectors.

Vibratory fixed machines can expose the operator mainly to WBV, but also - although more rarely - to HAV. For this reason Chapter 5 of the present research presents a case study regarding hand-held portable machines only, where the effective risks for health due to HAV appear higher.

2.3 Vibratory hand-held machines

Table 3 shows the most common industrial hand-held or hand-guided machines which are characterized by the presence of vibrations for different application sectors (and therefore potential exposure of operators to HAV). Such list is based on an analysis of the sources detailed above for fixed machines (Par. 2.2).

In particular, vibrations transmitted to the hand-arm system are typically generated by [UNI, 2004]:

i. portable machine tools held by employees in metalworking and carpentry plants, the mining industry, the construction sector, stone processing, forestry, etc.;
ii. objects handheld by workers while such objects are undergoing machine working;
iii. agricultural and garden machines which are hand-driven by the workers who follow the equipment on foot;
iv. self-propelled machines and means of transport driven by the workers through guide devices.

Only groups (i) and (iii) are represented in Tab. 3, since groups (ii) and (iv) can be considered to be included in the categories of fixed machines (see Paragraph 2.2, for example collaborative robots) and of mobile machines (not taken into account here), respectively.

Machine typology	**Sectors and activities**	**Machines details**
Percussive tools	Construction Stone processing	Percussive hammers and breakers
	Engineering industry	Impact drills Impact wrenches
	Foundries	Sandblasters Rammers for moulding
	Stone processing (chiselling) Rust and painting removal Engineering industry (percussion processing on metals)	Chipping hammers and scalers Hammers for corner breaking, shaping, riveting, flanging Shears and nibblers for metal
Rotary tools	Engineering industry Stone processing Wood	Orbital and random orbital sanders Circular saws and jig saws Angle and axial grinders Light duty straight grinders Rotary tools for deburring
	Foundry	Circular saw, miter saw for degating Portable grinding wheel for deburring
	Agricultural and forestry works	Chain saws, debarker
Other machines	Construction	Concrete compactors (needle vibrators or vibrator plates)
	Pallets Wood	Nailing machines
	Engineering industry Stone processing (fettling, polishing)	Rotating shaping machines with flexible shaft
	Stone processing (porphyry)	Cubing machines
	Agricultural, forestry and gardening works	Motor-cultivators Brush-cutters Shakers for hanging fruit (e.g. olives) Lawnmowers
	Shoe factories	Riveting machines
	Health care	Dentist's drills, orthopaedic saw

Table 3. Most common vibratory hand-held or hand-guided machines and application sectors.

3 Reducing vibration risk: interventions at source and additional solutions

The manufacturer's approach to preventing risks due to vibration emission must take into account the principles of safety integration [European Commission, 2017] and consequently:

1. the first priority is to reduce the generation of vibrations of products *at source* by acting on design phase and production processes;
2. the second priority is to introduce integrated protective measures, such as isolating and damping systems able to prevent or reduce the transmission of vibrations;
3. the third priority is to inform the final user about the residual vibration emission, so that they may take the necessary protective measures.

Subsequently, the final user (employer) can act further on the vibratory risk by:

i. favouring low vibratory machinery when updating the machinery fleet;
ii. introducing organizational measures, alternative or complementary to technical interventions on the machine, in order to control exposure (e.g. reorganization of the working tasks);
iii. in parallel, checking if lacking or limited maintenance could be – even partially – the cause of malfunctions and subsequent increment in vibration emission. Regular servicing can often help keeping vibration magnitudes down to the minimum [European Commission, 2008].

It should be noted that in general an optimal solution could be to eliminate the vibratory risks completely by substituting the existing processes with non-dangerous ones [CEN, 2016], but this may not be easily feasible in all cases.

The present work is mainly dedicated to point 1), 2) and i) of the lists above.

If the complete updating of a plant's machinery fleet is too complex or expensive, employers may sometimes prefer to act on the reduction of exposure times. From their point of view, indeed, the reduction of *A(8)* under the limits imposed by Directive 2002/44/EC is the main goal to be reached.

A machine manufacturer's point of view can be different, since they do not have exact limits to respect, but they must reduce the vibrations emitted to the lowest level anyway, by taking into account technical progress and means available for vibration reduction, in particular at source [European Parliament and Council, 2006]. In this way, they also acquire a better position on the market, compared to competitors.

For these reasons, in the present study the expression "low-vibrations machines" – as well as similar ones - must not be interpreted as referring to exact threshold vibratory values henceforth; rather, it refers to the vibratory values that could reasonably be reached by applying widely accepted technical rules or guidelines, while taking into account other comparative existing vibratory data too, compatibly with the marketing strategy of the company being considered.

The multi-criteria analysis that will be applied in Chapter 5 to an industrial case study matches the target of balancing costs and benefits perfectly.

3.1 Safety by design: technical solutions

In many cases, manufacturers decide to minimize the vibration emission of their machines *at source*, during the design phase, in a so-called "safety by design" approach, in order to offer costumers a product with reduced emitted (and transmitted) vibrations, according to the "Machinery Directive".

From a general point of view, the scientific "good practice" would suggest to address the problem through a dedicated research phase, based for example on experimental measurements, computational and lumped-mass models and test benches [Rempel et al., 2017; Neugebauer et al., 2010]. In many practical cases, however, such or similar analyses are hardly achievable, mainly due to cost and time constraints. The manufacturer can anyway adopt some general technical solutions which are already available in the industrial practice or suggested by international standards and guidelines. They will be detailed in the following paragraphs, distinguishing between fixed and hand-held machines.

3.1.1 Fixed machines

General specifications for the isolation of sources of vibration in fixed machines are given in standard UNI EN 1299:2009 [UNI, 2009], which offers guidelines to ensure that manufacturers provide users with useful and sufficient information for vibration isolation, in order to reduce all risks connected to vibrations that are generated by their machinery. In particular, the following typologies of passive isolation elements (which can be even combined) are suggested in UNI EN 1299:2009:

- springs (made of elastomeric material, or metal, or “air springs” constituted by a closed gas filled volume with elastic sides);
- dampers (such as friction dampers, liquid dampers or liquid viscous dampers), which limit the movement of elastically supported systems, for example while passing through resonances.

Active systems such as dynamic vibration absorbers and tuned mass dampers can also be used, though they are not covered by UNI EN 1299:2009.
However, possible solutions must be always "calculated" on the basis of specific type of machine [Chehab and El Naggar, 2003], also due to the importance of avoiding incurring resonances. Moreover, when designing or choosing the insulation system for a fixed machine (for example a press), it is fundamental to accompany the evaluation of the insulation efficiency with an assessment of the overall stability of the final machine [Salvetti, 2000].
It is important to note that Paragraph 1.7.4.2 (point *j*) of the Machinery Directive explicitly refers to the specific aspect of noise or vibration emission reduction in relation to installation and assembly instructions. Each Instruction Manual must indeed contain, where applicable, instructions relating to installation and assembly for reducing noise or vibration, including, for example, specifications for foundations with adequate damping characteristics.
Similar technical solutions can be applied to several industrial sectors, depending on the specific application, as has been verified by accessing the sources previously listed in Par. 2.2. Details about some specific production contexts are presented hereafter.
Hammer mills for rubble, used in constructions, for example, often do not rest on a proper floor but on unstable supports (such as soil just moved), and their weight associated with the vibrations could determine their sinking or even overturning despite precautions. In these cases, anti-vibration mounts can be an engineering solution to elastically isolate these machines and dissipate vibrations, including those produced by other equipment.
Hammer mills are used in the ceramics field too, for example in the production of cotto tiles, and they must be placed on isolated ground with suitable anti-vibration mass.
In the footwear sector (e.g. eyeleting machines), anti-vibration systems are applied under the base of the machines and in individual work stations.
In steelworks, the ingot mould is constantly subject to oscillations through the oscillating bench, because this favors the flow of steel and avoids gluing on the mould’s inner walls. This movement causes possible exposure of operators to vibrations. However, in the most modern steelwork plants the presence of operators is generally limited to critical phases, and to control and surveillance.

In foundries, the transmission of vibrations to the foundation is often too high in vibratory conveyors for shake-out. In this case a single-stage vibration isolation system of the conveyor can be ineffective and a significant reduction in vibration transmission can be achieved by implementing a passive two-stage vibration isolation system. It is also important to ensure that the stiffness of the supporting structure is minimum 10 times greater than the total stiffness of the vibration isolation system [Fiebig and Wróbel, 2017].
Anti-vibration devices are typically applied under the base of machine tools too (lathes, milling machines, ...), especially the numerically controlled ones, which can also produce strong noise.
Mechanical and hydraulic presses are also known as possible source of harmful effects caused by break through shocks, especially if working at high speed on rather thick mechanical pieces. In addition to the huge discomfort for press operators, fatigue cracks in the press components and premature wear in tooling can arise too. Any balancing of moving masses is generally not advisable, since it would be not very effective due to the enormous impact force. In order to reduce vibration transmission, presses can be oversized, usually with an over tonnage of 50% mass for continuous blanking and punching of high strength materials, and/or equipped with cushions or hydraulic shock dampers, which can absorb the shock energy partially [Ghiotti et al., 2010].

3.1.2 Hand-held machines

In the case of hand-held machines, in industrial practice several technical practical solutions are available to reduce HAV exposure, with general validity for all the machines involved. Some of them are recommended by documents produced by the European Commission [European Commission, 2008], but several feasible ways in which possible hand-arm vibration hazard, associated with hand-held, hand-guided and other machinery, may be reduced by machinery design is given by UNI/TR 11232-1:2007 [UNI, 2007], recently withdrawn (on December 14th, 2017), but anyway based on the currently valid international standard CEN CR 1030-1:1995 [CEN, 1995]. More recently, the CEN/TR 1030-2:2016 standard [CEN, 2016], also including management arrangements to minimize the risk of vibration exposure, has completed the scenario.
In particular, UNI/TR 11232-1:2007 covers four principal aspects of the reduction of the effects arising from exposure to hazardous machinery vibrations: (i) reduction of vibration magnitude at the source from which the vibration is generated; (ii) reduction of vibration transmission from the source to handles and other surfaces in contact with the hands; (iii) reduction of vibration transmission from the grips or handles of the machine to the operator's hand-arm system through ergonomic design measures; (iv) thermal design to optimise hand temperature.
In many cases, the use of jigs (and similar aids incorporating anti-vibration mounts) allows avoiding the need to hold vibrating surfaces; similarly, , the use of pedestal machines (possibly with support brackets directly connected to the floor rather than to the machine), or tension chains and manipulators to support vibrating tools, can be suggested for very heavy work pieces especially [European Commission, 2008].
However, other solutions must be found when the machine is to be held by hand. In the present paper, they have been divided into six groups (*a* to *f*) matching the concepts expressed in the standards mentioned above, but re-organized into a classification that is specifically thought for simplifying the use of the analysis framework presented in Chapter 4.
Such groups of solutions are detailed hereunder.

a. Insertion of anti-vibration systems

It can be useful to try to decouple the various machine components from the dynamic point of view, by interrupting vibration transmission along the path between vibration sources and handles or hand-held point. Isolating measures include the introduction of metal or elastomeric springs, or friction, liquid or gas dampers, combinations of springs and dampers and rubber components in general. Sometimes (e.g. chipping hammers) the vibration could be reduced by using compressed air too (in combination with springs) in order to isolate the tool body from the impacting parts. In specific cases, a Tuned Vibration Absorber (TVA) can be used [Hao and Ripin, 2013]: it consists in a secondary mass-spring-damper system which can be externally added to the already existing machine and that allows vibration reduction - in a narrow frequency range - through a suitable selection of its physical parameters, by channelling the vibration energy to a secondary system.

An anti-vibration system can also be applied on the vibration source directly, for example by acting on the engine mounting system.

Insulated (suspended) handles can be another useful instrument to reduce vibrations, but the handle dynamics influences the vibration transmissibility of the handle-isolation system, so the final user must choose them accurately, usually following suggestions given by the tool manufacturer, since their incorrect use (for example in an unsuitable frequency range) can even increase vibration at the hand. Moreover, in practical use, their effectiveness can be lower than expected because of constantly changing working conditions (e.g. frequent shut-off and power-on processes) [UNI, 2013]. In some cases, they can even worsen the machine's drivability at low frequencies, if their softness is excessive, so their use must always be preceded by a careful evaluation of their optimal stiffness. It can be observed, finally, that inserting anti-vibration systems can produce an increment in the machine weight that must be minimized anyway, since it can (i) worsen the effects of vibration exposure, (ii) interfere with the drivability of the machine, and even (iii) produce an unexpected vibration increment due to the subsequent greater gripping forces.

b. Changes to machine mechanics

Applying substantial modifications to the machine mechanics during the design phase could produce a significant reduction in emitted vibrations.

In particular, balancing of rotating or reciprocating parts can be obtained, for example, by introducing counter-rotating masses, lightening some moving parts or – e.g. for internal combustion engines – by switching from single-cylinder to multi-cylinders engines. Whole supplementary systems or similar solutions can also be added. Similarly, changes in the mechanisms of transmission of forces can be applied, for example by using belt drives instead of gear or chain drives (mainly on machines on tyres, such as tillers), or by substituting straight gears with helical gears.

c. Changes to geometry and/or materials of handles

Wrapping rubber or other resilient materials (e.g. viscoelastic polymers) can be put around vibrating handles with a subsequent improvement in comfort, even if a smaller reduction can

be generally observed in actual health risk. Their effectiveness is generally limited to frequencies above 200 Hz.
In addition, applying changes to texture and material of the grip surface can significantly reduce the gripping or pushing forces exerted through the hand (to support the tool or work piece, to control or guide the machine, or to achieve high working rates), thereby producing a reduction in vibration transmission. Similarly, the geometry of handles can be another important factor that can influence final vibration exposure.

d. Changes to geometry and/or materials of other components

In general, choosing materials that have high inherent damping characteristics can intuitively help in obtaining a general damping of vibrations along the machine, but a careful preliminary dynamical study of the machine and its components is always recommended, also to avoid a final reduction in the machine's efficiency.
Acting on materials, dimensions and boundary conditions of selected machine components during the design phase can help in optimally locating their resonance frequencies, moving them away from the excitation frequencies and therefore avoiding additional uncontrolled high-amplitude vibratory movements during the machine's functioning.

e. Implementation of strategies for producing/buying components with perfect feature repeatability

The efforts made by designers to obtain low-vibrations hand-held machines can be partially thwarted by possible shortcomings of the quality control system along the company production line (for internally produced components) or in the component choice criteria (for externally bought components). For example, components can be affected by non-repeatability of their main features due to inadequate quality checks as well as bad manufacturing tolerance, which can also produce eccentric masses (with unwanted unbalances and vibrations). Consequently, the production strategy of the company should take these aspects into account, by – at least - evaluating costs and benefits of preferring high-quality components, in order to ensure that the final product really corresponds to the one designed, even in terms of emitted vibrations.

f. Changes to expected conditions of use for workers

In the Instructions Manual the manufacturer generally describes how the final users must handle the portable machine and how they can manage its functioning in order to reach the desired goal in terms of mechanical processing. Consequently, the manufacturer can also help in reducing the final exposure of the workers to vibrations by specifying, for example, the optimal positions for hands or for the machine (working angle, etc.).
In parallel, solutions able to reduce the impact of the machine weight on the worker can be useful whenever possible, since additional loads generally contribute to increasing the negative effects of vibrations on human health. In this sense, back-pack type machines can contribute to reducing the global negative effects of HAV vibrations on the human body, even if their positive effect is generally evaluated only in terms of perceived comfort for the operator. Moreover, back-pack solutions can introduce an additional WBV risk, which is

usually neglected (or even not known), since there is currently no test method for vibrations transmitted to the operator's body, consequently no reference values either.

It could be also possible to thermally design machines against the effects of cold, since low temperatures are well-known as possible cause of worsening of the negative effects of HAV on the functionality of the hand-arm system. Warmed handles or poorly dissipative materials can be adopted when extreme environmental conditions are expected, as also suggested by UNI/TR 11232-1:2007, but they do not represent a technical solution which is able to reduce vibration emission, because they only reduce the negative effects of actual vibrations on the human body.
Similarly, the use of personal protective equipment, such as anti-vibration gloves, reduces the final exposure but is not a solution acting on vibrations *at source*.
For these reasons, only the six families of technical solutions listed above (*a* to *f*) will be taken into account in the present paper as possible instruments to reduce vibration exposure. In particular, in Chapter 5, they will be re-analysed for a specific case study and will constitute the possible alternatives for a dedicated multi-criteria analysis.

3.2 Safety by machine selection

In Italy, the above-mentioned "Consolidated Act on health and safety at work" states that the employer can assess the level of exposure to mechanical vibrations by observing the specific working conditions and subsequently referring to relevant information on possible vibration level for such equipment (or equipment typologies) in the particular conditions of use which Italian authorized databases - or, alternatively, information given by the manufacturer - specify. Consequently, an optimal machines selection typically goes through a careful analysis of such two official assessment instruments, as will be detailed in the following paragraphs.
In particular, by such data the final user can compare different manufacturers' models of the same class of machinery and identify different possible vibrational emissions, as well as the typical range of vibration values for normal use of a machine.
In case of non-applicability of the above-mentioned instruments (due to lack of machine maintenance, discrepancy in operative conditions, excessive differences between machine models, etc.), the reference method is still represented by experimental measurements to be performed by applying the international standard cited above [UNI, 2004].
It must be also observed that, in some cases, the "machine" taken into consideration is actually an "assembly" [European Commission, 2017]; in a production line, for example, an assembly of machinery may be constituted by two units such as a packaging machine and a labelling machine. In such cases, the concept of "safety by machine selection" becomes "safety by component selection", since every assembly can be thought of as a whole "machine" that is constituted by several "components" which are machines themselves. Whoever needs to introduce a new machine into the assembly line must pay particular attention to any hazard which may ensue [HSE, 2011b].

3.2.1 Use of data provided by manufacturers

In the specific case of hand-held and hand-guided machinery, in accordance with UNI EN 12096:1999 [UNI, 1999] and pursuant the general regulations set out in the Machinery Directive, the Instructions provided by manufacturers must show:

- the vibration total value *a* to which the hand-arm system is subjected, if it exceeds 2.5 m/s^2 (where this value does not exceed 2.5 m/s^2, this must be mentioned);
- the uncertainty of measurement *K*;

where the maximum achievable emission is $a+K$ [m/s^2].
Uncertainty is a parameter associated with the result of the measurement that characterizes the dispersion of the values that can reasonably be attributed to the physical quantity to be measured, for example due to the low repeatability of the measurement and especially, in case of lots, to variations in the production.
The values of *a* and *K* must be either the ones actually measured for the machinery in question or the ones established on the basis of measurements taken for technically comparable machinery; where harmonised standards (which generally guarantee a high level of data repeatability and reproducibility) are not applied, the vibration must be measured using the most appropriate measurement code for the machinery concerned. It is necessary to specify the existing operating conditions during measurements and the measurement codes applied. The lower the level of vibration emission from the machinery, the easier it is for users to respect the exposure limits set by Directive 2002/44/EC. Users thus have an interest in selecting machinery with as low vibration emission as possible for the performance required.
In the case of machines entering the European market before 2006 (when the most recent version of the Machinery Directive came into force), the vibration data declarations were issued according to pre-existing international standards, so they do not follow the new reference measuring methods, established by new specific standards for some machine categories and – generically – by UNI EN ISO 20643:2012 [UNI, 2012a], which are gradually substituting the older ones. In particular:

- measurements must currently be performed on three axes (while old data generally present one value only), in all the positions occupied by the hands, providing values representative of the upper quartile of vibration total values of the machines in their intended use;
- vibrations must be evaluated in realistic operative conditions, also representing the highest values reachable during real use.

In cases when old standards are still applied on hand-held power tools and hand-guided machines instead, the emission values declared should be interpreted following the indications given by UNI CEN/TR 15350:2013 [UNI, 2013]. This Technical Report clarifies the strategy to be used to understand if the value provided by the manufacturer in the machine's Instructions ("*a*") is a single-axis value or comes from a combination of measurements on three axes instead. This latter case is generally reported as "vibration total value" or "triaxial vibration value" or by *ahv* combined with uncertainty *K*. In all other cases, the value shall be considered a single-axis value *ahw* [UNI, 2004] (generally measured in the direction of vibration believed to be dominant) and

uncertainty K can be estimated according to the criteria included in the previously mentioned UNI EN 12096:1999.
When old standards are still applied and are explicitly named by the manufacturer, CEN/TR 15350:2013 helps make a rough estimate of the equivalent vibration total value. For example, some correction factors (in the range 1.0-1.7) can be applied if measurements have been performed on one axis only (applying old standards), and can be included in one of the four individual families of machinery (electric machines, pneumatic machines, machines with internal combustion engine, hydraulic machines) listed in Annexes E to H. For each of them, Table 4 reports the list of old/new standards that can be cited in the Instructions. It should be noted that, in case of machines with internal combustion engine, many standards (all distinguishing between different operating modes such as idling, rated speed, nominal maximum speed, full load) are cited in Annex G and no correction factor is generally suggested, excluding machines that are not listed in Annex G and for which a single-axis value only is declared: in such case, a correction factor of at least 1.5 must be applied. For this reason, Table 4 only shows the standard applicable to grass-trimmers and brush-cutters, which will be the specific object of study in Chapter 5.

	Old standards	New standards
Electric machines	EN 50144 First edition of EN 60745 (prior to 2007)	EN 60745 (starting from 2007)
Pneumatic machines	EN ISO 8662 (EN 28862)	EN ISO 28927
Machines with internal combustion engine (grass-trimmers and brush-cutters)	/	EN ISO 22867
Hydraulic machines	EN ISO 8662 (EN 28862)	EN ISO 28927

Table 4. Old and new standards for vibration assessment for four families of machines (as reported by CEN/TR 15350)

Nevertheless, a recent study [Brocal et al., 2018] has underlined that there is still a strong need for further clarification of the calculation methodologies suggested by CEN/TR 15350:2013. In particular, the study highlights that some misinterpretation can arise while evaluating how to apply the correction factors and proposes an amended methodology, pointing out that correction factors, if necessary, can be applied also to vibration data obtained following the new standards too (i.e., even in the case of triaxial measurements), and that there is no clear distinction between triaxial and uniaxial measurements cases in CEN/TR 15350 for machines not explicitly cited, causing ambiguities in the analysis.
Moreover, other investigators have shown that, in general, the manufacturers' declared values underestimate the workplace vibration emission, whereas the multiplication factors given in CEN/TR 15350 overestimate the workplace vibration emission of hand-held power tools typically found in the construction industry [Rimell et al., 2008].

3.2.2 Use of databases

The Italian National Vibration Database, set up in 2005 and available online on the Physical Agents Portal (PAF) [INAIL et al., 2018], was established by INAIL in collaboration with Tuscany Region, the National Health Service Prevention Departments of "USL Siena" and "USL Modena", and is continuously updated. It contains vibrational emission data for hundreds of machines (almost 2,800 machines in the HAV section of the portal and 1,100 machines in the WBV section), and consists in the manufacturer's as well as experimental data obtained for various operating conditions of the machinery in compliance with standard measurement protocols.

In Italy, the INAIL database is the instrument recommended for vibration assessment [Italian Government, 2008] and can be accessed separately for evaluating HAV or WBV exposure risk, but the latter category, however, is not taken into consideration in the present study.

A technical data sheet is present for each machine in the database section dedicated to HAV. It contains the main construction characteristics such as manufacturer's name, model, type of power supply, power, weight, a picture of the machine, and two types of vibration exposure data:

A. the emission values declared by the manufacturer according to the Machinery Directive (if available);
B. the vibration values measured in the field in accordance with specific international measurement standards (if available), for different operative conditions.

In case A, if the machine was produced before the enforcement of the new certification standards and therefore of UNI EN ISO 20643:2012, the manufacturers generally declares a single vibration emission value only by referring to the old standard itself. The Database reports this value and possibly the multiplicative correction factor to be applied, provided by CEN/TR 15350:2013 (as detailed in Paragraph 3.2.1.). When new standards have been applied by the manufacturer, instead, the Database reports the vibration value measured along three orthogonal axes, the uncertainty of the measurement and the operating conditions during the measurement. Consequently, value *A(8)*, to be used for vibration risk assessment, can be calculated starting from the sum of the mean value and the uncertainty declared by the manufacturer for each of the operating conditions reported in the Instructions Manual.

In case B, the Database contains vibration exposure values measured in the field by a specific referent for different machines under different operating conditions, in accordance with the measurement protocols set by UNI EN ISO 5349-1:2004 and UNI EN ISO 5349-2:2015 [UNI, 2015]. A summary table containing the average weighted values resulting from field measurements on the three measurement axes and the related standard deviations is available for each machine. The average value of the vector sum is also shown for every measurement, together with the extended uncertainty (i.e., standard deviation multiplied by 1.645), to be used for the final calculation of *A(8)*.

However, it should be noted [Monica et al., 2008] that difficulties often arise when using databases, namely:

- it is not always possible to find the data about a specific machine in the database (same manufacturer/model), although this problem has been progressively reduced in time;
- the information contained in the database (field measurements) can only be considered reliable for the machine tools and vehicles examined under the same operating, use and maintenance conditions (if not, new experimental measurements must be performed).

At the same time, the use of databases offers many advantages when trying to select the best machine in terms of vibration emission, since:

- databases allow obtaining easily the vibration values emitted by machines, both the certification values and the ones obtained experimentally under standard operating conditions, thus saving time and resources, also because the certification values are not always specified in the catalogues, but in the technical manual accompanying the machinery only after purchase;
- although in some cases the data provided by the manufacturer might underestimate exposure values under actual operating conditions, databases still allow identification of the lowest-vibration machines by comparison between different models;
- when data on the same type of machine tool/equipment indicate that the vibration values exceed a reference maximum threshold significantly (e.g. rock hammer drills with no shock-absorbers), direct measurements are superfluous, as the information available has already shown the high degree of hazard intrinsic to the type of machine.

4 Framework for component design in hand-held machines

When companies need to select machines (or machine components) in order to reduce transmission of vibrations to workers, the importance of combining such requirement with other internal business targets arises immediately. This is also true for machine manufacturers, since making "the best choice" indeed requires taking into account both costs and the machine's final performances too. For example, even when characterized by low vibration emission, a chipping hammer is required anyway to be able to reach a certain expected value of the energy/stroke ratio in its practical use [Nitti and De Santis, 2008]. In other words, many factors contribute to the choice of the optimal components and/or technical solutions in order to achieve the company objectives, with the aim of striking an even balance between work safety and productivity.
In this sense, multi-criteria analysis methods can be useful instruments when trying to make a good final choice while reaching multiple goals [Saaty, 2013]. This concept can apply to the machine optimal selection made by a final user (for example in the case of a complex plant owner) as well as to machines optimal design made by the machine manufacturer.
For the reasons mentioned above, attention in this paper focuses mainly on hand-held machines, that is on how manufacturers can apply AHP methodology in their optimal design of portable machines while minimizing vibration emission.

4.1 AHP methodology for multi-criteria decision analysis

Analytic Hierarchy Process (AHP) is a multi-criteria analysis method that allows to select one alternative from a given set where multiple decision criteria are involved, and to rank the alternatives available in a desirability order based on a rational framework of quantitative comparisons [Saaty, 1980].
AHP has been applied in many distinct sectors [Vaidya and Kumar, 2006] and, more specifically, even in the sectors of safety management and risk assessment [Cagno et al., 2003; Chan et al., 2004; Ha and Seong, 2004; Fera and Macchiaroli, 2010; Law et al., 2006]. It has also been used as a tool to select safety improvement strategies in spatial applications [Frank, 1995] and for the optimal selection of safeguards [Caputo et al., 2013].

In the present work, this classic method is applied for the first time to the specific case of designing hand-held machines with reduced vibratory emissions.
AHP is characterised by flexibility so that it can be integrated with different techniques such as Linear Programming, Quality Function Deployment, Fuzzy Logic. This enables the user to gain benefits from all the methods combined, thereby achieving the desired goal in a better way.
The AHP method applies the "decomposition and synthesis" approach, which mainly consists in three stages:

1. the development of a hierarchy structure;
2. the development of a pair-wise comparison matrix;
3. the method for calculating weights.

In this way, a complex decision may easily be represented if its factors are arranged into a hierarchical structure, with a certain number of levels ranging from the objective to the alternatives, and passing through the intermediate levels constituted by criteria and sub-criteria.
The hierarchy tree structure definition starts from the determination of the proposed goal, then criteria and sub-criteria are traditionally defined using group of experts [Saaty, 2006]; finally, the alternatives known a priori represent the leaves of the tree.
The methodology then forces the implementation of pair-wise comparisons of all the elements belonging to a certain level with the element of the upper level: the decision-making process starts by comparing the alternatives in relation to the criteria of the last level and the evaluation continues up to the criteria of the first level, which are then compared to the goal.
For each pair-wise comparison between n elements, in relation to a certain evaluation criterion, a n x n matrix of judgements a_{jk} can be obtained as follows:

$$A = \begin{pmatrix} 1 & \cdots & a_{1n} \\ \vdots & 1 & \vdots \\ \left(a_{n1} = 1/a_{1n}\right) & \cdots & 1 \end{pmatrix}. \qquad \text{Eq. (1)}$$

Each entry a_{jk} of matrix A represents the importance of the j_{th} element relative to the kth element; its value is equal to 1 when two alternatives have the same importance. Consequently, the diagonal elements of matrix A are equal to 1 and it is necessary to only fill the upper triangular matrix with judgements, since the lower triangular matrix can then be obtained by simply inserting the correspondent reciprocal values.
Afterwards, the principal eigenvector of matrix A needs to be calculated, for example by adopting the following approximated methodology [Saaty, 1980; Cabala, 2010]. First of all, a normalized pair-wise comparison matrix A_{norm} is derived from A by equalising the sum of the entries on each column to 1 and calculating each new term $a_{jk,norm}$ as:

$$a_{jk,norm} = a_{jk} / \sum_{j=1}^{n} a_{jk} \; . \qquad \text{Eq. (2)}$$

Then, a priority vector $\boldsymbol{w}$ (i.e. a n-dimensional column vector) is built by averaging the entries on each row of A_{norm} as follows:

$$\mathbf{w} = \left\{ w_1 \cdots w_j \cdots w_n \right\}^T , \qquad \text{Eq. (3)}$$

$$w_j = \left(\sum_{k=1}^{n} a_{jk,norm} \right) / n . \qquad \text{Eq. (4)}$$

Vector $\boldsymbol{w}$ also corresponds to the principal eigenvector of matrix A and, since it is normalized, the sum of all its elements is always 1. In this way, local priorities are computed for each pair-wise comparison, since a score w_j is assigned to each element considered: the higher the score, the better its performance in relation to the criterion considered.

By further applying this method along the complete bottom-up procedure (eventually including many sub-criteria), we derive a series of comparison (or decision) squared arrays with local priorities. They can be progressively multiplied by the priorities of the parent criterion, until the global priorities in relation to the goal are obtained, namely a priority vector that measures the relative degree of importance of all alternatives possible (the leaves).

This process allows: (i) obtaining values that weigh criteria; (ii) defining a ranking of the alternatives and identifying the best ones in relation to the target.

In order to be able to complete such procedure, it is necessary to establish a method to determine the intensity by which the elements of a certain level impact on each node in the upper level at the beginning. For this purpose, a sample of expert operators is generally interviewed in relation to the problem that needs to be solved. Each question should consider a group of alternatives in relation to the criteria in the level immediately above. In order to give a numerical judgement during such a qualitative assessment procedure, we must use a predetermined conversion scale. The 9-point scale proposed by Saaty [Saaty, 1980] reported in Table 5 can be used to translate linguistic judgments into numbers. The nine degrees derive from the human capability of comparing with a certain degree of consistency no more than nine different elements at a time.

Judgement	Score
Equal	1
Barely better	2
Weakly better	3
Moderately better	4
Definitely better	5
Strongly better	6
Very strongly better	7
Critically better	8
Absolutely better	9

Table 5. The conversion scale proposed by Saaty [Saaty, 1980] to be used in the qualitative assessment procedure.

Saaty also proposed the use of an Inconsistency Ratio (IR) to measure the correctness and the consistency of the above-mentioned pair-wise comparisons. Before determining an inconsistency measurement, the Consistency Index (CI) of an n x n matrix (of judgments) defined by the ratio must be introduced:

$$CI = \left(\lambda_{\max} - n\right) / \left(n - 1\right),\qquad \text{Eq. (5)}$$

where λ_{max} is the maximum eigenvalue of the matrix. Then, *IR* is defined as the ratio:

$$\mathrm{IR} = CI / RI,\qquad \text{Eq. (6)}$$

where *RI* is the Random Consistency Index, namely the corresponding average random value of *CI* for an $n \times n$ matrix. The judgments can be considered acceptable if and only if $IR \leq 0.1$, i.e. inconsistency cannot be more than 10% of the judgement itself.
Finally, a sensitivity analysis can be performed to investigate the consequences on the priority final ranking of the variation of the weights of single criteria. With the sensitivity analysis it is possible to (i) measure the robustness of the solution and (ii) determine the criteria that have more relevance on the final result.
The main advantages of using the AHP methodology are:

1. the hierarchical structure definition allows to understand all the variables involved and their relationship;
2. the decisional problem is represented in a structured way;
3. the method does not replace the personnel involved in the resolution process but integrates all the judgments with structured links;
4. from simple choice, the decision becomes process.

Moreover, this structured process is easy to be managed thanks to the availability of many dedicated software products on the market, such as *SuperDecisions*, free educational software that implements AHP (as well as the Analytic Network Process ANP) and was developed by the team of the above-mentioned creator of the method, Thomas Saaty. It has been used in the present paper in order to apply AHP method to the case study presented in Chapter 5.

4.2 AHP for optimal design of hand-held machines while reducing vibration emissions

The first fundamental step of AHP methodology consists in the development of the decisional structure. According to Saaty [Saaty, 2006], two constraints must be considered when determining the alternatives:

- the number of alternatives must be lower than nine for two reasons: (i) a simpler evaluation for the personnel who gives judgments, and (ii) computational efficiency;
- the alternatives must represent real cases.

Referring to the case of designing a generic hand-held machine including anti-vibration technical solutions, the six alternatives detailed in Paragraph 3.1.2 can be adopted, namely:

a) insertion of anti-vibration systems;
b) changes to machine mechanics;
c) changes to geometry and/or materials of handles;
d) changes to geometry and/or materials of other components;
e) implementation of strategies for producing/buying components with perfect feature repeatability;
f) changes to expected conditions of use for workers, including solutions for reducing weight impact.

In parallel, the following first level criteria have been adopted (based mainly on discussions between the authors and expert operators of the sectors potentially involved):

1) Costs
2) Health and safety
3) Machine efficiency
4) Compliance with other regulations

As far as ***Costs*** are concerned, several sub-criteria can be detailed. First of all, expenses generally derive from purchase of *components and raw materials* and from payment of *manpower work and training*. In particular, specific production processes could require operators with higher levels of specialization compared to standard workers. An additional cost is represented by the *design* phase, especially when the introduction of new technical solutions or the high-customization of the machine produced require preliminary phases of research, study and prototyping. The *storage* (of both final products and spare parts) is finally another non negligible cost factor.
As for ***Health and safety*** aspect, the main risks connected to the use of hand-held machines (accidents as well as professional diseases) are included in the AHP procedure adopted. They have been selected by analysing the safety requirements set by the harmonized standards related to the most important sectors of use of portable machines, as identifiable in the latest European official communication available on the subject [European Commission, 2018].
It emerged that *vibration*s and *noise* are commonly present risk factors; they have an intrinsic connection by nature, since vibrations typically produce noise, but the exposure is calculated on a lower and higher frequency range, respectively, so reducing vibrations does not necessarily produce an analogous reduction in the noise risk for workers, and vice versa.
Ergonomics is another fundamental aspect that must always be taken into account, since – for example – poor posture or lack of respect of the anthropometric factors (e.g. inadequate design or location of manual controls, or excessive weight of the tool) can have a negative effect on the workers' health, in terms of fatigue, onset of musculoskeletal pathologies, loss of control, and impediment to safe handling. Moreover, discomfort can also be produced, with subsequent possible impact on the demand for the machine by the market.
At the same time, *other concurrent risks* can be significant for hand-held machines, depending on the application sector, namely:

i. mechanical hazards (for example, cutting or severing of upper and lower extremities due to impact of ejected objects and movable parts, injuries from high-pressure fluid injection in case of presence of hydraulic and pneumatic systems);

ii. electrical hazards (for example, injuries from electric shock of the body or from touching the electrical parts of the ignition system in fastener driving tools operated through internal combustion);
iii. thermal hazards (for example, injury from burns and scalds from accidental contact, as with hot engine parts, or from radiation of heat sources; injuries due to being sprayed with hot fluids);
iv. material/substance hazards (for example, respiration problems through inhalation, or injuries to the skin from contact with dangerous gases, liquids, mists, fumes, dusts);
v. fire and explosion hazard (e.g., the use of oxygen or inflammable gases as energy for driving operations on compressed air operated tools);
vi. hazards caused by the energy supply (for example, for grinders, incorrect hydraulic fluid flow and outlet pressure, or unexpected return of energy supply after a breakdown);
vii. hazard caused by non-compliance with hygiene principles (for example, in the food processing sector, for operator as well as consumer safety);
viii. radiation hazard (for example, injuries due to direct or reflected laser beams, for hand-held laser processing devices).

In terms of ***Machine efficiency***, *the engine power performance* is fundamental, especially for heavy activities, where internal combustion engines are typically employed. The *adaptability* to different operational needs is another desirable feature, mainly related to the engine's ability to work in a large frequency range, depending on the application. The desired *machine efficiency level must also remain constant over an extended stretch of time* and this requirement is often guaranteed by a high *quality* manufacturing process, where production tolerance is kept within a predefined range. The usability of the machine, finally, is strictly related to its *drivability*, which is typically limited by excessive weight or stiffness of its components.
Finally, the ***Compliance with other regulations***, including mainly *electromagnetic compatibility (EMC)* and polluting *emissions*, is obviously another aspect that must be taken into account.
A general framework for AHP assessment has been obtained on the basis of the above and is reported in Table 6.

1st level criteria	Sub-criteria	Alternatives
1. Costs		a. Insertion of anti-vibration systems (springs, rubber components, Tuned Vibrations Absorbers, …)
	for components and materials	
	for manpower work and training	
	for design	
	for storage	
2. Health and Safety		b. Changes to machine mechanics (balancing with counter-rotating masses, changes in the mechanisms of transmission of forces, …)
	vibrations hazard	
	noise hazard	
	ergonomic hazard	
	other risks	c. Changes to geometry and/or materials of handles
3. Machine efficiency		
	drivability	
	product quality and good functionality over time	d. Changes to geometry and/or materials of other components
	engine performance (power, adaptability)	
4. Compliance with other regulations		e. Implementation of strategies for

	emissions (environmental impact)	producing/buying components with perfect feature repeatability
	electromagnetic compatibility	
		f. Changes in expected conditions of use for workers, including solutions for reducing weight impact

Table 6. Hierarchical structure developed for AHP analysis in designing a generic low-vibrations hand-held machine

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The weights for each criteria and sub-criteria must be assessed differently in each specific application, so they can vary significantly across case studies. In particular, in the following Chapter, the analysis will focus on a specific typology of hand-held machine: brush-cutters.

5 The case study: optimal design of brush-cutters with reduced vibration emission

An Italian company (Emak S.p.A.) whose business is in the sector of outdoor activities (gardening, forestry activity, agriculture) has been chosen as a case study to assess the occupational risk connected to the use of hand-held vibration equipment and evaluate possible solutions for vibration transmission reduction. Emak S.p.A. mainly produces grass-trimmers, brush-cutters, lawn mowers, hedge trimmers, chainsaws, tillers, but also pumps and high-pressure cleaning machines.

In this study, attention is focused on machines equipped with internal combustion engines, mainly two-stroke engines, since in most cases they present more significant vibration emission compared to the electric models. This difference is based on the engine typology,partially due to the fact that electric engines do not develop alternating motions inside, thanks to the rotation of the rotor; this was noticed by Emak S.p.A. technicians themselves when testing their portable machines, but has been also attested in literature. In particular, a recent Italian study [Leonardi et al., 2014] presents a detailed comparison between acoustic and vibratory emissions of some electric *versus* internal combustion portable machines, namely brush-cutters, hedge trimmers, blowers and chainsaws. Experimental measurements have shown that, in case of electric engines, accelerations (measured on the handles) are lower than in the case of petrol engines, excluding the case of blowers, which anyway generally shows limited accelerations. For other equipment, the vibratory difference can be significant, albeit variable, depending on the handle considered: a maximum reduction by 79%, 84% and 62% in *ahv* value (as defined in Chapter 2) has been observed in electric brush-cutters, hedge trimmers and chainsaws, respectively.

The case of portable harvesters for olives, widely used in the oil production sector, has been analysed in literature too [Catania et al., 2017]; in particular, a hook type harvester equipped with an internal combustion engine and an electric portable harvester have been compared in terms of vibratory emissions. Although the daily action value was exceeded in both cases, the *A(8)* values shown by the electric comb were approx half compared to the hook type (which showed almost 42 m/s^2 and 30 m/s^2 for right and left hand, respectively). However, in this case the comparison is less significant because not only is the typology of engine different, the whole machine has a different structure too.

Despite the disadvantage of a higher vibration emission, internal combustion machines still cover a substantial market share for all companies of the sector because they are more powerful (in proportion to mass), consequently have a wider range of action, especially in forestry activities, and have considerable autonomy, since simply adding fuel grant continuous use, without power cables that could be annoying, especially while working outdoors.
Since long-term good functionality of the main machine components (engines, in particular) must be guaranteed, Emak S.p.A. uses sound-proof equipped rooms for performance checks of machines and internal combustion engines at even high number of life-cycles (in harsher conditions than real cases, in order to obtain a 2 or 3-fold reduction in the cycle number and consequently test duration). Other small defects arising with time instead can easily be solved by the customer by substituting small parts. The technical quality of the products must however always be commensurate with all related economic aspects, with the aim of striking a satisfactory quality/cost balance.
In particular, brush-cutters have been chosen as the specific machine typology on which the decision-making approach described above is applied here. Indeed it can have a significant relevance to work safety, since large numbers of professionals and contract workers perform – for example - grass trimming jobs in the maintenance of parks and areas with undergrowth, including roadsides and railway tracks. Moreover, another significant part of the brush-cutters market is constituted by models that are intended for use by private citizens or farmers.
In general, Emak S.p.A. technicians have confirmed that the 1st and 2nd level criteria identified for an AHP approach, as listed and detailed in Paragraph 4.2, match the real company objectives; for this reason, they will be applied directly in Paragraph 5.2 in the analysis of the case study considered.

5.1 Brush-cutters: typical vibration exposure and technical solutions

Brush-cutters are petrol engine powered machines which use rotating nylon strings or metal heads to cut grass and shrubbery. Operators drive and hold them using handles that can have different geometries and locations.
The level of vibrations emitted and transmitted is generally not negligible and very variable, also depending on the final use typology (professional, semi-professional or DIY use). The workers involved in these activities are often private citizens or, in the case of business customers, contract workers, with little or no awareness of the effect of vibration on their health. The Italian National Vibration Database [INAIL et al., 2018] shows vibration values that go from almost 1.5 m/s^2 up to almost 16 m/s^2 for brush-cutters, referring to experimental data obtained by using the correct measurement system as defined by UNI EN ISO 22867 [UNI, 2012b]. Consequently, in the worst cases, the daily exposure value could exceed the action level for *A(8)*, but it should always be kept in mind that the above-mentioned exposure period *T* is often even shorter than half a working day, with a subsequent significant reduction in the global daily exposure value.
The EN ISO 11806-1:2011 [CEN, 2011a] harmonised standard for brush-cutters specifies that measures to reduce vibration *at source* should be adopted in particular, while evaluating their effect on actual vibration total values on each handle. It also points out that the main sources causing or influencing vibrations in brush-cutters are dynamic forces from the engine, cutting

means, unbalanced moving parts, impacts in gear sprockets, bearings and other mechanisms, as well as the interaction between operator, machine and material being worked.
The engine's fundamental frequency is typically the dominant component in the vibratory signals measured, together with some of its harmonics. In parallel to aerodynamics processes related to combustion, in the case of crank-piston mechanisms, the vibrations mainly occur because of backlash, mass unbalance, and also as a result of the piston hitting against the cylinder sliding surface [Figlus et al., 2013].
The second vibration source (in order of importance) at different frequencies is generally the rotating cutter head; its magnitude is small if compared with engine excitation [Patil, 2018].
The six general technical alternatives for vibration reduction in hand-held machines, as already detailed in Paragraph 3.1.2, are generally valid for brush-cutters, but some specifications and exclusions are necessary.
First of all, the isolation of the handle from the vibrating source by attenuating transmission along possible propagation paths is a feasible solution. It can consist in inserting rubber mounts between the handle and the source of excitation. The biggest challenge in designing rubber mounts is to make them statically stiff and dynamically soft. In general, their being too soft will cause large static displacement. This can be avoided by providing a mechanical stop or by installing rubber mounts in parallel [Hao et al., 2011]. This generally results in handles having large mass and little stiffness. It is therefore not advisable to insert excessive amounts of damping materials, since, especially if too soft, they can interfere with correct drivability of the machine. Moreover, the subsequent increment in the equipment's global weight could generate significant issues concerning ergonomics (difficulty in operator handling) and, to a lesser extent, also lower engine performance, especially for the smaller ones.
Handle geometry can vary significantly, especially due to the different types of handles available on the market (in particular, (i) loop handles and (ii) handlebars). For example, the possible resonance of handlebars, which can also have different lengths for different configurations, can influence vibrational behaviour significantly.
Handles must be also designed so that they can be fully gripped by the operator when wearing different types of gloves. It is also important to grant a secure grip through their shape and surface and a minimum hand grip length [Hao et al., 2011].
Changing material of the handles (steel, aluminium, polymer as Acrylonitrile Butadiene Styrene, etc.) also allows modifying their natural frequencies and therefore their final dynamic behaviour [Mallick, 2010]. In particular, in order to avoid resonance handles must be designed so that their natural frequency is distant from dominant frequencies.
Other changes can be applied to parts of the machine other than the handles. If a single string is used in the cutting head, substituting it with multiple strings can help reduce the effect of the subsequent unbalance. Resonance of some elements (e.g. handle pipe) can be also moved in terms of frequency by structurally modifying the components involved. Some constraints exist anyway: for example, the length of the brush-cutter rod cannot be changed significantly, since it must remain suitable for operators with different heights.
Hardness and placement of damping components along the machine can be optimized, too, as in the case of the rubber bushes which support the drive shaft in the pipe for the transmission of the engine power to the cutting blade [Okubo et al., 2014].

Theoretically, changes to the mechanics, for example introducing masses in order to balance or unbalance certain components and therefore obtain a global vibration reduction at the handle, can be another useful intervention in the design phase. In international research, for example, a recent attempt in this sense has been made by acting on the centrifugal clutch of a brush-cutter [Sugita et al., 2016], thereby obtaining a considerable reduction in handle vibration.

A reduction in vibration transmission can be also obtained by carefully selecting the optimum parameters for using the grass trimmer, such as hand-handle position, engine operating speed, length of nylon string and (minimally) sway angle [Mallick, 2008]. However, it could sometimes be difficult for the workers to adopt the optimum parameter suggested in the grass trimming operation since these parameters continue changing during operation (for example, operators generally change hand positions to relieve fatigue during their work).

A special note must be added in relation to the possibility of mounting a dynamic vibration absorber (TVA) on the source of vibrations, as hypothesized in Paragraph 3.1.2. Portable machines with internal combustion engine are generally designed to be used with an engine speed that is "around" the maximum power regime, but in practice the use regime can vary significantly, so technical solutions that operate in a limited frequency range (as TVA) might not be suitable for many of these applications. In the specific case of brush-cutters, the use of this solution is indeed often difficult, since their petrol engine can operate in a rather wide range, depending on grass density (for example it can vary from almost 6,000 to 10,000 r/min). Recent studies [Patil, 2018] have shown that an absorber can be effective (up to about 40% vibration reduction) for small speed ranges only (e.g. ±60 r/min over 7,250 r/min while cutting dense grass), otherwise the absorber resonance frequency needs to be changed.

At the same time, the engine operating frequency cannot be increased too much in an attempt to reduce exposure to vibrations, since this could produce excessive unwanted noise (see Par. 4.2).

Finally, it might be possible to give TVA adaptive capability by varying its stiffness, which is also known as adaptive TVA (ATVA), but this approach is complex, costly and not fully developed, nor is it applied on actual machines according to literature [Hao and Ripin, 2013].

Better results with classic TVA can be reached with lawn-cutters driven by an electric motor, whose speed can be kept relatively constant, but they are not considered in the present study.

Brush-cutters constitute an important market segment for Emak S.p.A., which produces almost 60-70 machine configurations (variable for engines, dimensions and, consequently dynamic behavior). In particular, three Emak S.p.A. brush-cutters have been selected by the authors (in agreement with the company technicians) as representative of professional, semi-professional and DIY models, respectively. Their vibrational levels and uncertainty values, as reported in the Instructions Manuals, are shown in Table 7, which distinguishes the cases of nylon strings or blades used as cutting heads. It can be observed that the vibration levels increase progressively while moving from professional models to DIY ones: this is due to the fact that the latter are designed for being used only a few tens of hours a year, so higher levels of vibrations are accepted on them because their cumulative effect on user health is expected to be very limited.

	Vibration level *a* [m/s²]				Uncertainty *K* [m/s²]			
	Nylon strings		Blade		Nylon strings		Blade	
	Left hand	Right hand	Left hand	Right hand	Left hand	Right hand	Left hand	Right hand
755 MASTER (professional model)	3.3	4.7	3.7	4.0	1.5	1.5	1.5	1.5
BC 350 S (semi-professional model)	5.5	5.2	5.2	4.6	2.5	1.1	1.3	1.1
DS 3000 S (DIY model)	6.3	5.4	5.1	4.5	2.4	2.4	2.0	2.0

Table 7. Vibration levels (weighted average values between ½ minimum rpm and ½ at full load (nylon strings) or ½ racing (blade)) and uncertainty values for three different Emak S.p.A. brush-cutter models as reported in their Instructions Manuals. Reference standards: EN 11806, EN 22867, EN 12096.

In many Emak S.p.A. machines, springs or rubber cylinders are used to dynamically separate handles (and the fuel tank, in the case of chainsaws) from the machine body so as to obtain vibration transmission reduction. Operational modal analysis and dedicated simulation codes are used to "calibrate" the possible anti-vibration solutions on every specific machine and, finally, to validate them. In the case of brush-cutters, different anti-vibrating systems (with specific features depending on the machine size) are applied, for example to reduce the vibrations transmitted in some models with handlebars, by adapting the machine ergonomics (handles, harness) to the typology of operator. In addition, self-lubricating anti-vibration bushes help ensure a smooth movement in the rod and minimize vibrations in transmission (since wear typically produces a huge increment in vibrations and only good maintenance – rarely carried out by users - could avoid it). Emak S.p.A. at the moment is not applying tuned vibration absorbers to its brush-cutters, according to the above-mentioned possible efficiency limitations; this is why TVAs are not included between the AHP alternatives for the case study considered, as presented in the following paragraph.

5.2 AHP methodology for design of low-vibrations brush-cutters

The AHP structure described in Paragraph 4.2 was applied to the specific case of brush-cutters, in order to identify the technical solutions most suitable to reduce their vibration emission at the design stage, while taking into account other important business goals.

Figure 2 shows the hierarchical structure obtained as implemented in *SuperDecision*s working environment. The expression "low-vibrations brush-cutters", reported in the caption, is not to be interpreted as referring to specific threshold vibratory values (see first part of Section 3). Emak S.p.A. in fact applies the EN ISO 11806-1:2011 standard, which only specifies that vibration reduction must be an integral part of the design process, and consequently suggests (i) following the technical rules and guidelines given by CEN CR 1030-1:1995 and (ii) obtaining information about comparative data on vibration levels of hand-held forestry machinery from ISO/TR 22521:2005 [ISO, 2005].

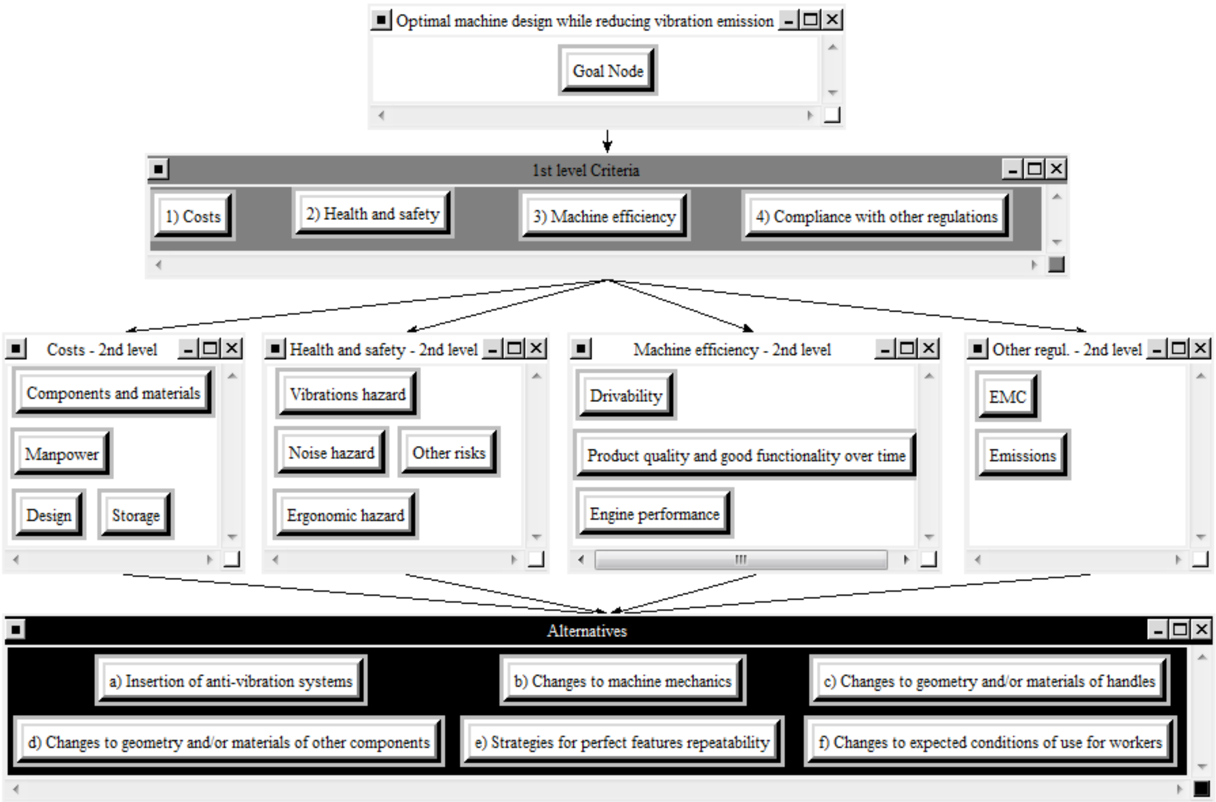

Figure 2. AHP hierarchical structure implemented for decision making in the design stage of low-vibrations brush-cutters.

Table 8 reports the pair-wise comparison concerning the 1st level criteria in relation to the main goal, adopting the judgment score shown in Table 5. The analyses were performed on the basis of the authors' expert opinion and educated guess for the specific case of brush-cutters, and relying on consultations with Emak S.p.A. industrial practitioners.

	Costs	**Health and safety**	**Machine efficiency**	**Compliance with other regulations**	**Calculated local priorities**
Costs	1	2	1/2	1/2	0.252
Health and safety	1/2	1	1/3	1/4	0.457
Machine efficiency	2	3	1	1/4	0.200
Compliance with other regulations	2	4	4	1	0.091

Table 8. Pair-wise comparison between 1st level criteria in relation to the main goal and calculated local priorities. IR is equal to 0.078.

Similarly, pair-wise comparison matrices between the alternatives and each 2nd level criterion, as well as between 2nd level criteria and each correspondent 1st level criterion are reported in Appendix A (Tables A.1-A.17).

Local priorities are shown for each matrix and IR values are also indicated in each figure caption. It should noted that IR is lower than 0.1 for all the pair-wise comparisons considered; the analysis is therefore to be considered consistent and the judgments congruent and reliable [Saaty, 2006]. For clarity Table 9 reports the whole hierarchical structure, including criteria and sub-criteria as well as alternatives, in particular specifying again (i) the calculated local priorities for the 1st level criteria in relation to the main goal (in bold), and (ii) the calculated local priorities for the 2nd level criteria with respect to each main criterion (in italics).

1st level criteria	Sub-criteria	Criteria priorities	Alternatives
1. Costs		**0.252**	a. Insertion of anti-vibration systems (springs, rubber components)
	for components and materials	*0.371*	
	for manpower work and training	*0.128*	
	for design	*0.422*	
	for storage	*0.079*	b. Changes to machine mechanics
2. Health and safety		**0.457**	
	vibrations hazard	*0.173*	
	noise hazard	*0.101*	c. Changes to geometry and/or materials of handles
	ergonomic hazard	*0.237*	
	other risks	*0.489*	d. Changes to geometry and/or materials of other components
3. Machine efficiency		**0.200**	
	drivability	*0.286*	
	product quality and good functionality over time	*0.143*	
	engine performance (power, adaptability)	*0.571*	e. Implementation of strategies for producing/buying components with perfect feature repeatability
4. Compliance with other regulations		**0.091**	
	emissions (environmental impact)	*0.667*	
	electromagnetic compatibility	*0.333*	
			f. Changes in expected conditions of use for workers, including solutions for reducing weight impact

Table 9. Main criteria priorities and alternatives in the AHP developed for the design stage of low-vibrations brush-cutters.

The global priority vector of different alternatives, as obtained from the global AHP weighted-hierarchical structure, was calculated starting from comparison matrices and local priority vectors and following the procedure detailed in Par.4.1. The values of its components, corresponding to the final ranking for the alternatives considered, are graphically reported in Figure 3.

The results point out that the preferable solution consists in the insertion of anti-vibration systems (29.2%), followed by changes to geometry and/or materials of handles (23.5%). The third preferable solution consists in implementing strategies for perfect feature repeatability (20.2%), followed by the application of changes to the expected conditions of use for workers (13.3%). Changes to other components (8.1%) and to machine mechanics (5.7%) are both at low levels.

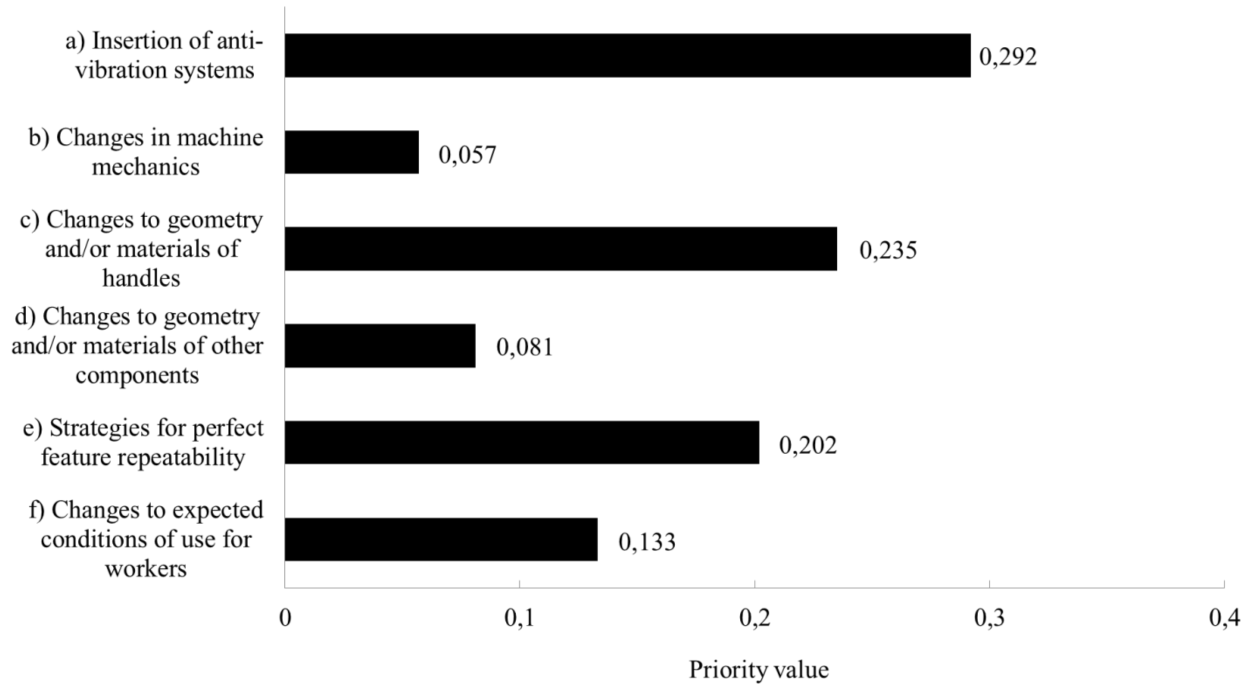

Figure 3. Results of AHP application when designing low-vibrations brush-cutters.

The robustness of the technique applied to potential shifts in priority of the different alternatives when designing a low-vibratorion-emission machine was then analysed by performing a sensitivity analysis on the 1st level criteria consisting in changing their local priority in relation to the main goal. The problem indeed lies in checking whether a few changes to the judgment evaluations can lead to significant modifications in the priority final ranking. For example, Figure 4 shows the result of the sensitivity analysis in relation to variations between 0 and 1 in the local priority obtained by the *Health and Safety* criterion.

It can be observed that, starting from the position identified for the case study considered (i.e. a local priority of the *Health and Safety* criterion equal to 0.457 - as reported in Table 9 - on the horizontal axis of Figure 4) and imagining an arbitrary variation in such value, alternatives *a)*, *c)* and *e)* maintain their initial ranking (as 1st, 2nd, 3rd position respectively) up to when the priority value decreases to 0.070 (where trend lines *a)* and *c)* intersect), or increases to 0.830 (where trend lines *e)* and *c)* intersect). This means that a variation in the global ranking is possible, but only for very significant variations in the local priority of the *Health and safety* criterion, which are not considered realistic in the present study. As for alternative *f)*, it has a decreasing trend in Figure 4, but it never intersects other lines, so its ranking (4th position) remains unchanged for all possible variations in the local priority of the *Health and safety* criterion, even though its calculated weight may vary. Alternatives *d)* e *b)* remain at lower values in the priority scale too, with almost parallel line trends and no change in priority ranking.

Similarly, even when considering a significant variation in the local priority for the *Compliance with other regulations* criterion in relation to the value that it has assumed in the case study considered, the sensitivity analysis showed that alternatives maintain their initial ranking positions (even though they progressively become closer as their priority increases).

While varying the local priority value of the *Machine efficiency* or *Costs* criterion, it was noticed that the lines of alternatives *c)* and *e)* intersect; however, the change in ranking positions can only occur in the presence of a significant (almost 50%) variation in the initial priority value for the criterion considered.

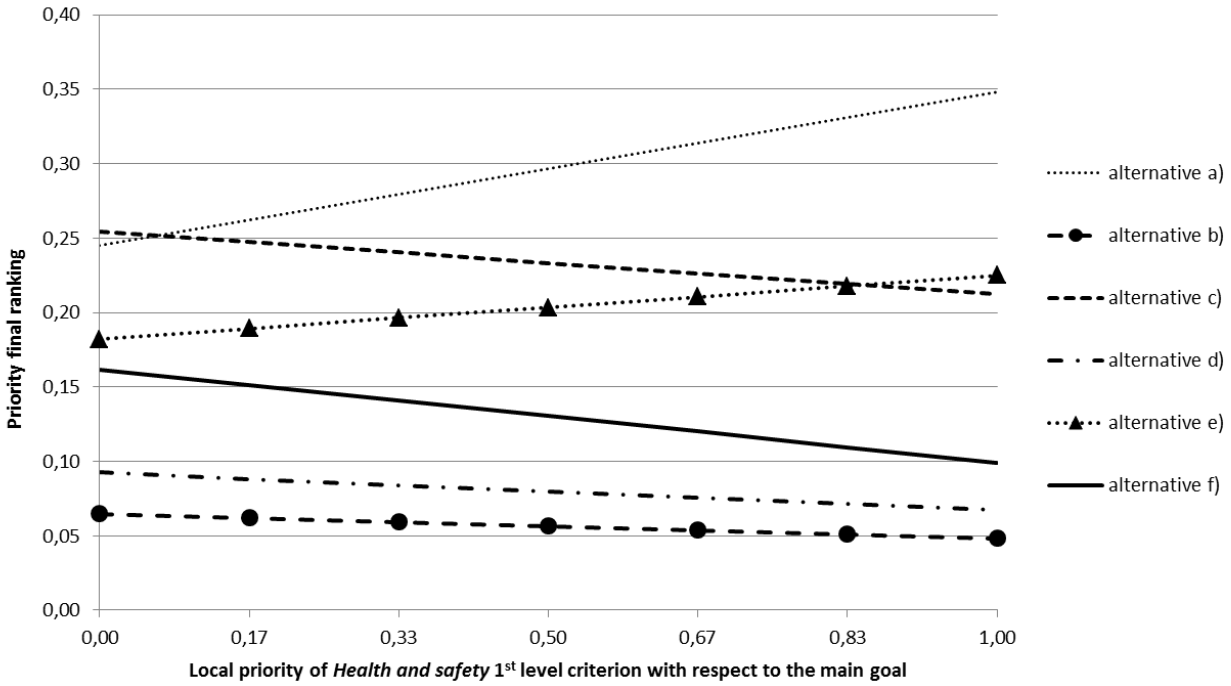

Figure 4. Sensitivity analysis in relation to the "Health andSafety " 1st level criterion.

Finally, it can be concluded that, for the four 1st level criteria assumed, the sensitivity analysis showed that the AHP model adopted displays good robustness.

6 Discussion and analysis of the results

Vibratory machines are currently widespread in the whole European context and they are also extremely diversified, since the same machine typology can be optimized to be adapted to specific sectors and activities, as the present study has detailed for the cases of fixed and portable machines. Several sub-sectors and activities involved have in fact been identified within the main productive contexts where vibration exposure is more significant (agriculture and forestry, industry, construction).

The present study has shown how a safer use of machines can be obtained by (i) a "safety by design" approach, which allows manufacturers to offer costumers a product with reduced emitted (and transmitted) vibrations, or (ii) an optimized choice of the machinery fleet by the employer, based on information about vibration levels provided by authorized databases or directly by the manufacturer.

The main aim of this research was to propose a multi-criteria approach for reducing HAV vibrations emission at the design stage of portable machines; such result was achieved in Chapter 4, where a hierarchical AHP structure was obtained by adopting four 1st level criteria (with relative sub-criteria) and six groups of possible technical alternatives. The implemented

framework was applied to the case study presented in Chapter 5, whose results match the conclusions and opinions that emerged from the company experts consulted.
However, a correct interpretation of the results requires taking into consideration some issues and limitations in mind. For example, the statistical representativeness of the data obtained can vary significantly depending on habits and strategies of the specific company considered. In literature, previous research [Chan et al., 2004] performed a variance analysis of the AHP pairwise comparisons obtained through questionnaires in three different types of construction enterprise and thereby identified similarities or differences in terms of "strategy towards safety".
In the present study, the scores in the AHP pairwise comparisons were assigned by taking into account the overall importance of the criterion (or alternative) considered in the design phase, despite the fact it sometimes does not coincide with the actual possibility of improvement that it can achieve through the design. For example, as for *Ergonomic hazard*, Emak S.p.A. typically applies the technical solutions suggested by the reference harmonized standard for the sector (EN ISO 11806-1:2011 [CEN, 2011a]), so further improving it during the design phase is not the main target during the development.
Moreover, some criteria achieved very different scores despite being regulated by binding European Directives of equal importance: for example, *Ergonomic hazard* obtained a higher score than *Vibrations hazard* and *Noise hazard*. Emak S.p.A. technicians have indeed underlined that in their experience bad ergonomics can prevent the operator from working even after just a few minutes (for example because of physical difficulties due to uncomfortable belts, or because of incorrect balancing that impede lateral movements of the machine), while even a medium-high level of vibrations does not render the activities immediately intolerable or ineffective. This aspect influenced the score assigned strongly.
As for acoustic safety, the use of personal protective equipment for this kind of machine is mandatory, so the minimization of noise in the design phase is less crucial than ergonomics for Emak S.p.A.
Similarly, the *Compliance with other regulations* priority is much lower than the *Health and Safety* priority, even though both are related to mandatory regulations. Emak S.p.A. engineers have highlighted that in the former case the manufacturer only needs the machine to be compliant with the standards, albeit at the limit of acceptability, and the certification of the product is only an added value. On the other hand, compliance with Health and Safety regulations is fundamental and must be enforced in this sector especially, if a company aims to preserve its workers' health.
In relation to the 2nd level criterion *Other risks*, it can be observed that not all hazards listed in Par. 4.2 were considered to be of equal importance in the considered case study. Mechanical risks were estimated in fact to be really significant (because of possible injuries due to knockbacks and cuts), while the risk related to hazardous substances for the operator (connected to possible respiration problems, according to EN ISO 11806-1:2011) was considered not very relevant. Indeed pollutant gas emissions have been considered here mainly in terms of environmental impact, especially since the machines considered are specifically devised for use in open-air environments only (as also indicated in the Instructions). EN ISO 11806-1:2011 only specifies that "the exhaust outlet shall be located such that it directs exhaust emissions away from the operator's face in normal working positions" [CEN, 2011a].
All the above-mentioned issues and observations confirm what was observed by other studies where the AHP technique was already applied in the field of occupational health and safety: AHP

ensures that decision parameters, priorities and judgments are explicit and consistent, but this does not produce a completely automated decision process. The decision maker has in fact full responsibility for establishing a subjective priority among decision factors, for example when the adequacy of safety elements (e.g. safeguards [Caputo et al., 2013]) must be assessed, together with the pair-wise preferences between different alternatives. This may affect the procedure's statistical representativeness, but does not nullify its usefulness.

A special note must be added about the high score achieved by alternative *a)* in relation to the *Engine performance* criterion (Table A.15): this solution is particularly effective in preventing the transmission of unwanted vibrations to the engine, where they could cause early wear of components and possible unbalance in the carburettor, with subsequent risk of engine seizure.

Finally, the results shown in Figure 3 (Global priorities) require some detailed comments, too.

In accordance with the judgements and comments made by Emak S.p.A. industrial practitioners, the alternatives with higher priority ranking (*a)* and *c)*) are the easiest, cheapest and most efficient solutions. However, the possible adverse effects of weight increment and/or excessive final softness must be assessed, quantified and limited, especially in terms of the machine's final drivability.

As for alternative *e)*, technicians have expressed their appreciation as a very useful instrument to guarantee greater certainty regarding the final vibrational behaviour of machines. Indeed, an important target for Emak S.p.A. is obtaining perfect repeatability of single component features (dimensions, roughness, weight, …) as much as possible and, consequently, perfect repeatability of every machine configuration. Internally produced components, as well as externally bought ones, can present qualitative dissimilarities that affect the machine's efficiency negatively or can render its performance extremely variable. After the identification of an optimal production tolerance range which guarantees correct functionality of components, it is fundamental to remain within such range, so as to avoid issues in performance as well as in safety (with subsequent customer dissatisfaction).

Regarding alternative *f)*, the calculated priority suggests that the machine's conditions of use for workers are fairly taken into account by the company, especially because they can influence ergonomics (as in the case of back-pack type machines).

Finally, a substantial action on the machine's mechanics, for example by adding whole supplementary systems or similar solutions – alternative *b)* – is considered to have excessive costs in terms of both time and money (for prototypes, moulds, etc.). Moreover, some solutions can often be counter-productive, since, for example, in the two-stroke engine, second-degree vibrations cannot be balanced, so unbalance is never completely compensated and undesired new resonance may occur at the same time. The latter risk often arises while modifying the geometry of components different from handles – alternative *d)* - in brush-cutters too.

Conclusions

A significant percentage of European workers is exposed to vibrations produced by tools or machines during working time, with consequent risks for health.

In the present work, the classic multi-criteria Analytic Hierarchy Process (AHP), already used in the past in other safety sectors, is applied for the first time to the specific case of designing hand-held machines with reduced hand-arm vibration emission. It is in fact proposed as a new useful instrument for companies to produce low-vibrations portable machines while striking a correct balance between work safety and productivity and, generally, between costs and benefits.

In particular, the proposed framework has been applied to the real context of an Italian company producing brush-cutters, and its consistence and robustness have been numerically verified in this specific case. The analysis has shown that the preferable solution for designing low-vibration brush-cutters – while satisfying the above-mentioned multiple criteria in the context of this specific company - consists in inserting anti-vibration systems (with 29.2% percentage ranking), while changes to geometry and/or materials of handles reach 23.5%. Another satisfactory solution is represented by the application of strategies for perfect feature repeatability (20.2%), while changes to the expected conditions of use for workers obtained lower ranking (13.3%). Finally, changes to other components (8.1%) and to machine mechanics (5.7%) appear to be the least suitable solutions.

Technical methodologies and regulations to be adopted while "safely designing" or "safely choosing" machines have also been detailed, starting from a preliminary description and analysis of the general industrial scenario where vibratory machines (fixed ones as well as portable ones) can be found.

The present research therefore intends to contribute to spreading the culture of safety among machines manufacturers, also by offering them practical evaluation instruments for implementation.

Future studies could extend the analysis to mobile machines or create an analogous AHP framework for vibration in fixed machines. The role of human error (e.g. lack of maintenance or incorrect use of machines) could be also an interesting object of further in-depth analysis.

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Appendix A. Additional AHP pair-wise comparison matrices.

	Components and materials	Manpower	Design	Storage	Calculated local priorities
Components and materials	1	1/3	1	1/4	0.371
Manpower	3	1	4	1/2	0.128
Design	1	1/4	1	1/5	0.422
Storage	4	2	5	1	0.079

Table A.1. Pair-wise comparison between 2nd level criteria in relation to "Costs" 1st level criterion and calculated local priorities. IR is equal to 0.012.

	Vibrations hazard	Noise hazard	Ergonomic hazard	Other risks	Calculated local priorities
Vibrations hazard	1	1/2	2	2	0.173
Noise hazard	2	1	3	3	0.101
Ergonomic hazard	1/2	1/3	1	4	0.237
Other risks	1/2	1/3	1/4	1	0.489

Table A.2. Pair-wise comparison between 2nd level criteria in relation to "Health and safety" 1st level criterion and calculated local priorities. IR is equal to 0.097.

	Drivability	Product quality and good functionality over time	Engine performance	Calculated local priorities
Drivability	1	1/2	2	0.286
Product quality and good functionality over time	2	1	4	0.143
Engine performance	1/2	1/4	1	0.571

Table A.3. Pair-wise comparison between 2nd level criteria in relation to "Machine efficiency" 1st level criterion and calculated local priorities. IR is equal to 0.000.

	EMC	Emissions	Calculated local priorities
EMC	1	2	0.333
Emissions	1/2	1	0.667

Table A.4. Pair-wise comparison between 2nd level criteria in relation to "Compliance with other regulations" 1st level criterion and calculated local priorities. IR is equal to 0.000.

	Alternative *a)*	Alternative *b)*	Alternative *c)*	Alternative *d)*	Alternative *e)*	Alternative *f)*	Calculated local priorities
Alternative *a)*	1	1/6	1	1/6	1/5	1/2	0.320
Alternative *b)*	6	1	6	2	4	3	0.040
Alternative *c)*	1	1/6	1	1/6	1/5	2	0.273
Alternative *d)*	6	1/2	6	1	4	2	0.055
Alternative *e)*	5	1/4	5	1/4	1	2	0.107
Alternative *f)*	2	1/3	1/2	1/2	1/2	1	0.205

Table A.5. Pair-wise comparison between alternatives in relation to "Components and materials" 2nd level criterion and calculated local priorities. IR is equal to 0.095.

	Alternative *a)*	**Alternative *b)***	**Alternative *c)***	**Alternative *d)***	**Alternative *e)***	**Alternative *f)***	**Calculated local priorities**
Alternative *a)*	1	1/6	1	1/6	1/5	1	0.2915
Alternative *b)*	6	1	6	2	4	4	0.039
Alternative *c)*	1	1/6	1	1/6	1/5	1	0.2915
Alternative *d)*	6	1/2	6	1	3	4	0.050
Alternative *e)*	5	1/4	5	1/3	1	3	0.095
Alternative *f)*	1	1/4	1	1/4	1/3	1	0.233

Table A.6. Pair-wise comparison between alternatives in relation to "Manpower" 2nd level criterion and calculated local priorities. IR is equal to 0.042.

	Alternative *a)*	**Alternative *b)***	**Alternative *c)***	**Alternative *d)***	**Alternative *e)***	**Alternative *f)***	**Calculated local priorities**
Alternative *a)*	1	1/6	3	1/6	1/5	2	0.218
Alternative *b)*	6	1	7	2	3	3	0.040
Alternative *c)*	1/3	1/7	1	1/7	1/5	1/2	0.394
Alternative *d)*	6	1/2	7	1	2	4	0.050
Alternative *e)*	5	1/3	5	1/2	1	3	0.077
Alternative *f)*	1/2	1/3	2	1/4	1/3	1	0.221

Table A.7. Pair-wise comparison between alternatives in relation to "Design" 2nd level criterion and calculated local priorities. IR is equal to 0.059.

	Alternative *a)*	**Alternative *b)***	**Alternative *c)***	**Alternative *d)***	**Alternative *e)***	**Alternative *f)***	**Calculated local priorities**
Alternative *a)*	1	1/5	1	1/5	1/4	1	0.276
Alternative *b)*	5	1	5	2	4	4	0.043
Alternative *c)*	1	1/5	1	1/5	1/4	1	0.276
Alternative *d)*	5	1/2	5	1	3	4	0.056

Alternative *e)*	4	1/4	4	1/3	1	3	0.107
Alternative *f)*	1	1/4	1	1/4	1/3	1	0.243

Table A.8. Pair-wise comparison between alternatives in relation to "Storage" 2nd level criterion and calculated local priorities. IR is equal to 0.037.

	Alternative *a)*	**Alternative *b)***	**Alternative *c)***	**Alternative *d)***	**Alternative *e)***	**Alternative *f)***	**Calculated local priorities**
Alternative *a)*	1	1/6	1/3	1/5	1/4	1/6	0.425
Alternative *b)*	6	1	5	3	4	2	0.039
Alternative *c)*	3	1/5	1	1/5	1/3	1/5	0.261
Alternative *d)*	5	1/3	5	1	4	1/2	0.074
Alternative *e)*	4	1/4	3	1/4	1	1/3	0.148
Alternative *f)*	6	1/2	5	2	3	1	0.053

Table A.9. Pair-wise comparison between alternatives in relation to "Vibrations hazard" 2nd level criterion and calculated local priorities. IR is equal to 0.066.

	Alternative *a)*	**Alternative *b)***	**Alternative *c)***	**Alternative *d)***	**Alternative *e)***	**Alternative *f)***	**Calculated local priorities**
Alternative *a)*	1	1/6	1/4	1/5	1/4	1/5	0.453
Alternative *b)*	6	1	4	3	4	2	0.043
Alternative *c)*	4	1/4	1	1/3	2	1/3	0.156
Alternative *d)*	5	1/3	3	1	3	2	0.070
Alternative *e)*	4	1/4	1/2	1/3	1	1/3	0.197
Alternative *f)*	5	1/2	3	1/2	3	1	0.081

Table A.10. Pair-wise comparison between alternatives in relation to "Noise hazard" 2nd level criterion and calculated local priorities. IR is equal to 0.056.

	Alternative *a)*	**Alternative *b)***	**Alternative *c)***	**Alternative *d)***	**Alternative *e)***	**Alternative *f)***	**Calculated local priorities**
Alternative *a)*	1	1/6	1/3	1/6	1/6	1/5	0.455
Alternative	6	1	5	3	1	3	0.045

b)							
Alternative *c)*	3	1/5	1	1/4	1/5	1/3	0.248
Alternative *d)*	6	1/3	4	1	1/3	2	0.089
Alternative *e)*	6	1	5	3	1	3	0.045
Alternative *f)*	5	1/3	3	1/2	1/3	1	0.118

Table A.11. Pair-wise comparison between alternatives in relation to "Ergonomic hazard" 2nd level criterion and calculated local priorities. IR is equal to 0.046.

	Alternative *a)*	**Alternative *b)***	**Alternative *c)***	**Alternative *d)***	**Alternative *e)***	**Alternative *f)***	**Calculated local priorities**
Alternative *a)*	1	1/4	1/2	1/4	2	1/3	0.248
Alternative *b)*	4	1	4	1	4	3	0.054
Alternative *c)*	2	1/4	1	1/4	3	1/3	0.189
Alternative *d)*	4	1	4	1	4	3	0.054
Alternative *e)*	1/2	1/4	1/3	1/4	1	1/3	0.345
Alternative *f)*	3	1/3	3	1/3	3	1	0.110

Table A.12. Pair-wise comparison between alternatives in relation to "Other risks" 2nd level criterion and calculated local priorities. IR is equal to 0.048.

	Alternative *a)*	**Alternative *b)***	**Alternative *c)***	**Alternative *d)***	**Alternative *e)***	**Alternative *f)***	**Calculated local priorities**
Alternative *a)*	1	2	3	1	3	1	0.088
Alternative *b)*	1/2	1	2	1/2	2	1/2	0.160
Alternative *c)*	1/3	1/2	1	1/3	2	1/3	0.249
Alternative *d)*	1	2	3	1	3	1	0.088
Alternative *e)*	1/3	1/2	1/2	1/3	1	1/4	0.332
Alternative *f)*	1	2	3	1	4	1	0.083

Table A.13. Pair-wise comparison between alternatives in relation to "Drivability" 2nd level criterion and calculated local priorities. IR is equal to 0.010.

	Alternative *a)*	Alternative *b)*	Alternative *c)*	Alternative *d)*	Alternative *e)*	Alternative *f)*	Calculated local priorities
Alternative *a)*	1	1/3	2	1	4	1/2	0.123
Alternative *b)*	3	1	4	3	5	3	0.047
Alternative *c)*	1/2	1/4	1	1/2	3	1/3	0.206
Alternative *d)*	1	1/3	2	1	4	1/2	0.123
Alternative *e)*	1/4	1/5	1/3	1/4	1	1/4	0.417
Alternative *f)*	2	1/3	3	2	4	1	0.084

Table A.14. Pair-wise comparison between alternatives in relation to "Product quality and good functionality over time" 2nd level criterion and calculated local priorities. IR is equal to 0.032.

	Alternative *a)*	Alternative *b)*	Alternative *c)*	Alternative *d)*	Alternative *e)*	Alternative *f)*	Calculated local priorities
Alternative *a)*	1	1/5	1/4	1/4	1/3	1/5	0.413
Alternative *b)*	5	1	4	3	4	2	0.045
Alternative *c)*	4	1/4	1	1/3	3	1/3	0.154
Alternative *d)*	4	1/3	3	1	3	1/2	0.092
Alternative *e)*	3	1/4	1/3	1/3	1	1/3	0.232
Alternative *f)*	5	1/2	3	2	3	1	0.064

Table A.15. Pair-wise comparison between alternatives in relation to "Engine performance" 2nd level criterion and calculated local priorities. IR is equal to 0.062.

	Alternative *a)*	Alternative *b)*	Alternative *c)*	Alternative *d)*	Alternative *e)*	Alternative *f)*	Calculated local priorities
Alternative *a)*	1	1	1	1	1	1	0.167
Alternative *b)*	1	1	1	1	1	1	0.167
Alternative *c)*	1	1	1	1	1	1	0.167
Alternative *d)*	1	1	1	1	1	1	0.167
Alternative *e)*	1	1	1	1	1	1	0.167
Alternative *f)*	1	1	1	1	1	1	0.167

Table A.16. Pair-wise comparison between alternatives in relation to "EMC" 2nd level criterion and calculated local priorities. IR is equal to 0.000.

	Alternative *a)*	**Alternative *b)***	**Alternative *c)***	**Alternative *d)***	**Alternative *e)***	**Alternative *f)***	**Calculated local priorities**
Alternative *a)*	1	1	3	3	3	3	0.072
Alternative *b)*	1	1	3	3	3	3	0.072
Alternative *c)*	1/3	1/3	1	1	1	1	0.214
Alternative *d)*	1/3	1/3	1	1	1	1	0.214
Alternative *e)*	1/3	1/3	1	1	1	1	0.214
Alternative *f)*	1/3	1/3	1	1	1	1	0.214

Table A.17. Pair-wise comparison between alternatives in relation to "Emissions" 2nd level criterion and calculated local priorities. IR is equal to 0.000.

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