Manuscript Details

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Abstract

Impact noise is increasingly becoming an important issue both in terms of technologies for its reduction and in terms of its perception inside buildings. In fact, a high level of noise clearly affects indoor comfort and liveability of confined spaces. For this reason, this study focuses on the influence which the screed static load has over time on the resilient material of a floating floor and on its final performance. Five different types of resilient materials have been tested for five years and the results are analysed in terms of material type, surface contact and thickness variation, dynamic stiffness measured on 8 different time steps and its application on 6 different bare floors. Obtained parameters values are therefore studied in terms of perceived comfort and compliance with 31 European countries regulations limits. Results clearly show that time has a paramount influence on all types of resilient materials (with the exception of one) in all configurations and that complete floor selection, in time, can greatly change perceived indoor living comfort and compliance with the limits imposed by laws.

Keywords	Dynamic stiffness; Regulation; Impact noise; creep; floating floor; comfort;
Taxonomy	Sound Transmission, Building Acoustics, Sound Insulation
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Submission Files Included in this PDF

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risposta ai reviewers 2.docx [Response to Reviewers]

CLEAN Comprehensive analysis V2.pdf [Manuscript File]

Fig.5-TG TS compact.tif [Figure]

Fig.5-TG TS fibrous.tif [Figure]

Fig.6-DTA RFF.tif [Figure]

Fig.6-STA RFF.tif [Figure]

fig.7 bis.tif [Figure]

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supplementary data.docx [Supporting File]

Research Data Related to this Submission

Data set https://data.mendeley.com/datasets/h3bxw5gpvs/draft?a=f57175ca-359f-4454-8707-5f70984d48a4

Data for: A comprehensive analysis of time influence on floating floors: effects on acoustic performance and occupants’ comfort

Researches Data used for the paper

A comprehensive analysis of time influence on floating floors: effects on acoustic performance and occupants' comfort

Dear Editor,

Hereafter we report our responses to reviewers' comments.

We thank them so much for their efforts, hoping to positively continue the verification procedure to a successfully ending!

Reviewer 1

Reviewer's comment	
The authors gave appropriate answers to all comments and improved requested informations .	Thank you very much for considering our paper!
Only the answer concerning point 3.4 didn't convince me (maybe it's about a misunderstanding). If You consider equation (11) to calculate frequency values of DL , this means that DL depends only on dynamic stiffness of resilient layer (and mass of top layer) and not on type of bare floor. Then DLw calculated according EN ISO 717-2 should be constant for the same resilient solution. It's evident that weigted impact sound pressure levels Lnw for different base floors with resilient layer are very different. Figure 10 shows DLw values with large differences for different base floors	Thank you for your comment. Ok, now your first comment is clearer. Thank you very much for your kind explanation. The DLw is not calculated DIRECTLY using equation 11. In fact we named it DLw,freq. With this term we wanted to distinguish the DLw from ISO 12354-2 appendix 2 from the frequency one. The procedure of calculation is the following. Formula 11, then 10, the calculation of the single number according to 717-2 for Ln,0 and Ln, then DLw,freq=Ln,0,w-Ln,w In this way the DLw,freq takes into account also the frequency trends of both DL and Ln,0 A clarification is added according to your comment
Table 7: I suppose the reported values concern the weighted	Thank you for your observation.

normalized impact sound pressure level L_{n0w} of different base floors (You report a single number and not frequency values)	A specification (as before) was added to the table caption
In Fig 10 the weighted reduction of impact sound pressure level ΔL_w are reported, and not frequency values	Thank you for your observation. Please refer to the first response.

A comprehensive analysis of time influence on floating floors: effects on acoustic performance and occupants' comfort

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Abstract

Impact noise is increasingly becoming an important issue both in terms of technologies for its reduction and in terms of its perception inside buildings. In fact, a high level of noise clearly affects indoor comfort and liveability of confined spaces.
For this reason, this study focuses on the influence which the static load over time impacts on the resilient material of a floating floor and on its final performance. Five different types of resilient materials have been tested for five years and the results are analysed in terms of material type, surface contact and thickness variation, dynamic stiffness measured on 8 different time steps and its application on 6 different bare floors. Obtained values are therefore studied in terms of perceived comfort and compliance with 31 European countries regulations limits.
Results clearly show that time has a paramount influence on all types of resilient materials (with the exception of one) in all configurations and that complete floor selection, in time, can greatly change perceived indoor living comfort and compliance with the limits imposed by laws.

1. Introduction

Acoustic comfort inside buildings is of primary importance for their correct use and proper liveability. This issue has been addressed in many researches and covers several areas such as (i) sound insulation between different apartments, (ii) façade sound insulation, (iii) sound insulation service equipment and (iv) reduction of impact noise.
By carrying out a research on Scopus using "sound insulation building" as a unique keyword and then adding "impact" together with it, the results shown in Figure 1 were obtained. It could be highlighted how research interest in this field has grown very significantly in recent years. It can also be seen that studies on the topic ″impact noise″ have recently been half of those on the whole building acoustic subject. This shows how this specific area is addressed and considered and it is denoted as a very important problem.
In Figure 2 results are reported by changing the research keywords focusing on the effect of load in time (compressive creep) in general and in relation to the acoustic properties (acoustic). As it is possible to see in this case, the first theme is much debated and in continuous growth, while researches related to the determination of acoustic properties have just begun, even if their number is increasing. Among all the considered articles, many of them are related to the instantaneous properties of resilient materials [1]-[3], few are related to the variations over time [4]-[6] and only one work is about the effect of the compressive creep in time, but not related to the acoustic properties [7].

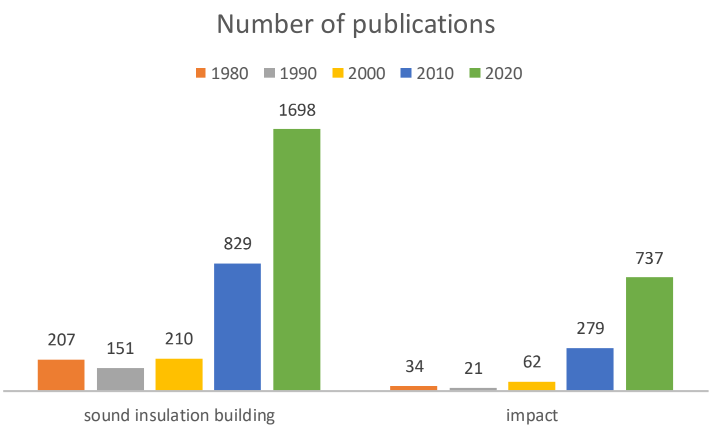


Figure 1 - Results of literature research using combination of the indicated keywords

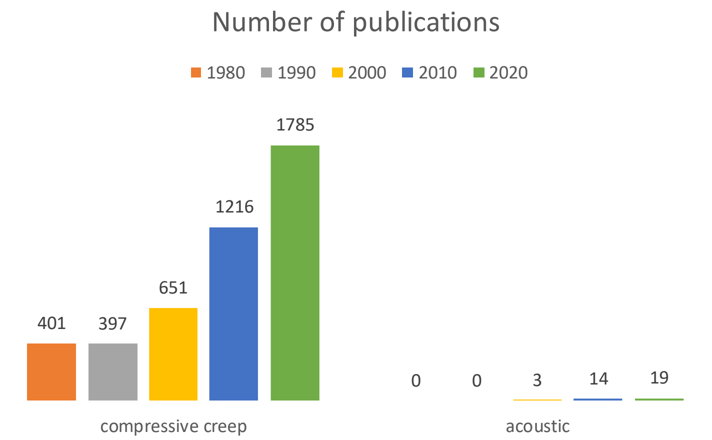


Figure 2 - Results of literature research using combination of the indicated keywords

From the point of view of scientific analysis, the problem of impact noise is relatively recent [8]-[9]. It appeared especially when the first floors were made using bricks, wood or light concrete [10]. These structures easily transmit noise and vibrations in addition to the airborne one [11].
At present, the problem of impact noise is mostly solved by means of a floating floor, consisting of a layer of resilient material, which, if properly installed, separates the upper screed from the bare floor and the flanking structures. The constituted mass-spring system thus greatly reduces the propagation of noise and vibrations from one room to the neighbouring ones [12].
The reference parameter, needed to quantify the attenuation of impact noise, is the dynamic stiffness per unit area. This represents the capability of the resilient layer to dissipate the vibration.
Since this layer is very important for the final acoustic performance, for a complete characterization of its physical-mechanical properties it is necessary to determine the possible decrease in acoustic performance depending on the static load over time. Thus, long term tests are needed.
Researches on recycled and virgin materials are always competing to demonstrate the good performances of former or latter ones [13]-[16]. In this view, most of the time the aim is to demonstrate that recycled materials behave as well as virgin ones. In the field of impact noise reduction, many recycled materials are present, mostly composed of waste from industry [17] or constructions [18].
Another very important component is the change of the floating floor performance depending on the type of bare floor where it is laid. In fact, very heavy bare floors such as concrete slabs or beam and pot structures can provide very different frequency results compared to lighter ones, such as timber frame or timber concrete.

Another paramount topic is the receivers' opinions. Perceived comfort may be affected by impact noise variation over time. Bard et al.[19] defined it as "a concept with opportunities for supportive acoustic conditions according to the activities taking place". In this view, they demonstrated how impact noise on several different buildings affect indoor comfort. Yang et al. [20] demonstrated how many parameters may affect it, but the influence of time was not taken into account.
Lastly, the compliance with regulations limits is very important. Higginson et al. [21] composed a comprehensive review of directive, standards and national requirements. Rasmussen [22] highlighted the difference between countries regulations on different building acoustics parameters, while Östman and Källsner [23] focused only on timber buildings. Nevertheless, no researches dealt with the compliance of multi-layered structures to noise regulation over time.
Therefore, the purposes of this research is to understand how the influence of static load over time can act on:
- dynamic stiffness value of the resilient material;
- overall and frequency reduction of impact noise;
- respect of regulations limits all over Europe.

Another purposes of this work is to understand if there is a possible link between:
- material (virgin or recycled) and acoustic behaviour over time;
- shape of the material (continuous or shaped) and acoustic behaviour over time;
- initial thickness of the material and final acoustic performance.

Another aim of the research is to understand if the acoustic properties related to the floating floor technology, taking into account the effect of the load over time, can be modified according to the different types of bare floors.
Finally, the last aim of this research is to understand if the load can have negative effects on the comfort perceived by the occupants over time.

2. Materials and Methods

In the present study, 5 resilient layers typically used for floating floors realization have been considered. Two of them come from recycled wastes: Tyres Shaves (TS) and Fibres of Recycled Fabrics (RFF). Three materials were chosen on the basis of their composition (expanded rubber), but with different shapes and therefore contact with the bare floor: Expanded Rubber (ER), Expanded Rubber Spot Shaped (ERSS) and Expanded Rubber Line Shaped (ERLS).
Time influence was studied over 5 year, using a static load and room temperature as depicted by standard requirements [24], using steel plates of 8 kg weight each (one per sample). For TS, every test was performed including all the compositions present in the layer. As a further step, chemical description of the two main composition is depicted in next sections. Thermal test were performed after 5 years. It is worthy to highlight that thermal tests results are not influenced by time, since materials composition won't vary in years. What may vary are the provided performances.

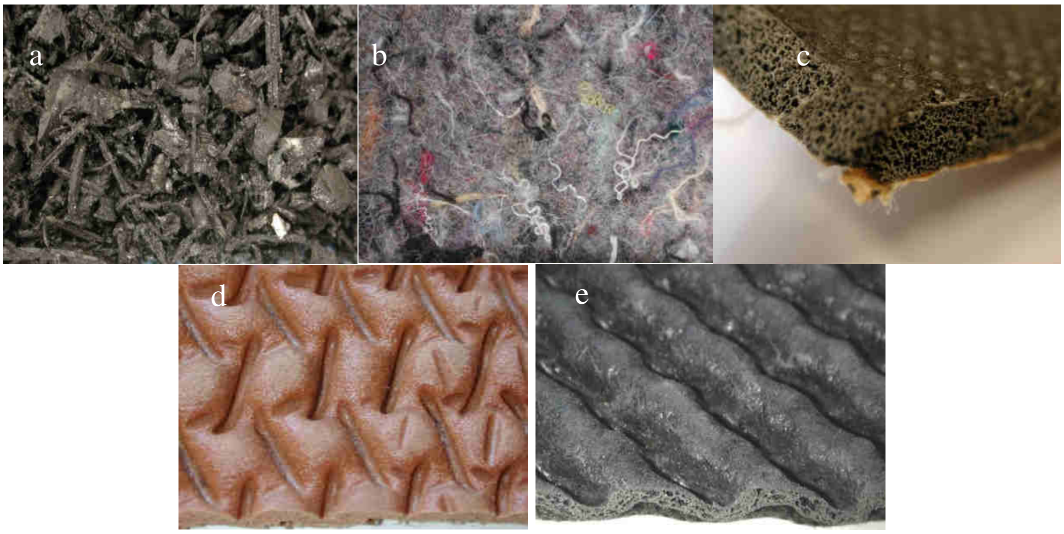


Figure 3 – picture of the considered materials: a) tyre shaves, b) fibres of recycled fabric, c) expanded rubber, d) expanded rubber spot shaped, e) expanded rubber line shaped

2.1. Material characterization

Materials were characterized by Simultaneous Thermal Analysis (STA) with the STA 409 Netzsch instrument (in air) in alumina crucibles from room temperature to 1050 °C, using a heating rate of 10 K/min. Performed analyses are ThermoGravimetric analysis (TG), Derivative Termo-Gravimetry (DTG) and Differential Thermal Analysis (DTA). These measurements are useful to determine precisely the composition of materials and then relate them to the acoustic performance variations caused by static load over time.

Thermogravimety (TG) is a procedure in which the mass of a sample is measured over time compared to temperature variation. This measurement gives information about physical and chemical phenomena including thermal decomposition and solid-gas reactions. DTG is the derivative of the TG curve in time (DTG [%/min]) and it is very useful for a good transition points assessments.

Differential Thermal Analysis (DTA) is a thermoanalytic methodology. In DTA, the material and an inert reference are run through identical thermal cycles, (i.e., same cooling or heating programme), while recording any temperature variations between the two samples. This differential temperature is then plotted versus time, or temperature. Exothermic or endothermic changes can be detected relative to the inert reference. Thus, a DTA curve highlights data on the occurred transformations, such as glass transitions, crystallization, melting and sublimation. The DTA peak area identifies the enthalpy change and it is not affected by the heat capacity of the sample.

2.2. Increment of resilient layer contact surface and thickness variation

In order to understand if the contact surface changes in time, the different contact areas at time t_0 and after 5 years load were analysed. Precise image captures of the deformed shapes were carefully shot and compared with the ones at t_0. Data were then graphically processed by Image Pro Plus (Media Cybernetics).

The contact surface is very important for the dynamics of the floating screed. In fact, the general equation of motion can be expressed as follows (1):

$$(1) \qquad x(t) = x_0 + A \cos(\omega t + \vartheta_0)$$

where x_0 is the initial thickness [m], A is the oscillation amplitude, ω is the angular pulsation [rad/s], t is time [s] and ϑ_0 is the initial phase shift.

The equivalence reported in eq. (2) and the Hooke's law for a spring – mass system reported in eq. (3) define the final force reported in eq. (4).

(2) $\ddot{F} = m\, x$

(3) $F = - k\,(x_0 - x)$

(4) $m\, x - k\,(x_0 - x) = 0$

where F is the exciting force [N], x is the displacement [m] and x_0 is the initial displacement [m].
In the specific case of floating floor the solution is harmonic and thus x(t) is defined as reported in eq. (5):

$$(5) \qquad x(t) = A\cos\left(\sqrt{\frac{k}{m}} \cdot t + \vartheta_0\right)$$

where $\omega = \sqrt{\frac{k}{m}} = 2\,\pi\, f$, where k is the elastic constant and m refers to load density [kg/m^2] and f is the frequency.
The resonance frequency f_0 is depicted by eq. (6):

$$(6) \qquad f_0 = \frac{\sqrt{\frac{k}{m}}}{2\,\pi}$$

Now, taking into account the Hooke's law for simple compression load, the final force could be written as eq. (7):

$$(7) \qquad \frac{F}{S} = E\,\frac{\Delta x}{x_0}$$

where E is the Young's Modulus [N/ m^2] and S is the surface [m^2]. It is evident how the contact area of the specimen and the final thickness could influence the resulting elastic modulus related to the resilient layer.

2.3. Acoustic characterization

Using EN 29052-1 procedure [25], the dynamic stiffness for unit area s' was investigated. This parameter is in close relation to the resonant frequency f_0 of system composed by the resilient layer and standard static load, as depicted by the equation (8):

$$(8) \qquad s' = 4\,\pi^2 m'\, f_0^2 \qquad [\mathrm{MN/m^3}]$$

where m' [kg/m^2] is the total mass per unit area of the static load.
Combining eq. (2) and eq. (8) it is possible to define the dynamic stiffness depending on the Young's Modulus as eq. (9):

$$(9) \qquad s' = \frac{E}{d}$$

where d is thickness of the specimen.
Resonance frequencies were determined according to ISO 7626-5 [26]. The measurement facilities (Figure 4) involve an impact hammer PCB Piezoeletronics, a vibration transducer Dytran and a digital recording system (24 bit, 48 kHz sampling).

Figure 4 - Apparent dynamic stiffness test measurement facilities.

Dynamic stiffness tests were performed at t_0 and then the static load was left up to 5 years, measuring the values at every time steps described in Table 1.

Table 1 – time steps of dynamic stiffness tests

t_o
90 days (3 months)
150 days (5 months)
210 days (7 months)
365 days (1 year)
730 days (2 years)
1095 days (3 years)
1461 days (4 years*)
1826 days (5 years*)

* with one leap year

2.4. Impact noise reduction in time

In order to understand how the static load influence over time modifies the reduction of impact noise, dynamic stiffness data have been used to evaluate the decrease of acoustic properties on six different types of bare floors.
The analytical model for the reduction of impact noise is based on the assumption that the bare floor normalised level of impact noise is known. Then, the effect offered by the floating floor is subtracted, according to eq. (10):

$$L_n = L_{n,0} - \Delta L \qquad (dB) \tag{10}$$

where L_n is the resulting impact noise (dB) for every 1/3 octave band frequency, $L_{n,0}$ is the bare floor impact (dB) for every 1/3 octave band frequency and ΔL is the floating floor noise reduction (dB) for every 1/3 octave band frequency.
As it can be seen, the influence of the bare floor is the reference to calculate the final floor performance. Knowing its behaviour is therefore of paramount importance. Moreover, as highlighted

by Cho [27], by changing the type of base floor, the noise reduction offered by the floating floor will change.
This system can be modelled as reported in equation (11):

$$(11) \qquad \Delta L = 30 \log \frac{f}{f_0} \qquad (dB)$$

where f_0 is updated considering the different composition and time-step.
Equation 11 was used to calculate the impact noise reduction in frequency. Thus, all bare floors and all floating floors' influences were considered in frequency.
After this procedure the final $\Delta L_{w,freq}$ is calculated, taking thus into account bare floors frequency behaviour and floating floors frequency reduction (eq. 12):

$$(12) \qquad \Delta L_{w,freq} = L_{n0,w} - L_{n,w} \qquad (dB)$$

Six bare floors were then chosen among the most used in Europe (Table 2) and the frequency impact noise reduction indexes are calculated for all configuration depicted in Table 1. The maximum differences between indexes are then highlighted.

Table 2 – bare floors used in this study

acronym	*description*	*Thickness [cm]*	*reference*
CLS	Reinforced concrete slab	14	[28]
B&P	Reinforced concrete beams of 12 to 14 cm width, together with reinforced concrete slab of 4 to 6 cm thickness and perforated bricks or polystyrene blocks	16 to 28	[29]
TC	Timber beams spaced of 400 to 750 mm between axis and to which were attached plywood boards of 22 mm thickness. Concrete slab of 40 to 60 mm height	8 to 10 (between beams)	[30]
CLT	Solid timber layers glued to form a solid slab	13.5 to 20	[31]-[32]
GL	Prefabricated panels composed by spaced glulam beams of 16 cm thickness with fibrous layers in between, closed by 22 mm plywood panels (top and bottom)	20	[33], [34]
CXPS	Two panels of 15 mm thickness of recycled materials, with a 200 mm chamber filled with two panels of polystyrene	20	[35]

2.5. Statistical analysis

ANOVA and the Mann-Whitney U tests were used in order to verify if the following hypotheses are statistically significant:

1) the 5-year impact noise is related to initial dynamic stiffness value;
2) the 5-year impact noise is related to the material type;
3) the final value of dynamic stiffness is related to the 7 years creep value;
4) the final value of the dynamic stiffness is related to the final contact area;
5) the final value of the dynamic stiffness is related to the final thickness;
6) the final dynamic stiffness value is related to the static load over time;
7) floors noise reduction index for the same material is related to the static load over time;
8) single floor performance for different materials is related to the static load over time;
9) subjective evaluation for all floors (the same material) is related to the static load over time;
10) subjective evaluation for single floor (different material) is related to the static load over time;

ANOVA represents a statistical test of whether two or more population means are equal. Statistically significant result, when a probability (p-value) is less than a pre-specified threshold (significance level), justifies the rejection of the null hypothesis. F is a function involving a ration of two variance. Mann-Whiteny U test can be used to study whether two samples were selected from populations having the same distribution. The test involves the calculation of a statistic, usually called U, whose distribution under the null hypothesis is known. Z-score shows how standard deviations below or above the population mean behave.
In the following, each hypothesis will be identified by its list number. The corresponding label is used to refer to each material.

2.6. European standards and regulation comparison

The influence of load over time can affect the limits fulfilment imposed by legislations. Thus, a comparison was made between all the steps listed in Table 1 and Table 2 and between the regulations of 31 European countries. To perform such evaluation, the data collected over the years by Rasmussen [36] and updated at 2019 [37] were used. The regulations limits do not adapt to changes due to load in time (within the same law), thus they are valid from t_0 to the end of the building life, or a new upgrade on the same regulation, operated by single country, by public bodies.

2.7. Subjective evaluation of impact noise modification

In order to understand how the variation caused by the load over time can affect the comfort of the occupants, an analysis has been made related to parameters associated with the 5 materials and calculated on the basis of the values of dynamic stiffness obtained in the various steps from t_0 to 5 years [38].
Even if the arithmetic mean was shown to be the factor that best relates to the perceived disturbance [39], referred to the tapping machine applied to composite floors with heating systems, Rindel and Rasmussen [40] proposed to use another parameter, namely $L_{n,w} + C_{I,50\text{-}2500}$, calculated according to the standard ISO 717-2 [41].
$L_{n,w} + C_{I,50\text{-}2500}$ is widely used in literature and many times demonstrated to have statistically significance especially for lightweight timber buildings [43]-[44].
Hopkins [45] used this parameter to highlight how it is very useful to identify the impact noise annoyance. The correlation by subjective evaluation compared to measurements show a successful agreement only comprising this correction. Rindel [46] highlighted that a good agreement is only possible when low frequency impact noise are included in the evaluation and thus the use the frequency adaptation term is compulsory for the best acoustic comfort assessment.
For these reasons, this parameter will be calculated and discussed.

3. Results

The results of the several test and analysis are reported in the following sections.

3.1. Materials characterization

From macroscopic observation (Figure 3a), TS sample is characterized by two types of shaves (Figure 3a): compact (rounded chips) and fibrous (longer chips). The thermal tests results are resumed in Figure 5 and Table 3.

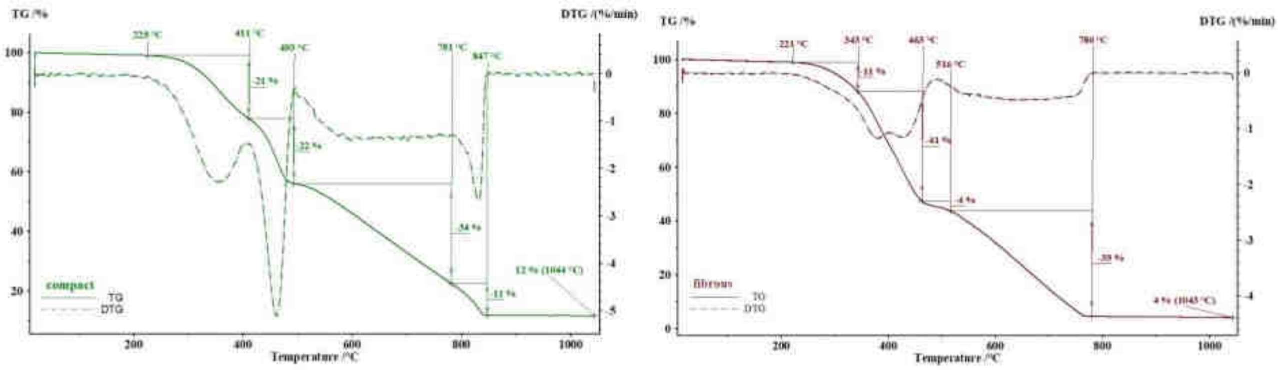


Figure 5 –TG and DTG results for TS. Green: compact; red: fibrous. TG [%] represents the percentage weight loss of the sample compared to initial stage. DTG [%/min] represents the derivative in time of the TG curve. DTA [µV/mg] represents the difference in temperature measured in µV per mg.

Table 3 – STA results for the TS sample

components	*Compact chips % by weight*	*Fibrous chips % by weight*
Rubber	42 % (NBR+SBR)*	52 % (NBR)
Carbon black	38 %	40 %
Calcium carbonate	16 %	--
Other filler	4 %	4 %
Residue @ 1000°C	12 %	4 %

*NBR: Nitrile Rubber; SBR: Styrene Butadiene Rubber

From macroscopic observations (Figure 3b), RFF sample is characterized by several kind of recycled fibres glued together. It is then important to know the nature of the components in this resilient layer. Thus, the results are resumed in Figure 6. Here it could be seen (right) that the main component is glue, composed by polyethylene and polypropylene.

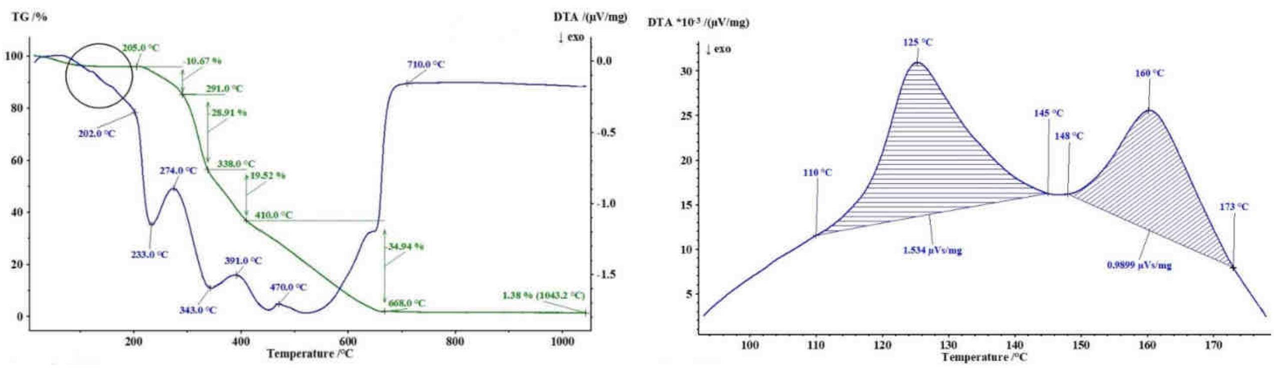


Figure 6 – TG and DTA results for RFF (TG green curve; DTA blue curve). LEFT complete plot, RIGHT highlight of the melting peaks, corresponding to the melting of PE (125°C) and PP (160°C). TG [%] represents the percentage weight loss of the sample compared to initial stage. DTG [%/min] represents the derivative in time of the TG curve. DTA [µV/mg] represents the difference in temperature measured in µV per mg.

For Expanded rubber (ER), Expanded Rubber Spot Shaped, (ERSS), Expanded Rubber Line Shaped (ERLS), it could be seen (Figure 3 c, d and e) that they are produced using the same components, but with different final shapes. For the sake of brevity in Figure 7 and Table 4 only the ER results are depicted, since the ERSS and ERLS are very similar.

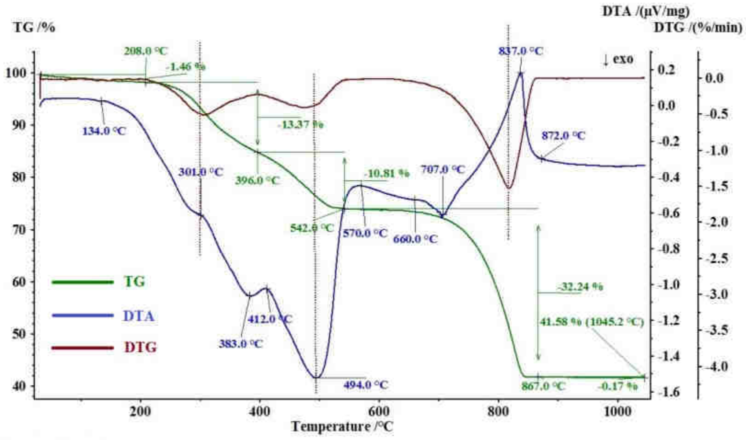


Figure 7 – TG, DTA and DTG results for ER, ERSS and ERLS samples .TG in green, DTA in blue and DTG in red. TG [%] represents the percentage weight loss of the sample compared to initial stage. DTG [%/min] represents the derivative in time of the TG curve. DTA [µV/mg] represents the difference in temperature measured in µV per mg.

Table 4 – STA results for the ER, ERSS and ERLS samples

components	*% by weight*
Polymer → PDMS	26.0
Carbon black (calculated)	1.0
Calcium carbonate	73.0
Residue @ 1045 °C (CaO)	41.6

3.2. Variation of contact surface and thickness

The layers TS, RFF, ERSS and ERLS were analysed in terms of increment of contact surface and thickness variation at t_0 and 5 years and the ER (flat sample) is used as control. The results are reported in Table 5.

Table 5 – contact surface and thickness variations of different resilient layers

	contact surface and thickness variations				
Material	**TS**	**RFF**	**ER**	**ERSS**	**ERLS**
% surface contact at t_0	17.4	12.1	96.0	26.4	19.9
% surface contact at 5 years	17.6	53.4	96.0	26.6	23.4
% surface increment	1.0	341.0	--	0.3	17.6
% thickness decrement	-29.4	-12.6	-21.2	-9.3	-12.2
% E variation based on (7)	-1.0	77.0	0.0	-0.3	-14.9

3.3. Acoustic characterization

In Table 6 the results of the dynamic stiffness tests are reported, for different time steps.

Table 6 – dynamic stiffness measurements

Time steps	*Dynamic stiffness value of different resilient layers [MN/m^3]*				
	TS	**RFF**	**ER**	**ERSS**	**ERLS**
t_0	15.1	16.5	44.0	20.3	27.0
3 months	30.0	20.3	53.9	36.3	38.8
5 months	30.0	23.6	59.3	36.2	43.5
7 months	24.5	39.9	59.7	38.4	38.4
1 year	54.9	41.7	150.2	47.8	40.0
2 years	64.8	37.2	63.5	58.7	43.5
3 years	72.2	36.6	63.5	63.0	41.0
4 years	48.0	44.0	70.7	56.0	44.8
5 years	49.2	53.4	71.2	52.3	43.5

In Figure 8, the results in terms of resonance frequency are depicted for t_0, 5 months and 7 months, while in Figure 9 the results are reported for each year. For the sake of brevity, only TS, RFF and ER are reported, since ERSS and ERLS frequency behaviours variation caused by static load in time are very similar.

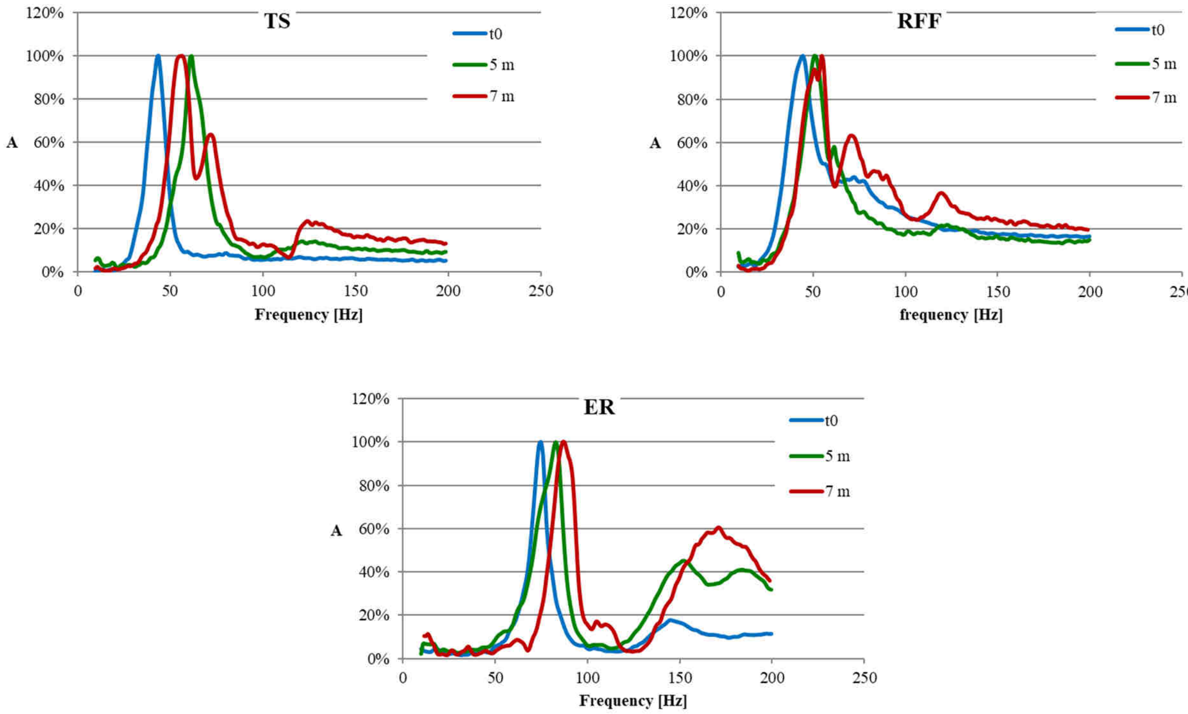


Figure 8 – Resonance frequency results for TS, RFF and ER for time steps t_0, 5 months and 7 months. A [%] represents the variation of amplitude response compared to the static system step, measured by accelerometer

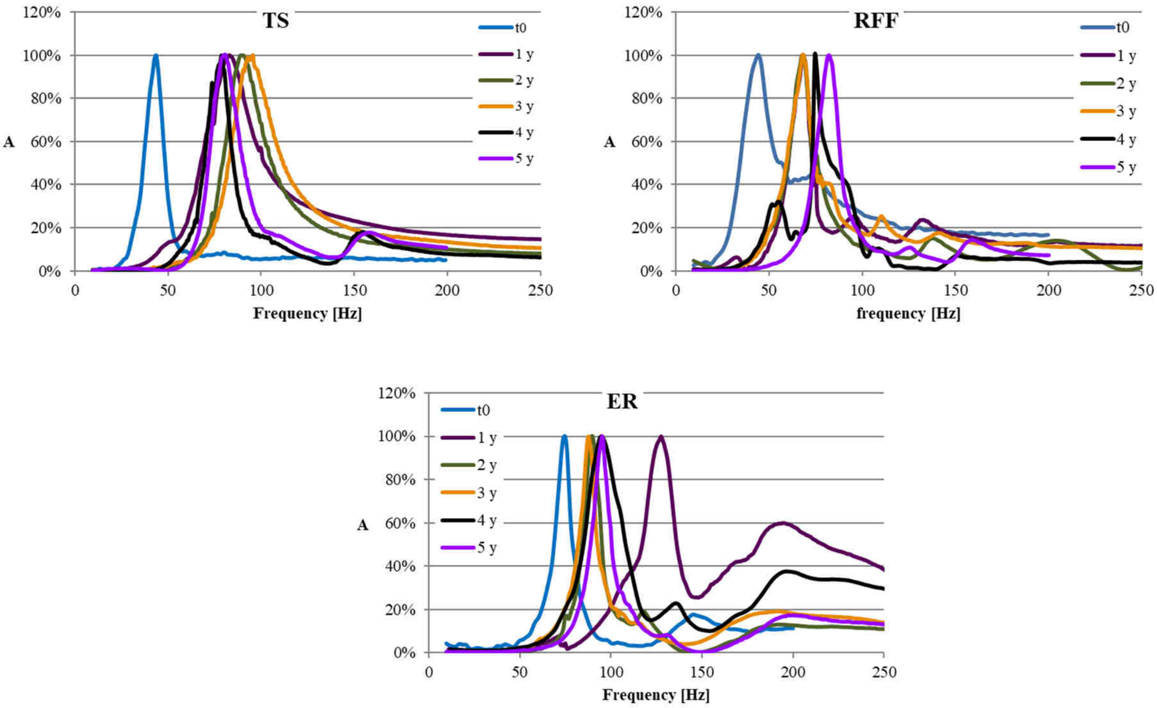


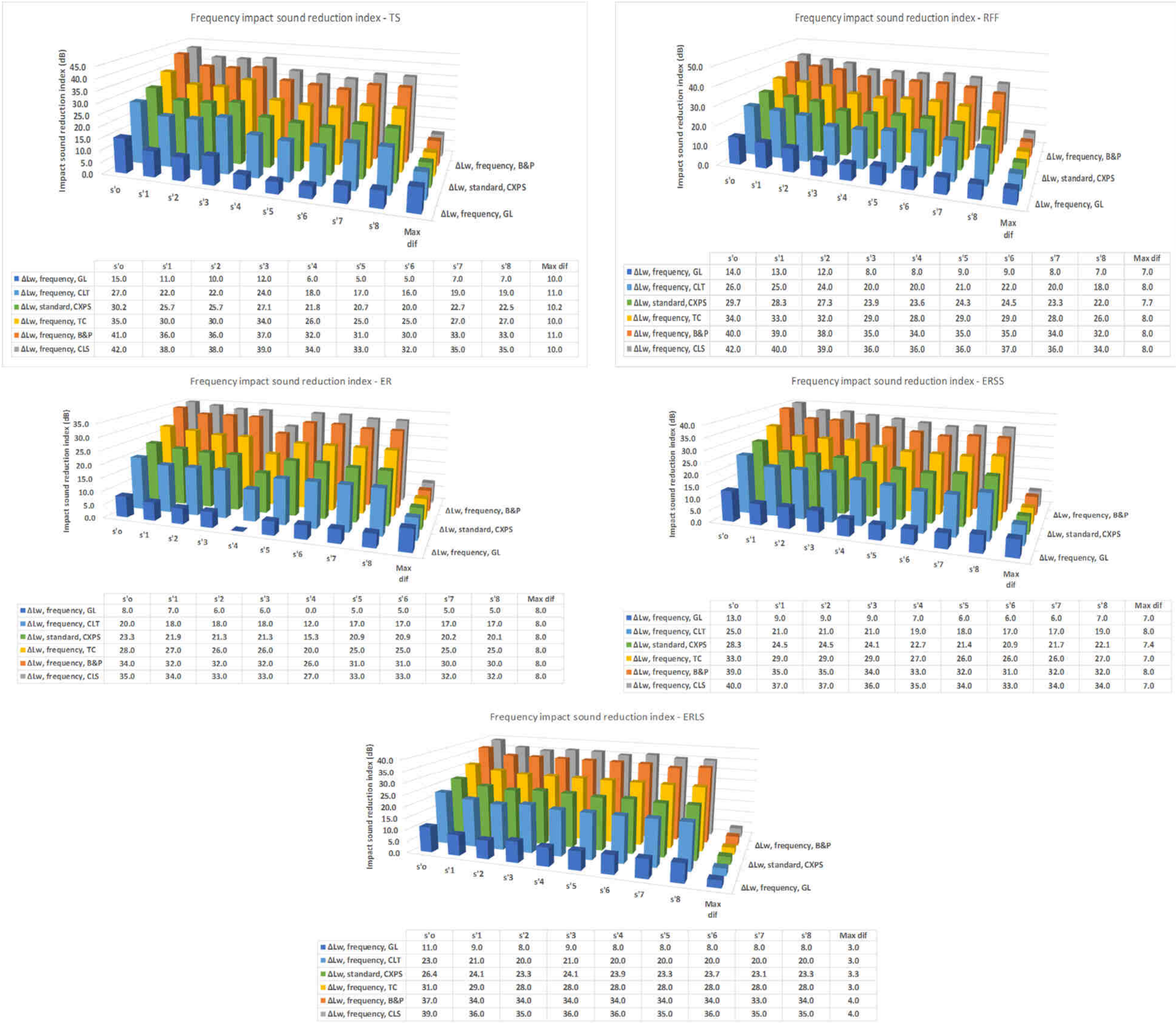
Figure 9 – Resonance frequency results for TS, RFF and ER for time steps t_0, 1, year, 2 years, 3 years, 4 years, 5 years. A [%] represents the variation of amplitude response compared to the static system step, measured by accelerometer

3.4. Impact noise reduction caused by load over time

In Figure 10, the frequency impact noise reduction indexes of all selection of bare floors combined with all dynamic stiffness values measured in time are reported and compared. The normalized sound pressure levels for every combination are present in the supplementary data (figure I – figure V). In Table 7, the bare floors L_{n0} values are reported, obtained from frequency trends.

Table 7 – bare floors $L_{n0,w}$ impact noise, calculated using frequency trends

Type of bare floor	*$L_{n0,w}$ (dB)*
GL	76
CLT	80
CXPS	82
TC	88
B&P	87
CLS	87



TS:

	s'o	s'1	s'2	s'3	s'4	s'5	s'6	s'7	s'8	Max dif
ΔLw, frequency, GL	15.0	11.0	10.0	12.0	6.0	5.0	5.0	7.0	7.0	10.0
ΔLw, frequency, CLT	27.0	22.0	22.0	24.0	18.0	17.0	16.0	19.0	19.0	11.0
ΔLw, standard, CXPS	30.2	25.7	25.7	27.1	21.8	20.7	20.0	22.7	22.5	10.2
ΔLw, frequency, TC	35.0	30.0	30.0	34.0	26.0	25.0	25.0	27.0	27.0	10.0
ΔLw, frequency, B&P	41.0	36.0	36.0	37.0	32.0	31.0	30.0	33.0	33.0	11.0
ΔLw, frequency, CLS	42.0	38.0	38.0	39.0	34.0	33.0	32.0	35.0	35.0	10.0

RFF:

	s'o	s'1	s'2	s'3	s'4	s'5	s'6	s'7	s'8	Max dif
ΔLw, frequency, GL	14.0	13.0	12.0	8.0	8.0	9.0	9.0	8.0	7.0	7.0
ΔLw, frequency, CLT	26.0	25.0	24.0	20.0	20.0	21.0	22.0	20.0	18.0	8.0
ΔLw, standard, CXPS	29.7	28.3	27.3	23.9	23.6	24.3	24.5	23.3	22.0	7.7
ΔLw, frequency, TC	34.0	33.0	32.0	29.0	28.0	29.0	29.0	28.0	26.0	8.0
ΔLw, frequency, B&P	40.0	39.0	38.0	35.0	34.0	35.0	35.0	34.0	32.0	8.0
ΔLw, frequency, CLS	42.0	40.0	39.0	36.0	36.0	36.0	37.0	36.0	34.0	8.0

ER:

	s'o	s'1	s'2	s'3	s'4	s'5	s'6	s'7	s'8	Max dif
ΔLw, frequency, GL	8.0	7.0	6.0	6.0	0.0	5.0	5.0	5.0	5.0	8.0
ΔLw, frequency, CLT	20.0	18.0	18.0	18.0	12.0	17.0	17.0	17.0	17.0	8.0
ΔLw, standard, CXPS	23.3	21.9	21.3	21.3	15.3	20.9	20.9	20.2	20.1	8.0
ΔLw, frequency, TC	28.0	27.0	26.0	26.0	20.0	25.0	25.0	25.0	25.0	8.0
ΔLw, frequency, B&P	34.0	32.0	32.0	32.0	26.0	31.0	31.0	30.0	30.0	8.0
ΔLw, frequency, CLS	35.0	34.0	33.0	33.0	27.0	33.0	33.0	32.0	32.0	8.0

ERSS:

	s'o	s'1	s'2	s'3	s'4	s'5	s'6	s'7	s'8	Max dif
ΔLw, frequency, GL	13.0	9.0	9.0	9.0	7.0	6.0	6.0	6.0	7.0	7.0
ΔLw, frequency, CLT	25.0	21.0	21.0	21.0	19.0	18.0	17.0	17.0	19.0	8.0
ΔLw, standard, CXPS	28.3	24.5	24.5	24.1	22.7	21.4	20.9	21.7	22.1	7.4
ΔLw, frequency, TC	33.0	29.0	29.0	29.0	27.0	26.0	26.0	26.0	27.0	7.0
ΔLw, frequency, B&P	39.0	35.0	35.0	34.0	33.0	32.0	31.0	32.0	32.0	8.0
ΔLw, frequency, CLS	40.0	37.0	37.0	36.0	35.0	34.0	33.0	34.0	34.0	7.0

ERLS:

	s'o	s'1	s'2	s'3	s'4	s'5	s'6	s'7	s'8	Max dif
ΔLw, frequency, GL	11.0	9.0	8.0	9.0	8.0	8.0	8.0	8.0	8.0	3.0
ΔLw, frequency, CLT	23.0	21.0	20.0	21.0	20.0	20.0	20.0	20.0	20.0	3.0
ΔLw, standard, CXPS	26.4	24.1	23.3	24.1	23.9	23.3	23.7	23.1	23.3	3.3
ΔLw, frequency, TC	31.0	29.0	28.0	28.0	28.0	28.0	28.0	28.0	28.0	3.0
ΔLw, frequency, B&P	37.0	34.0	34.0	34.0	34.0	34.0	34.0	33.0	34.0	4.0
ΔLw, frequency, CLS	39.0	36.0	35.0	36.0	36.0	35.0	36.0	35.0	35.0	4.0

Figure **10 –** Frequency impact reduction index $\Delta L_{w,freq}$ calculated over 5 years basing on measured dynamic stiffness values and applied to 6 different typical floors

3.5. Statistical analysis

The results of the statistical analysis using the Mann-Whitney U and ANOVA methods are given in Table 8 and Table 9.

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Table 8 – Mann–Whitney U test

hypothesis	z-score	U Test	p-level	Significance
1	-2.29783	1	0.02144	*No*
2	2.50672	0	0.01208	*No*
3	-2.50672	0	0.01208	*No*

Table 9 – Anova test

hypothesis	sum of squares	F test	p-level	Significance
4	123247.3	1.72	0.22536	*No*
5	71225.6	16.08	0.00389	Yes
6	119235.6	5.13	0.00196	Yes
7 TS	36434	93.87	< 0.00001	Yes
7 RFF	39378	170.55	< 0.00001	Yes
7 ER	27705	234.54	< 0.00001	Yes
7 ERSS	34391	208.91	<0 .00001	Yes
7 ERLSS	35400	1011.22	< 0.00001	Yes
8 CLS	57021	5.35	0.001508	Yes
8 B&P	52577	6.99	0.000228	Yes
8 CLT	18245	4.22	0.006028	Yes
8 TC	35754	4.08	0.007172	Yes
8 GL	3256	4.36	0.005027	Yes
9 CXPS	7326	5.18	0.001834	Yes
9 TS	119252.35	9.48	< 0.00001	Yes
9 RFF	113362.05	15.76	< 0.00001	Yes
9 ER	137355.63	21.68	< 0.00001	Yes
9 ERSS	122514.65	19.97	< 0.00001	Yes
9 ERLSS	119459.11	104.71	< 0.00001	Yes
10 CLS	97261.52	4.715	0.003266	Yes
10 B&P	96807.79	4.725	0.003229	Yes
10 CLT	104502.1	4.709	0.003292	Yes
10 TC	126850.96	4.666	0.003470	Yes
10 GL	81722.97	4.650	0.003542	Yes
10 CXPS	104798.45	4.62	0.003665	Yes

3.6. Comparison with European regulations

In Figure 11, the performance of the 6 complete floors calculated in different period of load in time are considered and compared with 31 European countries regulations. All the complete comparisons are included in the supplementary data.

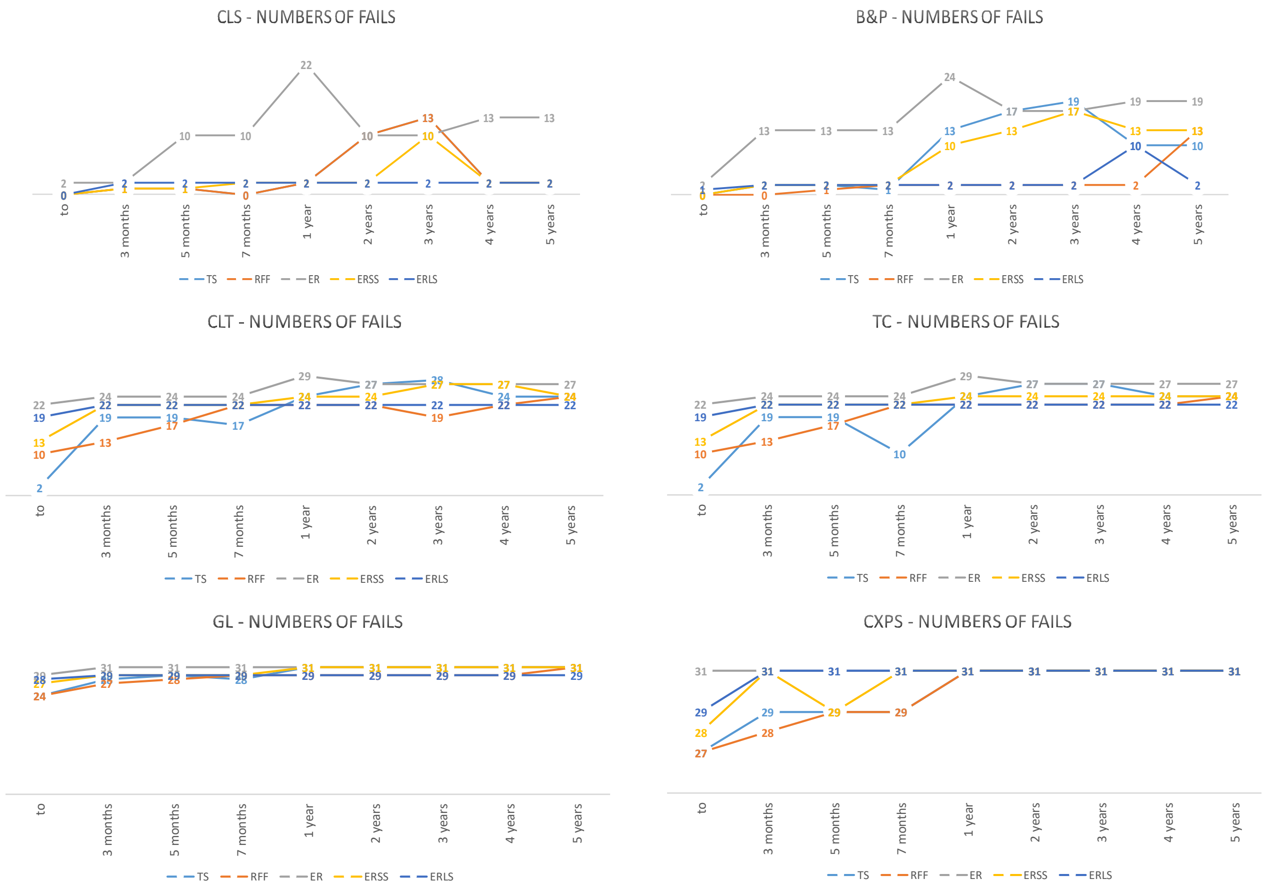

Figure 11 – Percentage of fails for different bare floors with floating floor referred to European regulations.

3.7. Subjective evaluation

In Figure 12, the complete floors after different period of load time are considered and the frequency adaptation term $C_{I,50\text{-}2500}$ is depicted, reporting also minimum and maximum values.

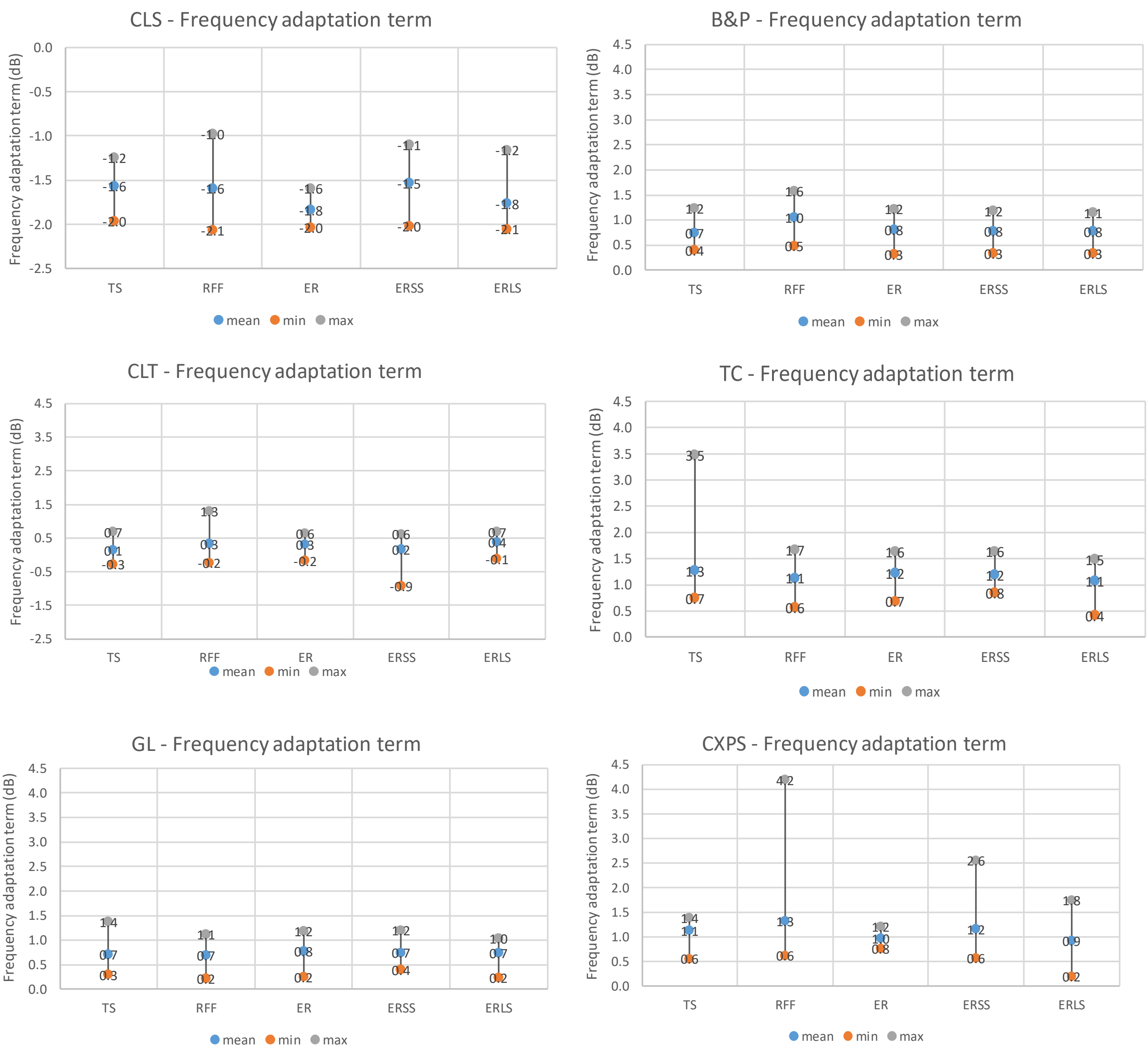

Figure 12 – graphical representation of frequency adaptation term $C_{I,50\text{-}2500}$.

4. Discussion

From the TS STA results (Figure 5), synthetically reported in Table 3, it results that the blends composing rounded chips and longer chips are different [47], [48], as well as the fillers quantities. It is worthy to highlight that all these two kind of chips compose always every TS sample (Figure 3a). Longer chips are taken from tyre recycle. According to literature [49], a tyre can be composed of 45 % by weight of rubber, 20 % of carbon black, 16 % of steel, 6 % of fabric, 3 % of zinc oxide, 3 % of sulphur and 6 % of other substances.

Accordingly, rubber includes steel. This fact affects the stiffness of the layer as the material compacts in time and this could explain the effect of the volcano-shape tendency at higher frequencies. In other words, the stiffness of the spring increases, because of the presence of a more compact phase. This can also be noticed from the curves examination related to the resonance frequencies depicted in Figure 8 and Figure 9.

As a matter of fact, at t_0 there is only one resonance peak (44 Hz); after 5 months the main peak moves to a higher frequency (62 Hz) and at an even higher frequency (125Hz) a smaller one appears. After 7 months, the main peak splits into two different peaks (56 Hz, 72 Hz) and smaller one (124 Hz) grows in importance.

This behaviour is explained by the fact that over time the material composing the tyre chips divides into two phases with clearly separated stiffness values. It should be noted that the splitting of the main peak after 7 months results from the segregation of the material. It is evident that the two phases stand apart one from the other, presenting different stiffnesses. This fact can also be deduced from the STA result, because the more compact phase presents a higher inorganic load and it is therefore more rigid. For longer load times (Figure 9), only one peak is present up to 3 years and continues to move to higher frequencies. This fact shows how the layer behaves again as a single phase (combing the two kinds of chips), more compact and therefore more rigid. After 4 years, the main resonance peak moves to lower frequencies and is still visible after 5 year, and a 155Hz smaller peak appears. It is known [51]-[55] that a viscoelastic material does not have a constant elastic modulus, which is instead influenced by the boundary conditions. Specifically, the load-in-time phenomenon provokes a decrease in modulus, namely, rubber softening effect. This explains the displacement of the main resonance peak toward lower frequencies. On the other hand, in this case it is likely that the present filler, certainly more rigid, will increase in importance with the appearance of the peak at 155 Hz.
For RFF, the STA results in Figure 6 show that there are cloth fibres glued together by a mixture of partially crystalline polyethylene (PE) and polypropylene (PP), easily identifiable by the melting peaks (Figure 6 right). The TG curve (Figure 6, green curve) is congruent with the thermal decomposition in air of a mixture of fabrics of natural and artificial origin [56]. The final residue of 1.4 % by weight suggests that there is also the presence of inorganic filler.
At t_0, 3 different peaks are present, the main one at 45 Hz and two others at slightly higher frequencies (56 Hz and 73 Hz). After 5 months, the first two peaks move to higher frequencies (51 Hz and 62 Hz) and new smoothed peak appears at higher frequency (123 Hz). After 7 months, the main peak splits into two peaks (51 Hz and 55 Hz) and other 3 peaks (71 Hz, 86 Hz, 119 Hz) appear, where the highest frequency one is the same peak present also after 5 months.
The material is composed of fibres waste glued by a two-phase polymeric adhesive: PE and PP. This fact explains the presence of three different resonance peaks. In order to understand the influence of the adhesive phase on the resonance frequency, the dynamic stiffness of a polymeric sheet composed of PP/PE (essentially PP with small content of PE) was considered. Figure 13 shows as an example the comparison between the latter material and RFF after 5 months. It is clearly evident how the interval between the two peaks of PP/PE is the same to the one found for RFF. The difference in frequency is attributed to fact that the PP/PE sheet is compact and therefore more rigid. Therefore it can be deduced that the main resonance peak of the RFF sample is caused mainly by the glue (PP+PE) and not by the fibres.

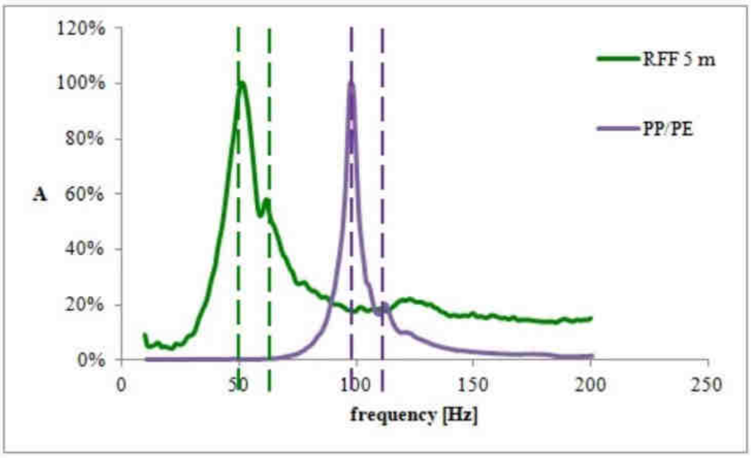

Figure 13 – Resonance frequency of the RFF sample after 5 months of creep and a compact sheet of PP-PE

Figure 9 (longer load time), shows that after 1 year there is a further shift of the main resonance peak at 68 Hz which remains constant until 3 years. At 4 years a small peak at 55 Hz appears, while the

main peak moves at a higher frequency (90 Hz). At 5 years, the main peak moves to 93 Hz, maintaining the second peak at higher frequencies.
For ER, the STA results in Figure 7 show that this layer is composed of polymers filled with calcium carbonate. The two-steps exothermic decomposition pattern appears to be consistent with silicone (PDMS = PolyDiMethylSiloxane) [57],[59]; the last step of decomposition, associated with an endothermic peak, is attributable to the thermal decomposition of calcium carbonate.
Table 4, which summarizes the composition derived from the thermal analysis, shows that it is calcium carbonate glued with black carbon foamed silicone. Even in this case the dynamic stiffness increases in time. For the sake of brevity, only the ER behaviour is reported in the following discussion.
At t_0, a peak at 75 Hz is present, but another peak appears at higher frequency (145 Hz). As time goes by, the main peak moves to higher frequencies (83Hz) and the 145 Hz peak increases in importance. After 5 months, this last peak splits in two (151 Hz + 184 Hz). After 7 months, the main peak moves further up (87 Hz), while the secondary peak at higher frequency becomes a single peak at 172 Hz.
Figure 9 shows how between 7 months and 1 year there is a significant shift of the main resonance peak at a frequency of 127 Hz and the status of the peak at 194 Hz increases. After 2 and 3 years, the behaviour changes and the main peak drops in frequency and the secondary one(s) move to lower frequencies too. After 4 years, the main resonance peak starts to rise slightly in frequency, while the secondary peak increases in importance at 195 Hz. At 5 years the main peak stand still but the peaks at higher frequency gain in importance.
The secondary peaks can be explained by the large presence of inorganic filler (73 % by weight of calcium carbonate), which is much more rigid than the rest of the polymer. For both peaks, there is an anomalous trend as the time proceeds, showing a clear increase between 7 months and 1 year and then a decrease after 2 years. In the case of the higher frequencies secondary peak(s), this phenomenon can be attributed to calcium carbonate. A partial separation with the formation of areas with higher concentrations of charge (more rigid) affect final results. For the polymeric foam phase, responsible for the main peak, the frequency reduction after 2 years is attributed to the phenomenon of rubber softening.
The above analysis shows how resilient materials change their elasticity over time due to static load and therefore modify their efficiency in reducing the impact noise. This fact is partly related to components and partly by how much the same material is produced in its various phases. It is clear that TS proposes inconstant behaviour because of the lack of a binder between the two macro-components, while for RFF it is clear that the resilient part is to be attributed exclusively to the glue and not to the recycled fibres. In this sense, however, the glue acts very well as a compacting agent and can give uniformity of response to the material over time. In fact, the peaks of resonance at higher frequencies, ignored by the ISO 29052 standard in the process of determining the dynamic stiffness, actually play an important role in reducing the impact noise. In fact, they can decrease the efficiency of the performance of the floating floor. Since they are real resonance frequencies, they will contribute to a poor acoustic performance. Therefore, it is evident how it is not important whether the material is recycled or not, but how well is produced and how much the binder is efficient.
The load over time therefore has an influence on floating floors. This is highlighted in Figure 10, where the frequency impact reduction index data are reported and calculated on the basis of dynamic stiffness values measured over time and applied to the six considered bare floors. It is clearly shown that, depending on the type of material, there are substantial differences. For example, for TS the maximum difference found is 11 dB, for RFF 8 dB, for ER 8 dB for ERSS 8 dB and for ERLS 4 dB. It is also possible to highlight how this difference is influenced by the type of bare floor, even if in this sense the maximum difference found is 1 dB for all materials. Since the final impact noise reduction is a combination of the floating floor and the bare floor, from the same figure (and from the figures I - V in the supplementary data), it is clear that, for the lightweight slabs, the load over time acts more significantly, while for the CLS and B&P the reduction of the acoustic performance is slightly lower. For all materials, an initial stiffening is verified and therefore a progressive reduction

in acoustic performance. However, for all materials there is also an improvement of dynamic stiffness values over time, due to the softening of the polymeric part. The greatest degradation occurs in the ER material, for which, when applied to the GL floor, it is even able to cancel the overall performance of the floating floor in s'_4 step (1 year). For all tested materials, a greater reduction in impact noise is achieved when the bare floor is heavier. In accordance with previous research [60], the heavier floors are able to compensate this, because of their overall stiffness. Specifically, for TS (figures I – V supplementary data) it is evident that for the CLS floor the behaviour of the impact noise, calculated according to the equation (10), is linear in the frequency trend, starting from about 50 dB at low frequencies (t_0) and ending at about 30 dB at high frequencies. A very similar trend can be verified for RFF, as it presents tendencies similar to TS (figures II - supplementary data). This is not repeated for the other floors, where the difference from low frequencies compared to high frequencies is higher. This variation grows in importance for the CLT, GL and CXPS floors. For the two last, values lower than zero at high frequency are present. In this case, the calculation is not able to take into account all the effects of flanking transmission and, in any case, a residual noise will be present in the receiving room, cancelling the impact one. For this reason, very low impact noise values, despite having maybe a physical reason, do not make sense in the reality of things.

In contrast, ER (figures III - supplementary data) shows a noticeable frequency modification in time, especially after 1 year, where the difference reaches values greater than 8 dB in frequency. The behaviour of ERLS is in line with what was presented for TS and especially for RFF, while for ERSS there are much less marked differences, given the excellent stability over time.

As a matter of fact, the surface contact variation in time does not influence final behaviour, while thickness difference does. In fact, from Table 5 and Table 9 itis possible to highlight that, while some surface contact variation are present from t_0 to 5 years, a related modification of the dynamic stiffness is not verified. Furthermore, using ER as control material (without surface contact variation), it is possible to state that only the thickness variation (and thus dynamic stiffness, eq. (9)) influences final results. Thus, the combination between Young's modulus modification determined by standard excitation (Figure 8 and Figure 9) and the decreasing thickness is the phenomenon that really affects impact noise reduction in time.

By means of statistical analysis, it was possible to correlate different behaviours with the initial listed hypotheses (section 2.5). From the Mann-Whitney U analysis reported in Table 8, it is clear that the final effect after 5 years of loading is not related to the initial value of dynamic stiffness, nor to the type of material, nor to the values of compressive creep that the material has after 7 years and calculated according to EN 1606 [24],[61]. This fact demonstrates how it is not possible to determine such behaviour in advance, but a reduction in performance of up to 11 dB relative to the frequency impact noise reduction index is possible.

The statistical analysis reported in Table 9 provides the results of the ANOVA parametric test, showing how the effect of the load over time clearly influences several factors such as (i) the dynamic stiffness value (ii) noise reduction index, using the same material as fixed parameter, (iii) single bare floor but with different resilient layers performance, (iv) subjective perception of diverse bare floors using the same material as fixed parameter and (v) subjective perception of single bare floor as fixed parameter, but with different resilient layers.

These facts highlights how the load in time highly affects the final noise reduction of floating floors and that the time is a parameter of paramount importance.

From Figure 11, it can clearly be noticed that using different resilient layers on different bare floors may provide very diverse results in term of final impact noise reduction index. In this figure, the number of countries regulations limits, which are not fulfilled by hypothetical complete floors using the 5 materials in time, are reported. The number of "fails" identifies how many limits are not fulfilled. It is clear that for the CLS floor up to 7 months there are few problems related to very few countries' limits. After the first year, however, apart from ERSS, which remains constant, the fails grow in quantity. For ER, 22 fails are reported, which means that in more than half of the European countries this solution would not be accepted, while at 3 years for ER, RFF and ERSS the legislation limits for

one third of the countries would not be fulfilled. This situation is reduced after 4 and 5 years only for RFF and ERSS, while for ER it remains almost constant, or with a little growth. For the B&P floor, things are very different. In fact, while up to one year, only the ER material presents criticalities in one third of the countries, after this time step ERSS and TS presents many fails and after 4 years ERLS presents similar results. For CLT the situation becomes more intricate. At t_0, only ERLS is able to satisfy almost all countries, but at 3 months the situation get worse for all materials, presenting most of the time more than half of fails, compared to the quantity of European countries. In time, all ER, TS and ERSS fail. The same trend can be found in the behaviour of TC floor. At t_0, GL, ER, TS and ERSS present all fails, while, after 3 months, the same happens for all materials. From 1 year on, almost all the limits imposed by European countries are not satisfied. For the CXPS floor, the conditions are similar to those of the GL floor but after 1 year the totality of them with all the materials is not able to satisfy any limit.
These considerations lead to the conclusion that impact noise is a great problem, manifesting itself in its entirety after one year of constant loading and it depends very much on the type of bare floor. This demonstrates the innovative character of this research and its importance for the comfort inside the buildings.
In order to evaluate this last aspect, the contribution provided by the frequency adaptation term $C_{I,50-2500}$ was taken into consideration. This term has been used many times as an indicator of the sound sensation related to walking noise. This parameter can assume positive or negative values. In the first case, the addition of this value will worsen the impact noise index, thus indicating an increase on occupants' perception, while in the second case it will reduce the index, denoting a positive change for sound sensation.
From Figure 12, it is clearly noticeable that for the CLS floor the variations are only negative and between values of -1 dB and -2 dB. The smallest difference is obtained with ER, while the largest variation is obtained with RFF. However, the range of frequency adaptation term variation is reduced for all materials, indicating that the time influence on noise perception for the CLS floor does not show any significant variations. Conversely, for the B&P floor the variation lays between 0.3 dB and 1.6 dB and the values are always positive. Also in this case, time, although implying variations for all materials, does not lead to significant differences between diverse materials. For this type of floor the maximum variation is provided by RFF, ER, ERSS and ERLS.
For the CLT floor the situation is quite neutral. In fact, the materials provide oscillating results between positive and negative with an average value close to 0 dB. The greatest variation is provided by RFF and ERSS and, however, it is not worthy reporting any noticeable variations.
For TC, the frequency adaptation term shows a strong oscillation for TS, while for the other resilient layers the variation is contained in about 1.5 dB. The values for this type of floor are always positive, indicating a deterioration related to noise perception compared to the initial value. Only for TS, the values reach 3.5 dB, denoting how there is an influence of the type of resilient layer for this kind of floor and thus of static load in time.
For GL, the various materials always provide positive values of the frequency adaptation term with considerations very similar to the B&P floor, while for CXPS the greatest variations are verified. In fact, for RFF almost 4 dB of possible worsening are denoted, while for ERSS and ERLS 2 dB and 1.4 dB respectively are reached. Concluding, for these kinds of bare floors the time always imposes a worsening in the perceived impact noise.

5. Conclusions

In this work, a comprehensive analysis of the time influence on impact noise reduction in presented. Five different materials were tested in time (5 years) in order to understand if their nature (recycled or not), shape, initial thickness and initial dynamic stiffness may be related to final floating floor acoustic performance. Furthermore, in order to understand the influence of the supporting structure, six bare floors were used to compose different complete constructions.

Many hypotheses were drawn in order to correlate static load over time effect to final values of impact noise, taking into consideration also European regulations limits and occupants' perceived comfort.
Results clearly demonstrate that no correlation is possible between impact noise (frequency behaviour or single index) and (i) initial dynamic stiffness, (ii) material type (recycled or not), (iii) creep values and (iv) increasing of the contact area of the shaped materials. The importance of an accurate materials production was demonstrated, highlighting the effect of binders both in recycled materials and synthetic ones.
On the other hand, there is a clear influence related to (i) thickness decreasing and (ii) Young's modulus variation. Thus the combination of these two parameter is the only phenomenon responsible for the impact noise reduction worsening.
Furthermore, a clear correlation between the static load over time and the selection of bare floors was found, showing how this effect is more evident and significant on lightweight floors. The selection of the material plays an important role too, because in one case it is even able to cancel the reduction provided at initial time step. These outcomes imply that it is not possible to forecast the influence of static load over time on final floating floor performances, but a reduction up to 11 dB (single index) was verified.
It was also demonstrated that, for many configuration of bare floors and materials, 31 European countries regulations are not fulfilled and that the most critical time step is 1 year. At this time the worst conditions were found. It was thus demonstrated that static load significantly modify the acoustic performances of floating floors comparing to the initial step.
Finally, the occupants' comfort is affected by this influence manly on periodic structures, while homogeneous ones seem not to be influenced by load over time.

Author Contributions: M.C. developed the research, elaborated the acoustic and statistical data and the numerical simulation, performed acoustics tests on materials and floors and wrote the manuscript. C.S. and M.C. performed thermal tests and digital data analysis. A.G. overviewed the research.

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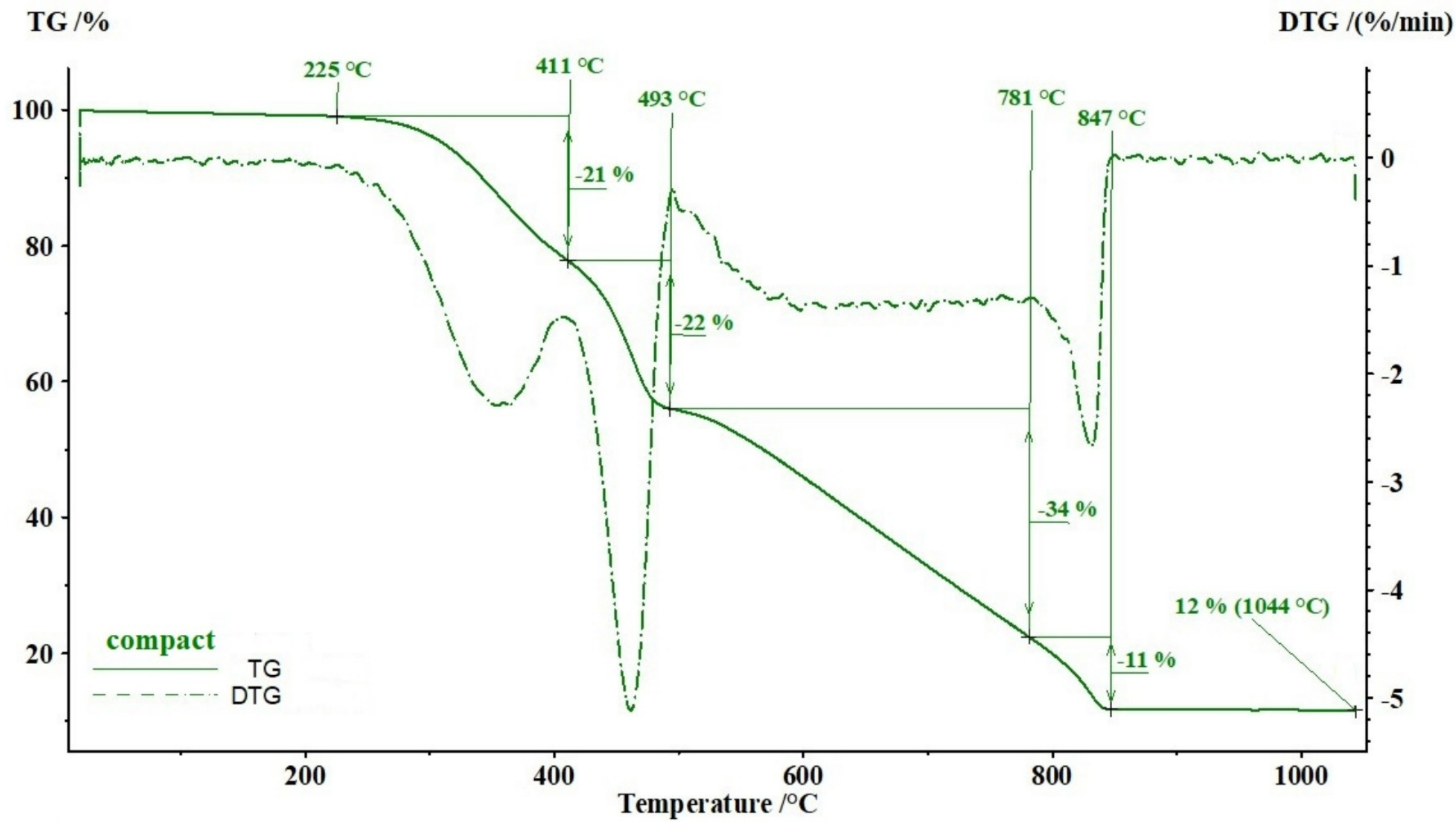
TG /%
DTG /(%/min)
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411 °C
493 °C
781 °C
847 °C
-21 %
-22 %
-34 %
-11 %
12 % (1044 °C)
100
80
60
40
20
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Temperature /°C
compact
TG
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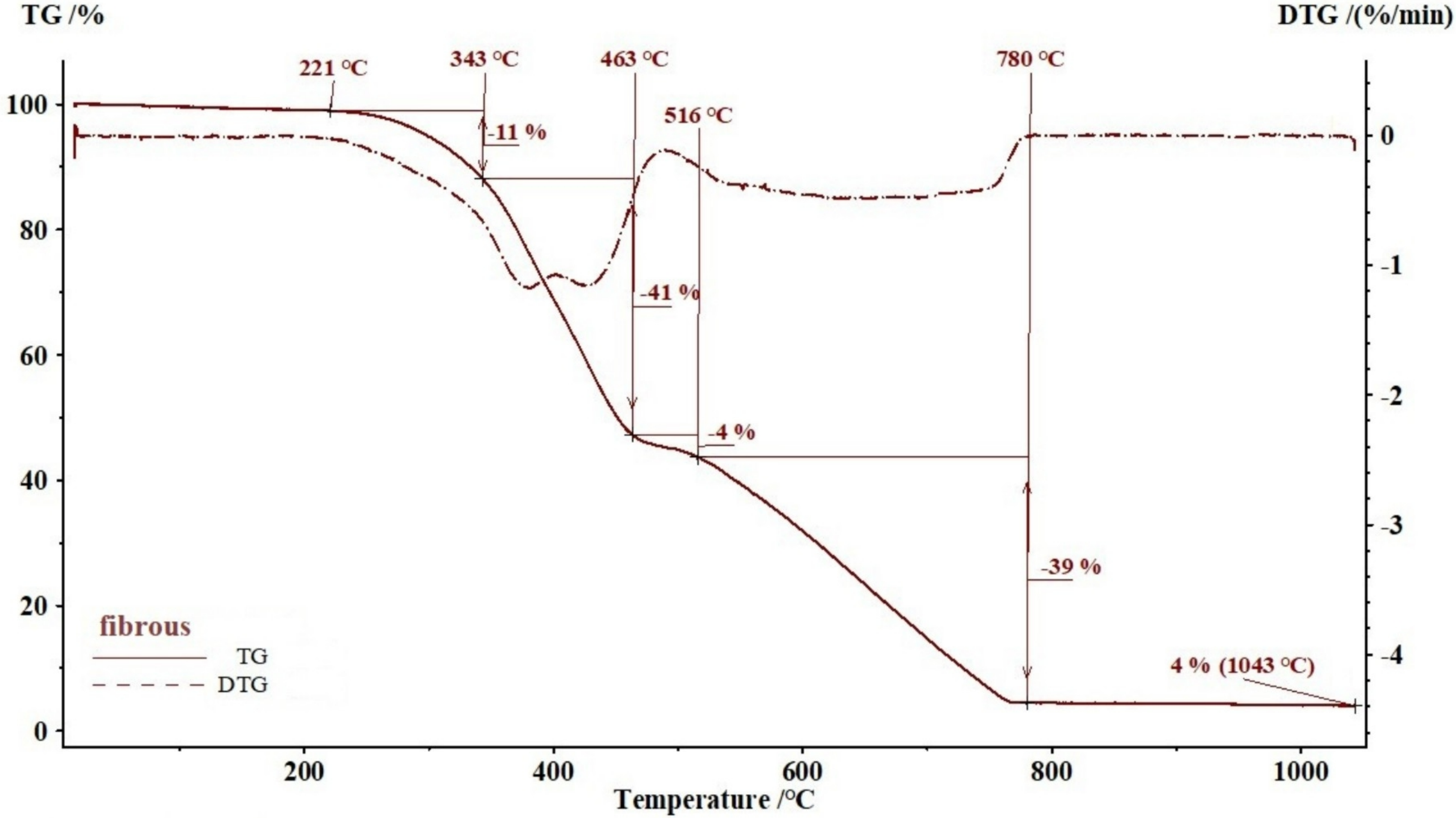
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516 °C
780 °C
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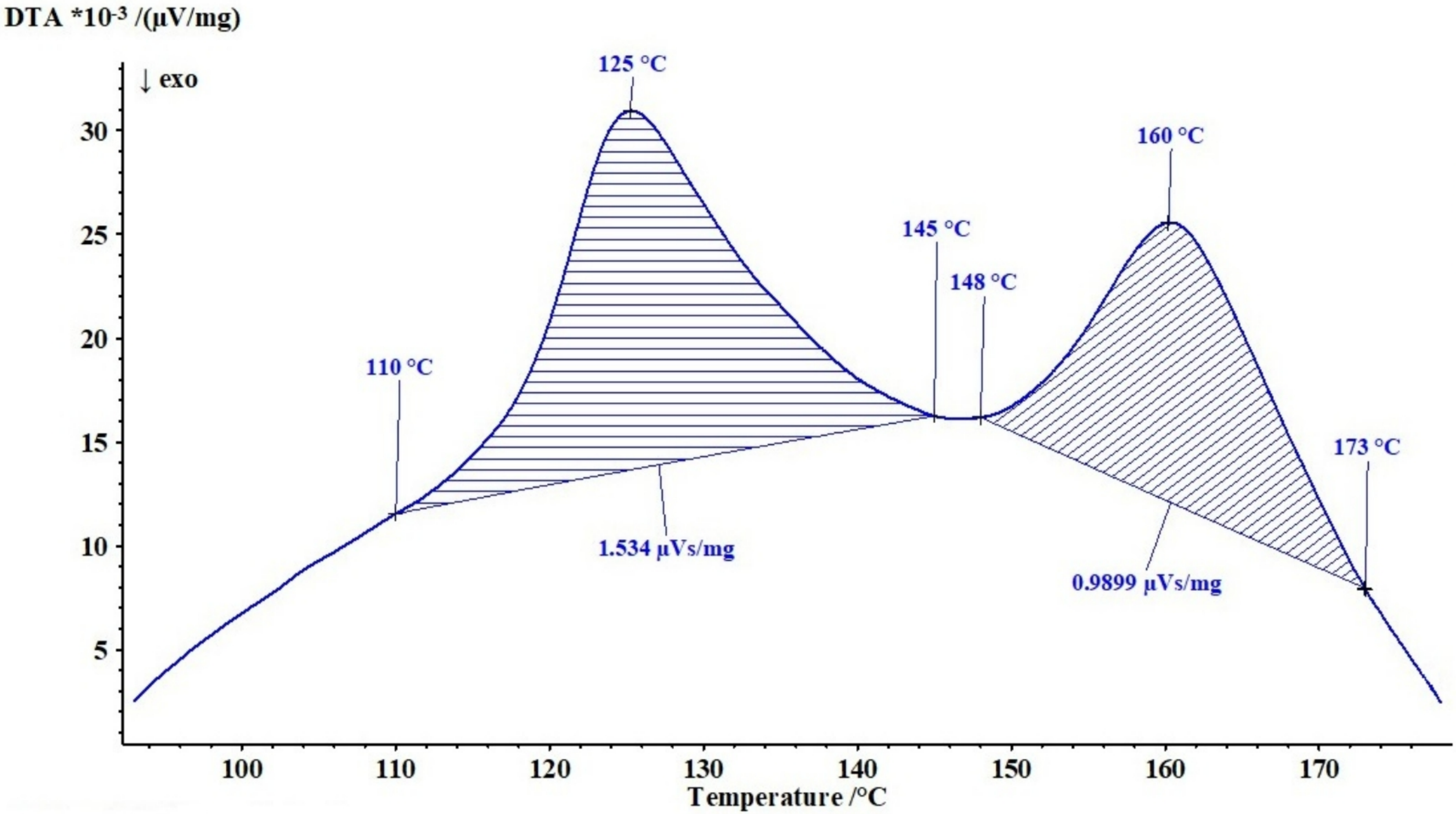
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110 °C
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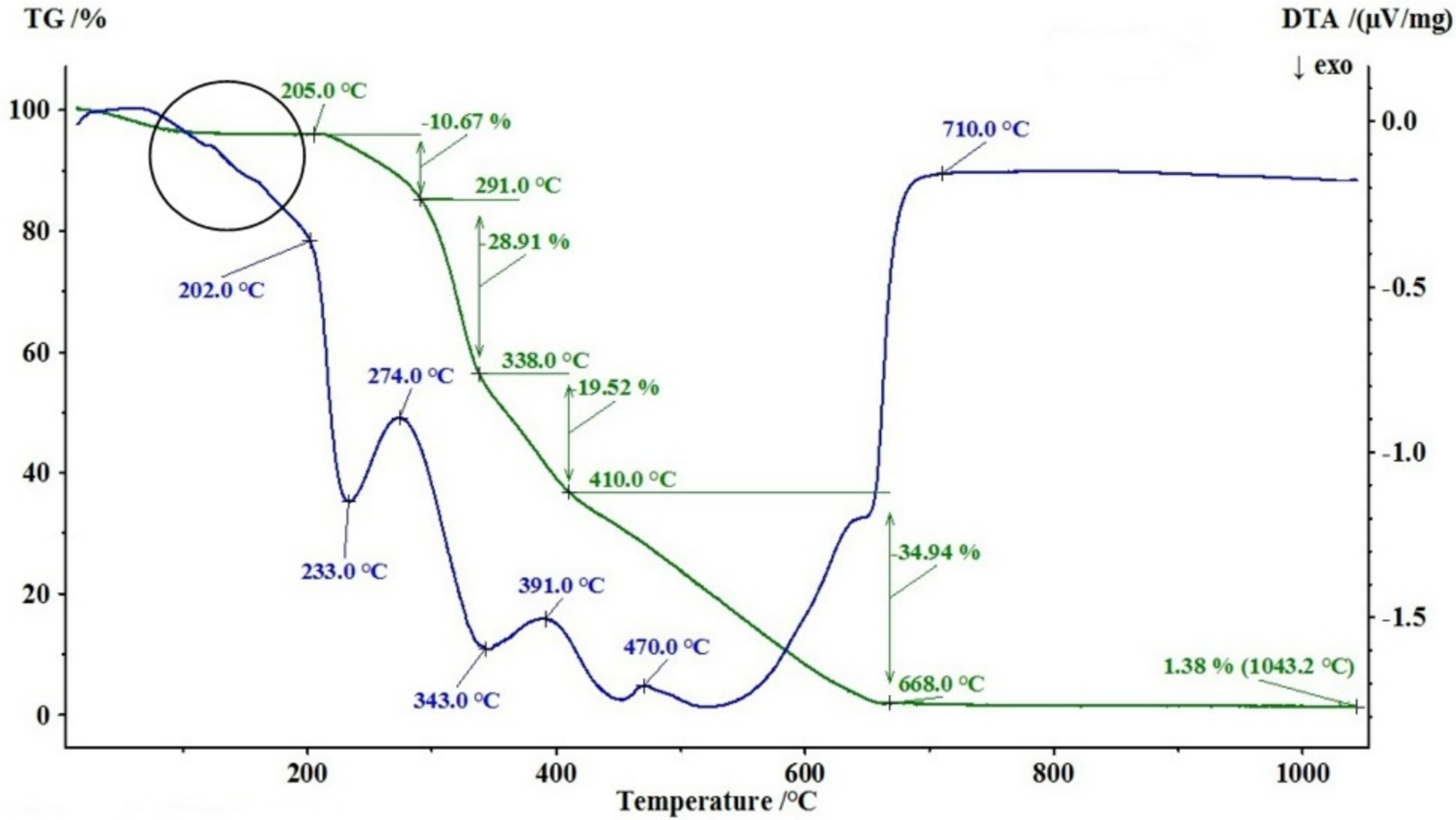
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DTA /(µV/mg)
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-19.52 %
410.0 °C
-34.94 %
668.0 °C
1.38 % (1043.2 °C)
202.0 °C
233.0 °C
274.0 °C
343.0 °C
391.0 °C
470.0 °C
710.0 °C
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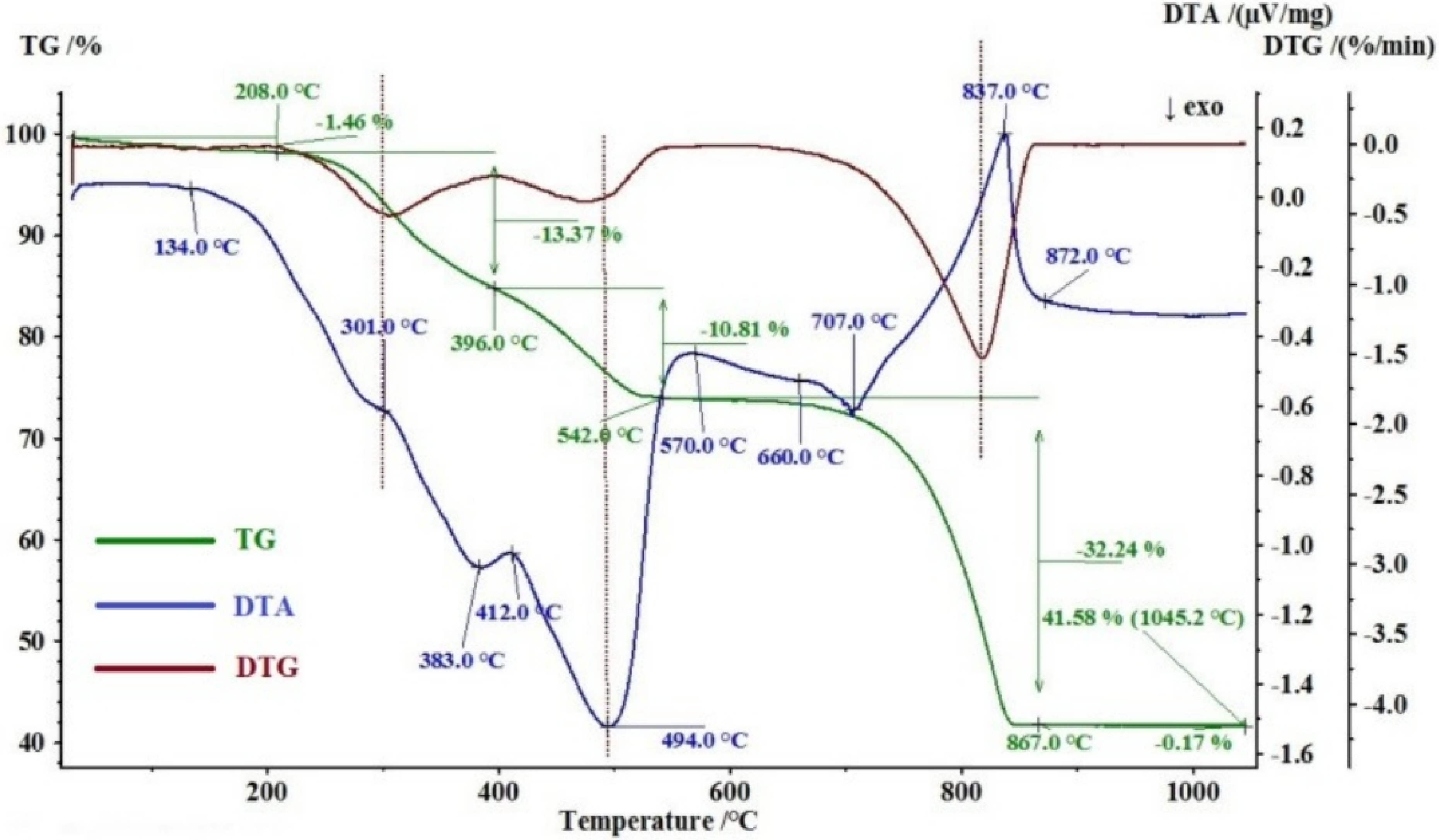
TG /%
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DTG /(%/min)
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208.0 °C
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-13.37 %
396.0 °C
-10.81 %
542.0 °C
-32.24 %
41.58 % (1045.2 °C)
867.0 °C
-0.17 %
134.0 °C
301.0 °C
383.0 °C
412.0 °C
494.0 °C
570.0 °C
660.0 °C
707.0 °C
837.0 °C
872.0 °C
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DTA
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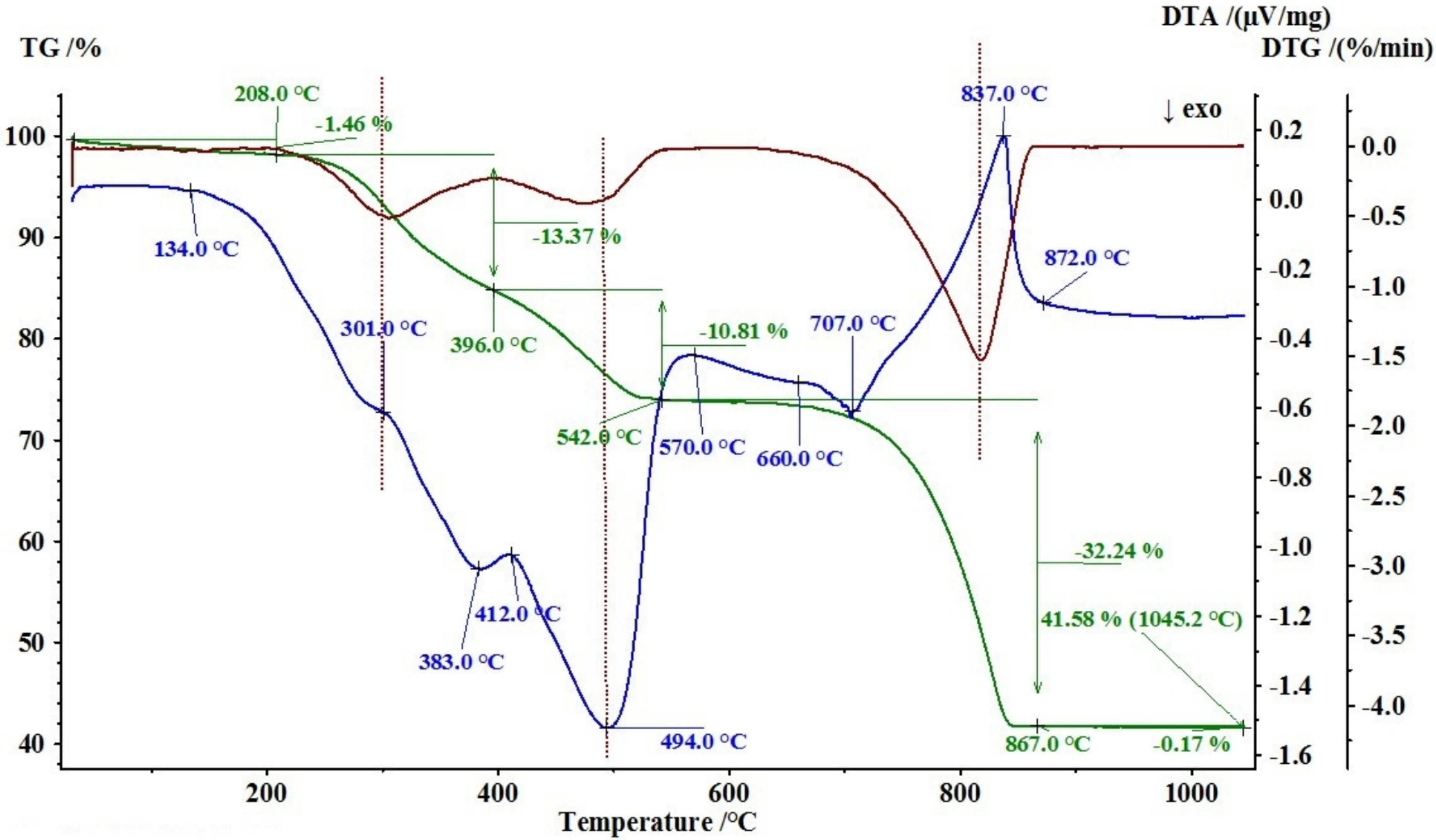
Temperature /°C



DTA /(µV/mg)
DTG /(%/min)
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208.0 °C
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Temperature /°C

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A comprehensive analysis of time influence on floating floors: effects on acoustic performance and occupants' comfort

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Abstract

Impact noise is increasingly becoming an important issue both in terms of technologies for its reduction and in terms of its perception inside buildings. In fact, a high level of noise clearly affects indoor comfort and liveability of confined spaces.
For this reason, this study focuses on the influence which the static load over time impacts on the resilient material of a floating floor and on its final performance. Five different types of resilient materials have been tested for five years and the results are analysed in terms of material type, surface contact and thickness variation, dynamic stiffness measured on 8 different time steps and its application on 6 different bare floors. Obtained values are therefore studied in terms of perceived comfort and compliance with 31 European countries regulations limits.
Results clearly show that time has a paramount influence on all types of resilient materials (with the exception of one) in all configurations and that complete floor selection, in time, can greatly change perceived indoor living comfort and compliance with the limits imposed by laws.

1. Introduction

Acoustic comfort inside buildings is of primary importance for their correct use and proper liveability. This issue has been addressed in many researches and covers several areas such as (i) sound insulation between different apartments, (ii) façade sound insulation, (iii) sound insulation service equipment and (iv) reduction of impact noise.
By carrying out a research on Scopus using "sound insulation building" as a unique keyword and then adding "impact" together with it, the results shown in Figure 1 were obtained. It could be highlighted how research interest in this field has grown very significantly in recent years. It can also be seen that studies on the topic ″impact noise″ have recently been half of those on the whole building acoustic subject. This shows how this specific area is addressed and considered and it is denoted as a very important problem.
In Figure 2 results are reported by changing the research keywords focusing on the effect of load in time (compressive creep) in general and in relation to the acoustic properties (acoustic). As it is possible to see in this case, the first theme is much debated and in continuous growth, while researches related to the determination of acoustic properties have just begun, even if their number is increasing. Among all the considered articles, many of them are related to the instantaneous properties of resilient materials [1]-[3], few are related to the variations over time [4]-[6] and only one work is about the effect of the compressive creep in time, but not related to the acoustic properties [7].

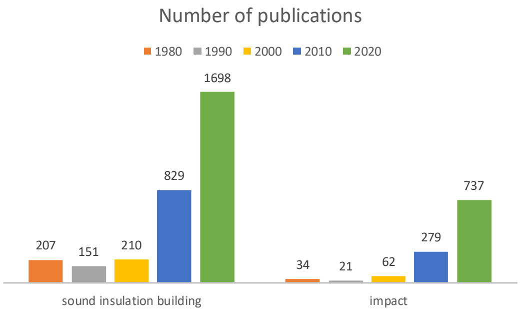

Figure 1 - Results of literature research using combination of the indicated keywords

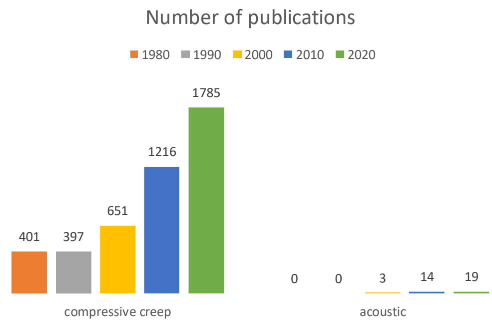

Figure 2 - Results of literature research using combination of the indicated keywords

From the point of view of scientific analysis, the problem of impact noise is relatively recent [8]-[9]. It appeared especially when the first floors were made using bricks, wood or light concrete [10]. These structures easily transmit noise and vibrations in addition to the airborne one [11].

At present, the problem of impact noise is mostly solved by means of a floating floor, consisting of a layer of resilient material, which, if properly installed, separates the upper screed from the bare floor and the flanking structures. The constituted mass-spring system thus greatly reduces the propagation of noise and vibrations from one room to the neighbouring ones [12].

The reference parameter, needed to quantify the attenuation of impact noise, is the dynamic stiffness per unit area. This represents the capability of the resilient layer to dissipate the vibration.

Since this layer is very important for the final acoustic performance, for a complete characterization of its physical-mechanical properties it is necessary to determine the possible decrease in acoustic performance depending on the static load over time. Thus, long term tests are needed.

Researches on recycled and virgin materials are always competing to demonstrate the good performances of former or latter ones [13]-[16]. In this view, most of the time the aim is to demonstrate that recycled materials behave as well as virgin ones. In the field of impact noise reduction, many recycled materials are present, mostly composed of waste from industry [17] or constructions [18].

Another very important component is the change of the floating floor performance depending on the type of bare floor where it is laid. In fact, very heavy bare floors such as concrete slabs or beam and pot structures can provide very different frequency results compared to lighter ones, such as timber frame or timber concrete.

Another paramount topic is the receivers' opinions. Perceived comfort may be affected by impact noise variation over time. Bard et al.[19] defined it as "a concept with opportunities for supportive acoustic conditions according to the activities taking place". In this view, they demonstrated how impact noise on several different buildings affect indoor comfort. Yang et al. [20] demonstrated how many parameters may affect it, but the influence of time was not taken into account.
Lastly, the compliance with regulations limits is very important. Higginson et al. [21] composed a comprehensive review of directive, standards and national requirements. Rasmussen [22] highlighted the difference between countries regulations on different building acoustics parameters, while Östman and Källsner [23] focused only on timber buildings. Nevertheless, no researches dealt with the compliance of multi-layered structures to noise regulation over time.
Therefore, the purposes of this research is to understand how the influence of static load over time can act on:
- dynamic stiffness value of the resilient material;
- overall and frequency reduction of impact noise;
- respect of regulations limits all over Europe.
Another purposes of this work is to understand if there is a possible link between:
- material (virgin or recycled) and acoustic behaviour over time;
- shape of the material (continuous or shaped) and acoustic behaviour over time;
- initial thickness of the material and final acoustic performance.

Another aim of the research is to understand if the acoustic properties related to the floating floor technology, taking into account the effect of the load over time, can be modified according to the different types of bare floors.
Finally, the last aim of this research is to understand if the load can have negative effects on the comfort perceived by the occupants over time.

2. Materials and Methods

In the present study, 5 resilient layers typically used for floating floors realization have been considered. Two of them come from recycled wastes: Tyres Shaves (TS) and Fibres of Recycled Fabrics (RFF). Three materials were chosen on the basis of their composition (expanded rubber), but with different shapes and therefore contact with the bare floor: Expanded Rubber (ER), Expanded Rubber Spot Shaped (ERSS) and Expanded Rubber Line Shaped (ERLS).
Time influence was studied over 5 year, using a static load and room temperature as depicted by standard requirements [24], using steel plates of 8 kg weight each (one per sample). For TS, every test was performed including all the compositions present in the layer. As a further step, chemical description of the two main composition is depicted in next sections. Thermal test were performed after 5 years. It is worthy to highlight that thermal tests results are not influenced by time, since materials composition won't vary in years. What may vary are the provided performances.

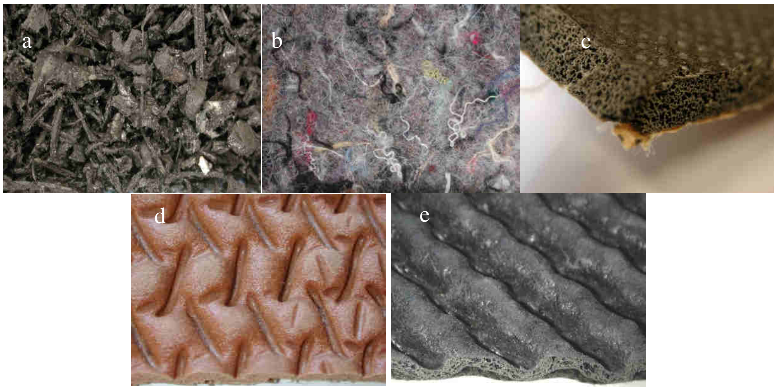

Figure 3 – picture of the considered materials: a) tyre shaves, b) fibres of recycled fabric, c) expanded rubber, d) expanded rubber spot shaped, e) expanded rubber line shaped

2.1. Material characterization

Materials were characterized by Simultaneous Thermal Analysis (STA) with the STA 409 Netzsch instrument (in air) in alumina crucibles from room temperature to 1050 °C, using a heating rate of 10 K/min. Performed analyses are ThermoGravimetric analysis (TG), Derivative Termo-Gravimetry (DTG) and Differential Thermal Analysis (DTA). These measurements are useful to determine precisely the composition of materials and then relate them to the acoustic performance variations caused by static load over time.

Thermogravimety (TG) is a procedure in which the mass of a sample is measured over time compared to temperature variation. This measurement gives information about physical and chemical phenomena including thermal decomposition and solid-gas reactions. DTG is the derivative of the TG curve in time (DTG [%/min]) and it is very useful for a good transition points assessments.

Differential Thermal Analysis (DTA) is a thermoanalytic methodology. In DTA, the material and an inert reference are run through identical thermal cycles, (i.e., same cooling or heating programme), while recording any temperature variations between the two samples. This differential temperature is then plotted versus time, or temperature. Exothermic or endothermic changes can be detected relative to the inert reference. Thus, a DTA curve highlights data on the occurred transformations, such as glass transitions, crystallization, melting and sublimation. The DTA peak area identifies the enthalpy change and it is not affected by the heat capacity of the sample.

2.2. Increment of resilient layer contact surface and thickness variation

In order to understand if the contact surface changes in time, the different contact areas at time t_0 and after 5 years load were analysed. Precise image captures of the deformed shapes were carefully shot and compared with the ones at t_0. Data were then graphically processed by Image Pro Plus (Media Cybernetics).

The contact surface is very important for the dynamics of the floating screed. In fact, the general equation of motion can be expressed as follows (1):

$$x(t) = x_0 + A \cos(\omega t + \vartheta_0) \quad (1)$$

where x_0 is the initial thickness [m], A is the oscillation amplitude, ω is the angular pulsation [rad/s], t is time [s] and ϑ_0 is the initial phase shift.

The equivalence reported in eq. (2) and the Hooke's law for a spring – mass system reported in eq. (3) define the final force reported in eq. (4).

(2) $\ddot{F} = m\,x$

(3) $F = -\,k\,(x_0 - x)$

(4) $m\,x - k\,(x_0 - x) = 0$

where F is the exciting force [N], x is the displacement [m] and x_0 is the initial displacement [m].
In the specific case of floating floor the solution is harmonic and thus x(t) is defined as reported in eq. (5):

(5) $$x(t) = A\cos\left(\sqrt{\frac{k}{m}}\cdot t + \vartheta_0\right)$$

where $\omega = \sqrt{\frac{k}{m}} = 2\,\pi\,f$, where k is the elastic constant and m refers to load density [kg/m^2] and f is the frequency.
The resonance frequency f_0 is depicted by eq. (6):

(6) $$f_0 = \frac{\sqrt{\frac{k}{m}}}{2\,\pi}$$

Now, taking into account the Hooke's law for simple compression load, the final force could be written as eq. (7):

(7) $$\frac{F}{S} = E\,\frac{\Delta x}{x_0}$$

where E is the Young's Modulus [N/ m^2] and S is the surface [m^2]. It is evident how the contact area of the specimen and the final thickness could influence the resulting elastic modulus related to the resilient layer.

2.3. Acoustic characterization

Using EN 29052-1 procedure [25], the dynamic stiffness for unit area s' was investigated. This parameter is in close relation to the resonant frequency f_0 of system composed by the resilient layer and standard static load, as depicted by the equation (8):

(8) $$s' = 4\,\pi^2 m'\,f_0^2 \qquad [\text{MN/m}^3]$$

where m' [kg/m^2] is the total mass per unit area of the static load.
Combining eq. (2) and eq. (8) it is possible to define the dynamic stiffness depending on the Young's Modulus as eq. (9):

(9) $$s' = \frac{E}{d}$$

where d is thickness of the specimen.
Resonance frequencies were determined according to ISO 7626-5 [26]. The measurement facilities (Figure 4) involve an impact hammer PCB Piezoeletronics, a vibration transducer Dytran and a digital recording system (24 bit, 48 kHz sampling).

Figure 4 - Apparent dynamic stiffness test measurement facilities.

Dynamic stiffness tests were performed at t_0 and then the static load was left up to 5 years, measuring the values at every time steps described in Table 1.

Table 1 – time steps of dynamic stiffness tests

t_o
90 days (3 months)
150 days (5 months)
210 days (7 months)
365 days (1 year)
730 days (2 years)
1095 days (3 years)
1461 days (4 years*)
1826 days (5 years*)

* with one leap year

2.4. Impact noise reduction in time

In order to understand how the static load influence over time modifies the reduction of impact noise, dynamic stiffness data have been used to evaluate the decrease of acoustic properties on six different types of bare floors.

The analytical model for the reduction of impact noise is based on the assumption that the bare floor normalised level of impact noise is known. Then, the effect offered by the floating floor is subtracted, according to eq. (10):

$$L_n = L_{n,0} - \Delta L \qquad \text{(dB)} \tag{10}$$

where L_n is the resulting impact noise (dB) for every 1/3 octave band frequency, $L_{n,0}$ is the bare floor impact (dB) for every 1/3 octave band frequency and ΔL is the floating floor noise reduction (dB) for every 1/3 octave band frequency.

As it can be seen, the influence of the bare floor is the reference to calculate the final floor performance. Knowing its behaviour is therefore of paramount importance. Moreover, as highlighted

by Cho [27], by changing the type of base floor, the noise reduction offered by the floating floor will change.
This system can be modelled as reported in equation (11):

$$\Delta L = 30 \log \frac{f}{f_0} \quad \text{(dB)} \qquad (11)$$

where f_0 is updated considering the different composition and time-step.
Equation 11 was used to calculate the impact noise reduction in frequency. Thus, all bare floors and all floating floors' influences were considered in frequency.
After this procedure the final $\Delta L_{w,freq}$ is calculated, taking thus into account bare floors frequency behaviour and floating floors frequency reduction (eq. 12):

$$\Delta L_{w,freq} = L_{n0,w} - L_{n,w} \quad \text{(dB)} \qquad (12)$$

Formattato: Numerazione automatica + Livello:1 + Stile numerazione: 1, 2, 3, … + Comincia da:1 + Allineamento: A destra + Allinea a: 3 cm + Imposta un rientro di: 3.64 cm

Six bare floors were then chosen among the most used in Europe (Table 2) and the frequency impact noise reduction indexes are calculated for all configuration depicted in Table 1. The maximum differences between indexes are then highlighted.

Table 2 – bare floors used in this study

acronym	*description*	*Thickness [cm]*	*reference*
CLS	Reinforced concrete slab	14	[28]
B&P	Reinforced concrete beams of 12 to 14 cm width, together with reinforced concrete slab of 4 to 6 cm thickness and perforated bricks or polystyrene blocks	16 to 28	[29]
TC	Timber beams spaced of 400 to 750 mm between axis and to which were attached plywood boards of 22 mm thickness. Concrete slab of 40 to 60 mm height	8 to 10 (between beams)	[30]
CLT	Solid timber layers glued to form a solid slab	13.5 to 20	[31]-[32]
GL	Prefabricated panels composed by spaced glulam beams of 16 cm thickness with fibrous layers in between, closed by 22 mm plywood panels (top and bottom)	20	[33], [34]
CXPS	Two panels of 15 mm thickness of recycled materials, with a 200 mm chamber filled with two panels of polystyrene	20	[35]

2.5. Statistical analysis
ANOVA and the Mann-Whitney U tests were used in order to verify if the following hypotheses are statistically significant:

1) the 5-year impact noise is related to initial dynamic stiffness value;
2) the 5-year impact noise is related to the material type;
3) the final value of dynamic stiffness is related to the 7 years creep value;
4) the final value of the dynamic stiffness is related to the final contact area;
5) the final value of the dynamic stiffness is related to the final thickness;
6) the final dynamic stiffness value is related to the static load over time;
7) floors noise reduction index for the same material is related to the static load over time;
8) single floor performance for different materials is related to the static load over time;
9) subjective evaluation for all floors (the same material) is related to the static load over time;
10) subjective evaluation for single floor (different material) is related to the static load over time;

ANOVA represents a statistical test of whether two or more population means are equal. Statistically significant result, when a probability (p-value) is less than a pre-specified threshold (significance level), justifies the rejection of the null hypothesis. F is a function involving a ration of two variance. Mann-Whiteny U test can be used to study whether two samples were selected from populations having the same distribution. The test involves the calculation of a statistic, usually called U, whose distribution under the null hypothesis is known. Z-score shows how standard deviations below or above the population mean behave.
In the following, each hypothesis will be identified by its list number. The corresponding label is used to refer to each material.

2.6. European standards and regulation comparison

The influence of load over time can affect the limits fulfilment imposed by legislations. Thus, a comparison was made between all the steps listed in Table 1 and Table 2 and between the regulations of 31 European countries. To perform such evaluation, the data collected over the years by Rasmussen [36] and updated at 2019 [37] were used. The regulations limits do not adapt to changes due to load in time (within the same law), thus they are valid from t_0 to the end of the building life, or a new upgrade on the same regulation, operated by single country, by public bodies.

2.7. Subjective evaluation of impact noise modification

In order to understand how the variation caused by the load over time can affect the comfort of the occupants, an analysis has been made related to parameters associated with the 5 materials and calculated on the basis of the values of dynamic stiffness obtained in the various steps from t_0 to 5 years [38].
Even if the arithmetic mean was shown to be the factor that best relates to the perceived disturbance [39], referred to the tapping machine applied to composite floors with heating systems, Rindel and Rasmussen [40] proposed to use another parameter, namely $L_{n,w} + C_{I,50\text{-}2500}$, calculated according to the standard ISO 717-2 [41].
$L_{n,w} + C_{I,50\text{-}2500}$ is widely used in literature and many times demonstrated to have statistically significance especially for lightweight timber buildings [43]-[44].
Hopkins [45] used this parameter to highlight how it is very useful to identify the impact noise annoyance. The correlation by subjective evaluation compared to measurements show a successful agreement only comprising this correction. Rindel [46] highlighted that a good agreement is only possible when low frequency impact noise are included in the evaluation and thus the use the frequency adaptation term is compulsory for the best acoustic comfort assessment.
For these reasons, this parameter will be calculated and discussed.

3. Results

The results of the several test and analysis are reported in the following sections.

3.1. Materials characterization

From macroscopic observation (Figure 3a), TS sample is characterized by two types of shaves (Figure 3a): compact (rounded chips) and fibrous (longer chips). The thermal tests results are resumed in Figure 5 and Table 3.

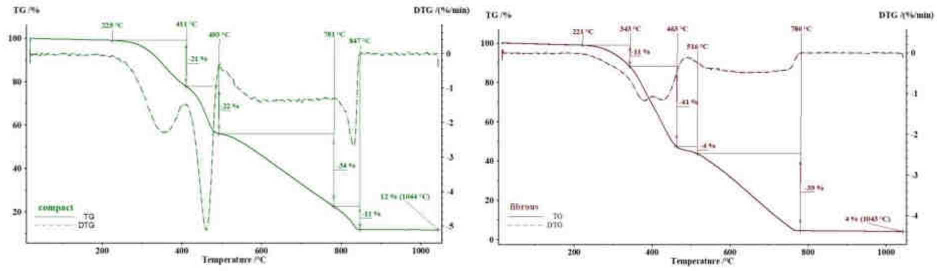

Figure 5 –TG and DTG results for TS. Green: compact; red: fibrous. TG [%] represents the percentage weight loss of the sample compared to initial stage. DTG [%/min] represents the derivative in time of the TG curve. DTA [µV/mg] represents the difference in temperature measured in µV per mg.

Table 3 – STA results for the TS sample

components	*Compact chips % by weight*	*Fibrous chips % by weight*
Rubber	42 % (NBR+SBR)*	52 % (NBR)
Carbon black	38 %	40 %
Calcium carbonate	16 %	--
Other filler	4 %	4 %
Residue @ 1000°C	12 %	4 %

*NBR: Nitrile Rubber; SBR: Styrene Butadiene Rubber

From macroscopic observations (Figure 3b), RFF sample is characterized by several kind of recycled fibres glued together. It is then important to know the nature of the components in this resilient layer. Thus, the results are resumed in Figure 6. Here it could be seen (right) that the main component is glue, composed by polyethylene and polypropylene.

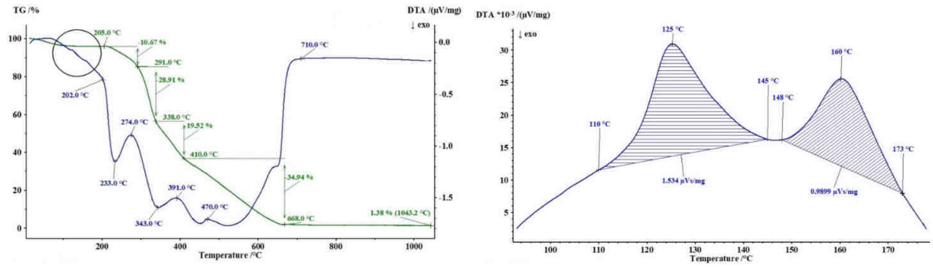

Figure 6 – TG and DTA results for RFF (TG green curve; DTA blue curve). LEFT complete plot, RIGHT highlight of the melting peaks, corresponding to the melting of PE (125°C) and PP (160°C). TG [%] represents the percentage weight loss of the sample compared to initial stage. DTG [%/min] represents the derivative in time of the TG curve. DTA [µV/mg] represents the difference in temperature measured in µV per mg.

For Expanded rubber (ER), Expanded Rubber Spot Shaped, (ERSS), Expanded Rubber Line Shaped (ERLS), it could be seen (Figure 3 c, d and e) that they are produced using the same components, but with different final shapes. For the sake of brevity in Figure 7 and Table 4 only the ER results are depicted, since the ERSS and ERLS are very similar.

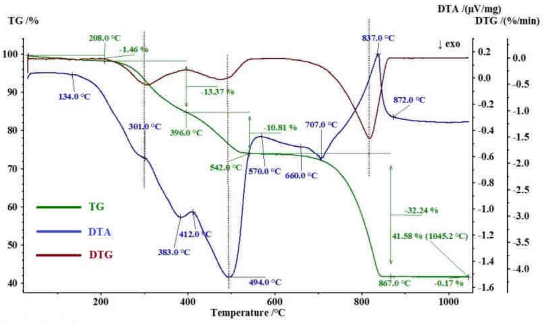

Figure 7 – TG, DTA and DTG results for ER, ERSS and ERLS samples .TG in green, DTA in blue and DTG in red. TG [%] represents the percentage weight loss of the sample compared to initial stage. DTG [%/min] represents the derivative in time of the TG curve. DTA [µV/mg] represents the difference in temperature measured in µV per mg.

Table 4 – STA results for the ER, ERSS and ERLS samples

components	*% by weight*
Polymer → PDMS	26.0
Carbon black (calculated)	1.0
Calcium carbonate	73.0
Residue @ 1045 °C (CaO)	41.6

3.2. Variation of contact surface and thickness

The layers TS, RFF, ERSS and ERLS were analysed in terms of increment of contact surface and thickness variation at t_0 and 5 years and the ER (flat sample) is used as control. The results are reported in Table 5.

Table 5 – contact surface and thickness variations of different resilient layers

	contact surface and thickness variations				
Material	**TS**	**RFF**	**ER**	**ERSS**	**ERLS**
% surface contact at t_o	17.4	12.1	96.0	26.4	19.9
% surface contact at 5 years	17.6	53.4	96.0	26.6	23.4
% surface increment	1.0	341.0	--	0.3	17.6
% thickness decrement	-29.4	-12.6	-21.2	-9.3	-12.2
% E variation based on (7)	-1.0	77.0	0.0	-0.3	-14.9

3.3. Acoustic characterization

In Table 6 the results of the dynamic stiffness tests are reported, for different time steps.

Table 6 – dynamic stiffness measurements

Time steps	*Dynamic stiffness value of different resilient layers [MN/m³]*				
	TS	**RFF**	**ER**	**ERSS**	**ERLS**
t_0	15.1	16.5	44.0	20.3	27.0
3 months	30.0	20.3	53.9	36.3	38.8
5 months	30.0	23.6	59.3	36.2	43.5
7 months	24.5	39.9	59.7	38.4	38.4
1 year	54.9	41.7	150.2	47.8	40.0
2 years	64.8	37.2	63.5	58.7	43.5
3 years	72.2	36.6	63.5	63.0	41.0
4 years	48.0	44.0	70.7	56.0	44.8
5 years	49.2	53.4	71.2	52.3	43.5

In Figure 8, the results in terms of resonance frequency are depicted for t_0, 5 months and 7 months, while in Figure 9 the results are reported for each year. For the sake of brevity, only TS, RFF and ER are reported, since ERSS and ERLS frequency behaviours variation caused by static load in time are very similar.

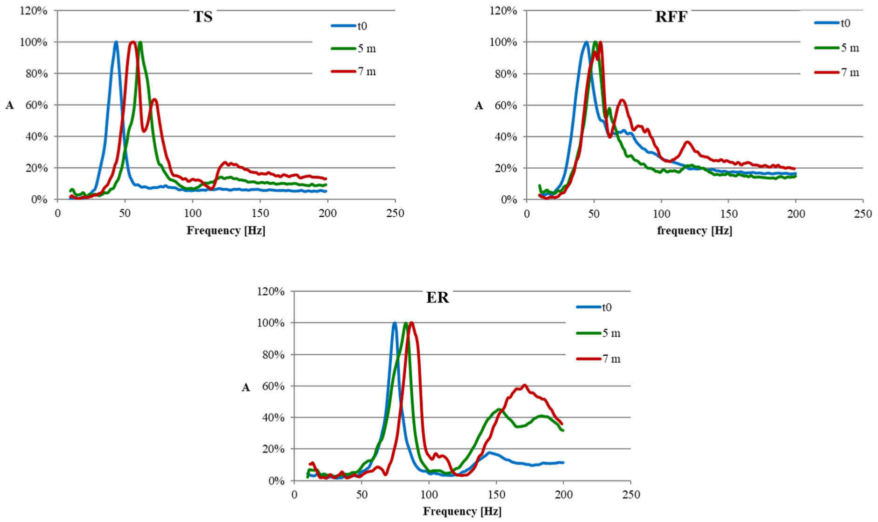

Figure 8 – Resonance frequency results for TS, RFF and ER for time steps t_0, 5 months and 7 months. A [%] represents the variation of amplitude response compared to the static system step, measured by accelerometer

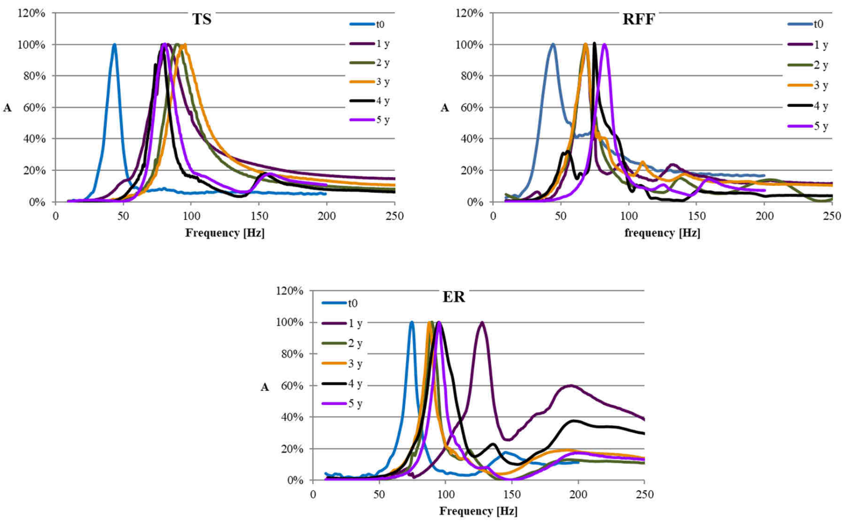

Figure 9 – Resonance frequency results for TS, RFF and ER for time steps t_0, 1, year, 2 years, 3 years, 4 years, 5 years. A [%] represents the variation of amplitude response compared to the static system step, measured by accelerometer

3.4. Impact noise reduction caused by load over time

In Figure 10, the frequency impact noise reduction indexes of all selection of bare floors combined with all dynamic stiffness values measured in time are reported and compared. The normalized sound pressure levels for every combination are present in the supplementary data (figure I – figure V). In Table 7, the bare floors L_{n0} values are reported, obtained from frequency trends.

Table 7 – bare floors $L_{n0,w}$ impact noise, calculated ~~in~~ using frequency trends

Type of bare floor	*$L_{n0,w}$ (dB)*
GL	76
CLT	80
CXPS	82
TC	88
B&P	87
CLS	87

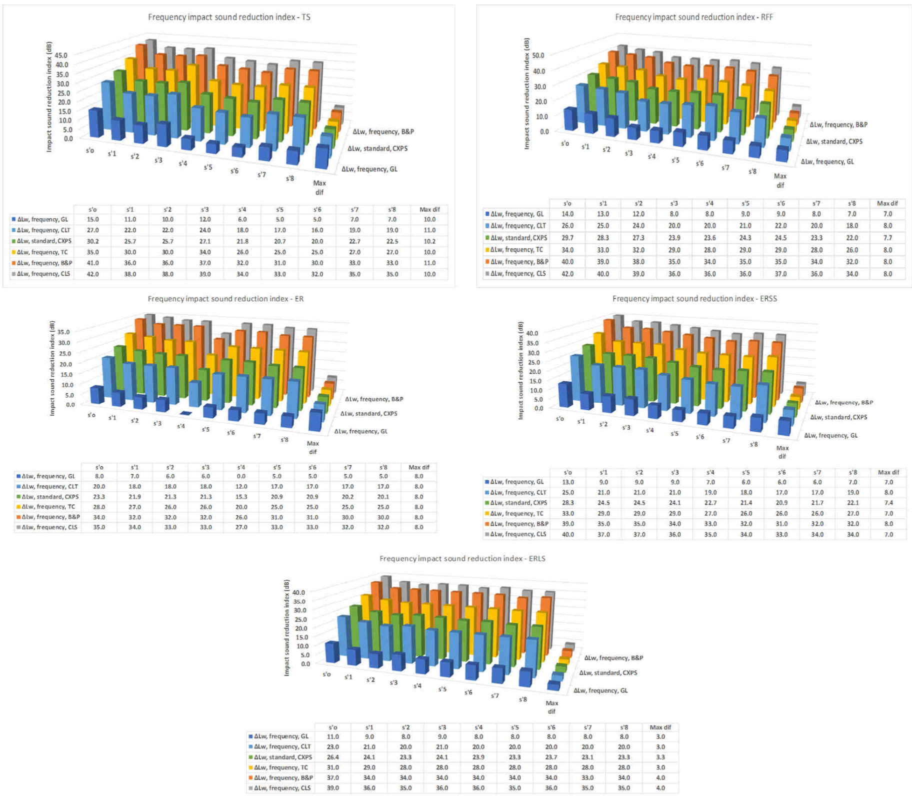

Figure **10 –** Frequency impact reduction index $\Delta L_{w,freq}$ calculated over 5 years basing on measured dynamic stiffness values and applied to 6 different typical floors

3.5. Statistical analysis

The results of the statistical analysis using the Mann-Whitney U and ANOVA methods are given in Table 8 and Table 9.

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Table 8 – Mann–Whitney U test

hypothesis	z-score	U Test	p-level	Significance
1	-2.29783	1	0.02144	*No*
2	2.50672	0	0.01208	*No*
3	-2.50672	0	0.01208	*No*

Table 9 – Anova test

hypothesis	sum of squares	F test	p-level	Significance
4	123247.3	1.72	0.22536	*No*
5	71225.6	16.08	0.00389	Yes
6	119235.6	5.13	0.00196	Yes
7 TS	36434	93.87	< 0.00001	Yes
7 RFF	39378	170.55	< 0.00001	Yes
7 ER	27705	234.54	< 0.00001	Yes
7 ERSS	34391	208.91	<0 .00001	Yes
7 ERLSS	35400	1011.22	< 0.00001	Yes
8 CLS	57021	5.35	0.001508	Yes
8 B&P	52577	6.99	0.000228	Yes
8 CLT	18245	4.22	0.006028	Yes
8 TC	35754	4.08	0.007172	Yes
8 GL	3256	4.36	0.005027	Yes
9 CXPS	7326	5.18	0.001834	Yes
9 TS	119252.35	9.48	< 0.00001	Yes
9 RFF	113362.05	15.76	< 0.00001	Yes
9 ER	137355.63	21.68	< 0.00001	Yes
9 ERSS	122514.65	19.97	< 0.00001	Yes
9 ERLSS	119459.11	104.71	< 0.00001	Yes
10 CLS	97261.52	4.715	0.003266	Yes
10 B&P	96807.79	4.725	0.003229	Yes
10 CLT	104502.1	4.709	0.003292	Yes
10 TC	126850.96	4.666	0.003470	Yes
10 GL	81722.97	4.650	0.003542	Yes
10 CXPS	104798.45	4.62	0.003665	Yes

3.6. Comparison with European regulations

In Figure 11, the performance of the 6 complete floors calculated in different period of load in time are considered and compared with 31 European countries regulations. All the complete comparisons are included in the supplementary data.

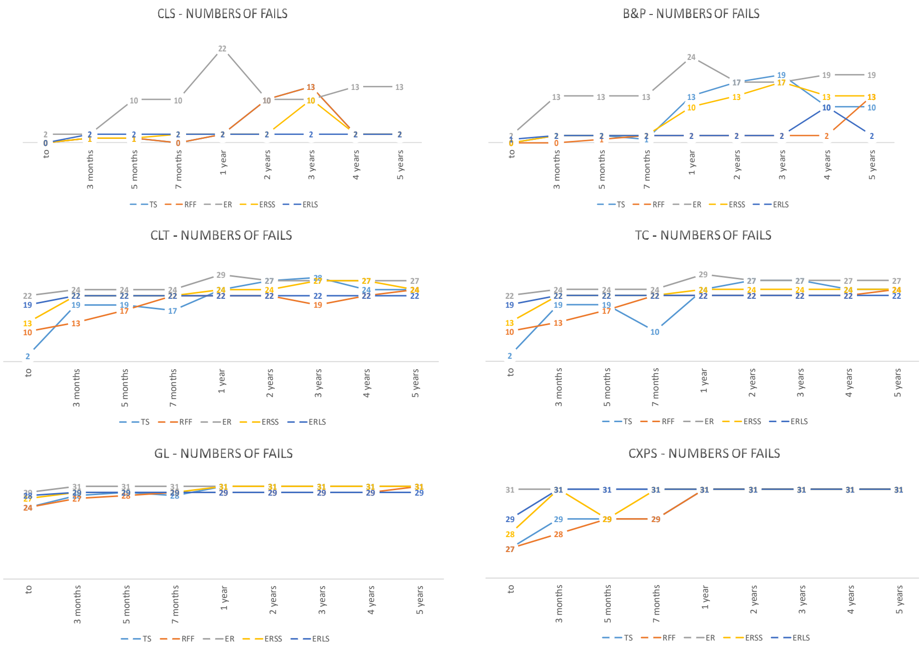

Figure 11 – Percentage of fails for different bare floors with floating floor referred to European regulations.

3.7. Subjective evaluation

In Figure 12, the complete floors after different period of load time are considered and the frequency adaptation term $C_{I,50\text{-}2500}$ is depicted, reporting also minimum and maximum values.

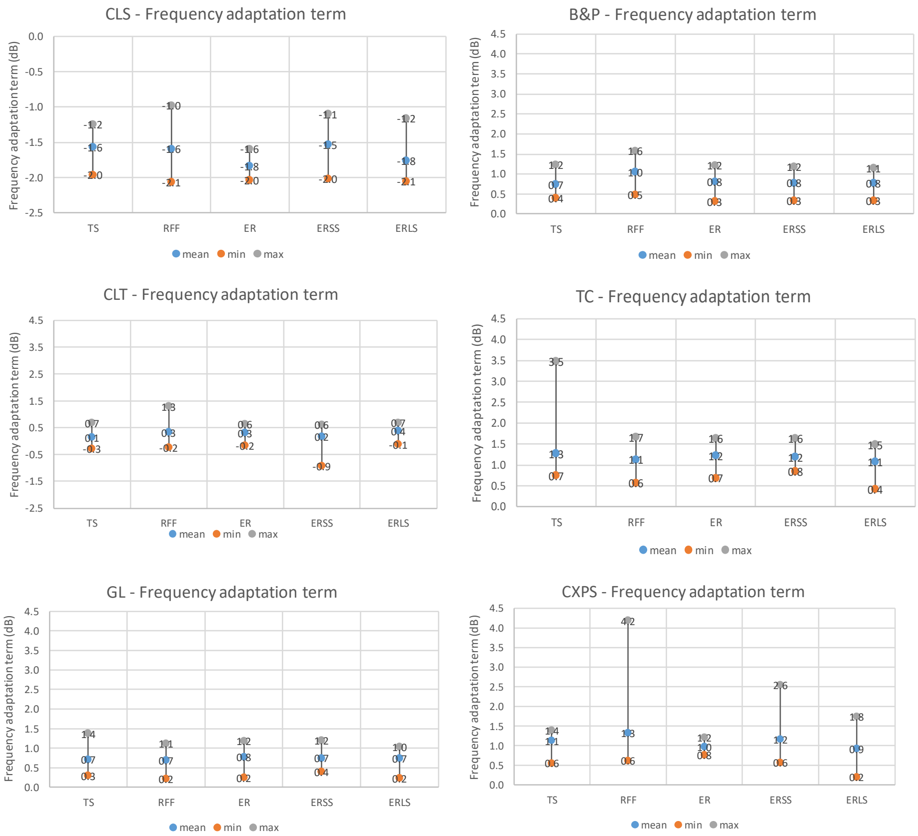

Figure 12 – graphical representation of frequency adaptation term $C_{I,50\text{-}2500}$.

4. Discussion

From the TS STA results (Figure 5), synthetically reported in Table 3, it results that the blends composing rounded chips and longer chips are different [47], [48], as well as the fillers quantities. It is worthy to highlight that all these two kind of chips compose always every TS sample (Figure 3a). Longer chips are taken from tyre recycle. According to literature [49], a tyre can be composed of 45 % by weight of rubber, 20 % of carbon black, 16 % of steel, 6 % of fabric, 3 % of zinc oxide, 3 % of sulphur and 6 % of other substances.

Accordingly, rubber includes steel. This fact affects the stiffness of the layer as the material compacts in time and this could explain the effect of the volcano-shape tendency at higher frequencies. In other words, the stiffness of the spring increases, because of the presence of a more compact phase. This can also be noticed from the curves examination related to the resonance frequencies depicted in Figure 8 and Figure 9.

As a matter of fact, at t_0 there is only one resonance peak (44 Hz); after 5 months the main peak moves to a higher frequency (62 Hz) and at an even higher frequency (125Hz) a smaller one appears. After 7 months, the main peak splits into two different peaks (56 Hz, 72 Hz) and smaller one (124 Hz) grows in importance.

This behaviour is explained by the fact that over time the material composing the tyre chips divides into two phases with clearly separated stiffness values. It should be noted that the splitting of the main peak after 7 months results from the segregation of the material. It is evident that the two phases stand apart one from the other, presenting different stiffnesses. This fact can also be deduced from the STA result, because the more compact phase presents a higher inorganic load and it is therefore more rigid. For longer load times (Figure 9), only one peak is present up to 3 years and continues to move to higher frequencies. This fact shows how the layer behaves again as a single phase (combing the two kinds of chips), more compact and therefore more rigid. After 4 years, the main resonance peak moves to lower frequencies and is still visible after 5 year, and a 155Hz smaller peak appears. It is known [51]-[55] that a viscoelastic material does not have a constant elastic modulus, which is instead influenced by the boundary conditions. Specifically, the load-in-time phenomenon provokes a decrease in modulus, namely, rubber softening effect. This explains the displacement of the main resonance peak toward lower frequencies. On the other hand, in this case it is likely that the present filler, certainly more rigid, will increase in importance with the appearance of the peak at 155 Hz.
For RFF, the STA results in Figure 6 show that there are cloth fibres glued together by a mixture of partially crystalline polyethylene (PE) and polypropylene (PP), easily identifiable by the melting peaks (Figure 6 right). The TG curve (Figure 6, green curve) is congruent with the thermal decomposition in air of a mixture of fabrics of natural and artificial origin [56]. The final residue of 1.4 % by weight suggests that there is also the presence of inorganic filler.
At t_0, 3 different peaks are present, the main one at 45 Hz and two others at slightly higher frequencies (56 Hz and 73 Hz). After 5 months, the first two peaks move to higher frequencies (51 Hz and 62 Hz) and new smoothed peak appears at higher frequency (123 Hz). After 7 months, the main peak splits into two peaks (51 Hz and 55 Hz) and other 3 peaks (71 Hz, 86 Hz, 119 Hz) appear, where the highest frequency one is the same peak present also after 5 months.
The material is composed of fibres waste glued by a two-phase polymeric adhesive: PE and PP. This fact explains the presence of three different resonance peaks. In order to understand the influence of the adhesive phase on the resonance frequency, the dynamic stiffness of a polymeric sheet composed of PP/PE (essentially PP with small content of PE) was considered. Figure 13 shows as an example the comparison between the latter material and RFF after 5 months. It is clearly evident how the interval between the two peaks of PP/PE is the same to the one found for RFF. The difference in frequency is attributed to fact that the PP/PE sheet is compact and therefore more rigid. Therefore it can be deduced that the main resonance peak of the RFF sample is caused mainly by the glue (PP+PE) and not by the fibres.

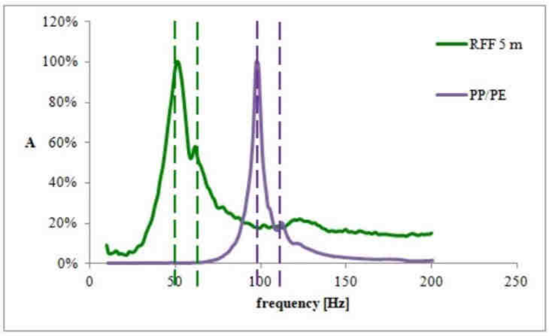

Figure 13 – Resonance frequency of the RFF sample after 5 months of creep and a compact sheet of PP-PE

Figure 9 (longer load time), shows that after 1 year there is a further shift of the main resonance peak at 68 Hz which remains constant until 3 years. At 4 years a small peak at 55 Hz appears, while the

main peak moves at a higher frequency (90 Hz). At 5 years, the main peak moves to 93 Hz, maintaining the second peak at higher frequencies.
For ER, the STA results in Figure 7 show that this layer is composed of polymers filled with calcium carbonate. The two-steps exothermic decomposition pattern appears to be consistent with silicone (PDMS = PolyDiMethylSiloxane) [57],[59]; the last step of decomposition, associated with an endothermic peak, is attributable to the thermal decomposition of calcium carbonate.
Table 4, which summarizes the composition derived from the thermal analysis, shows that it is calcium carbonate glued with black carbon foamed silicone. Even in this case the dynamic stiffness increases in time. For the sake of brevity, only the ER behaviour is reported in the following discussion.
At t_0, a peak at 75 Hz is present, but another peak appears at higher frequency (145 Hz). As time goes by, the main peak moves to higher frequencies (83Hz) and the 145 Hz peak increases in importance. After 5 months, this last peak splits in two (151 Hz + 184 Hz). After 7 months, the main peak moves further up (87 Hz), while the secondary peak at higher frequency becomes a single peak at 172 Hz.
Figure 9 shows how between 7 months and 1 year there is a significant shift of the main resonance peak at a frequency of 127 Hz and the status of the peak at 194 Hz increases. After 2 and 3 years, the behaviour changes and the main peak drops in frequency and the secondary one(s) move to lower frequencies too. After 4 years, the main resonance peak starts to rise slightly in frequency, while the secondary peak increases in importance at 195 Hz. At 5 years the main peak stand still but the peaks at higher frequency gain in importance.
The secondary peaks can be explained by the large presence of inorganic filler (73 % by weight of calcium carbonate), which is much more rigid than the rest of the polymer. For both peaks, there is an anomalous trend as the time proceeds, showing a clear increase between 7 months and 1 year and then a decrease after 2 years. In the case of the higher frequencies secondary peak(s), this phenomenon can be attributed to calcium carbonate. A partial separation with the formation of areas with higher concentrations of charge (more rigid) affect final results. For the polymeric foam phase, responsible for the main peak, the frequency reduction after 2 years is attributed to the phenomenon of rubber softening.
The above analysis shows how resilient materials change their elasticity over time due to static load and therefore modify their efficiency in reducing the impact noise. This fact is partly related to components and partly by how much the same material is produced in its various phases. It is clear that TS proposes inconstant behaviour because of the lack of a binder between the two macro-components, while for RFF it is clear that the resilient part is to be attributed exclusively to the glue and not to the recycled fibres. In this sense, however, the glue acts very well as a compacting agent and can give uniformity of response to the material over time. In fact, the peaks of resonance at higher frequencies, ignored by the ISO 29052 standard in the process of determining the dynamic stiffness, actually play an important role in reducing the impact noise. In fact, they can decrease the efficiency of the performance of the floating floor. Since they are real resonance frequencies, they will contribute to a poor acoustic performance. Therefore, it is evident how it is not important whether the material is recycled or not, but how well is produced and how much the binder is efficient.
The load over time therefore has an influence on floating floors. This is highlighted in Figure 10, where the frequency impact reduction index data are reported and calculated on the basis of dynamic stiffness values measured over time and applied to the six considered bare floors. It is clearly shown that, depending on the type of material, there are substantial differences. For example, for TS the maximum difference found is 11 dB, for RFF 8 dB, for ER 8 dB for ERSS 8 dB and for ERLS 4 dB. It is also possible to highlight how this difference is influenced by the type of bare floor, even if in this sense the maximum difference found is 1 dB for all materials. Since the final impact noise reduction is a combination of the floating floor and the bare floor, from the same figure (and from the figures I - V in the supplementary data), it is clear that, for the lightweight slabs, the load over time acts more significantly, while for the CLS and B&P the reduction of the acoustic performance is slightly lower. For all materials, an initial stiffening is verified and therefore a progressive reduction

in acoustic performance. However, for all materials there is also an improvement of dynamic stiffness values over time, due to the softening of the polymeric part. The greatest degradation occurs in the ER material, for which, when applied to the GL floor, it is even able to cancel the overall performance of the floating floor in s'_4 step (1 year). For all tested materials, a greater reduction in impact noise is achieved when the bare floor is heavier. In accordance with previous research [60], the heavier floors are able to compensate this, because of their overall stiffness. Specifically, for TS (figures I – V supplementary data) it is evident that for the CLS floor the behaviour of the impact noise, calculated according to the equation (10), is linear in the frequency trend, starting from about 50 dB at low frequencies (t_0) and ending at about 30 dB at high frequencies. A very similar trend can be verified for RFF, as it presents tendencies similar to TS (figures II - supplementary data). This is not repeated for the other floors, where the difference from low frequencies compared to high frequencies is higher. This variation grows in importance for the CLT, GL and CXPS floors. For the two last, values lower than zero at high frequency are present. In this case, the calculation is not able to take into account all the effects of flanking transmission and, in any case, a residual noise will be present in the receiving room, cancelling the impact one. For this reason, very low impact noise values, despite having maybe a physical reason, do not make sense in the reality of things.
In contrast, ER (figures III - supplementary data) shows a noticeable frequency modification in time, especially after 1 year, where the difference reaches values greater than 8 dB in frequency. The behaviour of ERLS is in line with what was presented for TS and especially for RFF, while for ERSS there are much less marked differences, given the excellent stability over time.
As a matter of fact, the surface contact variation in time does not influence final behaviour, while thickness difference does. In fact, from Table 5 and Table 9 itis possible to highlight that, while some surface contact variation are present from t_0 to 5 years, a related modification of the dynamic stiffness is not verified. Furthermore, using ER as control material (without surface contact variation), it is possible to state that only the thickness variation (and thus dynamic stiffness, eq. (9)) influences final results. Thus, the combination between Young's modulus modification determined by standard excitation (Figure 8 and Figure 9) and the decreasing thickness is the phenomenon that really affects impact noise reduction in time.
By means of statistical analysis, it was possible to correlate different behaviours with the initial listed hypotheses (section 2.5). From the Mann-Whitney U analysis reported in Table 8, it is clear that the final effect after 5 years of loading is not related to the initial value of dynamic stiffness, nor to the type of material, nor to the values of compressive creep that the material has after 7 years and calculated according to EN 1606 [24],[61]. This fact demonstrates how it is not possible to determine such behaviour in advance, but a reduction in performance of up to 11 dB relative to the frequency impact noise reduction index is possible.
The statistical analysis reported in Table 9 provides the results of the ANOVA parametric test, showing how the effect of the load over time clearly influences several factors such as (i) the dynamic stiffness value (ii) noise reduction index, using the same material as fixed parameter, (iii) single bare floor but with different resilient layers performance, (iv) subjective perception of diverse bare floors using the same material as fixed parameter and (v) subjective perception of single bare floor as fixed parameter, but with different resilient layers.
These facts highlights how the load in time highly affects the final noise reduction of floating floors and that the time is a parameter of paramount importance.
From Figure 11, it can clearly be noticed that using different resilient layers on different bare floors may provide very diverse results in term of final impact noise reduction index. In this figure, the number of countries regulations limits, which are not fulfilled by hypothetical complete floors using the 5 materials in time, are reported. The number of "fails" identifies how many limits are not fulfilled. It is clear that for the CLS floor up to 7 months there are few problems related to very few countries' limits. After the first year, however, apart from ERSS, which remains constant, the fails grow in quantity. For ER, 22 fails are reported, which means that in more than half of the European countries this solution would not be accepted, while at 3 years for ER, RFF and ERSS the legislation limits for

one third of the countries would not be fulfilled. This situation is reduced after 4 and 5 years only for RFF and ERSS, while for ER it remains almost constant, or with a little growth. For the B&P floor, things are very different. In fact, while up to one year, only the ER material presents criticalities in one third of the countries, after this time step ERSS and TS presents many fails and after 4 years ERLS presents similar results. For CLT the situation becomes more intricate. At t_0, only ERLS is able to satisfy almost all countries, but at 3 months the situation get worse for all materials, presenting most of the time more than half of fails, compared to the quantity of European countries. In time, all ER, TS and ERSS fail. The same trend can be found in the behaviour of TC floor. At t_0, GL, ER, TS and ERSS present all fails, while, after 3 months, the same happens for all materials. From 1 year on, almost all the limits imposed by European countries are not satisfied. For the CXPS floor, the conditions are similar to those of the GL floor but after 1 year the totality of them with all the materials is not able to satisfy any limit.

These considerations lead to the conclusion that impact noise is a great problem, manifesting itself in its entirety after one year of constant loading and it depends very much on the type of bare floor. This demonstrates the innovative character of this research and its importance for the comfort inside the buildings.

In order to evaluate this last aspect, the contribution provided by the frequency adaptation term $C_{I,50-2500}$ was taken into consideration. This term has been used many times as an indicator of the sound sensation related to walking noise. This parameter can assume positive or negative values. In the first case, the addition of this value will worsen the impact noise index, thus indicating an increase on occupants' perception, while in the second case it will reduce the index, denoting a positive change for sound sensation.

From Figure 12, it is clearly noticeable that for the CLS floor the variations are only negative and between values of -1 dB and -2 dB. The smallest difference is obtained with ER, while the largest variation is obtained with RFF. However, the range of frequency adaptation term variation is reduced for all materials, indicating that the time influence on noise perception for the CLS floor does not show any significant variations. Conversely, for the B&P floor the variation lays between 0.3 dB and 1.6 dB and the values are always positive. Also in this case, time, although implying variations for all materials, does not lead to significant differences between diverse materials. For this type of floor the maximum variation is provided by RFF, ER, ERSS and ERLS.

For the CLT floor the situation is quite neutral. In fact, the materials provide oscillating results between positive and negative with an average value close to 0 dB. The greatest variation is provided by RFF and ERSS and, however, it is not worthy reporting any noticeable variations.

For TC, the frequency adaptation term shows a strong oscillation for TS, while for the other resilient layers the variation is contained in about 1.5 dB. The values for this type of floor are always positive, indicating a deterioration related to noise perception compared to the initial value. Only for TS, the values reach 3.5 dB, denoting how there is an influence of the type of resilient layer for this kind of floor and thus of static load in time.

For GL, the various materials always provide positive values of the frequency adaptation term with considerations very similar to the B&P floor, while for CXPS the greatest variations are verified. In fact, for RFF almost 4 dB of possible worsening are denoted, while for ERSS and ERLS 2 dB and 1.4 dB respectively are reached. Concluding, for these kinds of bare floors the time always imposes a worsening in the perceived impact noise.

5. Conclusions

In this work, a comprehensive analysis of the time influence on impact noise reduction in presented. Five different materials were tested in time (5 years) in order to understand if their nature (recycled or not), shape, initial thickness and initial dynamic stiffness may be related to final floating floor acoustic performance. Furthermore, in order to understand the influence of the supporting structure, six bare floors were used to compose different complete constructions.

Many hypotheses were drawn in order to correlate static load over time effect to final values of impact noise, taking into consideration also European regulations limits and occupants' perceived comfort.
Results clearly demonstrate that no correlation is possible between impact noise (frequency behaviour or single index) and (i) initial dynamic stiffness, (ii) material type (recycled or not), (iii) creep values and (iv) increasing of the contact area of the shaped materials. The importance of an accurate materials production was demonstrated, highlighting the effect of binders both in recycled materials and synthetic ones.
On the other hand, there is a clear influence related to (i) thickness decreasing and (ii) Young's modulus variation. Thus the combination of these two parameter is the only phenomenon responsible for the impact noise reduction worsening.
Furthermore, a clear correlation between the static load over time and the selection of bare floors was found, showing how this effect is more evident and significant on lightweight floors. The selection of the material plays an important role too, because in one case it is even able to cancel the reduction provided at initial time step. These outcomes imply that it is not possible to forecast the influence of static load over time on final floating floor performances, but a reduction up to 11 dB (single index) was verified.
It was also demonstrated that, for many configuration of bare floors and materials, 31 European countries regulations are not fulfilled and that the most critical time step is 1 year. At this time the worst conditions were found. It was thus demonstrated that static load significantly modify the acoustic performances of floating floors comparing to the initial step.
Finally, the occupants' comfort is affected by this influence manly on periodic structures, while homogeneous ones seem not to be influenced by load over time.

Author Contributions: M.C. developed the research, elaborated the acoustic and statistical data and the numerical simulation, performed acoustics tests on materials and floors and wrote the manuscript. C.S. and M.C. performed thermal tests and digital data analysis. A.G. overviewed the research.

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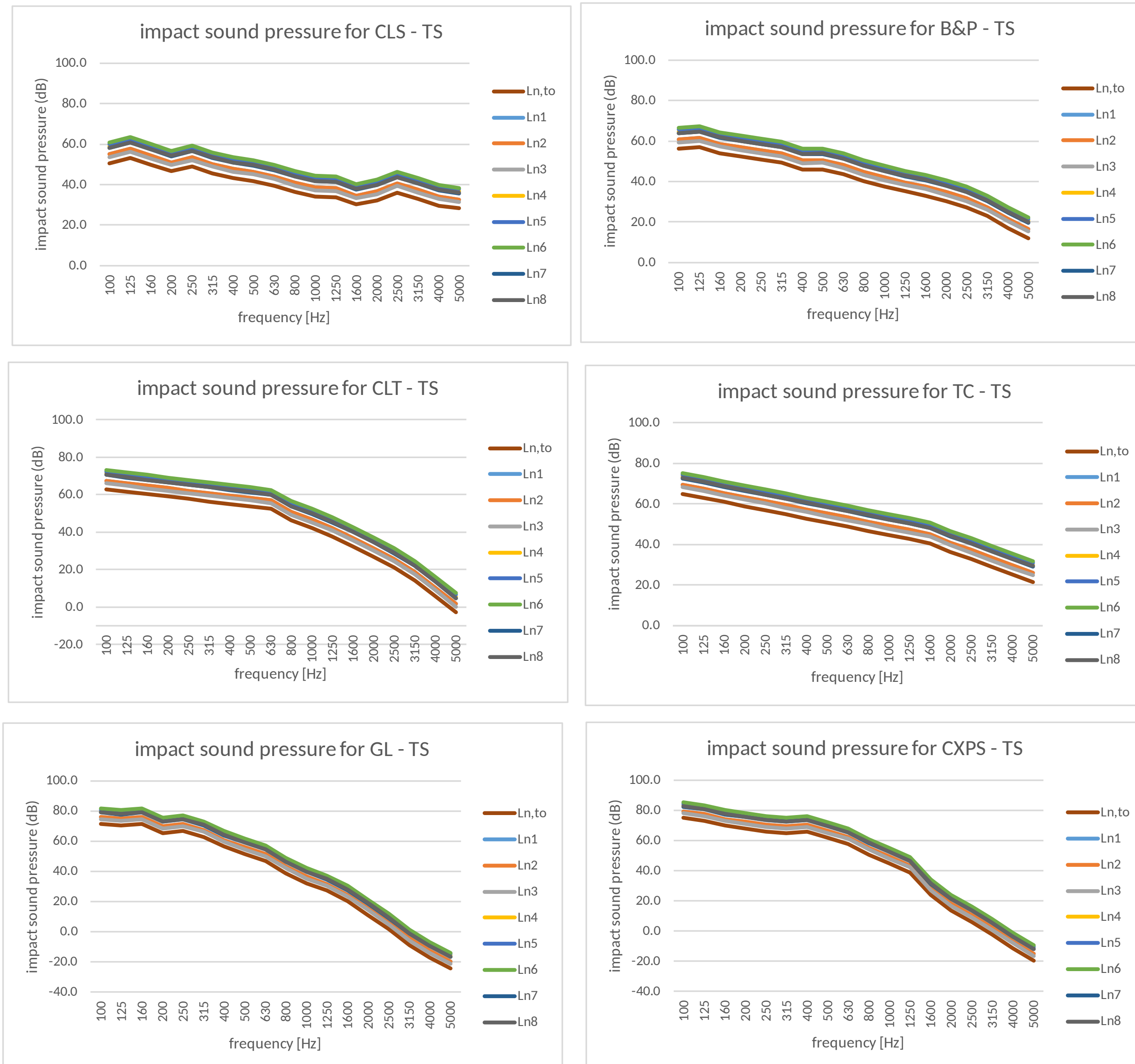

Figure I – normalized impact noise for 6 bare floors with floating floor using TS at different time steps

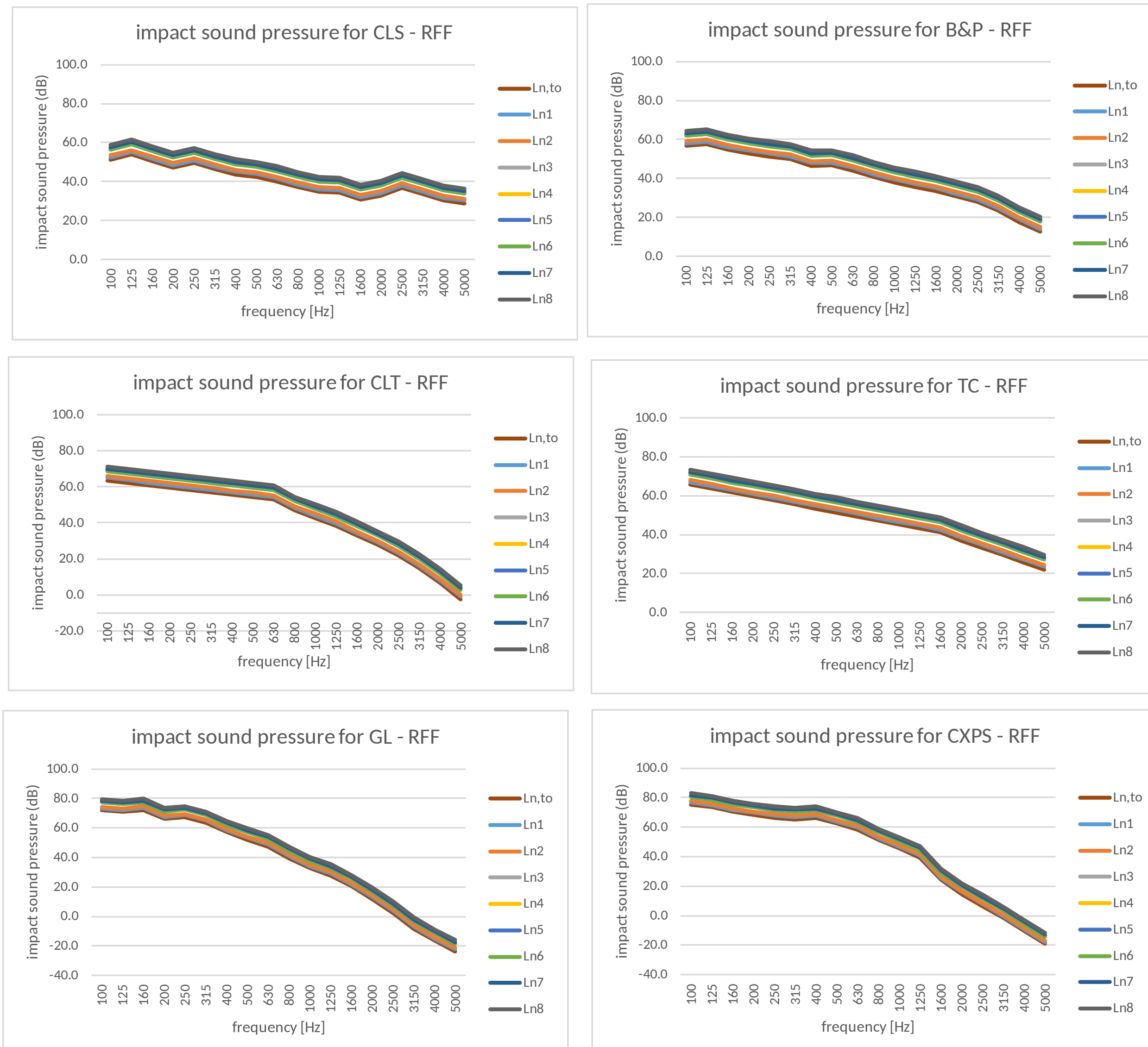

Figure II – normalized impact noise for 6 bare floors with floating floor using RFF at different time steps

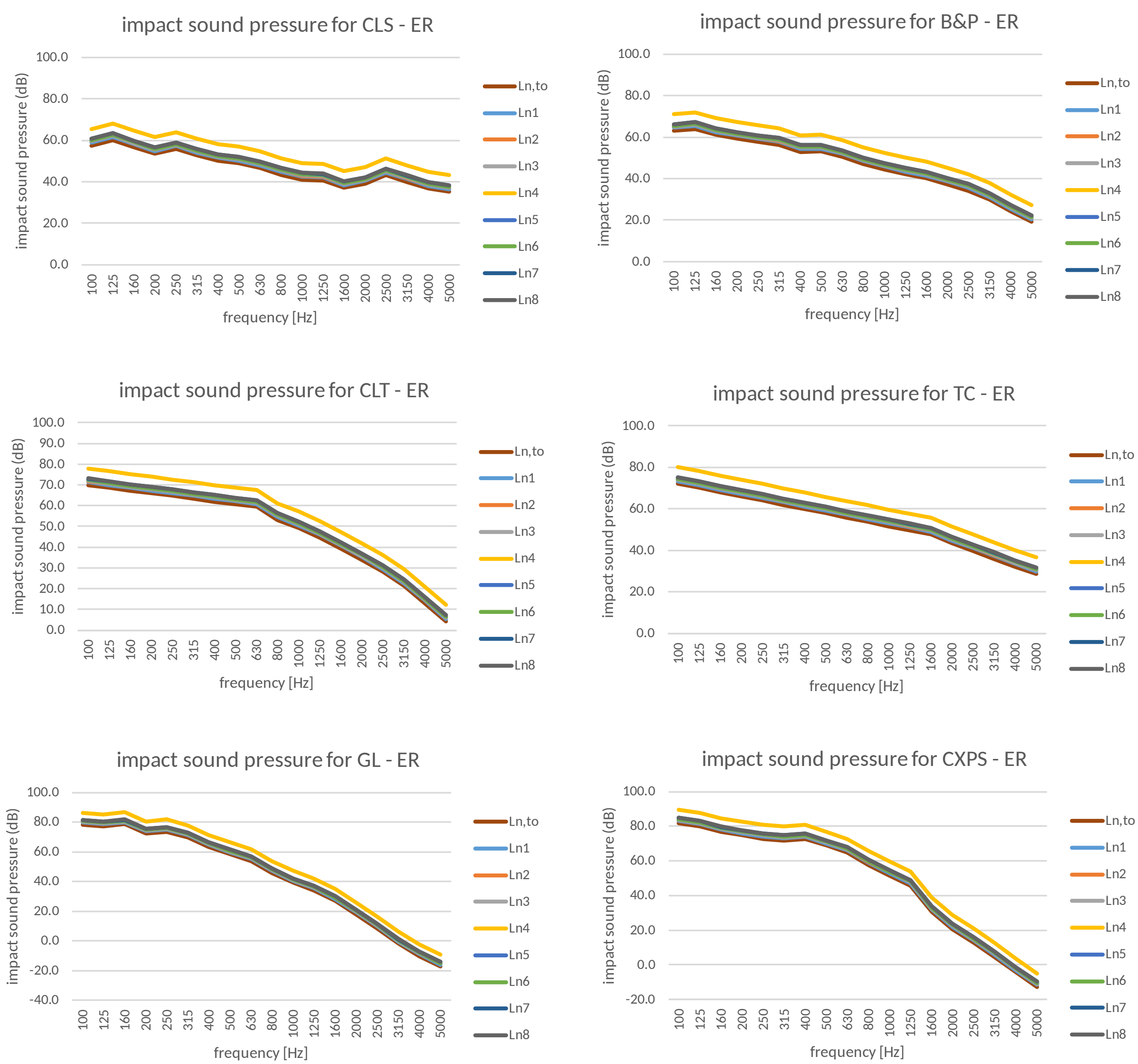

Figure III – normalized impact noise for 6 bare floors with floating floor using ER at different time steps

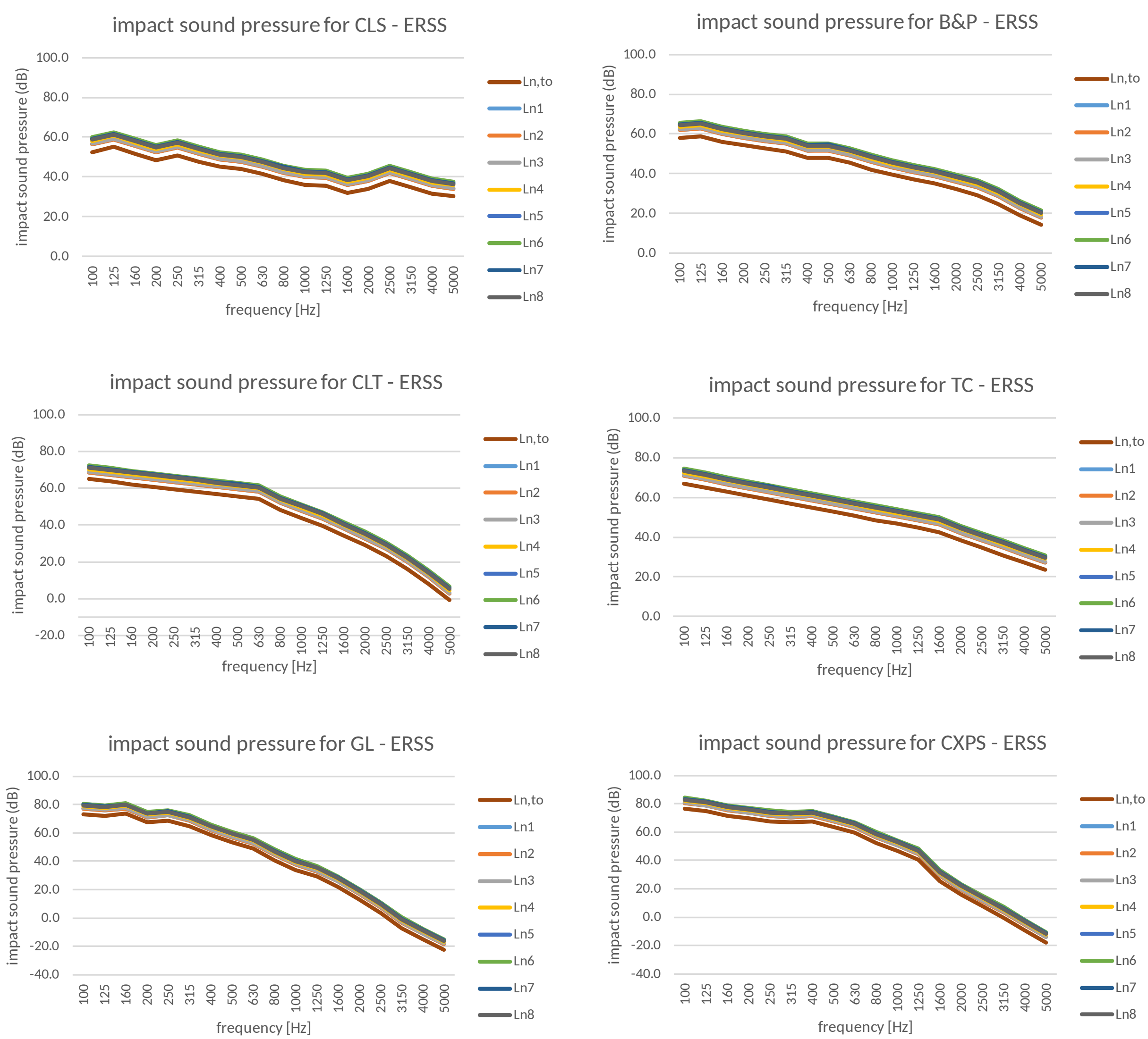

Figure IV – normalized impact noise for 6 bare floors with floating floor using ERSS at different time steps

Figure V – normalized impact noise for 6 bare floors with floating floor using ERLS at different time steps

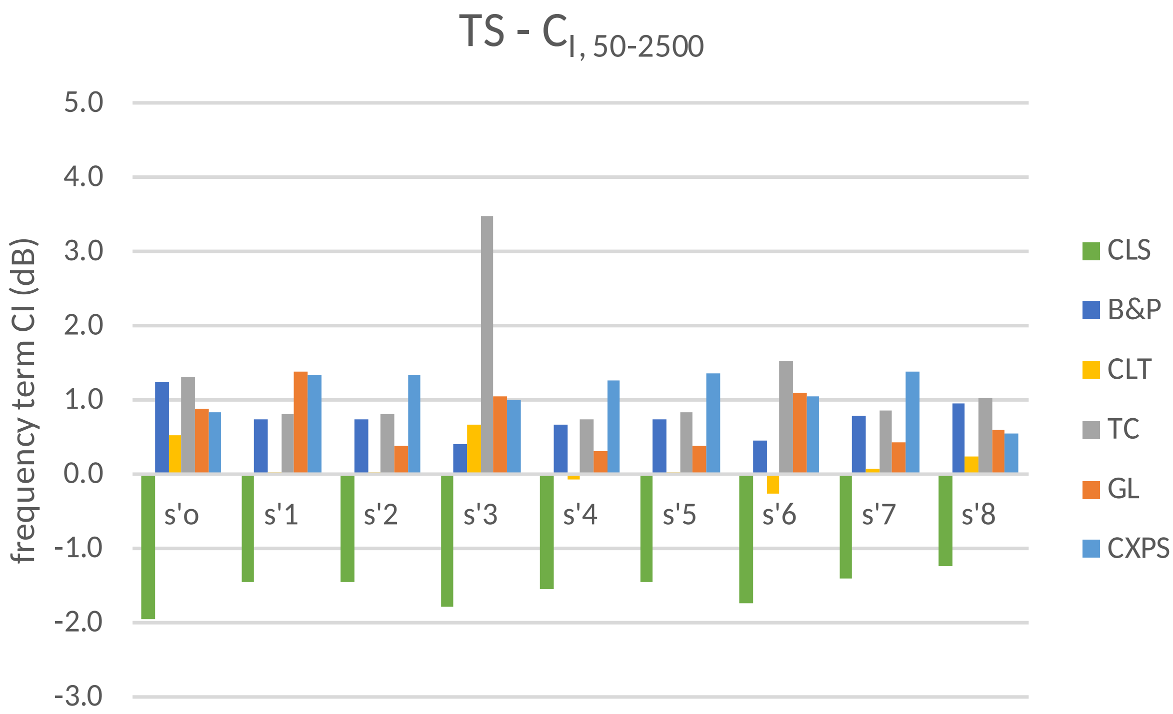

Figure VI – Frequency term $C_{I50,2500}$ for 6 bare floors with floating floor using TS at different time steps

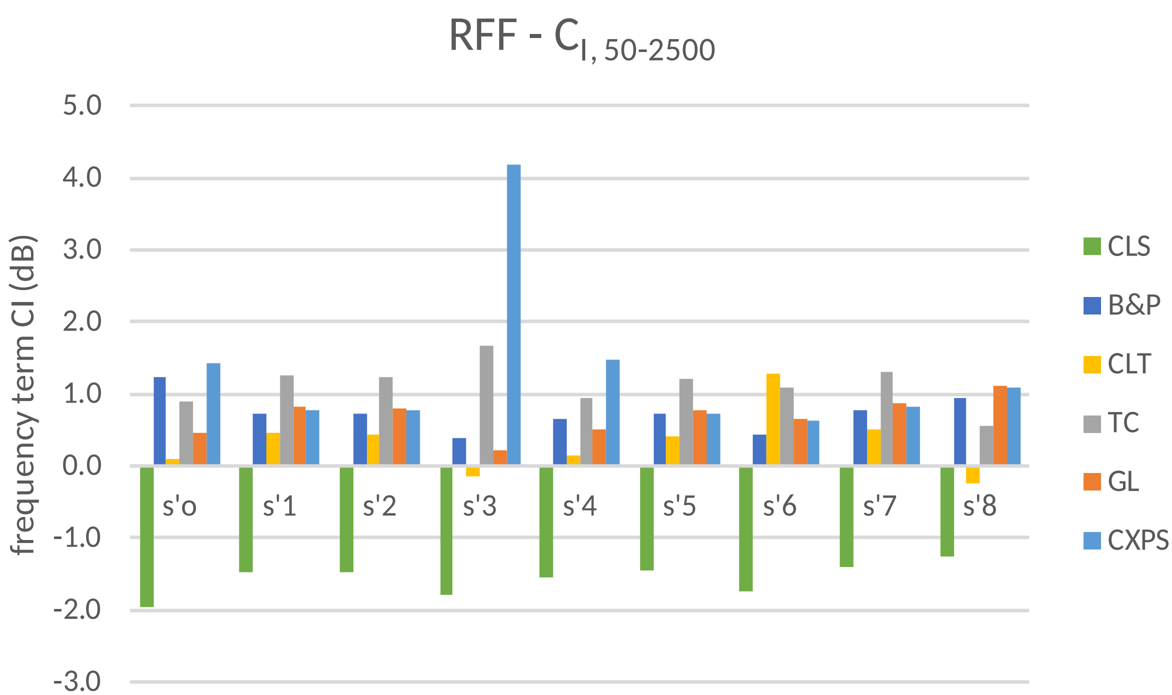

Figure VII – Frequency term $C_{I50,2500}$ for 6 bare floors with floating floor using RFF at different time steps

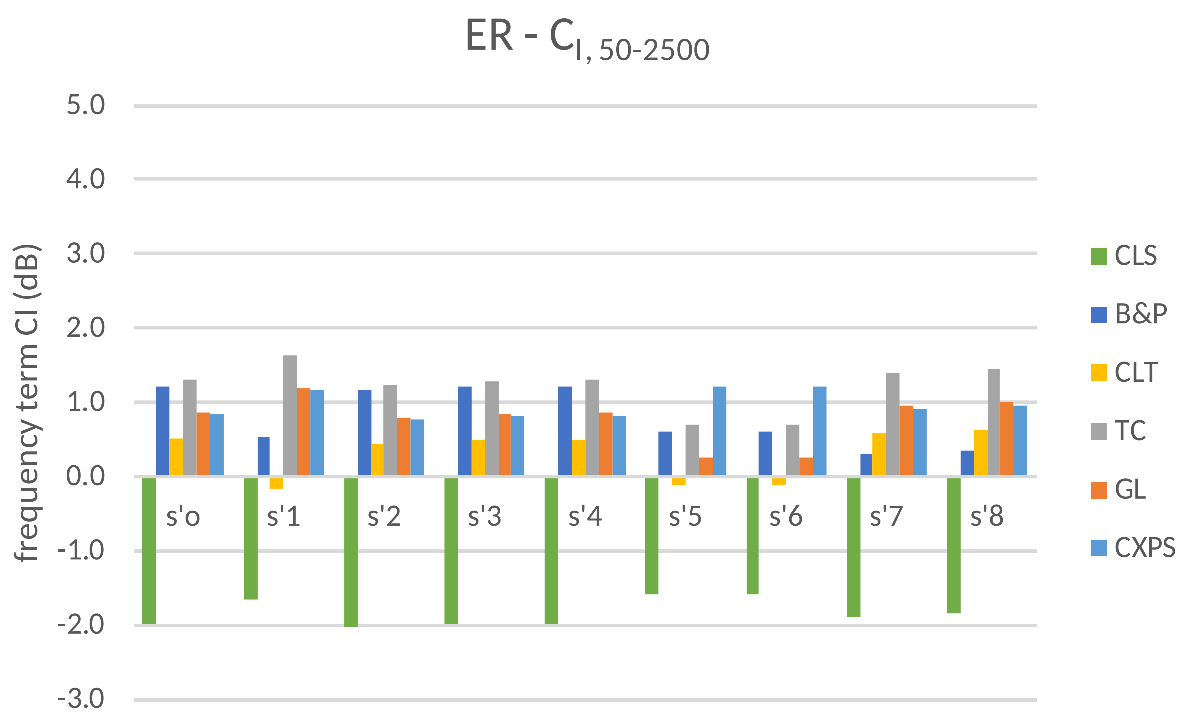

Figure VIII – Frequency term $C_{I50,2500}$ for 6 bare floors with floating floor using ER at different time steps

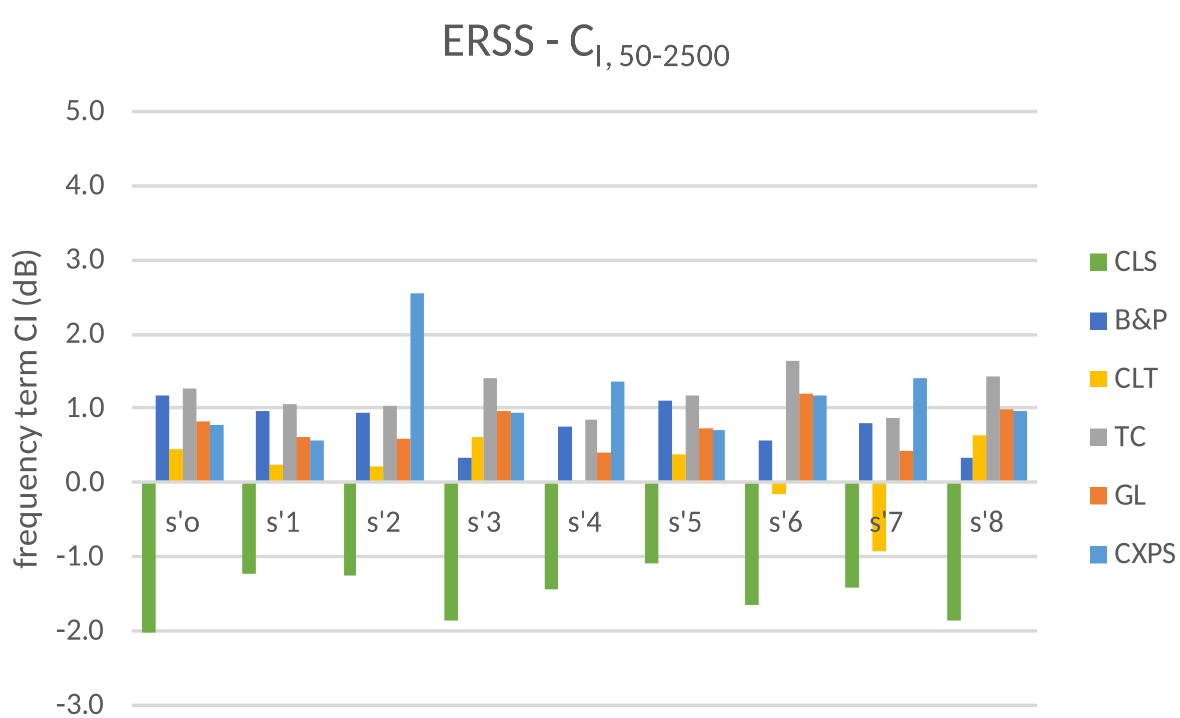

Figure IX – Frequency term $C_{I50,2500}$ for 6 bare floors with floating floor using ERSS at different time steps

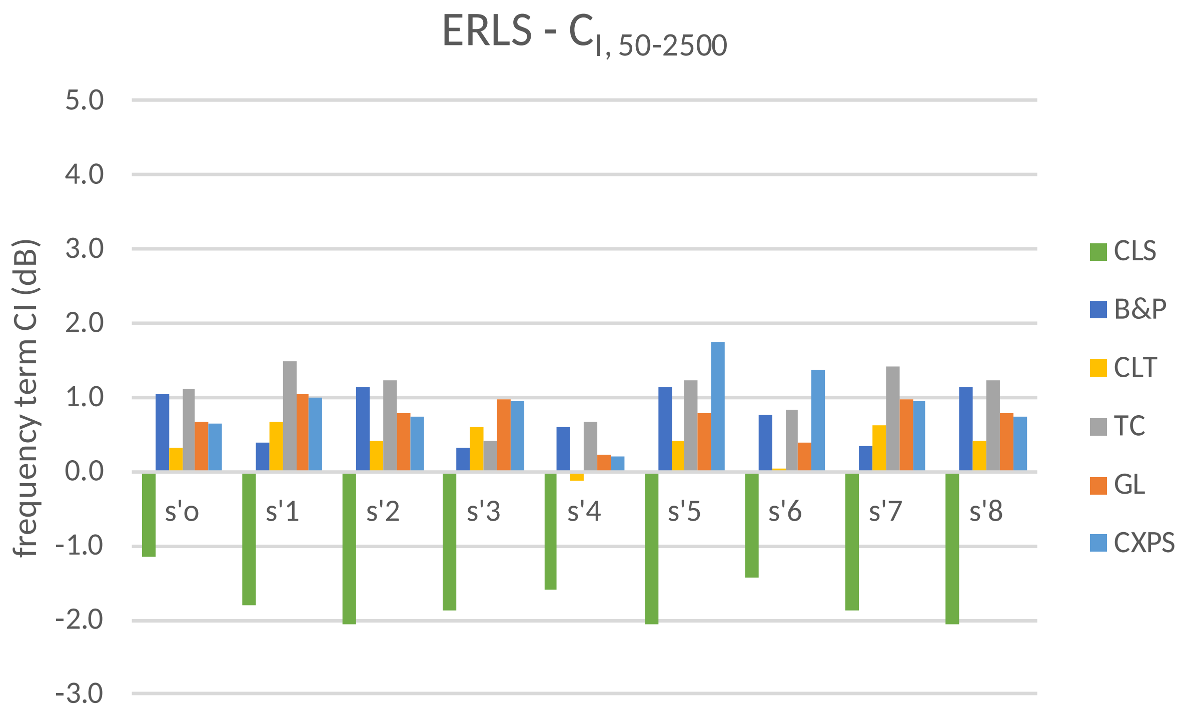

Figure X – Frequency term $C_{I50,2500}$ for 6 bare floors with floating floor using ERSS at different time

Table I – European Limits for $L'_{nT,w}$ compared to impact noise computed for different time steps. “x” indicates fails – CLS with TS

Country	Limit ($L'_{nT,w}$)	t_o	3 months	5 months	7 months	1 year	2 years	3 years	4 years	5 years
$L_{nt,w}$	--	45	49	49	48	53	54	55	52	52
Austria	48		x	x		x	x	x	x	x
Belgium	58									
Bulgaria	53						x	x		
Croatia	68									
Czech Rep.	55									
Denmark	53						x	x		
England & Wales	62									
Estonia	53						x	x		
Finland	53						x	x		
France	58									
Germany	50					x	x	x	x	x
Greece	60									
Hungary	55									
Iceland	53						x	x		
Ireland	62									
Italy	63									
Latvia	54							x		
Lithuania	53						x	x		
Netherlands	54							x		
Norway	53						x	x		
Poland	55									

Portugal	60									
Romania	62									
Scotland	56									
Serbia	68									
Slovakia	55									
Slovenia	58									
Spain	65									
Sweden	56									
Switzerland	53						x	x		
Turkey	54							x		

Table II – European Limits for $L'_{nT,w}$ compared to impact noise computed for different time steps. “x” indicates fails – CLS with RFF

Country	Limit ($L'_{nT,w}$)	t_o	3 months	5 months	7 months	1 year	2 years	3 years	4 years	5 years
$L_{nt,w}$		45	49	49	48	53	54	55	52	52
Austria	48		x	x		x	x	x	x	x
Belgium	58									
Bulgaria	53						x	x		
Croatia	68									
Czech Rep.	55									
Denmark	53						x	x		
England & Wales	62									
Estonia	53						x	x		
Finland	53						x	x		
France	58									
Germany	50					x	x	x	x	x
Greece	60									
Hungary	55									
Iceland	53						x	x		
Ireland	62									
Italy	63									
Latvia	54							x		
Lithuania	53						x	x		
Netherlands	54							x		
Norway	53						x	x		
Poland	55									

Portugal	60									
Romania	62									
Scotland	56									
Serbia	68									
Slovakia	55									
Slovenia	58									
Spain	65									
Sweden	56									
Switzerland	53						x	x		
Turkey	54							x		

Table III – European Limits for $L'_{nT,w}$ compared to impact noise computed for different time steps. "x" indicates fails – CLS with ER

Country	Limit ($L'_{nT,w}$)	t_o	3 months	5 months	7 months	1 year	2 years	3 years	4 years	5 years
$L_{nt,w}$		52	53	54	54	60	54	54	55	55
Austria	48	x	x	x	x	x	x	x	x	x
Belgium	58					x				
Bulgaria	53			x	x	x	x	x	x	x
Croatia	68									
Czech Rep.	55					x				
Denmark	53			x	x	x	x	x	x	x
England & Wales	62									
Estonia	53			x	x	x	x	x	x	x
Finland	53			x	x	x	x	x	x	x
France	58					x				
Germany	50	x	x	x	x	x	x	x	x	x
Greece	60									
Hungary	55					x				
Iceland	53			x	x	x	x	x	x	x
Ireland	62									
Italy	63									
Latvia	54					x			x	x
Lithuania	53			x	x	x	x	x	x	x
Netherlands	54					x			x	x
Norway	53			x	x	x	x	x	x	x

Poland	55					x				
Portugal	60									
Romania	62									
Scotland	56					x				
Serbia	68									
Slovakia	55					x				
Slovenia	58					x				
Spain	65									
Sweden	56					x				
Switzerland	53			x	x	x	x	x	x	x
Turkey	54					x			x	x

Table IV – European Limits for $L'_{nT,w}$ compared to impact noise computed for different time steps. “x” indicates fails – CLS with ERSS

Country	Limit ($L'_{nT,w}$)	t_o	3 months	5 months	7 months	1 year	2 years	3 years	4 years	5 years
$L_{nt,w}$		47	50	50	51	52	53	54	53	53
Austria	48		x	x	x	x	x	x	x	x
Belgium	58									
Bulgaria	53							x		
Croatia	68									
Czech Rep.	55									
Denmark	53							x		
England & Wales	62									
Estonia	53							x		
Finland	53							x		
France	58									
Germany	50				x	x	x	x	x	x
Greece	60									
Hungary	55									
Iceland	53							x		
Ireland	62									
Italy	63									
Latvia	54									
Lithuania	53							x		
Netherlands	54									
Norway	53							x		

Poland	55									
Portugal	60									
Romania	62									
Scotland	56									
Serbia	68									
Slovakia	55									
Slovenia	58									
Spain	65									
Sweden	56									
Switzerland	53							x		
Turkey	54									

Table V – European Limits for $L'_{nT,w}$ compared to impact noise computed for different time steps. “x” indicates fails – CLS with ERLS

Country	Limit ($L'_{nT,w}$)	t_o	3 months	5 months	7 months	1 year	2 years	3 years	4 years	5 years
$L_{nt,w}$		48	51	52	51	51	52	51	52	52
Austria	48		x	x	x	x	x	x	x	x
Belgium	58									
Bulgaria	53									
Croatia	68									
Czech Rep.	55									
Denmark	53									
England & Wales	62									
Estonia	53									
Finland	53									
France	58									
Germany	50		x	x	x	x	x	x	x	x
Greece	60									
Hungary	55									
Iceland	53									
Ireland	62									
Italy	63									
Latvia	54									
Lithuania	53									
Netherlands	54									
Norway	53									

Poland	55									
Portugal	60									
Romania	62									
Scotland	56									
Serbia	68									
Slovakia	55									
Slovenia	58									
Spain	65									
Sweden	56									
Switzerland	53									
Turkey	54									

Table VI – European Limits for $L'_{nT,w}$ compared to impact noise computed for different time steps. "x" indicates fails – B&P with TS

Country	Limit ($L'_{nT,w}$)	t_o	3 months	5 months	7 months	1 year	2 years	3 years	4 years	5 years
$L_{nt,w}$		46	51	51	50	55	56	57	54	54
Austria	48		x	x	x	x	x	x	x	x
Belgium	58									
Bulgaria	53					x	x	x	x	x
Croatia	68									
Czech Rep.	55						x	x		
Denmark	53					x	x	x	x	x
England & Wales	62									
Estonia	53					x	x	x	x	x
Finland	53					x	x	x	x	x
France	58									
Germany	50		x	x		x	x	x	x	x
Greece	60									
Hungary	55						x	x		
Iceland	53					x	x	x	x	x
Ireland	62									
Italy	63									
Latvia	54					x	x	x		
Lithuania	53					x	x	x	x	x
Netherlands	54					x	x	x		
Norway	53					x	x	x	x	x

Poland	55						x	x			
Portugal	60										
Romania	62										
Scotland	56							x			
Serbia	68										
Slovakia	55						x	x			
Slovenia	58										
Spain	65										
Sweden	56							x			
Switzerland	53					x	x	x	x	x	
Turkey	54					x	x	x			

Table VII – European Limits for $L'_{nT,w}$ compared to impact noise computed for different time steps. “x” indicates fails – B&P with RFF

Country	Limit ($L'_{nT,w}$)	t_o	3 months	5 months	7 months	1 year	2 years	3 years	4 years	5 years
$L_{nt,w}$		47	48	49	52	53	52	52	53	55
Austria	48			x	x	x	x	x	x	x
Belgium	58									
Bulgaria	53									x
Croatia	68									
Czech Rep.	55									
Denmark	53									x
England & Wales	62									
Estonia	53									x
Finland	53									x
France	58									
Germany	50				x	x	x	x	x	x
Greece	60									
Hungary	55									
Iceland	53									x
Ireland	62									
Italy	63									
Latvia	54									x
Lithuania	53									x
Netherlands	54									x
Norway	53									x

Poland	55										
Portugal	60										
Romania	62										
Scotland	56										
Serbia	68										
Slovakia	55										
Slovenia	58										
Spain	65										
Sweden	56										
Switzerland	53										x
Turkey	54										x

Table VII – European Limits for $L'_{nT,w}$ compared to impact noise computed for different time steps. "x" indicates fails – B&P with ER

Country	Limit ($L'_{nT,w}$)	t_o	3 months	5 months	7 months	1 year	2 years	3 years	4 years	5 years
$L_{nt,w}$		53	55	55	55	61	56	56	57	57
Austria	48	x	x	x	x	x	x	x	x	x
Belgium	58					x				
Bulgaria	53		x	x	x	x	x	x	x	x
Croatia	68									
Czech Rep.	55					x	x	x	x	x
Denmark	53		x	x	x	x	x	x	x	x
England & Wales	62									
Estonia	53		x	x	x	x	x	x	x	x
Finland	53		x	x	x	x	x	x	x	x
France	58					x				
Germany	50	x	x	x	x	x	x	x	x	x
Greece	60					x				
Hungary	55					x	x	x	x	x
Iceland	53		x	x	x	x	x	x	x	x
Ireland	62									
Italy	63									
Latvia	54		x	x	x	x	x	x	x	x
Lithuania	53		x	x	x	x	x	x	x	x
Netherlands	54		x	x	x	x	x	x	x	x
Norway	53		x	x	x	x	x	x	x	x

Poland	55					x	x	x	x	x
Portugal	60					x				
Romania	62									
Scotland	56					x			x	x
Serbia	68									
Slovakia	55					x	x	x	x	x
Slovenia	58					x				
Spain	65									
Sweden	56					x			x	x
Switzerland	53		x	x	x	x	x	x	x	x
Turkey	54		x	x	x	x	x	x	x	x

Table VIII – European Limits for $L'_{nT,w}$ compared to impact noise computed for different time steps. "x" indicates fails – B&P with ERSS

Country	Limit ($L'_{nT,w}$)	t_o	3 months	5 months	7 months	1 year	2 years	3 years	4 years	5 years
$L_{nt,w}$		48	52	52	53	54	55	56	55	55
Austria	48		x	x	x	x	x	x	x	x
Belgium	58									
Bulgaria	53					x	x	x	x	x
Croatia	68									
Czech Rep.	55							x		
Denmark	53					x	x	x	x	x
England & Wales	62									
Estonia	53					x	x	x	x	x
Finland	53					x	x	x	x	x
France	58									
Germany	50		x	x	x	x	x	x	x	x
Greece	60									
Hungary	55							x		
Iceland	53					x	x	x	x	x
Ireland	62									
Italy	63									
Latvia	54						x	x	x	x
Lithuania	53					x	x	x	x	x
Netherlands	54						x	x	x	x
Norway	53					x	x	x	x	x

Poland	55							x		
Portugal	60									
Romania	62									
Scotland	56									
Serbia	68									
Slovakia	55							x		
Slovenia	58									
Spain	65									
Sweden	56									
Switzerland	53					x	x	x	x	x
Turkey	54						x	x	x	x

Table IX – European Limits for $L'_{nT,w}$ compared to impact noise computed for different time steps. "x" indicates fails – B&P with ERSS

Country	Limit ($L'_{nT,w}$)	t_o	3 months	5 months	7 months	1 year	2 years	3 years	4 years	5 years
$L_{nt,w}$		50	53	53	53	53	53	53	54	53
Austria	48	x	x	x	x	x	x	x	x	x
Belgium	58									
Bulgaria	53								x	
Croatia	68									
Czech Rep.	55									
Denmark	53								x	
England & Wales	62									
Estonia	53								x	
Finland	53								x	
France	58									
Germany	50		x	x	x	x	x	x	x	x
Greece	60									
Hungary	55									
Iceland	53								x	
Ireland	62									
Italy	63									
Latvia	54									
Lithuania	53								x	
Netherlands	54									
Norway	53								x	

Poland	55									
Portugal	60									
Romania	62									
Scotland	56									
Serbia	68									
Slovakia	55									
Slovenia	58									
Spain	65									
Sweden	56									
Switzerland	53								x	
Turkey	54									

Table X – European Limits for $L'_{nT,w}$ compared to impact noise computed for different time steps. “x” indicates fails – CLT with TS

Country	Limit ($L'_{nT,w}$)	t_o	3 months	5 months	7 months	1 year	2 years	3 years	4 years	5 years
$L_{nt,w}$		53	58	58	56	62	63	64	61	61
Austria	48	x	x	x	x	x	x	x	x	x
Belgium	58					x	x	x	x	x
Bulgaria	53		x	x	x	x	x	x	x	x
Croatia	68									
Czech Rep.	55		x	x	x	x	x	x	x	x
Denmark	53		x	x	x	x	x	x	x	x
England & Wales	62						x	x		
Estonia	53		x	x	x	x	x	x	x	x
Finland	53		x	x	x	x	x	x	x	x
France	58					x	x	x	x	x
Germany	50	x	x	x	x	x	x	x	x	x
Greece	60					x	x	x	x	x
Hungary	55		x	x	x	x	x	x	x	x
Iceland	53		x	x	x	x	x	x	x	x
Ireland	62						x	x		
Italy	63							x		
Latvia	54		x	x	x	x	x	x	x	x
Lithuania	53		x	x	x	x	x	x	x	x
Netherlands	54		x	x	x	x	x	x	x	x
Norway	53		x	x	x	x	x	x	x	x

Poland	55		x	x	x	x	x	x	x	x
Portugal	60					x	x	x	x	x
Romania	62						x	x		
Scotland	56		x	x		x	x	x	x	x
Serbia	68									
Slovakia	55		x	x	x	x	x	x	x	x
Slovenia	58					x	x	x	x	x
Spain	65									
Sweden	56		x	x		x	x	x	x	x
Switzerland	53		x	x	x	x	x	x	x	x
Turkey	54		x	x	x	x	x	x	x	x

Table XI – European Limits for $L'_{nT,w}$ compared to impact noise computed for different time steps. “x” indicates fails – CLT with RFF

Country	Limit ($L'_{nT,w}$)	t_o	3 months	5 months	7 months	1 year	2 years	3 years	4 years	5 years
$L_{nt,w}$		54	55	56	60	60	59	58	60	62
Austria	48	x	x	x	x	x	x	x	x	x
Belgium	58				x	x	x		x	x
Bulgaria	53	x	x	x	x	x	x	x	x	x
Croatia	68									
Czech Rep.	55			x	x	x	x	x	x	x
Denmark	53	x	x	x	x	x	x	x	x	x
England & Wales	62									
Estonia	53	x	x	x	x	x	x	x	x	x
Finland	53	x	x	x	x	x	x	x	x	x
France	58				x	x	x		x	x
Germany	50	x	x	x	x	x	x	x	x	x
Greece	60									x
Hungary	55			x	x	x	x	x	x	x
Iceland	53	x	x	x	x	x	x	x	x	x
Ireland	62									
Italy	63									
Latvia	54		x	x	x	x	x	x	x	x
Lithuania	53	x	x	x	x	x	x	x	x	x
Netherlands	54		x	x	x	x	x	x	x	x
Norway	53	x	x	x	x	x	x	x	x	x

Poland	55			x	x	x	x	x	x	x
Portugal	60									x
Romania	62									
Scotland	56				x	x	x	x	x	x
Serbia	68									
Slovakia	55			x	x	x	x	x	x	x
Slovenia	58				x	x	x		x	x
Spain	65									
Sweden	56				x	x	x	x	x	x
Switzerland	53	x	x	x	x	x	x	x	x	x
Turkey	54		x	x	x	x	x	x	x	x

Table XII – European Limits for $L'_{nT,w}$ compared to impact noise computed for different time steps. “x” indicates fails – CLT with ER

Country	Limit ($L'_{nT,w}$)	t_o	3 months	5 months	7 months	1 year	2 years	3 years	4 years	5 years
$L_{nt,w}$		60	62	62	62	68	63	63	63	63
Austria	48	x	x	x	x	x	x	x	x	x
Belgium	58	x	x	x	x	x	x	x	x	x
Bulgaria	53	x	x	x	x	x	x	x	x	x
Croatia	68									
Czech Rep.	55	x	x	x	x	x	x	x	x	x
Denmark	53	x	x	x	x	x	x	x	x	x
England & Wales	62					x	x	x	x	x
Estonia	53	x	x	x	x	x	x	x	x	x
Finland	53	x	x	x	x	x	x	x	x	x
France	58	x	x	x	x	x	x	x	x	x
Germany	50	x	x	x	x	x	x	x	x	x
Greece	60		x	x	x	x	x	x	x	x
Hungary	55	x	x	x	x	x	x	x	x	x
Iceland	53	x	x	x	x	x	x	x	x	x
Ireland	62					x	x	x	x	x
Italy	63					x				
Latvia	54	x	x	x	x	x	x	x	x	x
Lithuania	53	x	x	x	x	x	x	x	x	x
Netherlands	54	x	x	x	x	x	x	x	x	x
Norway	53	x	x	x	x	x	x	x	x	x

Poland	55	x	x	x	x	x	x	x	x	x
Portugal	60		x	x	x	x	x	x	x	x
Romania	62					x	x	x	x	x
Scotland	56	x	x	x	x	x	x	x	x	x
Serbia	68									
Slovakia	55	x	x	x	x	x	x	x	x	x
Slovenia	58	x	x	x	x	x	x	x	x	x
Spain	65					x				
Sweden	56	x	x	x	x	x	x	x	x	x
Switzerland	53	x	x	x	x	x	x	x	x	x
Turkey	54	x	x	x	x	x	x	x	x	x

Table XIII – European Limits for $L'_{nT,w}$ compared to impact noise computed for different time steps. “x” indicates fails – CLT with ERSS

Country	Limit ($L'_{nT,w}$)	t_o	3 months	5 months	7 months	1 year	2 years	3 years	4 years	5 years
$L_{nt,w}$		55	59	59	59	61	62	63	63	61
Austria	48	x	x	x	x	x	x	x	x	x
Belgium	58		x	x	x	x	x	x	x	x
Bulgaria	53	x	x	x	x	x	x	x	x	x
Croatia	68									
Czech Rep.	55		x	x	x	x	x	x	x	x
Denmark	53	x	x	x	x	x	x	x	x	x
England & Wales	62							x	x	
Estonia	53	x	x	x	x	x	x	x	x	x
Finland	53	x	x	x	x	x	x	x	x	x
France	58		x	x	x	x	x	x	x	x
Germany	50	x	x	x	x	x	x	x	x	x
Greece	60					x	x	x	x	x
Hungary	55		x	x	x	x	x	x	x	x
Iceland	53	x	x	x	x	x	x	x	x	x
Ireland	62							x	x	
Italy	63									
Latvia	54	x	x	x	x	x	x	x	x	x
Lithuania	53	x	x	x	x	x	x	x	x	x
Netherlands	54	x	x	x	x	x	x	x	x	x
Norway	53	x	x	x	x	x	x	x	x	x

Poland	55		x	x	x	x	x	x	x	x
Portugal	60					x	x	x	x	x
Romania	62							x	x	
Scotland	56		x	x	x	x	x	x	x	x
Serbia	68									
Slovakia	55		x	x	x	x	x	x	x	x
Slovenia	58		x	x	x	x	x	x	x	x
Spain	65									
Sweden	56		x	x	x	x	x	x	x	x
Switzerland	53	x	x	x	x	x	x	x	x	x
Turkey	54	x	x	x	x	x	x	x	x	x

Table XIV – European Limits for $L'_{nT,w}$ compared to impact noise computed for different time steps. “x” indicates fails – TC with TS

Country	Limit ($L'_{nT,w}$)	t_o	3 months	5 months	7 months	1 year	2 years	3 years	4 years	5 years
$L_{nt,w}$		53	58	58	54	62	63	63	61	61
Austria	48	x	x	x	x	x	x	x	x	x
Belgium	58					x	x	x	x	x
Bulgaria	53		x	x	x	x	x	x	x	x
Croatia	68									
Czech Rep.	55		x	x		x	x	x	x	x
Denmark	53		x	x	x	x	x	x	x	x
England & Wales	62						x	x		
Estonia	53		x	x	x	x	x	x	x	x
Finland	53		x	x	x	x	x	x	x	x
France	58					x	x	x	x	x
Germany	50	x	x	x	x	x	x	x	x	x
Greece	60					x	x	x	x	x
Hungary	55		x	x		x	x	x	x	x
Iceland	53		x	x	x	x	x	x	x	x
Ireland	62						x	x		
Italy	63									
Latvia	54		x	x		x	x	x	x	x
Lithuania	53		x	x	x	x	x	x	x	x
Netherlands	54		x	x		x	x	x	x	x
Norway	53		x	x	x	x	x	x	x	x

Poland	55		x	x		x	x	x	x	x
Portugal	60					x	x	x	x	x
Romania	62						x	x		
Scotland	56		x	x		x	x	x	x	x
Serbia	68									
Slovakia	55		x	x		x	x	x	x	x
Slovenia	58					x	x	x	x	x
Spain	65									
Sweden	56		x	x		x	x	x	x	x
Switzerland	53		x	x	x	x	x	x	x	x
Turkey	54		x	x		x	x	x	x	x

Table XV – European Limits for $L'_{nT,w}$ compared to impact noise computed for different time steps. “x” indicates fails – TC with RFF

Country	Limit ($L'_{nT,w}$)	t_o	3 months	5 months	7 months	1 year	2 years	3 years	4 years	5 years
$L_{nt,w}$		54	55	56	59	60	59	59	60	62
Austria	48	x	x	x	x	x	x	x	x	x
Belgium	58				x	x	x	x	x	x
Bulgaria	53	x	x	x	x	x	x	x	x	x
Croatia	68									
Czech Rep.	55			x	x	x	x	x	x	x
Denmark	53	x	x	x	x	x	x	x	x	x
England & Wales	62									
Estonia	53	x	x	x	x	x	x	x	x	x
Finland	53	x	x	x	x	x	x	x	x	x
France	58				x	x	x	x	x	x
Germany	50	x	x	x	x	x	x	x	x	x
Greece	60									x
Hungary	55			x	x	x	x	x	x	x
Iceland	53	x	x	x	x	x	x	x	x	x
Ireland	62									
Italy	63									
Latvia	54		x	x	x	x	x	x	x	x
Lithuania	53	x	x	x	x	x	x	x	x	x
Netherlands	54		x	x	x	x	x	x	x	x
Norway	53	x	x	x	x	x	x	x	x	x

Poland	55			x	x	x	x	x	x	x
Portugal	60									x
Romania	62									
Scotland	56				x	x	x	x	x	x
Serbia	68									
Slovakia	55			x	x	x	x	x	x	x
Slovenia	58				x	x	x	x	x	x
Spain	65									
Sweden	56				x	x	x	x	x	x
Switzerland	53	x	x	x	x	x	x	x	x	x
Turkey	54		x	x	x	x	x	x	x	x

Table XVI – European Limits for $L'_{nT,w}$ compared to impact noise computed for different time steps. "x" indicates fails – TC with ER

Country	Limit ($L'_{nT,w}$)	t_o	3 months	5 months	7 months	1 year	2 years	3 years	4 years	5 years
$L_{nt,w}$		60	61	62	62	68	63	63	63	63
Austria	48	x	x	x	x	x	x	x	x	x
Belgium	58	x	x	x	x	x	x	x	x	x
Bulgaria	53	x	x	x	x	x	x	x	x	x
Croatia	68									
Czech Rep.	55	x	x	x	x	x	x	x	x	x
Denmark	53	x	x	x	x	x	x	x	x	x
England & Wales	62					x	x	x	x	x
Estonia	53	x	x	x	x	x	x	x	x	x
Finland	53	x	x	x	x	x	x	x	x	x
France	58	x	x	x	x	x	x	x	x	x
Germany	50	x	x	x	x	x	x	x	x	x
Greece	60		x	x	x	x	x	x	x	x
Hungary	55	x	x	x	x	x	x	x	x	x
Iceland	53	x	x	x	x	x	x	x	x	x
Ireland	62					x	x	x	x	x
Italy	63					x				
Latvia	54	x	x	x	x	x	x	x	x	x
Lithuania	53	x	x	x	x	x	x	x	x	x
Netherlands	54	x	x	x	x	x	x	x	x	x
Norway	53	x	x	x	x	x	x	x	x	x

Poland	55	x	x	x	x	x	x	x	x	x
Portugal	60		x	x	x	x	x	x	x	x
Romania	62					x	x	x	x	x
Scotland	56	x	x	x	x	x	x	x	x	x
Serbia	68									
Slovakia	55	x	x	x	x	x	x	x	x	x
Slovenia	58	x	x	x	x	x	x	x	x	x
Spain	65					x				
Sweden	56	x	x	x	x	x	x	x	x	x
Switzerland	53	x	x	x	x	x	x	x	x	x
Turkey	54	x	x	x	x	x	x	x	x	x

Table XVII – European Limits for $L'_{nT,w}$ compared to impact noise computed for different time steps. "x" indicates fails – TC with ERSS

Country	Limit ($L'_{nT,w}$)	t_o	3 months	5 months	7 months	1 year	2 years	3 years	4 years	5 years
$L_{nt,w}$		55	59	59	59	61	62	62	62	61
Austria	48	x	x	x	x	x	x	x	x	x
Belgium	58		x	x	x	x	x	x	x	x
Bulgaria	53	x	x	x	x	x	x	x	x	x
Croatia	68									
Czech Rep.	55		x	x	x	x	x	x	x	x
Denmark	53	x	x	x	x	x	x	x	x	x
England & Wales	62									
Estonia	53	x	x	x	x	x	x	x	x	x
Finland	53	x	x	x	x	x	x	x	x	x
France	58		x	x	x	x	x	x	x	x
Germany	50	x	x	x	x	x	x	x	x	x
Greece	60					x	x	x	x	x
Hungary	55		x	x	x	x	x	x	x	x
Iceland	53	x	x	x	x	x	x	x	x	x
Ireland	62									
Italy	63									
Latvia	54	x	x	x	x	x	x	x	x	x
Lithuania	53	x	x	x	x	x	x	x	x	x
Netherlands	54	x	x	x	x	x	x	x	x	x
Norway	53	x	x	x	x	x	x	x	x	x

Poland	55		x	x	x	x	x	x	x	x
Portugal	60					x	x	x	x	x
Romania	62									
Scotland	56		x	x	x	x	x	x	x	x
Serbia	68									
Slovakia	55		x	x	x	x	x	x	x	x
Slovenia	58		x	x	x	x	x	x	x	x
Spain	65									
Sweden	56		x	x	x	x	x	x	x	x
Switzerland	53	x	x	x	x	x	x	x	x	x
Turkey	54	x	x	x	x	x	x	x	x	x

Table XVIII – European Limits for $L'_{nT,w}$ compared to impact noise computed for different time steps. "x" indicates fails – TC with ERLS

Country	Limit ($L'_{nT,w}$)	t_o	3 months	5 months	7 months	1 year	2 years	3 years	4 years	5 years
$L_{nt,w}$		57	59	60	60	60	60	60	60	60
Austria	48	x	x	x	x	x	x	x	x	x
Belgium	58		x	x	x	x	x	x	x	x
Bulgaria	53	x	x	x	x	x	x	x	x	x
Croatia	68									
Czech Rep.	55	x	x	x	x	x	x	x	x	x
Denmark	53	x	x	x	x	x	x	x	x	x
England & Wales	62									
Estonia	53	x	x	x	x	x	x	x	x	x
Finland	53	x	x	x	x	x	x	x	x	x
France	58		x	x	x	x	x	x	x	x
Germany	50	x	x	x	x	x	x	x	x	x
Greece	60									
Hungary	55	x	x	x	x	x	x	x	x	x
Iceland	53	x	x	x	x	x	x	x	x	x
Ireland	62									
Italy	63									
Latvia	54	x	x	x	x	x	x	x	x	x
Lithuania	53	x	x	x	x	x	x	x	x	x
Netherlands	54	x	x	x	x	x	x	x	x	x
Norway	53	x	x	x	x	x	x	x	x	x

Poland	55	x	x	x	x	x	x	x	x	x
Portugal	60									
Romania	62									
Scotland	56	x	x	x	x	x	x	x	x	x
Serbia	68									
Slovakia	55	x	x	x	x	x	x	x	x	x
Slovenia	58		x	x	x	x	x	x	x	x
Spain	65									
Sweden	56	x	x	x	x	x	x	x	x	x
Switzerland	53	x	x	x	x	x	x	x	x	x
Turkey	54	x	x	x	x	x	x	x	x	x

Table XIX – European Limits for $L'_{nT,w}$ compared to impact noise computed for different time steps. “x” indicates fails – GL with TS

Country	Limit ($L'_{nT,w}$)	t_o	3 months	5 months	7 months	1 year	2 years	3 years	4 years	5 years
$L_{nt,w}$		61	65	66	64	70	71	71	69	69
Austria	48	x	x	x	x	x	x	x	x	x
Belgium	58	x	x	x	x	x	x	x	x	x
Bulgaria	53	x	x	x	x	x	x	x	x	x
Croatia	68					x	x	x	x	x
Czech Rep.	55	x	x	x	x	x	x	x	x	x
Denmark	53	x	x	x	x	x	x	x	x	x
England & Wales	62		x	x	x	x	x	x	x	x
Estonia	53	x	x	x	x	x	x	x	x	x
Finland	53	x	x	x	x	x	x	x	x	x
France	58	x	x	x	x	x	x	x	x	x
Germany	50	x	x	x	x	x	x	x	x	x
Greece	60	x	x	x	x	x	x	x	x	x
Hungary	55	x	x	x	x	x	x	x	x	x
Iceland	53	x	x	x	x	x	x	x	x	x
Ireland	62		x	x	x	x	x	x	x	x
Italy	63		x	x	x	x	x	x	x	x
Latvia	54	x	x	x	x	x	x	x	x	x
Lithuania	53	x	x	x	x	x	x	x	x	x
Netherlands	54	x	x	x	x	x	x	x	x	x
Norway	53	x	x	x	x	x	x	x	x	x

Poland	55	x	x	x	x	x	x	x	x	x
Portugal	60	x	x	x	x	x	x	x	x	x
Romania	62		x	x	x	x	x	x	x	x
Scotland	56	x	x	x	x	x	x	x	x	x
Serbia	68					x	x	x	x	x
Slovakia	55	x	x	x	x	x	x	x	x	x
Slovenia	58	x	x	x	x	x	x	x	x	x
Spain	65			x		x	x	x	x	x
Sweden	56	x	x	x	x	x	x	x	x	x
Switzerland	53	x	x	x	x	x	x	x	x	x
Turkey	54	x	x	x	x	x	x	x	x	x

Table XX – European Limits for $L'_{nT,w}$ compared to impact noise computed for different time steps. “x” indicates fails – GL with RFF

Country	Limit ($L'_{nT,w}$)	t_o	3 months	5 months	7 months	1 year	2 years	3 years	4 years	5 years
$L_{nt,w}$		62	63	64	68	68	67	67	68	69
Austria	48	x	x	x	x	x	x	x	x	x
Belgium	58	x	x	x	x	x	x	x	x	x
Bulgaria	53	x	x	x	x	x	x	x	x	x
Croatia	68									x
Czech Rep.	55	x	x	x	x	x	x	x	x	x
Denmark	53	x	x	x	x	x	x	x	x	x
England & Wales	62		x	x	x	x	x	x	x	x
Estonia	53	x	x	x	x	x	x	x	x	x
Finland	53	x	x	x	x	x	x	x	x	x
France	58	x	x	x	x	x	x	x	x	x
Germany	50	x	x	x	x	x	x	x	x	x
Greece	60	x	x	x	x	x	x	x	x	x
Hungary	55	x	x	x	x	x	x	x	x	x
Iceland	53	x	x	x	x	x	x	x	x	x
Ireland	62		x	x	x	x	x	x	x	x
Italy	63			x	x	x	x	x	x	x
Latvia	54	x	x	x	x	x	x	x	x	x
Lithuania	53	x	x	x	x	x	x	x	x	x
Netherlands	54	x	x	x	x	x	x	x	x	x
Norway	53	x	x	x	x	x	x	x	x	x

Poland	55	x	x	x	x	x	x	x	x	x
Portugal	60	x	x	x	x	x	x	x	x	x
Romania	62		x	x	x	x	x	x	x	x
Scotland	56	x	x	x	x	x	x	x	x	x
Serbia	68									x
Slovakia	55	x	x	x	x	x	x	x	x	x
Slovenia	58	x	x	x	x	x	x	x	x	x
Spain	65				x	x	x	x	x	x
Sweden	56	x	x	x	x	x	x	x	x	x
Switzerland	53	x	x	x	x	x	x	x	x	x
Turkey	54	x	x	x	x	x	x	x	x	x

Table XXI – European Limits for $L'_{nT,w}$ compared to impact noise computed for different time steps. "x" indicates fails – GL with ER

Country	Limit ($L'_{nT,w}$)	t_o	3 months	5 months	7 months	1 year	2 years	3 years	4 years	5 years
$L_{nt,w}$		68	69	70	70	76	71	71	71	71
Austria	48	x	x	x	x	x	x	x	x	x
Belgium	58	x	x	x	x	x	x	x	x	x
Bulgaria	53	x	x	x	x	x	x	x	x	x
Croatia	68		x	x	x	x	x	x	x	x
Czech Rep.	55	x	x	x	x	x	x	x	x	x
Denmark	53	x	x	x	x	x	x	x	x	x
England & Wales	62	x	x	x	x	x	x	x	x	x
Estonia	53	x	x	x	x	x	x	x	x	x
Finland	53	x	x	x	x	x	x	x	x	x
France	58	x	x	x	x	x	x	x	x	x
Germany	50	x	x	x	x	x	x	x	x	x
Greece	60	x	x	x	x	x	x	x	x	x
Hungary	55	x	x	x	x	x	x	x	x	x
Iceland	53	x	x	x	x	x	x	x	x	x
Ireland	62	x	x	x	x	x	x	x	x	x
Italy	63	x	x	x	x	x	x	x	x	x
Latvia	54	x	x	x	x	x	x	x	x	x
Lithuania	53	x	x	x	x	x	x	x	x	x
Netherlands	54	x	x	x	x	x	x	x	x	x
Norway	53	x	x	x	x	x	x	x	x	x

Poland	55	x	x	x	x	x	x	x	x	x
Portugal	60	x	x	x	x	x	x	x	x	x
Romania	62	x	x	x	x	x	x	x	x	x
Scotland	56	x	x	x	x	x	x	x	x	x
Serbia	68		x	x	x	x	x	x	x	x
Slovakia	55	x	x	x	x	x	x	x	x	x
Slovenia	58	x	x	x	x	x	x	x	x	x
Spain	65	x	x	x	x	x	x	x	x	x
Sweden	56	x	x	x	x	x	x	x	x	x
Switzerland	53	x	x	x	x	x	x	x	x	x
Turkey	54	x	x	x	x	x	x	x	x	x

Table XXII – European Limits for $L'_{nT,w}$ compared to impact noise computed for different time steps. "x" indicates fails – GL with ERSS

Country	Limit ($L'_{nT,w}$)	t_o	3 months	5 months	7 months	1 year	2 years	3 years	4 years	5 years
$L_{nt,w}$		63	67	67	67	69	70	70	70	69
Austria	48	x	x	x	x	x	x	x	x	x
Belgium	58	x	x	x	x	x	x	x	x	x
Bulgaria	53	x	x	x	x	x	x	x	x	x
Croatia	68					x	x	x	x	x
Czech Rep.	55	x	x	x	x	x	x	x	x	x
Denmark	53	x	x	x	x	x	x	x	x	x
England & Wales	62	x	x	x	x	x	x	x	x	x
Estonia	53	x	x	x	x	x	x	x	x	x
Finland	53	x	x	x	x	x	x	x	x	x
France	58	x	x	x	x	x	x	x	x	x
Germany	50	x	x	x	x	x	x	x	x	x
Greece	60	x	x	x	x	x	x	x	x	x
Hungary	55	x	x	x	x	x	x	x	x	x
Iceland	53	x	x	x	x	x	x	x	x	x
Ireland	62	x	x	x	x	x	x	x	x	x
Italy	63		x	x	x	x	x	x	x	x
Latvia	54	x	x	x	x	x	x	x	x	x
Lithuania	53	x	x	x	x	x	x	x	x	x
Netherlands	54	x	x	x	x	x	x	x	x	x
Norway	53	x	x	x	x	x	x	x	x	x

Poland	55	x	x	x	x	x	x	x	x	x
Portugal	60	x	x	x	x	x	x	x	x	x
Romania	62	x	x	x	x	x	x	x	x	x
Scotland	56	x	x	x	x	x	x	x	x	x
Serbia	68					x	x	x	x	x
Slovakia	55	x	x	x	x	x	x	x	x	x
Slovenia	58	x	x	x	x	x	x	x	x	x
Spain	65		x	x	x	x	x	x	x	x
Sweden	56	x	x	x	x	x	x	x	x	x
Switzerland	53	x	x	x	x	x	x	x	x	x
Turkey	54	x	x	x	x	x	x	x	x	x

Table XXIII – European Limits for $L'_{nT,w}$ compared to impact noise computed for different time steps. “x” indicates fails – GL with ERLS

Country	Limit ($L'_{nT,w}$)	t_o	3 months	5 months	7 months	1 year	2 years	3 years	4 years	5 years
$L_{nt,w}$		65	67	68	67	68	68	68	68	68
Austria	48	x	x	x	x	x	x	x	x	x
Belgium	58	x	x	x	x	x	x	x	x	x
Bulgaria	53	x	x	x	x	x	x	x	x	x
Croatia	68									
Czech Rep.	55	x	x	x	x	x	x	x	x	x
Denmark	53	x	x	x	x	x	x	x	x	x
England & Wales	62	x	x	x	x	x	x	x	x	x
Estonia	53	x	x	x	x	x	x	x	x	x
Finland	53	x	x	x	x	x	x	x	x	x
France	58	x	x	x	x	x	x	x	x	x
Germany	50	x	x	x	x	x	x	x	x	x
Greece	60	x	x	x	x	x	x	x	x	x
Hungary	55	x	x	x	x	x	x	x	x	x
Iceland	53	x	x	x	x	x	x	x	x	x
Ireland	62	x	x	x	x	x	x	x	x	x
Italy	63	x	x	x	x	x	x	x	x	x
Latvia	54	x	x	x	x	x	x	x	x	x
Lithuania	53	x	x	x	x	x	x	x	x	x
Netherlands	54	x	x	x	x	x	x	x	x	x
Norway	53	x	x	x	x	x	x	x	x	x

Poland	55	x	x	x	x	x	x	x	x	x
Portugal	60	x	x	x	x	x	x	x	x	x
Romania	62	x	x	x	x	x	x	x	x	x
Scotland	56	x	x	x	x	x	x	x	x	x
Serbia	68									
Slovakia	55	x	x	x	x	x	x	x	x	x
Slovenia	58	x	x	x	x	x	x	x	x	x
Spain	65		x	x	x	x	x	x	x	x
Sweden	56	x	x	x	x	x	x	x	x	x
Switzerland	53	x	x	x	x	x	x	x	x	x
Turkey	54	x	x	x	x	x	x	x	x	x

Table XXIV – European Limits for $L'_{nT,w}$ compared to impact noise computed for different time steps. “x” indicates fails – CXPS with TS

Country	Limit ($L'_{nT,w}$)	t_o	3 months	5 months	7 months	1 year	2 years	3 years	4 years	5 years
$L_{nt,w}$		63	67	67	66	71	72	73	70	71
Austria	48	x	x	x	x	x	x	x	x	x
Belgium	58	x	x	x	x	x	x	x	x	x
Bulgaria	53	x	x	x	x	x	x	x	x	x
Croatia	68					x	x	x	x	x
Czech Rep.	55	x	x	x	x	x	x	x	x	x
Denmark	53	x	x	x	x	x	x	x	x	x
England & Wales	62	x	x	x	x	x	x	x	x	x
Estonia	53	x	x	x	x	x	x	x	x	x
Finland	53	x	x	x	x	x	x	x	x	x
France	58	x	x	x	x	x	x	x	x	x
Germany	50	x	x	x	x	x	x	x	x	x
Greece	60	x	x	x	x	x	x	x	x	x
Hungary	55	x	x	x	x	x	x	x	x	x
Iceland	53	x	x	x	x	x	x	x	x	x
Ireland	62	x	x	x	x	x	x	x	x	x
Italy	63		x	x	x	x	x	x	x	x
Latvia	54	x	x	x	x	x	x	x	x	x
Lithuania	53	x	x	x	x	x	x	x	x	x
Netherlands	54	x	x	x	x	x	x	x	x	x
Norway	53	x	x	x	x	x	x	x	x	x

Poland	55	x	x	x	x	x	x	x	x	x
Portugal	60	x	x	x	x	x	x	x	x	x
Romania	62	x	x	x	x	x	x	x	x	x
Scotland	56	x	x	x	x	x	x	x	x	x
Serbia	68					x	x	x	x	x
Slovakia	55	x	x	x	x	x	x	x	x	x
Slovenia	58	x	x	x	x	x	x	x	x	x
Spain	65		x	x	x	x	x	x	x	x
Sweden	56	x	x	x	x	x	x	x	x	x
Switzerland	53	x	x	x	x	x	x	x	x	x
Turkey	54	x	x	x	x	x	x	x	x	x

Table XXV – European Limits for $L'_{nT,w}$ compared to impact noise computed for different time steps. “x” indicates fails – CXPS with RFF

Country	Limit ($L'_{nT,w}$)	t_o	3 months	5 months	7 months	1 year	2 years	3 years	4 years	5 years
$L_{nt,w}$		63	65	66	66	69	69	69	70	71
Austria	48	x	x	x	x	x	x	x	x	x
Belgium	58	x	x	x	x	x	x	x	x	x
Bulgaria	53	x	x	x	x	x	x	x	x	x
Croatia	68					x	x	x	x	x
Czech Rep.	55	x	x	x	x	x	x	x	x	x
Denmark	53	x	x	x	x	x	x	x	x	x
England & Wales	62	x	x	x	x	x	x	x	x	x
Estonia	53	x	x	x	x	x	x	x	x	x
Finland	53	x	x	x	x	x	x	x	x	x
France	58	x	x	x	x	x	x	x	x	x
Germany	50	x	x	x	x	x	x	x	x	x
Greece	60	x	x	x	x	x	x	x	x	x
Hungary	55	x	x	x	x	x	x	x	x	x
Iceland	53	x	x	x	x	x	x	x	x	x
Ireland	62	x	x	x	x	x	x	x	x	x
Italy	63		x	x	x	x	x	x	x	x
Latvia	54	x	x	x	x	x	x	x	x	x
Lithuania	53	x	x	x	x	x	x	x	x	x
Netherlands	54	x	x	x	x	x	x	x	x	x
Norway	53	x	x	x	x	x	x	x	x	x

Poland	55	x	x	x	x	x	x	x	x	x
Portugal	60	x	x	x	x	x	x	x	x	x
Romania	62	x	x	x	x	x	x	x	x	x
Scotland	56	x	x	x	x	x	x	x	x	x
Serbia	68					x	x	x	x	x
Slovakia	55	x	x	x	x	x	x	x	x	x
Slovenia	58	x	x	x	x	x	x	x	x	x
Spain	65			x	x	x	x	x	x	x
Sweden	56	x	x	x	x	x	x	x	x	x
Switzerland	53	x	x	x	x	x	x	x	x	x
Turkey	54	x	x	x	x	x	x	x	x	x

Table XXVI – European Limits for $L'_{nT,w}$ compared to impact noise computed for different time steps. “x” indicates fails – CXPS with ER

Country	Limit ($L'_{nT,w}$)	t_o	3 months	5 months	7 months	1 year	2 years	3 years	4 years	5 years
$L_{nt,w}$		70	71	72	72	78	72	72	73	73
Austria	48	x	x	x	x	x	x	x	x	x
Belgium	58	x	x	x	x	x	x	x	x	x
Bulgaria	53	x	x	x	x	x	x	x	x	x
Croatia	68	x	x	x	x	x	x	x	x	x
Czech Rep.	55	x	x	x	x	x	x	x	x	x
Denmark	53	x	x	x	x	x	x	x	x	x
England & Wales	62	x	x	x	x	x	x	x	x	x
Estonia	53	x	x	x	x	x	x	x	x	x
Finland	53	x	x	x	x	x	x	x	x	x
France	58	x	x	x	x	x	x	x	x	x
Germany	50	x	x	x	x	x	x	x	x	x
Greece	60	x	x	x	x	x	x	x	x	x
Hungary	55	x	x	x	x	x	x	x	x	x
Iceland	53	x	x	x	x	x	x	x	x	x
Ireland	62	x	x	x	x	x	x	x	x	x
Italy	63	x	x	x	x	x	x	x	x	x
Latvia	54	x	x	x	x	x	x	x	x	x
Lithuania	53	x	x	x	x	x	x	x	x	x
Netherlands	54	x	x	x	x	x	x	x	x	x
Norway	53	x	x	x	x	x	x	x	x	x

Poland	55	x	x	x	x	x	x	x	x	x
Portugal	60	x	x	x	x	x	x	x	x	x
Romania	62	x	x	x	x	x	x	x	x	x
Scotland	56	x	x	x	x	x	x	x	x	x
Serbia	68	x	x	x	x	x	x	x	x	x
Slovakia	55	x	x	x	x	x	x	x	x	x
Slovenia	58	x	x	x	x	x	x	x	x	x
Spain	65	x	x	x	x	x	x	x	x	x
Sweden	56	x	x	x	x	x	x	x	x	x
Switzerland	53	x	x	x	x	x	x	x	x	x
Turkey	54	x	x	x	x	x	x	x	x	x

Table XXVII – European Limits for $L'_{nT,w}$ compared to impact noise computed for different time steps. “x” indicates fails – CXPS with ERSS

Country	Limit ($L'_{nT,w}$)	t_o	3 months	5 months	7 months	1 year	2 years	3 years	4 years	5 years
$L_{nt,w}$		65	69	67	69	70	72	72	71	71
Austria	48	x	x	x	x	x	x	x	x	x
Belgium	58	x	x	x	x	x	x	x	x	x
Bulgaria	53	x	x	x	x	x	x	x	x	x
Croatia	68		x		x	x	x	x	x	x
Czech Rep.	55	x	x	x	x	x	x	x	x	x
Denmark	53	x	x	x	x	x	x	x	x	x
England & Wales	62	x	x	x	x	x	x	x	x	x
Estonia	53	x	x	x	x	x	x	x	x	x
Finland	53	x	x	x	x	x	x	x	x	x
France	58	x	x	x	x	x	x	x	x	x
Germany	50	x	x	x	x	x	x	x	x	x
Greece	60	x	x	x	x	x	x	x	x	x
Hungary	55	x	x	x	x	x	x	x	x	x
Iceland	53	x	x	x	x	x	x	x	x	x
Ireland	62	x	x	x	x	x	x	x	x	x
Italy	63	x	x	x	x	x	x	x	x	x
Latvia	54	x	x	x	x	x	x	x	x	x
Lithuania	53	x	x	x	x	x	x	x	x	x
Netherlands	54	x	x	x	x	x	x	x	x	x
Norway	53	x	x	x	x	x	x	x	x	x

Poland	55	x	x	x	x	x	x	x	x	x
Portugal	60	x	x	x	x	x	x	x	x	x
Romania	62	x	x	x	x	x	x	x	x	x
Scotland	56	x	x	x	x	x	x	x	x	x
Serbia	68		x		x	x	x	x	x	x
Slovakia	55	x	x	x	x	x	x	x	x	x
Slovenia	58	x	x	x	x	x	x	x	x	x
Spain	65		x	x	x	x	x	x	x	x
Sweden	56	x	x	x	x	x	x	x	x	x
Switzerland	53	x	x	x	x	x	x	x	x	x
Turkey	54	x	x	x	x	x	x	x	x	x

Table XXVIII – European Limits for $L'_{nT,w}$ compared to impact noise computed for different time steps. “x” indicates fails – CXPS with ERLS

Country	Limit ($L'_{nT,w}$)	t_o	3 months	5 months	7 months	1 year	2 years	3 years	4 years	5 years
$L_{nt,w}$		67	69	70	69	70	69	69	70	70
Austria	48	x	x	x	x	x	x	x	x	x
Belgium	58	x	x	x	x	x	x	x	x	x
Bulgaria	53	x	x	x	x	x	x	x	x	x
Croatia	68		x	x	x	x	x	x	x	x
Czech Rep.	55	x	x	x	x	x	x	x	x	x
Denmark	53	x	x	x	x	x	x	x	x	x
England & Wales	62	x	x	x	x	x	x	x	x	x
Estonia	53	x	x	x	x	x	x	x	x	x
Finland	53	x	x	x	x	x	x	x	x	x
France	58	x	x	x	x	x	x	x	x	x
Germany	50	x	x	x	x	x	x	x	x	x
Greece	60	x	x	x	x	x	x	x	x	x
Hungary	55	x	x	x	x	x	x	x	x	x
Iceland	53	x	x	x	x	x	x	x	x	x
Ireland	62	x	x	x	x	x	x	x	x	x
Italy	63	x	x	x	x	x	x	x	x	x
Latvia	54	x	x	x	x	x	x	x	x	x
Lithuania	53	x	x	x	x	x	x	x	x	x
Netherlands	54	x	x	x	x	x	x	x	x	x
Norway	53	x	x	x	x	x	x	x	x	x

Poland	55	x	x	x	x	x	x	x	x	x
Portugal	60	x	x	x	x	x	x	x	x	x
Romania	62	x	x	x	x	x	x	x	x	x
Scotland	56	x	x	x	x	x	x	x	x	x
Serbia	68		x	x	x	x	x	x	x	x
Slovakia	55	x	x	x	x	x	x	x	x	x
Slovenia	58	x	x	x	x	x	x	x	x	x
Spain	65	x	x	x	x	x	x	x	x	x
Sweden	56	x	x	x	x	x	x	x	x	x
Switzerland	53	x	x	x	x	x	x	x	x	x
Turkey	54	x	x	x	x	x	x	x	x	x