ENVIRONMENTAL COMPARISON OF INDOOR FLOOR COVERINGS

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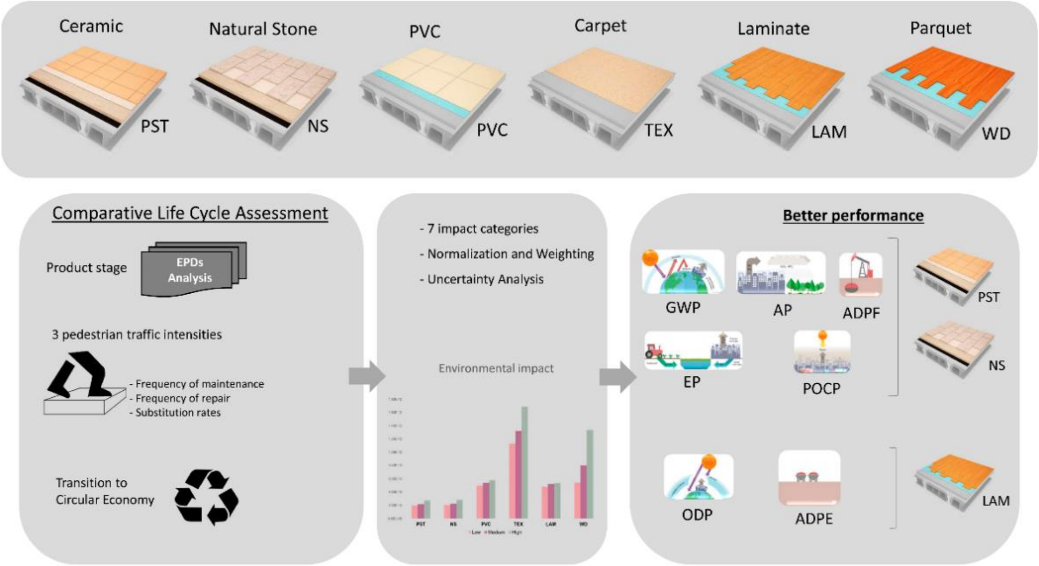
Graphical abstract



Abstract

Appropriate selection of construction materials plays a major role in a building's sustainable profile. The study sets out a comparative life cycle assessment of indoor flooring systems of different nature. The flooring systems consisted of coverings and, where required, bonding material and/or impact soundproofing material. The following coverings were assessed: inorganic (natural stone and ceramic tiles), polymer (carpeting and PVC), and wood-based (laminate and parquet) coverings. The life cycle assessment scope was defined cradle to cradle, i.e. product stage, transport to the construction site, installation of all construction elements, use, and valorisation by recycling, as end-of-life transition scenario towards a circular economy. In the use stage, three scenarios were defined as a function of pedestrian traffic intensity, which determined maintenance, repair, and replacement operations and frequencies. The environmental impacts of the coverings product stage were taken from previously assessed and selected Environmental Product Declarations (EPDs), as these are standardised public documents devised to provide environmental life cycle information. The method adopted in the study suggests that, though the use of EPDs as information source is interesting, erroneous conclusions may be drawn if the EPDs are not comparable and/or if the comparison is not made in the building context. The results indicate that the flooring systems with inorganic coverings performed best in the global warming, acidification, eutrophication, photochemical ozone creation, and abiotic depletion for fossil resources impact categories, whereas laminates performed best in the abiotic depletion for non-fossil resources and ozone layer depletion impact categories. The carpet flooring system performed worst in every impact category except photochemical ozone creation potential.

Key words:

Floor Systems; Life Cycle Assessment; Environmental Product Declaration

Highlights

- Six indoor flooring systems were compared through Life Cycle Assessment, considering three pedestrian traffic intensity scenarios in the use stage.
- 149 EPDs were analysed as starting point in the comparative study.
- The importance of considering the whole life cycle vs. just the product stage was evidenced on comparing different alternative construction solutions.
- Cradle-to-cradle scope was considered, based on a transition to the circular economy.
- Floor systems with inorganic coverings (natural stone and ceramics) performed best in most’ of the environmental impact categories studied.

List of abbreviations

ADPE: abiotic depletion potential for non-fossil resources

ADPF: abiotic depletion potential for fossil resources

AP: acidification potential

EP: eutrophication potential

EPD: environmental product declaration

FU: functional unit

GWP: global warming potential (100 years)

LAM: laminate

LCA: life cycle assessment

MSL: material service life

NS: natural stone

ODP: ozone layer depletion potential (steady state)

PA: polyamide

POCP: photochemical ozone creation potential

PST: ceramic tile, mainly porcelain stoneware tile

PVC: polyvinyl chloride

RSP: reference study period

TEX: synthetic carpet

VOC: volatile organic compound

WD: multilayer and solid parquet

1. Introduction

The construction sector is a major materials consumer. In fact, the European Union deems it a key sector in the attainment of the objectives in the Roadmap to a Resource Efficient Europe

(RERM) (COM/2011/0571 final, 2011) and the EU Action Plan for the Circular Economy (COM/2015/0614 final, 2015), as about 50% of materials extraction, 30% of water consumption, and 30% of waste generation are associated with this sector (COM/2014/445 final, 2014). In addition, buildings account for most of the total final energy consumption in the EU (42%) (COM/2007/0860 final), the use stage being the most noteworthy regarding energy consumption (Cuéllar-Franca and Azapagic, 2012). A literature review carried out by Iribarren et al., 2015, confirmed the enormous efforts being made to reduce the impacts of this stage, albeit often at the expense of using energy-intensive materials, thus counterbalancing energy consumption. In this sense, Asif et al., 2007, identified cement, wood, and ceramic tiles as the three major energy expensive materials. Consequently, appropriate selection of construction materials plays a major role in a building's environmental profile (Akadiri, 2015; COM/2014/445 final, 2014; Häfliger et al., 2017; Zabalza et al., 2011).

Life Cycle Assessment (LCA) is unquestionably the most widely used methodology for evaluating product environmental impacts, particularly those of construction products (Basbagill et al., 2013; Iribarren et al., 2015; Zabalza Bribián et al., 2009). LCA applications in this sector include sustainability assessments of materials (Balaguera et al., 2018), construction systems (Albertí et al., 2019), building designs (Assiego de Larriva et al., 2014; Häfliger et al., 2017; Khasreen et al., 2009; Zabalza Bribián et al., 2009); as well as of cities (Albertí et al., 2017); innovation and ecodesign (Chang et al., 2014; Fazeni et al., 2014; Ortiz et al., 2009; Puig et al., 2017); and marketing, for example, through Environmental Product Declarations (EPDs) (Gazulla Santos, 2012).

In the particular case of floor covering materials, the application of LCA has consistently drawn attention in the literature (Abeysundara et al., 2009; Almeida et al., 2016a; Benveniste et al., 2011; Bovea et al., 2010; Gazi et al., 2012; Günther and Langowski, 1997; Ibáñez-Forés et al., 2011; Islam et al., 2015; Jönsson et al., 1997; Jönsson, 1999; Minne and Crittenden, 2015; Nebel et al., 2006; Nicoletti et al., 2002; Paulsen, 1999; Pini et al., 2014; Potting and Blok, 1995; Reza et al., 2011; Ros-Dosdá et al., 2018a, 2018b; Tikul and Srichandr, 2010; Traverso et al., 2010). Appendix 1 presents a synoptic analysis of these literature references based on the coverings, applied methods and impacts considered, as well as on the scope and boundaries of the system and functional or declared unit. Analysis of this information allows important differences to be noted, which prevent direct comparison of the results for conclusions to be drawn. Generally speaking, certain coincidences were identified, in which it was concluded that linoleum was the most interesting flooring, followed by vinyl, from an environmental viewpoint, when soft and/or resilient floorings were compared (Jönsson et al., 1997; Minne and Crittenden, 2015; Potting and Blok, 1995). However, hardly any comparative studies were found on hard floor coverings (Nicoletti et al., 2002) and no individual or comparative LCA studies were found that included laminate floorings. Finally, it may be noted that none of these studies addressed the integration of the coverings into the construction system as a whole, and only a minority considered the use stage.

On the other hand, drawing up LCAs for EPDs has mainly been driven by the increasing demand for sustainable construction certificates (Anand and Amor, 2017; Ganassali et al., 2018; Gelowitz and McArthur, 2016; Monfort, 2012) and by approval of the construction materials regulation (Regulation (EU) No 305/ 2011, 2011), which insists on using EPDs where available, for sustainability assessment in the efficient use of construction resources and impacts. In fact, EPDs are a basic and very valuable resource in the early stages of building design (Anand and Amor, 2017; Passer et al., 2015), as these are often the only information architects and planners have to compare and decide on different construction and/or component options (Bovea et al., 2014; IBU-EPD programme).

However, certain precautions need to be taken into account in performing comparative analyses. Such use requires understanding EPDs contents, limitations, and the underpinning PCRs to be able to interpret EPDs properly (Gazulla Santos, 2012) and draw accurate conclusions. In the case of comparisons, these must be made considering the functionality and environmental performance either on a whole building level or on lower levels, for example for construction systems, assembled systems, components or products (construction solutions), assuring a series of principles that ensure objectivity and transparency (EN 15804+A1, 2013).

Thanks to the publication of the Basic Product Category Rules for Construction Products (EN 15804+A1, 2013), the European EPDs for floor coverings are relatively homogeneous with regard to the stages that must be declared (A1–A3). However, in subsequent stages, inconsistencies are to be found among EPDs of the same category with different and even with the same PCRs. This is because these stages contain more assumptions and, at present, PCRs do not always establish reference scenarios to avoid inconsistencies among EPDs of the same program (e.g. default values in waste management, bonding materials, and maintenance operations), besides the differences in the verification process of the different programs (Gelowitz and McArthur, 2017; Hunsager et al., 2014; Minkov et al., 2015). For example, the PCRs for ceramic coverings in the GlobalEPD (GlobalEPD, 2018) and IBU-EDP (Institut Bauen und Umwelt e.V., 2017a) programs are very detailed in these stages, whereas the PCRs for carpeting in IBU-EPD (Institut Bauen und Umwelt e.V., 2017b) allow the declarer greater freedom.

This study sets out a comparative analysis of six floor coverings, together with the respective construction system that contains each. The study was conducted on six materials deemed most representative of those used as indoor floor coverings (Table 1).

The industry and business stakeholders request information to compare construction products to make decisions and also to know the positioning of their products against the competitors, from an environmental point of view. Considering that there are no current publications that: i) include the most common types of coverings in Spain and Europe; ii) the existing publications on environmental impacts of the life cycle of coverings do not allow comparison among them; and iii) there is a lack of studies that are supported by objective, complete and available information for companies and industry (i.e. EPDs), the present work is proposed.

Table 1 Production in 2016 of the studied floor coverings.

	Production (million m^2)		
Covering	**World**	**Europe**	**US(6)**
Ceramic tile(1)	13056.0	1304.0	321
Textile floor covering(2)	12095.0	848.0	1150
Natural Stone(3)	514.3	87.4	33.5
Laminate(4)	477.0	371.0	104
Parquet(5)	n.a.	80.4	163
PVC	n.a.	n.a.	447
n.a. Not available			
Sources of information: World and European data: Baraldi, 2017; European Carpet and Rug Association (ECRA), 2018; Carlo Montani, 2018; European Producers of Laminate Flooring (EPLF), 2018; European Federation of the Parquet Industry (FEP), 2017 US data: Floor covering weekly, 2018			

In this context, the main purpose of this study was to perform a comparative LCA study of flooring systems with a cradle-to-cradle scope, using the information contained in the relevant EPDs (as these are public documents issued by the industry, which are verified and updated (<5 years)) to assess the product stage (A1–A3), modelling the other life cycle stages in the same building context in terms of three scenarios in the use stage (maintenance, repair, and replacement operations) as a function of different pedestrian traffic intensities, and applying a progressive transition towards a circular economy, both in the use stage and in the end-of-life stage.

2. Method

2.1. Objective and scope

The study sought to quantify the environmental impact of six major flooring systems (FSs) installed indoors throughout their life cycles, starting out from the information contained in their EPDs.

To do so, an LCA was performed of each FS with a cradle-to-cradle scope, also known as an end-of-life recycling approach (or avoided burden approach) (Frischknecht, 2010; Häfliger et al., 2017; Silvestre et al., 2014), modelled within a building use context under the same system boundaries, scenarios, scope, and considerations for each transport, installation, use and end-of-life stage, in order to allow subsequent comparison, observing the requirements set in standard ISO 14025, 2006, Section 6.7.2.

The LCAs were carried out in accordance with the international standards (ISO 14040, 2006; ISO 14044, 2006) and the core construction PCRs (EN 15804+A1, 2013). The standards on sustainability of construction works (EN 15978, 2011) were also taken into account. The LCA software GaBi 8 (Thinkstep AG, 2018a) and related databases (Thinkstep AG, 2018b), as well as carefully selected EPDs of coverings, were used in the environmental assessment.

A Reference Study Period (RSP) of 50 years was used. The Functional Unit was defined as the quantity of construction elements required to build 1 m2 of indoor flooring system in Spain intended to last for 50 years. The study considered the useful life of the coatings and the number of installations needed to cover the RSL, rounded up to the next integer value, as shown in Table 2.

2.2. Life cycle inventory analysis

2.2.1. Studied flooring system compositions

Types of materials and their arrangement in construction systems vary according to types of buildings and countries (IEE Project TABULA, 2012; Ortiz et al., 2009). To define the FSs for this study, the construction solutions that contained them were first defined, using the following Spanish documents and regulations as references: Código Técnico de la Edificación (the Technical Building Code) (Ministerio de Fomento de España, 2011); Catálogo de Elementos constructivos (Catalogue of Construction Elements) (IETcc-CSIC, 2011); and Documento Básico de protección frente al ruido (Basic Document on Protection against Noise) (Ministerio de Fomento de España, 2009). The studied construction system of horizontal partitions was a *Floating floor screed of cement mortar*, as the authors deemed this to be the most generic alternative described in these documents. The system involved a floor made up of a layer of about 5-cm-thick cement mortar installed on a sheet of impact sound insulation material, the screed being covered with a finish. A schematic illustration of this type of floor is shown in Fig. 1.

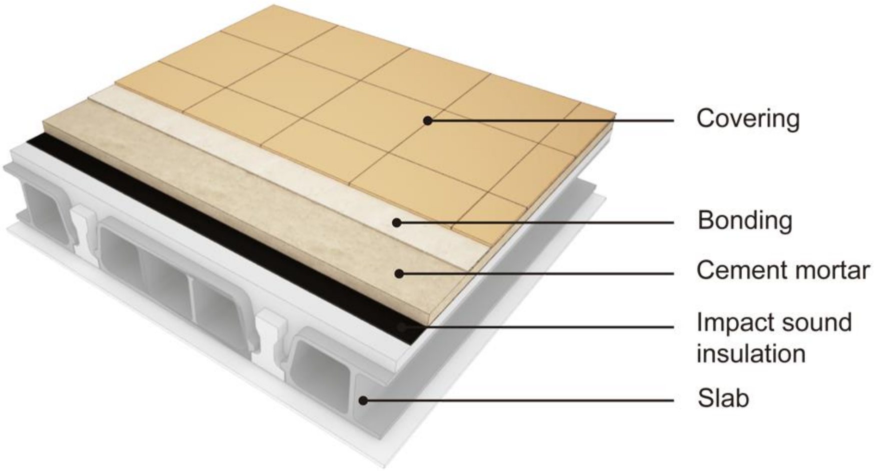


Fig. 1 Horizontal partition systems (Source: own figure from IETcc-CSIC, 2011)

Fig.1 illustrates the five layers making up a construction solution of this type, namely covering, bonding material, cement mortar screed, impact sound insulation, and slab. In this comparative study, the common components in the construction solutions, i.e. the cementitious mortar and slab, were excluded. In this study, the remaining system is designated the flooring system (FS).

The studied FSs are detailed in Table 2. The coverings properties regarding product mass, thickness, varieties and Material Service Life (MSL) were obtained from the selected EPDs (appendix 2); the arrangement and mass of the materials in the different intermediate layers were drawn from CYPE Ingenieros, 2018, databases. To facilitate discussion of the results, the coverings were divided into three groups, based on their nature: inorganic (ceramic tiles and natural stone), polymer (carpeting and PVC), and wood-based (parquet and laminate) coverings.

Table 2 Description of the studied FSs

FS	Classification	Covering (1)					Bonding (2)		Impact sound (2)		MSL	Number of installs during RSP
		Material	Covering Standard	Product varieties considered	Mean mass (kg/m^2)	Mean thickness (mm)	Material	Mean mass (kg/m^2)	Material	Mean mass (kg/m^2)		
PST	Inorganic	Ceramic	ISO 13006, 2012	Mainly Porcelain Stoneware Tiles (water absorption coefficient <0.5%)	24	10.5	Cementitious adhesive	3.5 dry	PE foam sheet (5mm thick)	0.11	>50	1
NS		Natural Stone	EN 12058, 2015	Igneous, Sedimentary and Metamorphic rocks	52	20	Cementitious adhesive	6.4 dry	PE foam sheet (5mm thick)	0.11	>50	1
PVC	Polymer	Polyvinyl| chloride	ISO 10581, 2011; ISO 10582, 2017	Luxury, homogeneous and heterogeneous vinyl, with different finish properties, backings and formats (tiles, planks, and rolls),	3.4	2.6	Contact adhesive	0.3	PE foam sheet (5mm thick)	0.11	20	3
TEX		Carpet	EN 1307+A1, 2016	Made of synthetic polyamide fibres of different recycled content, densities, and backings. Class 33 or less	3.9	-	Contact adhesive	0.25	Not needed		15	4
LAM	Wood	Laminate	EN 13329, 2017	Direct Pressure Laminate floor coverings with different finish properties	7.5	8	Not needed (mechanical assembly)		PE foam sheet (3mm thick)	0.07	15	4
WD		Parquet	EN 14342, 2013	Multilayer and solid parquet	9.5	14	Contact adhesive	0.8	PE foam sheet (5mm thick)	0.11	45/30/15(3)	2/2/4

(1) Mean values in the selected EPDs

(2) Values taken from CYPE Ingenieros, 2018

(3) Depending on the refurbishing operations

2.2.2. Description of the FSs life cycles

The environmental information on the FSs life cycles was organised in terms of the following stages: product, distribution, construction, use (differentiating maintenance, repair, and replacement operations), and end-of-life management.

The *product stage* included raw materials extraction, transport and manufacturing.

The *distribution stage* covered transport from the manufacturing plants to the construction site. These distances have been calculated from each EPD's company site to Madrid (Spain), obtaining a weighted average value by the number of EPDs of each type of covering (see Figure A2.1. in Appendix 2). The distances considered and means of transport applied are those shown in Table 3.

Table 3 Distance and means of transport applied in the distribution stage

Means of transport	PST	PVC	LAM	TEX	NS	WD
Truck	595 km	5357 km	2170 km	2414 km	3000 km	1216 km
Cargo	180 km	714 km	180 km	184 km	0 km	2500 km

The *construction stage* included the following operations: manufacture and transport (average distance: 100 km) of the bonding materials and impact-proof soundproofing sheets, where needed; managing of packaging and construction waste, 5% loss being assumed; and manual installation of each FSs element in the building. The impact caused by unloading and movement of the material at the construction site was excluded. As to waste managing, recycling of 70% and landfilling of the rest (Eurostat, 2019), except for laminate floorings were applied. Laminate flooring waste recycling at the moment of the study was estimated to be nil owing to the multicomponent nature of laminates, so that 100% of the laminate flooring waste was deemed to be landfilled (Parador GmbH & Co.KG, 2013).

The *FSs use stage* included maintenance, repair, and replacement operations. The emissions generated during use of the coverings were excluded as, in their EPDs, most manufacturers declared that, due to known VOC-decay curves of the product, after the first year no product-related VOC emissions were relevant, though studies are to be found that contradict this criterion (Saarela, 1999; Sollinger et al., 1993; Tuomainen et al., 2004). In comparative analysis, aspects such as comfort, visual warmth, and aesthetic versatility have been omitted owing to the subjectivity and/or difficulty involved in quantifying these, thus avoiding adding greater uncertainty to the results.

If a system lasts for a long time, values for some of the variables influencing the impact may vary and using data of the current year may consequently lead to uncertainty. The longevity of construction systems, such as flooring systems, leads to uncertainty in the use stage (Akadiri, 2015), especially because of auxiliary products and technologies involved in operations relating to this stage, such as the energy mix. To lessen this uncertainty, the evolution of the Spanish electricity mix over the next 50 years was considered, according to the predictions of Capros et al., 2013.

Moreover, certain data, such as those for cleaning, highly depend on user habits and installation site demands (Jönsson, 1999; Nebel et al., 2006). In order to cope with this fact, three use scenarios were considered, based on low, medium, and high pedestrian traffic intensity, consistently assuming certain cleaning, repair, and replacement operations and frequencies. To specify the maintenance operations (cleaning) and their frequencies as a function of these three scenarios, the following literature sources were consulted: EPDs that included information in this regard; Diputación de Castellón, 2018; and Minne and Crittenden, 2015.

The differences found in cleaning frequencies and intensity, which explain the different energy and cleaning product (water and detergents) consumptions, stem from the unequal cleanability of the surfaces, owing to differences in surface microstructure and properties of the materials. For example, in the case of TEX, a bed is cleaned, whereas in WD, little water is used.

The cleaning operations and pedestrian traffic intensity scenario for each floor covering are detailed in Table 4.

Table 4 FSs maintenance scenarios (cleaning operations)

FS	SCENARIO	CLEANING ACTIVITIES					
		Wet mop	Wet mop+cleaner	Household vacuum	Professional cleaning system - Water	Professional cleaning system - Water+cleaner	Professional vacuum
PST	Low	1x/week	0.5x/week				
	Medium	7x/week	3.5x/week				
	High				14x/week	7x/week	
NS	Low	1x/week	0.5x/week				
	Medium	7x/week	3.5x/week				
	High				14x/week	7x/week	
PVC	Low		1x/week	2x/week			
	Medium		7x/week	5x/week			
	High					14x/week	
TEX	Low		1x/year	3x/week			
	Medium		2x/year	7x/week			
	High					4x/year	14x/week
LAM	Low		1x/week	3x/week			
	Medium		7x/week	7x/week			
	High					7x/week	14x/week
WD	Low	1x/month	0.5x/month	3x/week			
	Medium	2x/month	1x/month	7x/week			
	High				1x/week	0.5x/week	14x/week

The amount of water and cleaning agent, as well as the electricity consumptions of the domestic and professional equipment in each cleaning operation, together with the information sources and FSs involved, are detailed in Table 5.

Table 5 Water, detergent, and energy consumptions for each cleaning cycle

Consumable in cleaning operations	FSs involved	Amount	Sources
Water per cleaning (l/m^2)	All except TEX	0.1	Mean from EPDs, Diputación de Castellón, 2018; and Minne and Crittenden, 2015.
	TEX	2.1	
Cleaner per cleaning (kg/m^2)	All except TEX	1.0E-04	
	TEX	5.0E-02	
Energy in domestic vacuuming (kWh/m^2)	All except TEX	2.3E-03	Power information provided by 10 commercial models. Vacuum efficiency from Minne and Crittenden, 2015
	TEX	1.4E-02	Power information provided by 10 commercial models. Vacuum efficiency from Minne and Crittenden, 2015
Energy in professional vacuuming (kWh/m^2)	All except TEX	5.4E-04	Power information and vacuum efficiency provided by 4 commercial models.
	TEX	6.6E-03	Power information and vacuum efficiency provided by 4 commercial models.
Energy in professional cleaning (kWh/m^2)	All except TEX	6.3E-04	Power information and vacuum efficiency provided by 7 commercial models.
	TEX	1.6E-02	Power information and vacuum efficiency provided by 6 commercial models.

The *repair operations* were solely applied to natural stone and parquet. Natural stone repair consisted of polishing, buffing, and waxing; parquet repair consisted of sanding or scraping followed by varnishing. The repair operations were solely applied to natural stone and parquet. Natural stone repair consisted of polishing, buffing, and waxing; parquet repair consisted of sanding or scraping followed by varnishing. The possibility of replacing accidently broken parts was not considered in the scope of this study, as any estimation would appear to be quite subjective. Table 6 details the number of repairs during RSP service life, power and efficiency of the electrical equipment, and amount of wax or varnish for surface treatment.

Table 6 Number of coverings repairs in 50 years

	Natural Stone	Parquet
Number of repairs: low/medium/high	1/3/5	5/10/15
Equipment power	2.2 kW(1)	1.5 kW(2)
Operation efficiency	30 s/m^2(1)	30 s/m^2(1)
Wax/varnish	0.02 kg/m^2(3)	0.33 kg/m^2(4)

(1) Nicoletti et al., 2002
(2) Information provided by Holzmann Maschinen GmbH, 2018
(3) Information provided by Fila Industria Chimica S.p.A., 2018
(4) Consulted EPDs

To define the *replacement operations*, the number of coverings replacements required as a function of the coverings MSL during the 50-year RSP was calculated (Table 2).

The operations involved in each replacement were as follows: disassembly of the coverings and, where applicable, of the bonding material; transport of the material removed; treatment and/or disposal of this material; manufacture of replacement material; transport to the construction site; and installation.

In the end-of-life management of the replaced materials waste, a progressive transition to 100% recycling in the course of 50 years, in a phase-in to a circular economy, was applied, as detailed in Table 7.

Table 7 Scenarios in the course of 50 years' construction and demolition waste management

Time elapsed since installation	Laminates		Other coverings	
	Recycling (%)	Landfilling (%)	Recycling (%)	Landfilling (%)
0 years (losses on installation)	0	100	70	30
15–20 years	25	75	80	20
30 years	50	50	90	10
40 years	75	25	95	5
50 years	100	0	100	0

The *end-of-life stage* considered the dismantling and demolition of all FSs elements, transport, and end-of-life management. The dismantling and demolition operations of each FSs element were assumed to be either manual or mechanised, depending on the hardness of the covering and bonding material (CYPE Ingenieros, 2018). The construction materials end-of-life stage entailed great uncertainty, as it was to take place in a distant future (Silvestre et al., 2014). In this case, applying a cradle-to-cradle approach (Häfliger et al., 2017; Silvestre et al., 2014; Wolf et al., 2010), it was assumed that within 50 years, the scenario would be 100% recycling for every type of studied covering, incineration and landfilling options being excluded. For this scenario to materialise, it will be necessary to promote changes in building design in order to facilitate dismantling of the different construction materials (Zabalza et al., 2011).

In this sense, the processes prior to the end-waste state condition for the materials exiting the system as secondary material were considered, as well as all operations beyond the system required for processing this secondary material and the benefits obtained from recycling, were included. Specifically, in this LCA comparative study, it was assumed that the impacts of these operations were those declared by modules C3 (waste treatment) and D (benefits and loads beyond system boundaries) (Silvestre et al., 2014) of the consulted EPDs that provided this information. The theoretical replacement ratios of the recovered inert and wood materials were 1:1, those of the polymer materials being 1:0.81 (Mercante et al., 2012).

In the particular case of the wood-based coverings (parquet and laminates), biogenic carbon was quantified by means of the -1/+1 calculation method (method currently defined by the TC 350 and ISO 21930, 2017 standards), the stored amount of biogenic carbon thus being emitted in the end-of-life stage.

All transport considered in this study occurred with a 27t truck, which conforms to the Euro 6 standard.

2.2.3. Data sources

The characteristics of each element making up the FSs were drawn from CYPE Ingenieros, 2018.

The environmental information relative to the coverings product stage (A1–A3) was taken from the published EPDs (Anand and Amor, 2017; Lasvaux et al., 2014; Passer et al., 2015), while the information on the other constituents was obtained from the GaBi (Thinkstep AG, 2018b) and ELCD (Joint Research Centre, 2015) databases.

For the subsequent stages (A4–C4/D), the EPD values were not used directly, owing to the inhomogeneity of the assumptions made in drawing up the scenarios (Hill et al., 2018). To reduce uncertainty and provide comparability, common scenarios based on the descriptions supplied by the manufacturers in their EPDs and on the literature sources (appendix 1) were defined. On the other hand, the inventory data of the inputs and outputs were selected from the GaBi (Thinkstep AG, 2018b) and ELCD (Joint Research Centre, 2015) databases.

EPD information processing

To obtain representative environmental information on the product stage (A1–A3) of the different coverings, the following EPD programs were consulted: the International EPD® System; Institut Bauen und Umwelt e. V. (IBU-EPD); DAPcons; GlobalEPD; Inies and EPDnorge, carrying out the following procedure:

1) EPDs selection. The following criteria were applied: suitability of the functional characteristics of the product in the building context; conformity to standard EN 15804:2012+A1:2013; verification by a third party; current validity; exclusion of EPDs not written in English, French, German, or Spanish (the authors' mother tongue).

2) EPDs comparability assessment. The criteria set out in standards ISO 14025:2006 and EN 15804:2012+A1:2013 were applied. To simplify application of these criteria, a method similar to that used by Gelowitz and McArthur, 2017, (Table 8) was adopted.

3) Data representativeness. A unit conversion process was performed where necessary, in addition to statistical processing of the impact values. In general, the 50th percentile of the sample was taken as representative value of each covering (Häfliger et al., 2017; Hill et al., 2018).

The analysis of the consulted EPDs is set out in appendix 2.

Table 8 Comparability assessment criteria

Concept	Criterion
FU/DU	The Functional or Declared Unit must be the same or be convertible
Characterisation factors	The characterisation factors must be the same or their units must at least be convertible, e.g. from ounces to kg or m^3 to litres
Mandatory content for comparison according to 14025/15804	Description of the product; PCR identification; Listing of materials and substances to be declared; The list of environmental impacts of the product stage (A1–A3) is presented separately from those of the other life cycle modules
Cut-off rules	The cut-off rules must be identical regarding the mass, volume percentage that may be excluded from the calculations

2.3. Assessment of the environmental impact

The information relative to each FS was modelled with the LCA software GaBi 8 (Thinkstep AG, 2018a), following the considerations of standards ISO 14040-44, 2006, EN 15804+A1, 2013, and EN 15978, 2011.

The studied environmental impact categories, in accordance with standard EN 15804+A1, 2013, are listed in Table 9.

Table 9 Assessed environmental impact categories

Impact category	Acronym	Unit
Global Warming Potential (100 years)	GWP	kg CO_2 Equivalent
Acidification Potential	AP	kg SO_2 Equivalent
Eutrophication Potential	EP	kg PO_4^{3-} Equivalent
Ozone Layer Depletion Potential (steady state)	ODP	kg CFC-11 Equivalent
Photochemical. Ozone Creation Potential	POCP	kg C_2H_4 Equivalent
Abiotic Depletion – elements	ADPE	kg Sb Equivalent
Abiotic Depletion – fossil fuels	ADPF	MJ

Finally, beyond the scope of standard ISO 14040-44, 2006, owing to the subjectivity of the process, to simplify comparison of the six FSs and seven impact categories and to visualise the relative magnitude of the impacts and handle the trade-offs (Laurin et al., 2016), weighting and normalisation factors were applied (Table 10). This enabled a single dimensionless value for each FS and use scenario to be obtained. The applied weighting factors were those obtained by Thinkstep "LCIA Survey 2012, Global, CML 2016, incl. biogenic carbon (global equivalents weighted)". The applied normalisation factors were taken from "CML2001 - Jan. 2016, World, year 2000, incl. biogenic carbon (global equivalents)" (Table 10). Further information on the results for each impact category may be found in appendix 3.

Table 10 Weighting and normalisation factors

Environmental indicators	Weighting Factors	Normalisation Factors
GWP	0.193	4.22E+13
AP	0.127	2.39E+11
EP	0.137	1.58E+11
ODP	0.129	2.27E+08
POCP	0.135	3.68E+10
ADPE	0.133	3.61E+08
ADPF	0.146	3.80E+14

2.4. Uncertainty analysis

As all environmental studies, this comparative study carries a certain degree of uncertainty. In particular, the environmental impacts associated with the coverings product stage stemmed from median data, whose original sample in some cases exhibited a very scattered distribution (appendix 2), in addition to displaying differences regarding source, input data uncertainty, etc. Moreover, assumptions with a high degree of subjectivity were defined in other life cycle stages, such as cleaning or repair operations and frequencies.

The Monte Carlo simulation was programmed, randomly distributing the median data of each life cycle stage and its standard deviation for each FS, represented by a normal distribution, performing a number of 1000 iterations.

Scenario analyses were also carried out on maintenance operations, material service life and end-of-life management of the FS.

3. Results and discussion

Applying the above methodology yielded Fig. 2, which exhibits the contribution of each studied FS to each environmental impact category, differentiating the FS life cycle stages and representing the three use scenarios considered as a function of low, medium, and high pedestrian traffic intensity (from left to right). The results are then discussed from the viewpoint of each impact category, first indicating the results of the comparative analysis based on a cradle-to-gate scope and then on a cradle-to-cradle scope, highlighting the most noteworthy stages in each case.

Limitations

It may be noted that the impact values of the coverings associated with the product stage (cradle to gate) stemmed from previously selected EPDs. This methodology implies some considerations to be taken into account:

- The discussion of the results associated with this life stage is, therefore, limited to the generic information on floorings in scientific publications and from the interpretation of the results included in some EPDs (13.6% of the consulted EPDs).
- The selected EPDs are registered in different programs, they have been carried out with the support of different software and databases, the data correspond to different years and come from different geographical origins (see Appendix 2). However, all EPDs were in force at the time of conducting the study and comply with EN 15804:2012+A1:2013,

which means that the validity of the data and the time constrains were checked during the third party verification processes demanded by the EPD programmes. Moreover, in this study, a uncertainty and quality analysis of data has been carried out to ensure that neither this procedure nor choices lead to biased conclusions in the study.

- This approach reliably reflects the method followed by non-academic users of EPDs.”

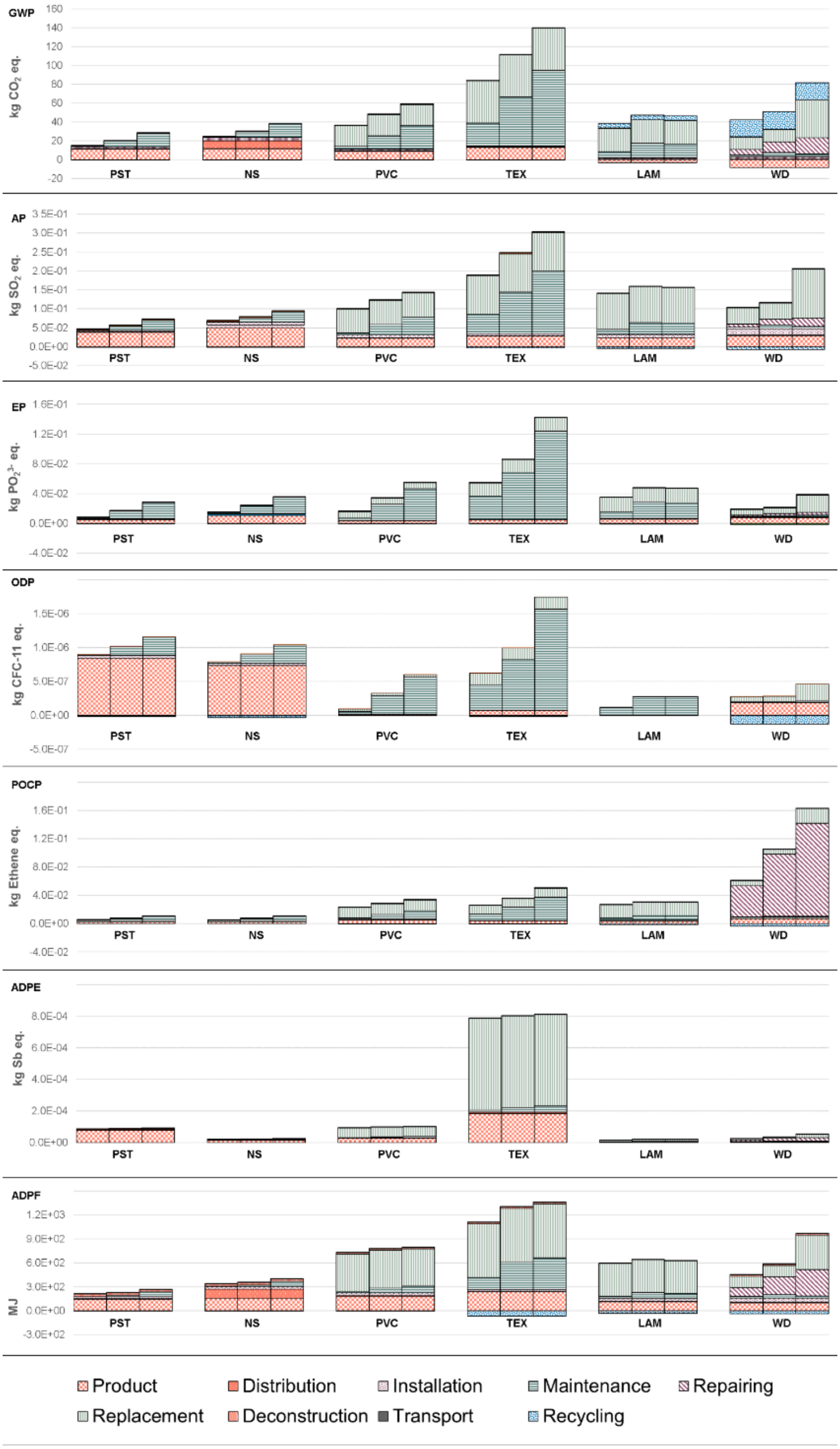


Fig. 2 Environmental impacts of the FSs studied in each defined use scenario, indicating the contribution of each life cycle stage. The values refer to the FU. For each FS, the bars represent low, medium, and high intensity pedestrian traffic, from left to right.

3.1. Global warming potential (GWP)

Comparison solely of the mandatory information contained in the EPDs product stages might lead to the erroneous conclusion that the wood-based coverings performed best, as they generated positive impacts owing to the carbon sequestered by the biomass (Jungmeier et al., 2002; Nebel et al., 2006; Nebel and Cowell, 2003). However, analysis of the FSs from a life cycle perspective revealed that the FSs with inorganic coverings generated a lower environmental impact in every one of the three traffic intensity scenarios defined in the use stage. The lowest values were obtained for PST: 14.2; 16.7; and 23.2 kg CO_2 eq./FU for low, medium, and high pedestrian traffic intensity, respectively. The order of magnitude was similar to that obtained in other studies (Almeida et al., 2016 (20.1–23.3 kg CO_2 eq./m^2; Ibañez-Forés et al., 2011 (18 kg CO_2 eq./m^2); Ros-Dosdá et al., 2018a (11.14–16 kg CO_2 eq./m^2)). The values determined for NS were slightly higher than those for PST, in contrast to the conclusion drawn by Nicoletti et al, 2002, though in that study different MSL and another impact assessment methodology based on eco-indicators was applied. In contrast, the most unfavourable values were obtained for TEX (77.5, 99.0, and 141.1 kg CO_2 eq./FU) in the three studied traffic scenarios, which matched the conclusions of the study by Minne and Crittenden, 2015.

With regard to the stages that exhibited the greatest repercussion, it may be observed that, in the inorganic coverings, the product stage displayed the greatest impact in every analysed scenario, just as in other studies (Almeida et al., 2016b; Benveniste et al., 2011; Bovea et al., 2010; Ibáñez-Forés et al., 2011; Nicoletti et al., 2002; Ros-Dosdá et al., 2018a), stemming from the great energy consumption in the manufacturing stage, combined with the ease of maintenance in the use stage and the high product lifespan (CET, 2014; DAPcons, 2015; GlobalEPD, 2018; Minne and Crittenden, 2015; Thuring et al. 2013). Conversely, in LAM and PVC, the greatest impact was found in the replacement stage, the coverings being penalised by their short lifespans: 15 and 20 years, respectively. TEX, whose origins lie in polyamide manufacture, obtained the worst results in all use scenarios, owing to high energy consumption in the manufacturing and maintenance stages, together with a relatively short lifespan (15 years). WD was the second most unfavourable covering, with a significantly higher impact when installed in areas with high pedestrian traffic because, on requiring more repair operations, its service life decreased, and it needed to be replaced more frequently. The WD end-of-life stage had a significant effect (>25% of the life cycle), as it was in this stage in which part of stored biogenic carbon was theoretically released (Jungmeier et al., 2002). To be noted is further the impact stemming from the varnish used in the WD repair operations (26% in an average scenario).

3.2. Acidification potential (AP)

In a cradle-to-gate scope, all coverings exhibited very similar impact values, those of the inorganic coverings being slightly higher. However, in a cradle-to-cradle scope, the FSs with inorganic coverings again performed best, regardless of the use stage scenario, PST performing best, with values of 0.048–0.074 kg SO_2 eq./FU in low and high traffic scenarios, respectively, yielding similar values to NS, whose impact was slightly greater as both its specific weight and cementitious adhesive consumption were twice as high. In contrast, TEX performed worst owing to maintenance, its impact stemming from electricity in vacuuming, use of detergent, and replacement operations. For the medium traffic scenario both stages accounted for 85% of the total life cycle. In low and medium traffic scenarios, PVC and WD yielded similar values, with differences in the WD cleaning frequencies, repair, and installation stages. In the installation stage, WD needed a greater amount of adhesive (0.8 kg/m^2) than PVC (0.3 kg/m^2) (CYPE

Ingenieros, 2018). In high traffic scenarios, WD required additional replacement as repair sanding diminished WD thickness. In general, the cleaning operations seemed to have no determining importance, except for TEX.

3.3. Eutrophication potential (EP)

In a cradle-to-gate scope, the NS covering exhibited the greatest impacts, and the PVC covering the lowest. On extending the scope, the PST FSs performed best even when installed in areas with high maintenance demands, exhibiting impact values (2.85E-02 kg PO_4^{3-} eq./FU) similar to those calculated by Almeida et al., 2016. PST impact was mainly caused by the product stage, specifically the NOx emissions generated during raw materials extraction and transport (Bovea et al., 2007) and by natural gas combustion in the tile drying and firing stages (Bovea et al., 2010). In this impact category, TEX again performed worst due to the ammonia emissions associated with the high detergent and chemicals demand in cleaning (0.06 kg/m^2 per annum according to the EPDs), matching the conclusions drawn by Minne and Crittenden, 2015. Although the water and detergent cleaning frequency was much lower than that of the other coverings; the amount used per cleaning operation was higher, according to the specifications provided by the manufacturers' EPDs. Solely the maintenance stage accounted for 73% of the total life cycle impact of this FS in a medium traffic intensity scenario.

3.4. Ozone layer depletion potential (ODP)

The surveyed EPDs exhibited a great data scatter in this impact category, both in the product category itself and among the different categories. In all coverings, differences exceeding one or more orders of magnitude were found for the same category. For example, values ranging from 3.4E-11 to 1.5E-06 kg CFC-11 eq./m^2 were found for WD, while values ranging from 7.9E-09 to 2.8E-5 kg CFC-11 eq./m^2 were found for PVC in the EPDs. This scatter meant that the results of the comparative analysis could vary if the outermost EPD values were taken. In this category, assuming a cradle-to-cradle scope, the FSs with inorganic coverings generated the greatest impact, with a difference of 2 orders of magnitude with respect to LAM, which yielded the best results. According to Bovea et al, 2010, the inorganic FS product stage by itself exhibited a higher potential impact, caused by the contribution of diesel vehicles in extraction and transport. In spite of the significant impacts exhibited by WD during the product stage, the recycling benefits obtained offset 67% of the manufacturing impacts (medium traffic scenario), thanks to its recycling ease and potential (Heisterberg-Moutsis et al., 2017). Once again, the TEX FS displayed the greatest impact because of the chemical agents containing chloromethane used in defoamer synthesis, applied in cleaning operations (~76% of the total life cycle impact).

3.5. Photochemical ozone creation potential (POCP)

In a cradle-to-gate scenario, all coverings EPDs declared very similar impacts. In a cradle-to-cradle scope, the inorganic FSs again exhibited the lowest environmental impact in every scenario (about 1.1E-02 kg ethene eq./FU), followed by PCV and LAM with quite similar values (3.3E-02 and 2.9E-02 kg ethene eq./FU, respectively), whose impact was mainly determined by the required replacements. These results differed from those obtained by Minne and Crittenden, 2015, which positioned vinyl slightly better than the ceramic covering, albeit without considering the FSs as a whole. In this impact category, TEX was also penalised by intensive use of cleaning agents, which matched the results obtained by Minne and Crittenden, 2015. The worst-performing FS was WD, which exhibited values ranging from 5.7E-02 to 1.6E-01 kg ethene eq./FU, it being penalised by the repairs required during the entire RSP owing to VOCs (56%) as well as to NO_x and SO_2 emissions (44%) generated by the solvents contained in the varnishes. For example, in a medium traffic scenario, WD needed 10 sanding and varnishing operations (with 0.33 kg/m^2 varnish/repair according to the consulted EPDs), accounting for 86% of the total service life impact. In this study, two types of specific parquet varnishes (namely solvent-based and water-based varnishes) were considered, the impact of which was averaged; the choice of either one or the other could vary the contribution of this stage to the total life cycle impact by up to ±7%.

3.6. Depletion potential for non-fossil resources (ADPE)

The contribution to this impact category stemmed from raw materials extraction for the different coatings. Fig. 2 clearly evidences the high impact of TEX, for two main reasons: sulphur input in the manufacturing process (Thinkstep AG, 2018b) and the short lifespan. The former accounted for 23% of the total life cycle impact and the latter involved the need for 3 replacements in the RSP, therefore accounting for 73% (medium scenario). On the other hand, the PST product stage accounted for 93% of the total life cycle impact. These values stemmed from the use of raw materials such as borates, zinc and tin oxides in the manufacture of PST ceramic glazes (Ros-Dosdá et al., 2018a). Wood-based and NS coverings performed best, LAM yielding the best results.

3.7. Depletion potential for fossil resources (ADPF)

In a cradle-to-gate scenario, the polymer coverings performed worst, matching the conclusions drawn by Jönsson et al., 1997. In this case TEX exhibited the greatest impact (236 MJ/m^2) while wood-based coverings, WD and LAM, exhibited a lower impact (100 MJ/m2 and 113 MJ/m^2, respectively), these values being similar to those obtained by Nebel et al., 2006. On extending the scope to the entire life cycle, inorganic FSs performed better, particularly in high traffic scenarios, with values of 290 MJ/FU and 357 MJ/FU for PST and NS, respectively. Analysis of each PST and NS stage revealed that the greatest differences occurred in the distribution stage. The distribution impact was basically determined by the specific weight (using the same means of transport and distance travelled), with values of 55.5 kg/m^2 and 24.1 kg/m^2 for NS and PST, respectively. The polymer coverings performed worst on extending the scope (cradle to cradle). TEX performed worst in every scenario owing to the environmental loads of raw materials supply (derived from crude oil), and manufacture (Günther and Langowski, 1997; Islam et al., 2015; Potting and Blok, 1995), thus directly affecting the 3 replacements required in the RSP. The necessary replacements and repairs involving the use of varnishes were primarily responsible for the WD impacts, WD being positioned as the second most unfavourable covering.

3.8. Weighting and normalisation

Fig. 3 shows the weighted and normalised environmental impacts of the FSs life cycles for each scenario defined in the use stage according to the factors detailed in Table 10.

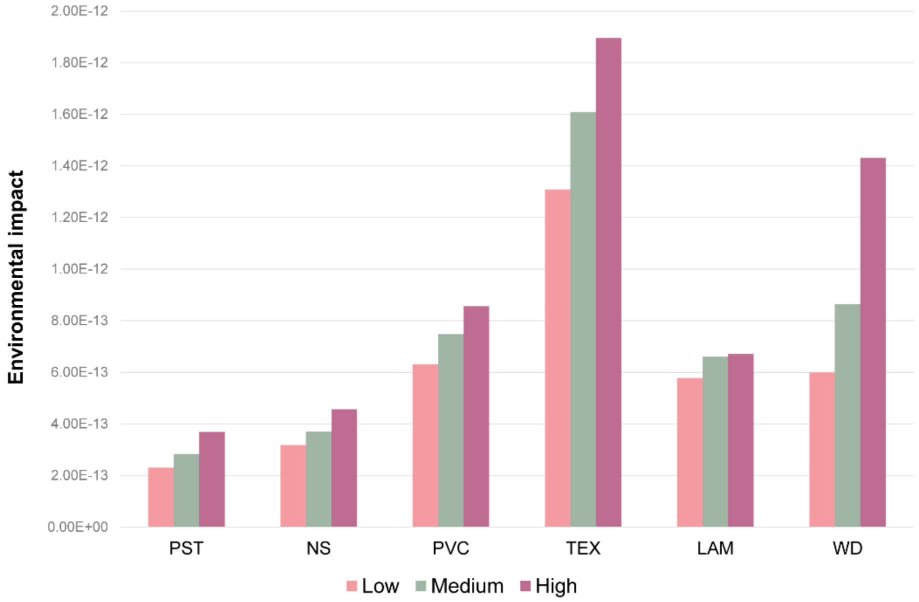


Fig. 3 Weighted and normalised values of the environmental impact results

The FSs with inorganic coverings (PST and NS) performed best, exhibiting differences of less than 5%. These were followed by the FSs with LAM and PVC coverings, whose impact was 25% greater than that of the inorganic coverings, LAM and PVC exhibiting differences not exceeding 10%. The FSs with WD coverings installed in low traffic areas exhibited a similar impact to that of LAM and PVC. However, the higher the traffic, the greater the impact, not just because the cleaning requirements increased but also because, with a greater number of repairs, WD service life decreased (Table 2).

In accordance with this methodology, TEX coverings exhibited the worst environmental performance, largely matching the results obtained in each impact category.

3.9. Uncertainty and sensitivity analysis

3.9.1. Monte Carlo analysis

A Monte Carlo analysis was applied to the entire life cycle of the FSs, using all EPDs starting data and every use scenario. Fig. 4 and Table 11 show the scatter in the results for each type of FS at 95% confidence level on performing 1000 iterations of the global warming potential values. The data are displayed in a box and whisker plot, simultaneously showing the central trend, scatter, and symmetry of the study data. The boxes represent the interquartile range between the 25th and 75th percentile (Q_1 and Q_3, respectively); the cross (X) represents the mean value; the line represents the median value corresponding to (Q_2); and the whiskers represent the 95% confidence interval.

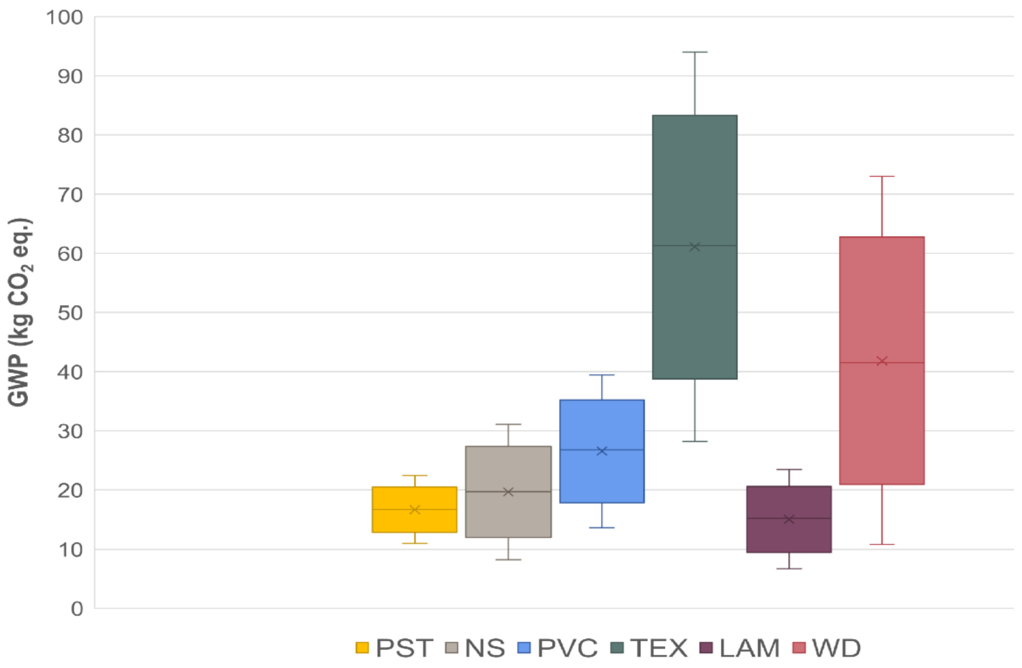


Fig. 4 Monte Carlo analysis of input/output variations in all FSs scenarios

Table 11 shows the number of EPDs used in the study, the mean, median, standard deviation (SD), and the 2.5 and 97.5 percentiles that limit the 95% confidence interval associated to each FS.

Table 11 Uncertainties for Global Warming Potential results related to each FS

FS	Number of EPDs	Mean	Median	SD	95% confidence interval	
					Min	Max
PST	20	16.7	16.7	2.91	11.0	22.4
NS	2	19.6	19.7	5.8	8.2	31.1
PVC	14	26.5	26.8	6.6	13.6	39.4
TEX	27	61.1	61.3	16.8	28.2	94
LAM	5	15.1	15.2	4.3	6.7	23.4
WD	5	41.9	41.5	15.9	10.8	73.0

The samples were observed to be quite symmetrical and the mean and median values, when not identical, lay quite close to each other, evidencing the normality of the data distribution obtained by the Monte Carlo analysis.

TEX and WD were the FSs with the greatest data distribution in this impact category. The interquartile difference between Q_3-Q_1 is 23.3 y 21.5 kg CO_2 eq. respectively. This distribution might be due to the different product varieties included and hypothesis in the use stage (maintenance, repair and replacement). TEX included different densities, recycled material content, backings, etc. WD included solid and multilayer parquet. In the case of TEX, the median value and the value corresponding to the upper limit of the 95% confidence level were the highest in the FSs analysed.

LAM displayed the lowest contribution in values between the 25th and 75th percentile. This range overlapped by 70% with the PST values. PST exhibited the FS with the least uncertainty in this impact category.

3.9.2. Scenario analysis

Scenario analyses were performed to evaluate the influence and significance of some of the environmental parameters that had either been defined by assumptions or entailed significant life cycle impacts. The analyses focused in particular on maintenance operations in the coverings use stage, on length of service life and end-of-life management of the FS.

The operations relating to maintenance (cleaning) were defined by type of covering and pedestrian traffic intensity, the resulting impacts being mainly determined by: i) dry cleaning: electricity consumption in air extraction; ii) wet cleaning: water and detergent consumption.

Fig.5, shows the effect of a 99% reduction in detergent consumption in the maintenance stage of each studied FS. It was verified that the environmental impact categories most sensitive to detergent were ODP and EP. The contribution to ODP was practically determined in its entirety by the emission of chloromethane, used as a chemical intermediary in the production of silicone polymers added as antifoamers. Although the amount of chloromethane was very small (5.0E-05 kg/kg detergent considered (Thinkstep AG, 2018b), it had a powerful destructive capacity on the ozone layer. The detergent's contribution to EP was principally influenced by the inorganic emissions of nitrogen compounds (mainly NH_3 and NO_x) and discharges into the water of phosphates and nitrogen compounds during their fabrication.

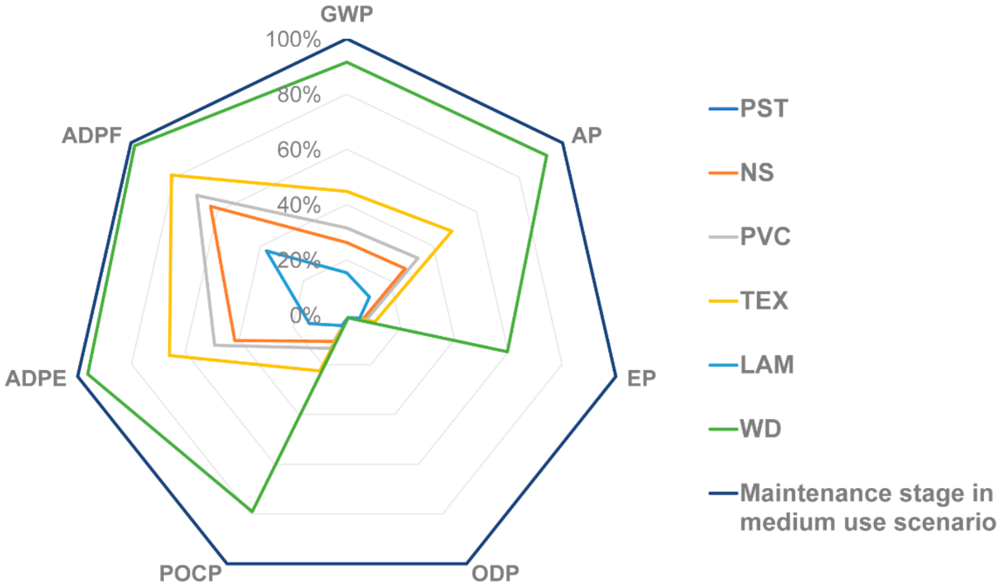


Fig. 5 Effect of 99% reduction in the amount of detergent on the environmental impacts of the maintenance stage in each type of FS

In dry cleaning, a 99% reduction in electricity consumption in a medium use scenario notably decreased the weighted and normalised values of the TEX and WD maintenance stage by 90 and 47%, respectively. The most affected impact categories were ADPF and GWP owing to the make-up of the Spanish electricity mix, with a 44% fossil energy source (REE, 2018).

On the other hand, to analyse the contribution of the maintenance stage to that of the total life cycle, an analysis was performed in which the FS life cycle with and without this stage was compared. The weighted and normalised results obtained are shown in Fig.6. Note the great importance of this stage in TEX (accounting for 33% of the life cycle impact) because TEX cleaning required a much greater amount of detergent and energy than cleaning of the other FSs.

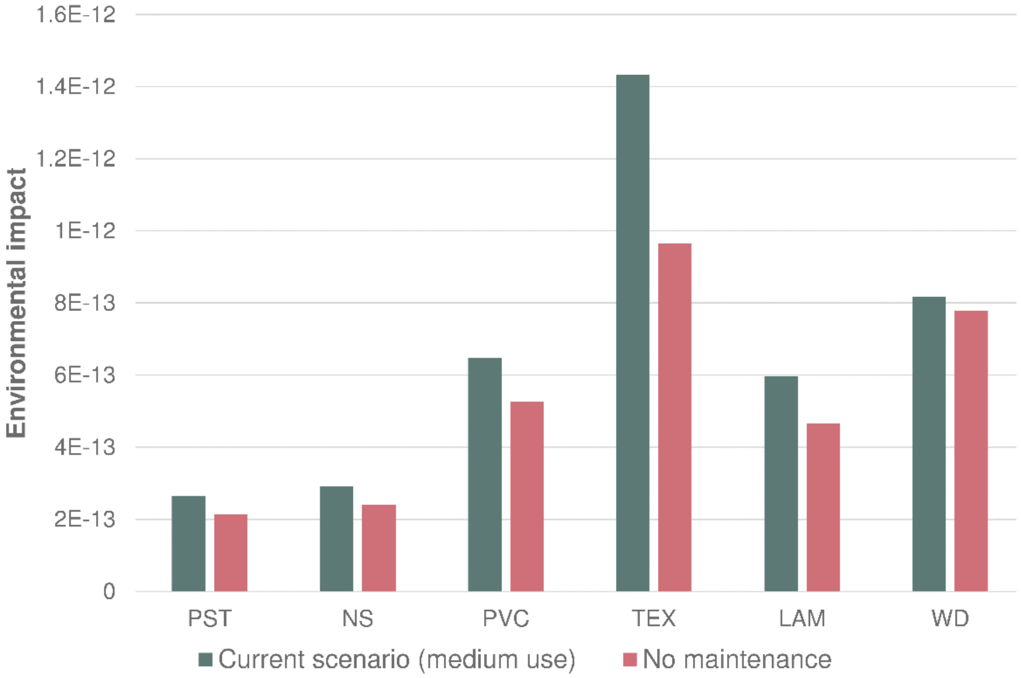


Fig.6 Comparative analysis of the weighted and normalised impacts of the FSs life cycle, considering the maintenance stage in a medium use scenario versus the FSs life cycle without a maintenance stage.

To analyse the influence of product service life, all the coverings were assumed to have an MSL of 15 years, so that the 50-year RSP required 3 replacements (Fig.7). The analysis showed that a premature replacement of the coverings that had a longer theoretical technical (or functional) service life (NS, PST, and WD) gave rise to significant increases in environmental impact (+247, 187, and 134%, respectively, in a medium use maintenance scenarios).

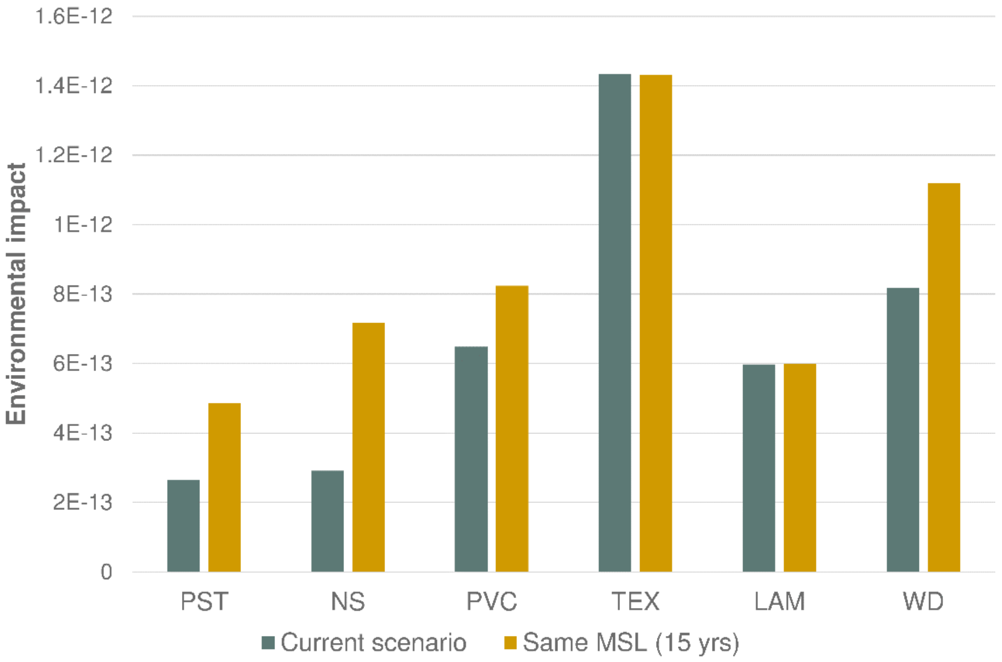


Fig.7 Environmental impacts of the studied FSs in a medium use scenario assuming a service life of 15 years.

Finally, the influence of the FS end-of-life scenarios has been analysed, considering the ideal hypothetical scenario (100% recycling), considered in this study and the current recycling rate for the different materials according to Eurostat, 2019: 71% for PST and NS; 89% for PVC; 79% for TEX; 0% for LAM; and 91% for WD.

Comparing both scenarios, all coverings show variations of less than 8% for all impact categories, except LAM, whose variation in GWP and POCP is 21% and 16%, respectively, attributed to the methane emissions, originated in the decomposition of wood in landfills.

4. Conclusions

The method adopted in the study suggests that the use of EPDs as information source in comparative studies may be really useful, as was to be expected. However, their use currently requires high expertise in LCA and EPDs to avoid erroneous interpretations. To widen the use of this method for comparing materials with the same functionality, the following recommendations may be made to programs administrators: i) procedure harmonisation: verification methods, specific allocation rules, and criteria for obtaining the information provided by EPDs; and ii) scenario harmonisation beyond the gate, i.e. in the use and end-of-life stages.

Considering the background information, the methodology applied and the results obtained, the following recommendations may be made to EPD users when selecting building materials: i) always consider all the stages of the life cycle; ii) include in the analysis the rest of the elements of the construction systems in the context of the building; iii) include in the analysis products and operations necessary for the maintenance and repair of the construction solution; and iv) establish a reference study period and consider the material service life, being aware that an intentional shortening of the theoretical material service life will always lead to increases in environmental impacts.

The inorganic floor coverings (PST, NS) behaved worst in the manufacturing stage in almost every impact category. However, they were least affected by pedestrian traffic intensity scenarios, as they required low-intensity maintenance operations and needed no replacement during the RSP. The whole life cycle of the FSs with inorganic coverings thus performed best in impact categories GWP, AP, EP, POCP, and ADPF.

The life cycle of the polymer FS, TEX, entailed the highest impacts in every impact category, except in POCP. The main contributions stemmed from the chemical agents used in wet cleaning operations (GWP, AP, EP, ODP) and the electricity consumed in vacuuming (GWP, AP, ADPF). In addition, the short lifespan played a key role.

In the wood-based FSs, WD appeared to be most affected by repair operations. The decrease in WD thickness from sanding/scraping, which shortened time between replacements and the use of varnish generated significant impacts on GWP, ADPF, and especially on POCP. LAM presented the most favourable results in ODP and ADPE.

Despite being classified in different groups in this study, LAM and PVC exhibited similar overall impacts in the rest of the impact categories, though their contribution came from different stages: while LAM had a shorter lifespan, the impacts from the PVC product stage were higher.

The application of normalisation and weighting factors allowed a simplified comparison to be made. According to this method, the inorganic FSs (PST and NS) performed best, followed by LAM and PVC whose impacts were, on average, 25% higher. WD exhibited a similar impact to that of LAM and PVC in low traffic areas, while they clearly behaved worse in high-intensity traffic scenarios. TEX showed the worst environmental impact in all traffic scenarios.

The maintenance stage was probably the stage with the most subjective component and was one of the most influential stages in most FSs. A sensitivity analysis was therefore carried out varying the parameters that defined this stage. It was observed that detergent caused significant impacts on ODP and EP, while electricity did so on ADPF and GWP. This stage had a special relevance in TEX, as it accounted for 33% of its (normalised and weighted) impact. However, though omission of the cleaning operations reduced the absolute value in each impact category, it should be noted that it did not vary the relative position of the FSs. In this sense, a fundamental parameter in determining FSs position was service life (MSL), as it determined the number of replacements within the set time frame (RSP) and hence the magnitude of the related environmental impacts. In this study, these values were drawn from the consulted EPDs, which exhibited no significant scatter in this sense. A sensitivity analysis was performed matching the MSLs of all coverings, it being observed that premature substitution of coverings resulted in significant increases in environmental impact.

The Monte Carlo analysis showed that it was necessary to bear in mind that, though the comparisons were based on mean values, the same product category contained variations in product and/or impact, so that the results could not be individualised for each particular case.

5. Acknowledgements

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6. Appendices

The following complementary information is attached to the online version of this article:

- Literature review
- Analysis of the EPDs considered in this study
- Normalisation and Weighting

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Appendix 1:

Literature review

Table A1.1 Literature review

Reference	Coverings	Environmental impact categories	Evaluation method	Scope/limits	Functional Unit
Jönsson et al., 1997	Linoleum Vinyl Wood	Resouce use Energy use Emissions to the air Waste generation	EPS (Environmental Priority Strategies in product design) Environmental Theme method Ecological Scarcity method	Cradle to grave	The covering of one square meter of flooring during one year of operation
Potting and Block, 1997	Cushion vinyl Woollen carpet PA carpet Linoleum	CED (MJ) GWP (g CO_2eq.) EP (g PO_4^{3-} eq.) AP (g SO_2 eq.) POCP (g ethylene eq.) Waste (g hazardous and g non-hazardous)	CED: From (1) and (2) GWP, EP, AP, POCP: from (3)	Extraction and processing of raw materials; use (only lifespan, no maintenance); and waste processing	'The amount of floor covering of good quality which is needed to cover one m^2 of floor surface in a normal Dutch house over a period of 15 years'.
Günther and Langowski, 1997	PVC Cushioned PVC Polyolefins Parquet Linoleum Rubber Textile	Gross energy (MJ) Water demand (m^3) Municipal and chemical waste (kg) AP (Mol H+) GWP (kg CO_2)	"Münchner Kreis"	Cradle to grave	The typical use of 20m^2 flooring over a period of 20 years
Nicoletti et al., 2002	Marble tile Ceramic tile	ADP, GWP, ODP, HT, ECA, AP, POCP, NP	Heijungs et al., 1992 (3) IPPC (4) Normalization (5) Weighting (6)	Extraction, manufacturing, disposal in landfills. Excluding: fixing materials; cleaning operation; ceramic: lime from the abatement of combustion fumes and sludge waste; marble: wax and diamond wire	1 m^2 of flooring tile over a period of 40 years

Reference	Coverings	Environmental impact categories	Evaluation method	Scope/limits	Functional Unit
Nebel et al., 2006	8 mm parquet 10 mm parquet 22 mm parquet Multilayer parquet (floated) Multilayer parquet (glued) Floor wood boards Wood blocks	GWP (g CO_2eq.) EP (g PO_4^{3-} eq.) AP (g SO_2 eq.) POCP (g ethylene eq.) ODP (CFC11-eq.) Primary Energy (MJ)	Guinée et al., 2002 (7)	Cradle to grave. Regular cleaning excluded but vacuum once a week is considered in the sensitivity analysis. Exclusion f oil and wax finish	1 m² of laid wood floor covering assuming average wear and tear in a home that is completely refurbished after 50 years
Abeysundara et al., 2009	Ceramic tile Vinyl tile	GWP (kg CO_2eq.) AP (kg SO_2 eq.) Nutrient enrichment potential (kg SO_2 eq.)	Wenzel et al., 1997 (8)	Raw materials extraction and production; use and maintenance and disposal	"area to be paved in a room of 20 feet (6096 mm) long and 20 feet (6096 mm) wide built in a typical single storey school building of 80 feet (24,384 mm) long and 20 feet (6096 mm) wide, for 50 years"

Table A1.1 Literature review (continued)

Reference	Coverings	Environmental impact categories	Evaluation method	Scope/limits	Functional Unit
Traverso et al., 2010	Sicilian marble (marble chips floor tile and marble slabs)	GWP (kg CO_2eq.) EP (kg PO_4^{3-} eq.) AP (kg SO_2 eq.) POCP (kg ethylene eq.) Embodied energy (MJ)	CML-IA-Aug.2007 (9) Embodied energy: Cole and Rousseau, 1992 (10)	Extraction and production	1 m^3 of marble
Bovea et al., 2010	Ceramic tiles	ADP: kg Sb eq. AP: kg SO_2 eq. EP: kg PO^{-3}_4 eq. GWP: kg CO_2 eq. ODP: kg R11 eq. POCP: kg C_2H_4 eq. Noise dBA	CML 2001 (Guinée 2002) (7)	Extraction of red clay and glaze raw materials, transport, production of the tiles and glazes, and delivery to customer.	1 m^2 of manufactured and classified ceramic tile, ready for sale
Benveniste et al., 2011	Ceramic tiles	ADP: kg Sb eq. AP: kg SO_2 eq. EP: kg PO^{-3}_4 eq. GWP: kg CO_2 eq. ODP: kg R11 eq. POCP: kg C_2H_4 eq. Primary energy consumption: MJ water consumption: m^3	CML 2001 (Guinée 2002) (7)	Cradle to grave, including fixing material and 3 scenarios of use: residential, commercial and sanitary	"Covering 1 m^2 of surface (wall or floor) of a building with ceramic tiles for 50 years considering a residential, commercial or sanitary use".
Ibañez-Forés et al., 2011	Glazed stoneware tile	ADP: kg Sb eq. AP: kg SO_2 eq. EP: kg PO^{-3}_4 eq.	CML 2001 (Guinée 2002) (7)	Cradle to grave except use stage	1 m^2 of ceramic tile over a period of 20 years

		GWP: kg CO_2 eq. ODP: kg R11 eq. POCP: kg C_2H_4 eq. Human toxicity kg1.4 DB eq.			
Gazi et al., 2012	Marble	CO_2 eq.	CO_2 equivalent based on energy consumption	Cradle to gate	1 m^3 of marble
Minne and Crittenden, 2015	Carpet of nylon 6.6 Hardwood Linoleum Vinyl Ceramic	Climate Change: kg CO_2 eq. Fossil depletion (kg oil eq.) POCP (kg NMVOC) Particulate matter formation (kg PM_{10} eq.) Water depletion (m^3) Fresh water eutrophication (kg P eq.) Land occupation (m^2a) Human toxicity kg1.4 DB eq.	ReCiPe mindpoint and endpoint hierarchist	Raw materials, manufacturing, installation, use (several scenarios) and end-of-life	1 m^2 of flooring in residential scenario for 61 years

Table A1.1 Literature review (continued)

Reference	Coverings	Environmental impact categories	Evaluation method	Scope/limits	Functional Unit
Islam et al. 2015	Carpet Plywood Concrete slabs Ceramic tiles	Australian Impact Method with Normalization	Greenhouse gases (tCO_2-eq); CED (GJ); Solid waste (tonne);	Construction, operation 8heating and cooling energy), maintenance and final disposal. It considers all the constructive solution system. Different types of floor depending on the room.	House over its 50-year lifetime
Almeida et al., 2016	Ceramic tiles (glazed tiles and unglazed)	ADPE: kg Sb eq. ADPF: MJ AP: kg SO_2 eq.	CML2001 (ADP – elements; ADP – fossil; AP; EP; GWP; ODP; POCP) (11)	Cradle to grave	1 m^2 of ceramic tile with a lifespan of 50 years

		EP: kg PO^{-3}_4 eq. GWP: kg CO_2 eq. ODP: kg R11 eq. POCP: kg C_2H_4 eq. Human toxicity: CTUh particulate matter: $PM_{2.5}$ land use: kg C deficit water depletion m^3 Ecotoxicity: CTUe	ILCD (Human toxicity particulate matter, land use, water depletion and ecotoxicity) (12)		

Ruschi Mendes Saade et al. 2014	Ceramic tiles	Embodied energy (MJ); embodied CO_2e; blue water footprint (m^3); non-renewable minerals (kg); volatile organic compound emissions (kg)	Method unknown	Cradle to gate	1 m^2 of gross floor area (GFA)
Reza et al., 2011	Three block joisted flooring system: concrete, clay and polystyrene blocks	Resources depletion Wastes and emissions Waste management Climate change Environmental risk Embodied energy Energy loss	Method unknown	Cradle to grave	Construction on 1 m^2 horizontal floor area over the design period of 30 years
Hesser et al., 2017	Multilayer wood parquet	Non-renewable energy use (MJ) Global warming potential (kg CO_2 eq.)	from datasets mainly for transportation and electricity from GEMIS database (13)	Cradle to grave	covering of 1 m^2 of ground
Tikul, 2014	Ceramic tile Marble tiles Untreated solid parquet	Global warming Acidification Eutrophication Ozone depletion	Eco-indicator 95	Cradle to grave	1 m^2 of flooring materials

Table A1.1 Literature review (continued)

Reference	Coverings	Environmental impact categories	Evaluation method	Scope/limits	Functional Unit
Tikul and Srichandr, 2010	Ceramic tile	Global warming (kg CO_2) Ozone depletion (kg CFC11) Acidification (kg SO_2) Eutrophication (kg NO_3) Photochemical smog (kg ethene) Human toxicity air (m^3) Human toxicity water (m^3) Human toxicity soil (m^3) Ecotoxicity water chronic (m^3) Ecotoxicity water acute (m^3) Ecotoxicity soil chronic (m^3)	EDIP methodology and Eco-indicator 99 methodology	Cradle to gate	one megagram (Mg) of double-fired glazed plain white and pink ceramic tiles, size 98 mm x 98 mm x 5 mm thick
Pini et al., 2016	Thin ceramic stoneware slab reinforced with a fibreglass backing	Human health; Ecosystem quality; Climate change; Resources; Single score (Pt)	IMPACT 2002+	Raw materials supply, transport of raw materials, manufacturing, distribution and end of life	1 m^2 of a black, large, thin ceramic tile (3.5mm) reinforced with fibreglass backing
Ros-Dosdá et al., 2018	Porcelain stoneware tile (15 varieties)	ADPE: kg Sb eq. ADPF: MJ AP: kg SO_2 eq. EP: kg PO^{-3}_4 eq. GWP: kg CO_2 eq. ODP: kg R11 eq. POCP: kg C_2H_4 eq.	CML2001 (11)	Cradle to grave	Covering 1 m^2 of household floor surface for 50 years with different varieties of porcelain stoneware tile.

Present study	Porcelain stoneware tile Natural stone PVC Carpet PA6.6 Laminate Parquet	ADPE: kg Sb eq. ADPF: MJ AP: kg SO_2 eq. EP: kg PO^{-3}_4 eq. GWP: kg CO_2 eq. ODP: kg R11 eq. POCP: kg C_2H_4 eq.	CML2001 (11)	Cradle to grave (with several scenarios of use according to different traffic intensity scenarios)	the quantity of building elements needed to form 1 m^2 of indoor flooring system in Spain for 50 years.

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Appendix 2:

Use of EPDs as information source

Using the methodology set out in Section 2.4.1. of the paper, several EPDs were selected and processed to obtain information on environmental impacts relating to the product stage (life cycle modules A1–A3) and other additional information relative to the description of subsequent life cycle stages.

A total of 149 EPDs of indoor floor coverings registered in the following programs were consulted: the International EPD® System; Institut Bauen und Umwelt e. V. (IBU-EPD); DAPcons; GlobalEPD; Inies and EPDnorge.

Table A2.1 details the EPDs consulted in this study.

Table A2.1 List of EDPs evaluated in this study

Coverings	EPD program	Database	Country	Year of publication	Year of data	FU/DU	Interpretation of results	Description of the product	PCR identification	List of materials to be declared	Information of stages not considered	Cut-off rules
LAM1	IBU	GaBi 2017	BE, RU	2017	2015	1 m^2	Yes	Yes	Yes	Yes	No	1% / 5%
LAM2	IBU	GaBi	DE	2016	2014	1 m^2	No	Yes	Yes	Yes	No	No (1)
LAM3	IBU	GaBi	EU	2015	2013	1 m^2	No	Yes	Yes	Yes	No	No (1)
LAM4	IBU	Ecoinvent v.2.2	DE	2013	2012	1 m^2	Yes	Yes	Yes	No	No	<5% Mass
LAM5	IBU	GaBi	IT	2016	2014	1 m^2	No	Yes	Yes	Yes	No	No (1)
WD1	INIES	n.d.	FR	2015	n.d.	1 m^2	No	Yes	Yes	No	Yes	No
WD2	INIES	n.d.	FR	2015	n.d.	1 m^2	No	Yes	Yes	No	Yes	No
WD3*	IBU	GaBi 6.412	DE	2015	2009	1 m^2	Yes	Yes	Yes	-	No	1% / 5%
WD4-5	Int EPD Sys	GaBi	AU sector	2017	2015_2016	1 m2	No	Yes	Yes	No	Yes	No
PVC1	IBU	n.d.	EU	2013	2011	1 m^2	No	Yes	Yes	Yes	No	No (1)
PVC2	IBU	GaBi 6	CH	2013	2010	1 m^2	Yes	Yes	Yes	Yes	No	1% / 5%
PVC3	IBU	n.d.	EU	2013	2011	1 m^2	No	Yes	Yes	Yes	No	No (1)
PVC4	IBU	n.d.	EU	2013	2011	1 m^2	No	Yes	Yes	Yes	No	No (1)
PVC5	IBU	n.d.	EU	2013	2011	1 m^2	No	Yes	Yes	Yes	No	No (1)
PVC6	IBU	n.d.	EU	2013	2011	1 m^2	No	Yes	Yes	Yes	No	No (1)
PVC7	IBU	n.d.	EU	2013	2011	1 m^2	No	Yes	Yes	Yes	No	No (1)
PVC8	IBU	n.d.	EU	2013	2011	1 m^2	No	Yes	Yes	Yes	No	No (1)
PVC9	IBU	n.d.	EU	2013	2011	1 m^2	No	Yes	Yes	Yes	No	No (1)
PVC10	Int EPD Sys	Ecoinvent v3.1	AU, NZ	2017	2014	1 m^2	Yes	Yes	Yes	Yes	No	1% / 5%
PVC11	Int EPD Sys	Ecoinvent v3.1	KR	2016	2014/2015	1 m^2	Yes	Yes	Yes	Yes	No	<5%
PVC12	Int EPD Sys	Ecoinvent v3.1	CH, KR, TW	2016	2011/2012	1 m^2	Yes	Yes	Yes	Yes	No	<5%
PVC13	Int EPD Sys	Ecoinvent v3.1	KR	2016	2014/2015	1 m^2	Yes	Yes	Yes	Yes	No	<5%

Coverings	EPD program	Database	Country	Year of publication	Year of data	FU/DU	Interpretation of results	Description of the product	PCR identification	List of materials to be declared	Information of stages not considered	Cut-off rules
PVC14	Int EPD Sys	Ecoinvent v3.1	CH, KR, TW	2016	2011/2012	1 m^2	Yes	Yes	Yes	Yes	No	<5%
NS1	IBU	n.d.	EU	2014	2009/2011	1t*	No	Yes	Yes	No	No	No (1)
NS2	EPDNorge	Ecoinvent v3.2	NO	2018	2017	1t*	No	Yes	Yes	Yes	Yes	<1%
PST1	IBU	GaBi 6/ELCD 3.2	IT	2016	2014	1 m^2	Yes	Yes	Yes	Yes	Yes	1% / 5%
PST2	IBU	GaBi 6/ELCD 3.2	IT	2016	2014	1 m^2	Yes	Yes	Yes	Yes	Yes	1% / 5%
PST3	DAPcons	ELCD/DAPcons DB	ES	2017	2016	1 m^2	No	Yes	Yes	Yes	Yes	<5%
PST4	DAPcons	ELCD/DAPcons DB	ES	2017	2016/2017	1 m^2	No	Yes	Yes	No	Yes	<5%
PST5	DAPcons	ELCD/DAPcons DB	ES	2016	2015	1 m^2	No	Yes	Yes	No	Yes	<5%
PST6	DAPcons	ELCD/DAPcons DB	ES	2017	2016/2017	1 m^2	No	Yes	Yes	No	Yes	<5%
PST7	DAPcons	ELCD/DAPcons DB	ES	2016	2015	1 m^2	No	Yes	Yes	No	Yes	<5%
PST8	DAPcons	ELCD/DAPcons DB	ES	2017	2015	1 m^2	No	Yes	Yes	No	Yes	<5%
PST9	DAPcons	ELCD/DAPcons DB	ES	2018	2016	1 m^2	No	Yes	Yes	No	Yes	<5%
PST10	GlobalEPD	GaBi 4.4	ES	2013	n.d.	1 m^2	No	Yes	Yes	No	Yes	No (1)
PST11	GlobalEPD	GaBi 4.4	ES	2013	2010	1 m^2	No	Yes	Yes	Yes	Yes	No (1)
PST12	GlobalEPD	GaBi 4.4	ES	2013	n.d.	1 m^2	No	Yes	Yes	Yes	Yes	No (1)
PST13	GlobalEPD	GaBi 4.4	ES	2013	2011/2012	1 m^2	No	Yes	Yes	Yes	Yes	No (1)
PST14	GlobalEPD	GaBi 4.4	ES	2015	2013	1 m^2	No	Yes	Yes	Yes	Yes	No (1)
PST15	GlobalEPD	GaBi 4.4	ES	2013	2011	1 m^2	No	Yes	Yes	Yes	Yes	No (1)
PST16	GlobalEPD	GaBi 4.4	ES	2016	2014	1 m^2	No	Yes	Yes	Yes	Yes	No (1)
PST17	GlobalEPD	GaBi 4.4	ES	2016	2014	1 m^2	No	Yes	Yes	Yes	Yes	No (1)
PST18	IBU	GaBi 7 (SP30)	DE sector	2016	2009/2014	1 m^2	Yes	Yes	Yes	No	Yes	<1%
PST19	IBU	GaBi/ELCD	IT sector	2016	2014	1 m^2	Yes	Yes	Yes	No	Yes	0%
PST20	IBU	GaBi 2016	IT	2017	n.d.	1 m^2	No	Yes	Yes	No	Yes	No (1)
TEX1-21	IBU	n.d.	DK	2013-2018	n.d.	1 m^2	No	Yes	Yes	No	Yes	No (1)

Coverings	EPD program	Database	Country	Year of publication	Year of data	FU/DU	Interpretation of results	Description of the product	PCR identification	List of materials to be declared	Information of stages not considered	Cut-off rules
TEX22-26	IBU	GaBi	EU	2015-2016	n.d.	1 m^2	No	Yes	Yes	No	Yes	No (1)
TEX27-54	IBU	n.d.	NL	2013-2018	n.d.	1 m^2	No	Yes	Yes	No	Yes	No (1)
TEX55-58	IBU	n.d.	DE	2014	n.d.	1 m^2	No	Yes	Yes	No	Yes	No (1)
TEX59-67	IBU	n.d.	UK	2014-2018	n.d.	1 m^2	No	Yes	Yes	No	Yes	No (1)
TEX67-69	IBU	n.d.	DK	2014	n.d.	1 m^2	No	Yes	Yes	No	Yes	No (1)
TEX70-71	IBU	Ecoinvent 3.3/ GaBi SP33	NL	2014	n.d.	1 m^2	No	Yes	Yes	No	Yes	No (1)
TEX72-75	IBU	n.d.	DE	2013-2017	n.d.	1 m^2	No	Yes	Yes	No	Yes	No (1)
TEX76-84	IBU	n.d.	NL	2015-2016	n.d.	1 m^2	No	Yes	Yes	No	Yes	No (1)
TEX85-92	IBU	n.d.	BE	2015-2017	n.d.	1 m^2	No	Yes	Yes	No	Yes	No (1)
TEX93-102	IBU	n.d.	DE	2015-2018	n.d.	1 m^2	No	Yes	Yes	No	Yes	No (1)
TEX103	Int EPD Sys	n.d.	US	2018	2015	1 m^2	Yes	Yes	Yes	No	Yes	1% / 5%

n.d.: no declared

(1): no declared in the EPD but considered in the PCR

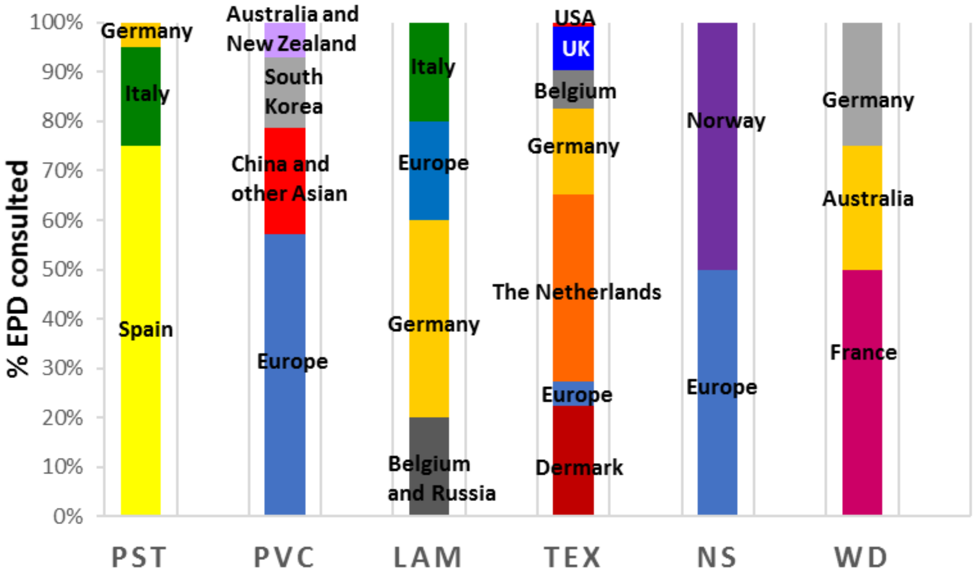

Fig. A2.1 Distribution of the consulted EPDs

Fig A.2.2 shows a box and whisker plot of the data published in the EPDs on the product stage (A1–A3), which includes raw materials extraction and transport and manufacture. At the same time, the graph provides information on the central trend, scatter, and symmetry of the study data. The boxes represent the interquartile range from the 25th to the 75th percentile (Q_1 and Q_3, respectively); the cross (X) represents the mean value and the line represents the value corresponding to the median (Q_2). The whiskers represent the standard deviation and the circles the atypical values calculated from the interquartile range ($RI=Q_3-Q_1$), the lower atypical values being the values below $f_{min}=Q_1-1.5RI$ and the upper atypical values being the values above $f_{max}=Q_3+1.5\ RI$

Note that the justification of the data in Fig. A.2.2 is limited to product description, the scarce interpretation included in some EPDs (only 13.6% of the consulted EPDs provided some type of information in this regard), and the literature surveyed that could provide comparable values in relation to scope, calculation methodology, and impact assessment methods. However, the study's main objective was not detailed interpretation of the values published in the EPDs or comparative analysis with own environmental data of a cradle–gate scope. Consequently, only simple comments of a statistical nature are made.

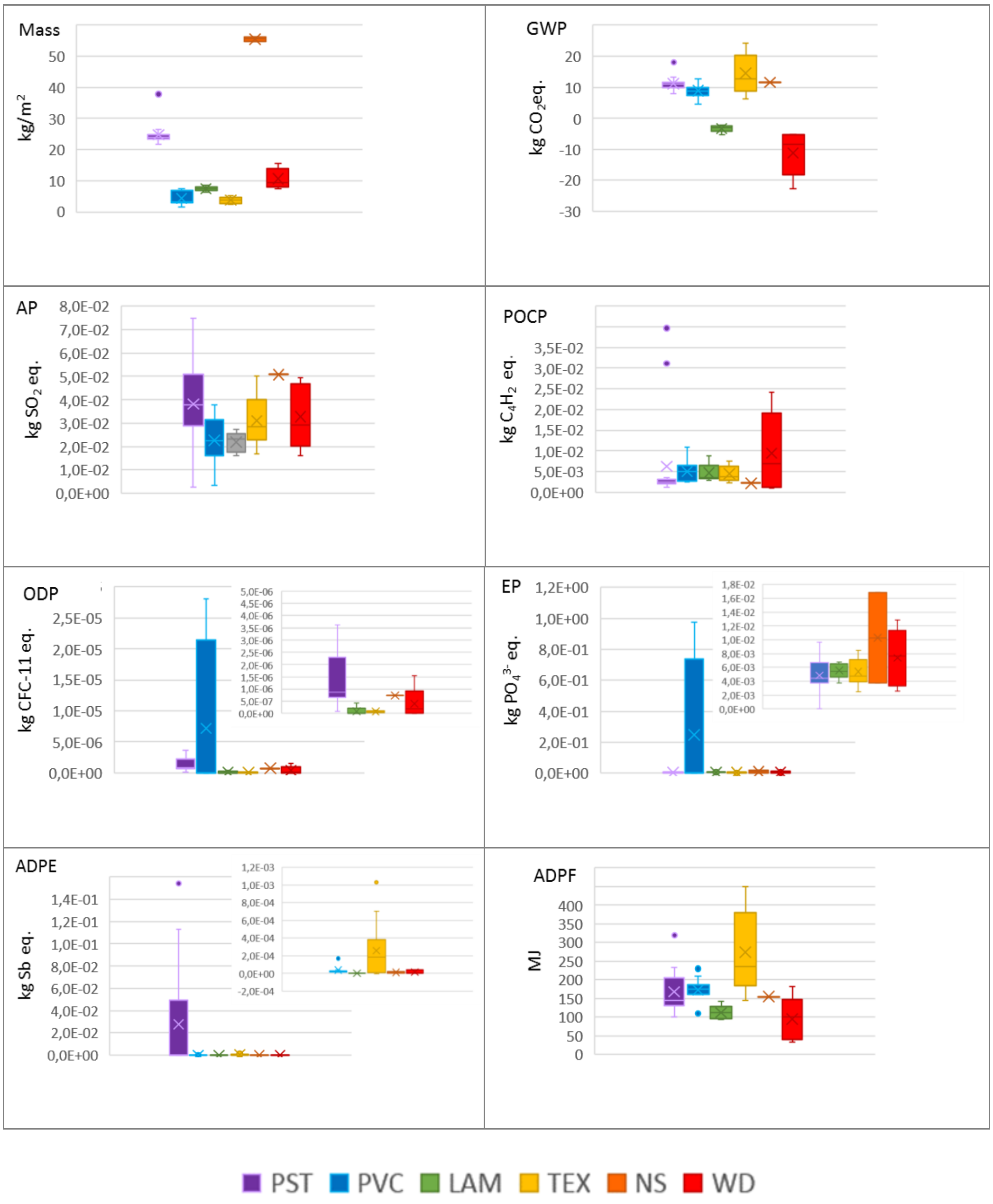

Fig. A2.2 Environmental impacts of the studied coverings. Cradle-to-gate scope from the consulted EDPs
(Table A1)

The inorganic coverings were the heaviest, whereas the polymer coverings were the lightest. NS was by far the heaviest covering: 52.1 kg/m^2, with densities ranging from 2600 to 2800 kg/m^3, and 20-mm thickness. This was followed by PST: 24.1 kg/m^2, with a density of 2300 kg/m^3, and 10.5-mm average thickness. The other floor coverings weighed less than10 kg/m^2.

The studied coverings exhibited similar contributions (of the same order of magnitude) in the AP, POCP, and ADPF impact categories. In the GWP impact category, the wood-based coverings (laminates and parquet) provided negative values owing to stored biogenic carbon, whereas the other coverings exhibited similar behaviours. In the other categories there was a data scatter of at least two orders of magnitude.

Appendix 3:

Normalization and Weighting

Normalization expresses the values of each impact category with respect to a reference situation (ISO 14044:2006; Laurin et al., 2016). The applied normalization factors were taken from "CML2001 - Jan. 2016, World, year 2000 , incl biogenic carbon (global equivalents)" (Table S3.1).

Weighting is a subjective process aiming to rank the results based on the relative importance of each impact category given from factors based on value-choices (ISO 14040-44:2006; Huppes et al. 2012; Cortés-Borda et al. 2013). The weighting factors applied were those obtained by Thinkstep "LCIA Survey 2012, Global, CML 2016, incl biogenic carbon (global equivalents weighted" (Table S3.1).

Table S3.1 Weighting and normalization factors

Environmental indicators	Weighting Factors	Normalization Factors
GWP	0.193	4.22E+13
AP	0.127	2.39E+11
EP	0.137	1.58E+11
ODP	0.129	2.27E+08
POCP	0.135	3.68E+10
ADPE	0.133	3.61E+08
ADPF	0.146	3.80E+14

The tables S3.2, table S3.3. and table S3.4 show the absolute, normalized and weighted values of the FS evaluation, respectively, considering the three use scenarios.

Table S3.2 Results of the life cycle analysis of each FS. Absolute values

Impact categories		GWP	AP	EP	ODP	POCP	ADPE	ADPF
		kg CO_2 Eq.	kg SO_2 Eq.	kg PO_4^{3-} Eq.	kg CFC-11 Eq.	kg C_2H_4 Eq.	kg Sb Eq.	MJ
PST	Low	14.8	4.7E-02	7.8E-03	8.9E-07	5.2E-03	8.6E-05	205.6
	Medium	20.1	5.6E-02	1.7E-02	1.0E-06	7.6E-03	8.8E-05	221.6
	High	28.3	7.3E-02	2.8E-02	1.1E-06	1.1E-02	9.2E-05	265.7
NS	Low	24.5	6.8E-02	1.5E-02	7.5E-07	5.1E-03	1.9E-05	336.9
	Medium	29.8	7.8E-02	2.4E-02	8.7E-07	7.5E-03	2.1E-05	353.0
	High	38.1	9.5E-02	3.5E-02	1.0E-06	1.1E-02	2.5E-05	397.3

Table S3.2 Results of the life cycle analysis of each FS. Absolute values (continued)

Impact categories		GWP	AP	EP	ODP	POCP	ADPE	ADPF
		kg CO_2 Eq.	kg SO_2 Eq.	kg PO_4^{3-} Eq.	kg CFC 11 Eq.	kg C_2H_4 Eq.	kg Sb Eq.	MJ
PVC	Low	36.3	1.0E-01	1.6E-02	9.6E-08	2.3E-02	9.3E-05	724.5
	Medium	47.7	1.2E-01	3.4E-02	3.3E-07	2.8E-02	9.8E-05	770.3
	High	58.5	1.4E-01	5.5E-02	6.0E-07	3.3E-02	1.0E-04	793.3
TEX	Low	83.1	1.9E-01	5.4E-02	6.1E-07	2.5E-02	7.9E-04	1042.0
	Medium	110.6	2.4E-01	8.5E-02	9.8E-07	3.5E-02	8.0E-04	1232.4
	High	139.1	3.0E-01	1.4E-01	1.7E-06	5.0E-02	8.1E-04	1290.3
LAM	Low	35.3	1.4E-01	3.4E-02	1.2E-07	2.6E-02	1.5E-05	559.9
	Medium	44.3	1.5E-01	4.6E-02	2.8E-07	2.9E-02	1.9E-05	605.5
	High	43.4	1.5E-01	4.6E-02	2.8E-07	2.9E-02	1.8E-05	594.2
WD	Low	34.2	9.6E-02	1.7E-02	1.5E-07	5.7E-02	2.3E-05	412.1
	Medium	42.3	1.1E-01	1.9E-02	1.6E-07	1.0E-01	3.3E-05	550.2
	High	73.1	2.0E-01	3.6E-02	3.3E-07	1.6E-01	5.3E-05	926.8

Table S3.3 Results of the life cycle analysis of each FS. Normalized values

Impact categories		GWP	AP	EP	ODP	POCP	ADPE	ADPF
PST	Low	3.5E-13	2.0E-13	5.0E-14	3.9E-15	1.4E-13	2.4E-13	5.4E-13
	Medium	4.8E-13	2.4E-13	1.1E-13	4.4E-15	2.1E-13	2.4E-13	5.8E-13
	High	6.7E-13	3.0E-13	1.8E-13	5.0E-15	2.9E-13	2.5E-13	7.0E-13
NS	Low	5.8E-13	2.9E-13	9.5E-14	3.3E-15	1.4E-13	5.4E-14	8.9E-13
	Medium	7.1E-13	3.3E-13	1.5E-13	3.8E-15	2.0E-13	5.9E-14	9.3E-13
	High	9.0E-13	4.0E-13	2.2E-13	4.4E-15	2.9E-13	6.9E-14	1.0E-12
PVC	Low	8.6E-13	4.2E-13	1.0E-13	4.2E-16	6.3E-13	2.6E-13	1.9E-12
	Medium	1.1E-12	5.1E-13	2.2E-13	1.4E-15	7.6E-13	2.7E-13	2.0E-12
	High	1.4E-12	6.0E-13	3.5E-13	2.6E-15	9.1E-13	2.8E-13	2.1E-12
TEX	Low	2.0E-12	7.8E-13	3.4E-13	2.7E-15	6.9E-13	2.2E-12	2.7E-12
	Medium	2.6E-12	1.0E-12	5.4E-13	4.3E-15	9.5E-13	2.2E-12	3.2E-12
	High	3.3E-12	1.3E-12	9.0E-13	7.6E-15	1.3E-12	2.2E-12	3.4E-12

Table S3.3 Results of the life cycle analysis of each FS. Normalized values (continued)

Impact categories		GWP	AP	EP	ODP	POCP	ADPE	ADPF
LAM	Low	8.4E-13	5.7E-13	2.1E-13	5.3E-16	7.0E-13	4.2E-14	1.5E-12
	Medium	1.0E-12	6.4E-13	2.9E-13	1.2E-15	7.9E-13	5.2E-14	1.6E-12
	High	1.0E-12	6.4E-13	2.9E-13	1.2E-15	7.9E-13	5.0E-14	1.6E-12
WD	Low	8.1E-13	4.0E-13	1.1E-13	6.8E-16	1.6E-12	6.4E-14	1.1E-12
	Medium	1.0E-12	4.5E-13	1.2E-13	7.0E-16	2.8E-12	9.1E-14	1.4E-12
	High	3.5E-13	2.0E-13	5.0E-14	3.9E-15	1.4E-13	2.4E-13	5.4E-13

Table S3.4 Results of the life cycle analysis of each FS. Weighting of normalized values

Impact categories		GWP	AP	EP	ODP	POCP	ADPE	ADPF
PST	Low	6.8E-14	2.5E-14	6.8E-15	5.0E-16	1.9E-14	3.2E-14	7.9E-14
	Medium	9.2E-14	3.0E-14	1.5E-14	5.7E-16	2.8E-14	3.2E-14	8.5E-14
	High	1.3E-13	3.9E-14	2.4E-14	6.5E-16	3.9E-14	3.4E-14	1.0E-13
NS	Low	1.1E-13	3.6E-14	1.3E-14	4.3E-16	1.9E-14	7.2E-15	1.3E-13
	Medium	1.4E-13	4.2E-14	2.1E-14	4.9E-16	2.8E-14	7.8E-15	1.4E-13
	High	1.7E-13	5.0E-14	3.1E-14	5.7E-16	3.9E-14	9.2E-15	1.5E-13
PVC	Low	1.7E-13	5.3E-14	1.4E-14	5.4E-17	8.5E-14	3.4E-14	2.8E-13
	Medium	2.2E-13	6.5E-14	3.0E-14	1.9E-16	1.0E-13	3.6E-14	2.9E-13
	High	2.7E-13	7.6E-14	4.8E-14	3.4E-16	1.2E-13	3.7E-14	3.0E-13
TEX	Low	3.8E-13	9.9E-14	4.7E-14	3.4E-16	9.4E-14	2.9E-13	4.0E-13
	Medium	5.1E-13	1.3E-13	7.4E-14	5.6E-16	1.3E-13	3.0E-13	4.7E-13
	High	6.4E-13	1.6E-13	1.2E-13	9.8E-16	1.8E-13	3.0E-13	4.9E-13
LAM	Low	1.6E-13	7.2E-14	2.9E-14	6.9E-17	9.4E-14	5.5E-15	2.1E-13
	Medium	2.0E-13	8.2E-14	4.0E-14	1.6E-16	1.1E-13	7.0E-15	2.3E-13
	High	2.0E-13	8.1E-14	4.0E-14	1.6E-16	1.1E-13	6.7E-15	2.3E-13
WD	Low	1.6E-13	5.1E-14	1.5E-14	8.7E-17	2.1E-13	8.5E-15	1.6E-13
	Medium	1.9E-13	5.8E-14	1.7E-14	9.0E-17	3.7E-13	1.2E-14	2.1E-13
	High	3.4E-13	1.1E-13	3.2E-14	1.9E-16	5.8E-13	2.0E-14	3.5E-13

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