



Comparative life cycle assessment of traditional timber jack arch slab refurbishment solutions: Eco-efficient proposal versus conventional ones

M. A. Sánchez-Burgos¹ · M. A. Pedreño-Rojas² · F. Pérez-Gálvez¹ · P. Rubio-de-Hita¹

Received: 17 January 2023 / Accepted: 9 November 2023 / Published online: 5 December 2023
© The Author(s) 2023

Abstract

Purpose In the context of worldwide efforts to reduce plastic waste, the authors of this document patented a cement mortar floor slab interjoist prefab vault incorporating recycled plastic. This piece was designed to be used for the refurbishment of Spanish traditional timber jack arch floor slabs. Taking into account nowadays context, it is essential to assess the environmental benefits of this product.

Methods A cradle to gate LCA has been performed following ISO 14044 and ISO 15804 recommendations. Thus, the aim of this research is both to provide a measure of the environmental improvement that this material adds to the building process and to compare it with current most used construction elements used for the same function. It is stressed that this study is based mainly on primary data obtained from Spanish producers.

Results The results obtained show that the reference scenario, corresponding to the new patented vault, is the system with lower impacts in six out of the seven categories assessed. Furthermore, when adding the LCA normalisation step, the conducted analysis show that for the most influential impact categories, GWP100a and AD fossil fuels, the reference scenario bears the lowest scores.

Conclusions It can be concluded that the new patented vault has a better environmental performance than the assessed commercial vaults. Therefore, in this research, the benefits for the construction sector to incorporate recycled plastics are shown. Furthermore, these results can encourage the research on construction products that include recycled plastics in their composition. Bearing in mind that this study assesses the impacts corresponding to the production of a prototype of the newly vault, it is considered that there is room for further improvement through the optimisation of the production process.

Keywords Building refurbishment · Plastic waste · Recycling · Sustainable construction · Life cycle assessment, Comparative LCA

1 Introduction

Nowadays, plastic waste is a matter of concern worldwide. Specifically in Europe, we must take into account that recent data showed that in 2020, there was a total of 29.5 million tons of plastic waste in Europe. Of this, 34.6% of which was

recycled, yielding 10.21 million ton, and 42% was sent to energy recovery facilities, leaving a 23.4% of plastic waste sent to landfill, which means a yearly amount of 6.9 million tons of plastics waste (Plastics Europe 2021). On the other hand, there is a growing demand of plastics in industry. In Europe, during 2020, this demand has reached 49.1 million tons (Plastics Europe 2021). As a result of this situation, there is a growing interest in recycling plastic waste. In Europe, the administration has launched specific regulation for this issue within the Plastics Strategy, including reduction targets (European Union 2018), setting a minimum recycling rate of 50% for all plastics by 2025 and maximum waste plastic landfill for municipal waste of 10% by 2035, together with Directive (EU 2018) 2019/904 which sets a minimum of 77% separate collection for plastic bottles by 2025 and 90% by 2029 (European Union 2019).

Communicated by Holger Wallbaum.

✉ M. A. Sánchez-Burgos
msanchez2@us.es

¹ Departamento de Construcciones Arquitectónicas I, Escuela Técnica Superior de Arquitectura, Universidad de Sevilla, Avenida Reina Mercedes, n_2, 41012 Sevilla, Spain

² Universidad Politécnica de Madrid, Grupo de investigación TEMA, Avenida Juan de Herrera, 6 28040 Madrid, Spain

In the case of Spain, plastic demand during 2020 was 3.6 million tons; of this consumption, 20.4% correspond to the building sector (INE Spain) (RD 293/2018). Most recent data in Spain show that a total of 356,320 tons of waste plastics were produced, of which 17.652 tons were due to the construction sector; this yields a 5% out of the total amount (INE, Spain). In addition to this, plastic packaging recycling rate in Spain in 2018 was 41.9%, being the 2nd highest national rate out of EU members (Plastics Europe 2020).

European efforts to deal with this problem have been focused on plastic waste recycling rate increase. This is an effort included in the European Strategy for Plastics in a Circular Economy (European Union 2018; European Union 2019). Furthermore, this is a sensible practice that helps avoiding waste, reducing a growing environmental problem (Syberg et al. 2021; Elliott et al. 2020), and a way to extend plastic raw material useful life (Eriksen et al. 2020; Hahladakis and Iacovidou 2019) reducing plastic demand. Currently, 46% of recycled plastics in Europe are used in building and construction sector (Plastics Europe 2020). Therefore, there are many research projects aimed to incorporate recycled plastics in building materials (Lamba et al. 2021); specifically, some of them are focused on the use of recycled plastics as cement mortar aggregates (Usman et al. 2018) and concrete aggregates (Almeshal et al. 2020; Kamal et al. 2021).

In that sense, it is highlighted that in 2018, the authors of this document developed a research and patented a cement mortar floor slab interjoist prefab vault incorporating recycled plastic (Rubio-de Hita et al. 2018). This piece was designed to cope with the question of the refurbishment of Spanish traditional timber jack arch floor slabs (Fig. 1).

This is an issue in South Spain and Portugal as they are very frequent in traditional domestic architecture (Rubio-de Hita et al. 2018; Diodato et al. 2015). These slabs are characterised by its curved infill made of masonry (Rubio-de Hita et al. 2018), and due to today's shortage of qualified bricklayers, in most cases, refurbishment method for these floorings consists of demolition and construction of new slabs with current construction technology. This means that

existing slabs and their timber beams, often useful, are discarded, thus increasing construction waste and all associated problems (Assefa and Ambler 2017; Ferreira et al. 2015). Although there are commercial models of prefab pieces for slab interjoist beam-filling, incorporating inferior arched surface, their interjoists are wider than common dimensions of existing traditional timber jack arch slabs; therefore, they are not compatible with existing traditional joist arch slabs. The new designed interjoist prefab vault incorporating recycled plastic contributes both to the reduction of construction waste, enabling the refurbishment of slabs otherwise demolished, and the increase in plastic waste recycling.

Finally, nowadays, it is essential to assess the environmental benefits of products and strategies associated to recycling and reducing waste, and the most accepted methodology for this purpose is the Life Cycle Assessment (LCA) (ILCD 2010; Guinée and Lindeijer 2002), which has been adopted in many researches on construction materials' environmental performance, specifically regarding floor slab environmental assessment (Demertzi et al. 2020a, b).

In this paper, the environmental impacts of the above-mentioned new floor slab vault are assessed using LCA methodology. The aim of this research is both to provide a measure of the environmental improvement that this material adds to the building process and to compare it with current most used construction elements used for the same function. While most published research on this scheme is based on statistical database and general considerations for complete systems such as steel, timber, or concrete structure (Demertzi et al. 2020b), or ceramic versus concrete bricks for exterior walls (Muneron et al. 2021), in this study, one specific construction piece is assessed. Furthermore, all meaningful data has been obtained either from leading companies currently working for the building sector in Spain or from the new patented floor slab vault production process. Therefore, a real case is presented here, with data and results that depicts Spain current building sector environmental performance, regarding these construction pieces. Moreover,

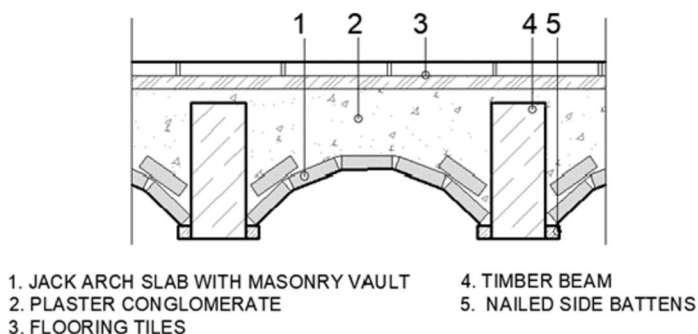


Fig. 1 Traditional timber jack arch floor slabs (Rubio-de Hita et al. 2018; Diodato et al. 2015)

a comparison with other slab typologies is presented. This way, in this study, all agents involved in the building sector are provided with the information necessary to make decisions based on environmental criteria (Guinée and Lindeijer 2002).

2 Materials and methods

2.1 Description of assessed floor slabs

In this research, four slab systems have been assessed (models A to D). Commercial models (B to D) have been chosen representing the most widespread commercial typology of pieces currently available in the construction market in Spain; in fact, there is no other type for this pieces offered in Spanish market. All chosen interjoist filling prefab pieces have an arched inferior surface, thus providing the corresponding slab with a traditional image. Therefore, it is considered that all of them have equal aesthetic value. Furthermore, the elements in all assessed systems have been calculated to bear a 4-m span, which is the typical dimension for traditional floor slabs (Rubio-de Hita et al. 2018). The structural design loads adopted comply with standards included in CTE-DB-SE, the national adaptation of related Eurocodes (Eurocode), which currently are of mandatory compliance in Spain. Consequently, the following values have been considered: permanent loads (1.5 kN/m^2), self-weight loads for each system slab composition, and live loads intended for residential use (2.0 kN/m^2). Furthermore, according to the above-mentioned Eurocode, the Reference Service Life (RSL) of all assessed systems equals the RSL of the corresponding building structure which is 50 years, and it is applied to the slab once it has been refurbished. Therefore, all considered systems have equal functional characteristics and it is not necessary to define a weighting coefficient to compare them (EN 15804 2012). Finally, it is noted that, as a consequence of the shorter interjoist length for slabs with the new prefab piece made of cement mortar with recycled mixed polypropylene (model A), corresponding timber beam height is 20 cm instead of 25 cm, for the rest of assessed models:

- Model A: Prefab piece made of cement mortar including recycled mixed PP. This model includes the recently patented prefab cement mortar with recycled mixed polypropylene interjoist filling piece (recycled mixed PP vault).
- Model B: Ceramic piece with horizontal upper surface. This model includes a prefab ceramic interjoist filling piece. The upper side of this piece is horizontal.
- Model C: Ceramic piece with arched upper surface. This model includes a ceramic prefab interjoist filling piece. Both the upper side and the inferior side of this piece are arch shaped; this commercial model is considered a traditional piece.
- Model D: Concrete piece with horizontal upper surface. This model includes a prefab concrete mortar interjoist filling piece. The upper side of this piece is horizontal.

All slab components and typical cross section are represented in Table 1 and Fig. 2.

In Table 2, the amounts of each material needed in 1 m^2 floor slab of the assessed models are shown.

2.2 Methodology

In this study, a cradle-to-gate approach of LCA to assess four types of prefab interjoist filling pieces has been performed. For the reference scenario, where a slab with recycled mixed PP vault (model A) is considered, data corresponding to prototype production has been used. The data used for commercial products (models B, C, and D) represent the current average technology in Spain provided by building sector companies.

The conducted LCA calculation process fulfils EN 15804 (2012), ISO 14044 (2006), and CEN/TR 15941 (2010).

For the modelling of the assessed processes and impacts calculation, SIMAPRO by PRé Sustainability B.V. software has been used (PRé Sustainability 2016).

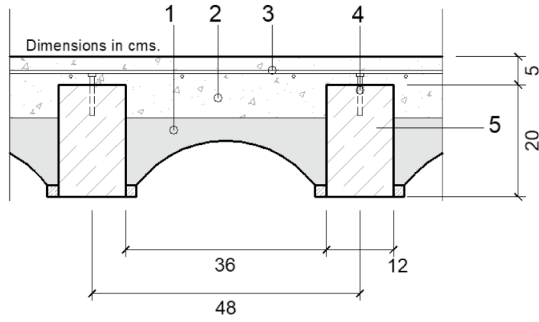
2.2.1 Goal definition

The aim of this study is to provide the environmental impacts of the reference scenario (model A) using the LCA methodology and to compare it with mainstream

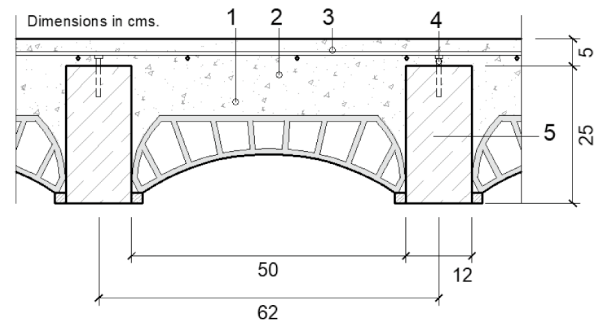
Table 1 Assessed slab vault characteristics

	Length (cm)	Height (cm)	Width (cm)	Weight per unit (kg)
Model A: slab with recycled mixed PP vault	36.00	12.00	25.00	8.32
Model B: ceramic piece with horizontal upper surface	50.00	14.00	25.00	8.50
Model C: ceramic piece with arched upper surface	50.00	14.5	22.00	3.00
Model D: cement mortar vault	60.00	20.00	18.00	14.50

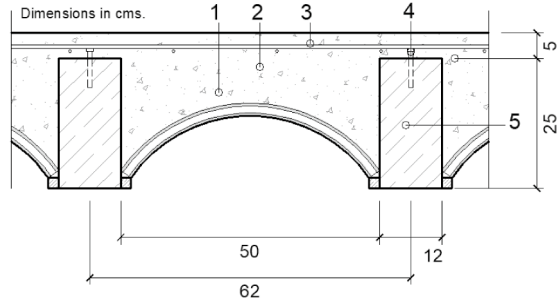
Model A: Slab with recycled mixed PP vault



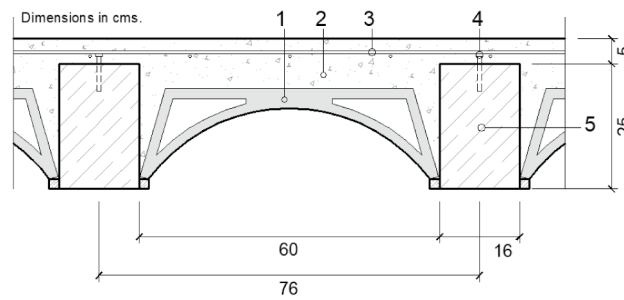
Model B: Ceramic piece, horizontal upper surface



Model C: Ceramic piece, arched upper surface



Model D: Cement mortar vault



- 1. INTERJOIST FILLING PIECE
- 2. CONCRETE
- 3. STEEL MESH REINFORCEMENT
- 4. STAINLESS STEEL BEAM CONNECTOR
- 5. TIMBER BEAM
- 6. TIMBER INTERJOIST SUPPORT

Fig. 2 Assessed floor slab cross section; dimensions are in centimetres

technology currently available in the building market for this purpose. According to this considerations, the LCA approach adopted is attributional (ILCD 2010; EN 15804 2012; ISO 14044 2006). Thus, data used correspond to average current technology in Spain. Finally, regarding recycled plastic included in reference scenario (model A), adopted cut-off rules correspond to the so-called 0:100 approach, which is in line with EN 15804 (2012) (Allacker et al. 2017). In that sense, all impacts, until end-of-life stage, are allocated to the primary production of plastics.

2.2.2 Functional unit

The declared unit considered in the LCA study is 1 m² of timber floor slab, including each of the assessed interjoist filling pieces. To ease the comparison of results, the material flows of each elementary component of the slab are presented separately. These elementary components are common to the four assessed systems: reinforced concrete, timber beams, interjoist filling pieces and stainless-steel connectors.

All four assessed slab models have been designed to comply with current Structural regulations in Spain and,

Table 2 Weight of elementary components per 1 m² of floor slab

	Interjoist filler (kg/m ²)	Concrete (kg/m ²)	Timber beam (kg/m ²)	Stainless steel beam connectors (kg/m ²)	Reinforcement steel mesh (kg/m ²)
Model A: slab with recycled mixed PP vault	69.33	239.58	16.00	0.42	2.20
Model B: ceramic piece with horizontal upper surface	54.84	319.6	15.48	0.32	2.20
Model C: ceramic piece with arched upper surface	21.99	373.9	15.48	0.32	2.20
Model D: cement mortar vault	105.99	252.63	16.84	0.35	2.20

Interjoist filler weight according to commercial data (Tables 1, 2, 3 and 4). Concrete slab density 2500 kg/m³. Timber beam C18 average density 320 kg/m³. Stainless steel M8.10 connector weight is 0.032 kg/ud (commercial data). Reinforcement B 500 SD reinforcement Steel mesh is 2.20 g/m² (commercial data)

therefore, in EU country members (Eurocode). In this regulation, a life span of in 50 years is established for these structures category. Consequently, this has been the RSL for the functional unit adopted in this study.

On the other hand, all assessed interjoist models bear the CE marking. Therefore, they comply with UNE-EN 15037 (2009). In consequence, in this study, models A to D are considered equal regarding structural performance and durability.

Moreover, the use of these pieces is usually associated with some aesthetic requirement; therefore, all assessed models have an arched inferior surface so as to provide this requirement.

As a result, in this study, it is considered that the function of each model within the building is equivalent, and there is no need to define any equivalence coefficient.

Finally, this functional unit has been defined in accordance with EN 15804 (2012); thus, the resulting impacts for the four assessed models can be compared.

2.2.3 System boundary

The system boundaries have been adopted according to the cradle to gate modular structure established in EN 15804 (2012), as it is shown in Fig. 3.

Once produced, the assessed models for floor slab vaults remain integrated within the building structure system throughout its complete life span. Furthermore, according to current trends, the end-of-life treatment for all of them is mechanic recycling (Gebremariam et al. 2020; Wang et al. 2021). Therefore, differences are negligible in building life cycle stages corresponding to construction (A4-5), use stage (B1-B7) and end of life (C1-4). Consequently, taking into account that this study goal is the comparison of the impacts for the four assessed models, the above-mentioned stages have not been included. Therefore, according to this life cycle standard (EN 15804 2012), the following stages have been assessed:

- A1: Extraction and processing of raw materials, secondary materials input processing.
- A2: Transport to the manufacturer.
- A3: Production at factory, to the final product at the gate of the factory. Including energy consumption and processing of wastes.

The result is a cradle to gate LCA for all components included in the four slab models assessed. The boundaries include the acquisition and processing of raw materials for

LIFE CYCLE STAGES AND MODULES ACCORDING TO EN 15804 .

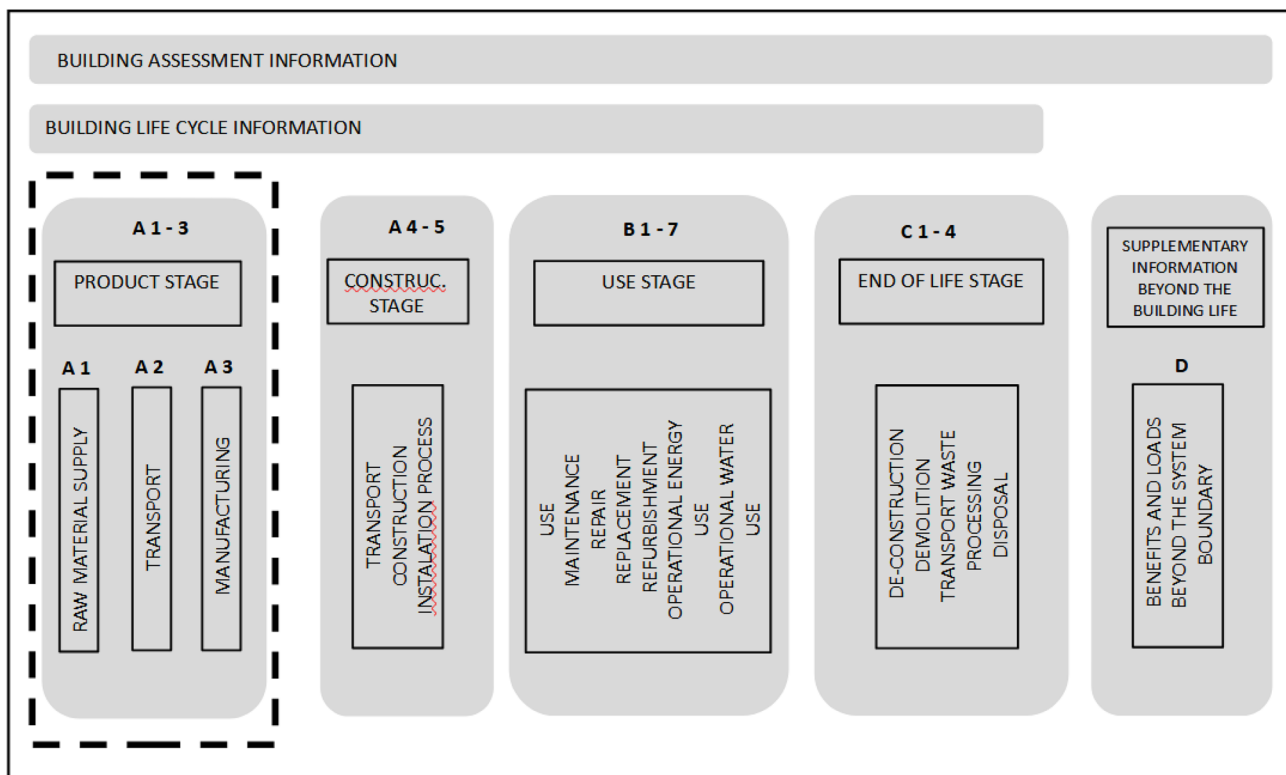


Fig. 3 Life cycle stages according to EN 15804 (2012). Considered stages

the production of components used in the construction of the four models of assessed slab, as well as transportation and energy consumption during all processes until these components are at the corresponding manufacturers’ gate, ready to be delivered and transported to the construction site to produce the slab. It is noted that factories administrative consumption are not included as well as consumption associated to factory plants maintenance and construction.

Regarding the end of life of compared products, it is noted that they result in inert material that usually goes through a crushing recycling process to obtain different size granulate products which are appropriate for applications such as roads and concrete recycled aggregates (Gebremariam et al. 2020).

In the case of the vault incorporating mixed recycled PP scales, the above-mentioned process always include a screening step where all impurities such as timber, steel, and plastic rests are removed from the obtained granulate (Tam 2008; Wang et al. 2021). This way, the plastic used can be recovered, and the final fate for this material should be either recycling or energy valorisation, thus avoiding the disposal of plastic in the environment. Finally, it is noted that the end-of-life stage of assessed products is not included in this study; as a consequence, it is a limitation for it.

2.2.4 Allocation criteria

Regarding the production of recycled mixed PP vault in model A, two allocations decisions have been adopted to perform this study.

The first one is the consideration of plastic recycling process loads. Recommendations in EN 15804 (2012) have been followed. Therefore, the cut-off approach has been adopted (EN 15804 2012; Allacker et al. 2017), which is in line with this standard. This means that all burdens until the end-of-life stage of the product are allocated to primary product system. Taking into account the product end-of-life criteria established in EN 15804 (2012), the life cycle inventory of recycled plastic product starts at plastic waste sorting facility gate.

The second allocation issue is related to the impacts associated to the production of recycled mixed polypropylene. In this case, the data corresponding to the assessed facility (ANVIPLAST 2019) represent the consumption for final products including an extrusion process, but the mixed polypropylene (mixed PP) scale used as recycled raw material is the previous stage to this extrusion. Consequently, to adequately represent the production process, the energy consumption of the extrusion system (Starlinger) has been removed.

Considering the above-mentioned criteria, the included elementary flows are the following: firstly, transportation from the plastic waste sorting facility to recycling plant, calculated as an average of 74.25 ton km per ton of recycled plastic obtained (ECOEMBES 2016), considering that 20% of transport way back goes (EUROSTAT 2021). Secondly, flows obtained from primary data of the plastic recycler plant (ANVIPLAST 2019; Starlinger), which consist of the consumption of 168 kWh of electricity at low voltage, 2.29 L of fuel and 1.32 m³ of water per ton of obtained recycled mixed PP (Fig. 5). Resulting flows are presented in Fig. 4,

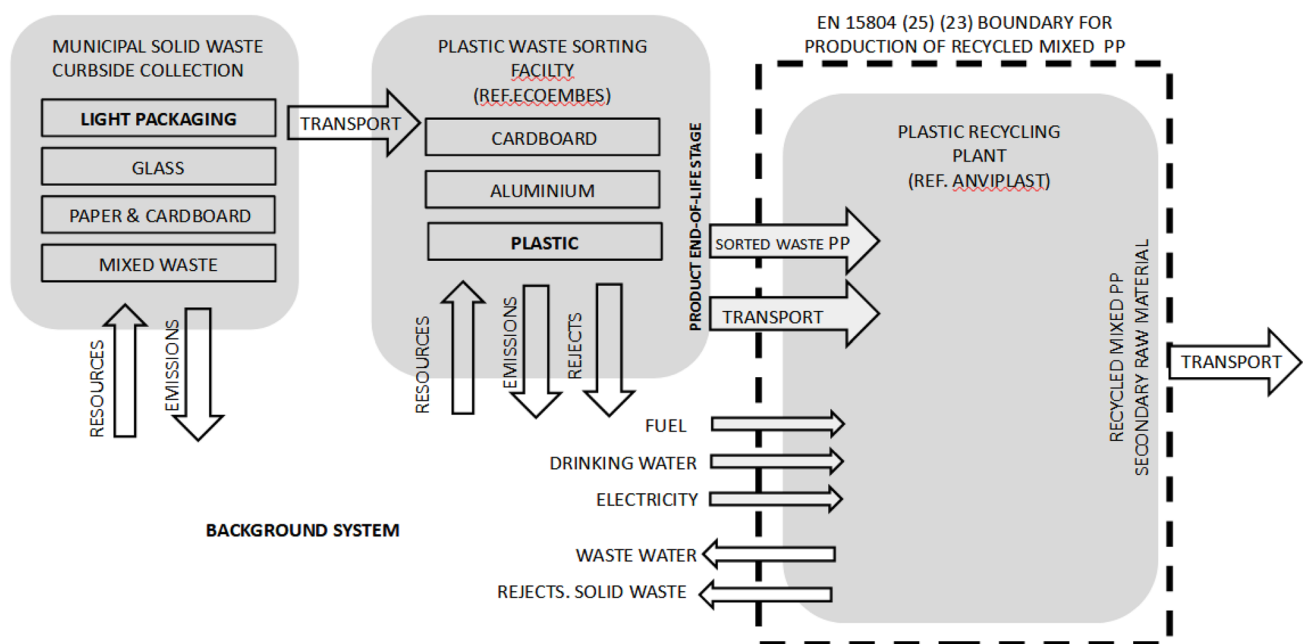


Fig. 4 Production of recycled mixed PP system boundaries (EN 15804 2012; Allacker et al. 2017)

Table 3 Production of 1 ton of recycled mixed PP. Obtained impacts

Impact category	1 ton recycled mixed PP production
Abiotic depletion (ADPE)	2.91E−04
Abiotic depletion (fossil fuels) (ADPF)	1.59E+03
Global warming (GWP100a)	1.63E+02
Ozone layer depletion (ODP)	1.90E−05
Photochemical oxidation	4.29E−02
Acidification	9.74E−01
Eutrophication	2.85E−01

and obtained impacts for the production of 1 ton of recycled mixed PP raw material are shown in Table 3.

2.2.5 Life cycle inventory

Data collection has been performed following ISO 14044 and ISO 15804 recommendations. This way, the impact scores obtained for model A vault can be compared with the results included in EPDs of commercial models C, D, and E. It is noted that it has not been performed a complete EPD for model A vault.

All data related to specific products have been collected from manufacturers in Spain, aiming to represent real processes and therefore to obtain their corresponding impacts. Only data related to generic processes have been calculated from generic databases, as it is shown in Table 4.

Regarding the characteristics of specific data used, information corresponding to the assessed commercial prefabricated vault models (corresponding to slab models B, C and D) has been obtained from the producers' Environmental Product Declaration (EPD) (AENOR 2017; ANDECE 2020), which represent the current average production for these products

in Spanish building market. These EPD have been conducted according ISO 15804 standard, and they assess the cradle to gate LCA of the product (stages A1–A3). This is the method adopted in this study; therefore, we consider that this information is appropriated for the comparison of products.

Specific data for model A: Reference scenario For the reference scenario (model A) which is the slab with recycled mixed PP vault, in the form of scales (Fig. 5), the information has been obtained from the process established to produce the patented piece, including data from Spanish plastic recycling companies. The LCI considered for this vault has been performed considering standards included in ISO 15804. Considered system boundaries are shown in Fig. 6; the resulting elementary flows are presented in Table 5, and finally, the obtained impacts for 1 ton of mixed PP vault production is included in Table 6.

It is noted that, although human toxicity impact category is not included in ISO 15804 standard, in this study, it is presented as additional information for the reference system. However, it cannot be compared with assessed commercial vault models impact scores because the available information for them to their EPDs, and human toxicity is not included in them.

Specific data for models B and C: Ceramic vault models For models B and C, including ceramic vault models, specific data has been obtained from available Environmental Product Declaration (EPD) (AENOR 2017), representing the fourth major producer of ceramic products in Spain. This EPD has been conducted following EN 15804 (2012) rules. Declared included processes are raw materials extraction and processing, transportation, moulding, drying, ceramic firing and packaging of resulting products, ready to be delivered. In Fig. 7, considered system boundaries are represented. In

Table 4 Use of data. Life cycle inventory (LCI)

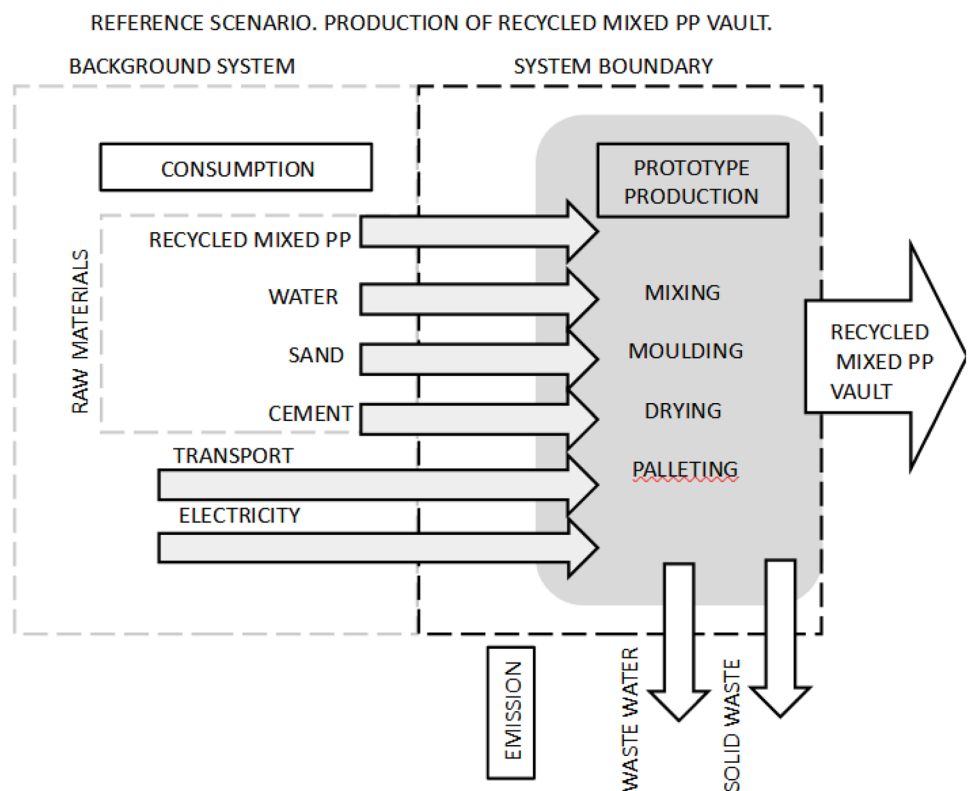
Elementary component	Data	Process	Source
Materials common to all models			
Concrete	Generic database	Market for concrete, normal, GLO.	Ecoinvent database
Timber beam	Generic database	Market for sawnwood, hardwood, raw, GLO.	Ecoinvent database
Stainless steel beam connectors	Generic database	Market for steel, chromium steel 18/8, GLO.	Ecoinvent database
Reinforcement steel mesh	Generic database	Market for reinforcing steel, GLO.	Ecoinvent database
Specific materials for each model			
Model A	Specific	Prefab piece made of cement mortar including recycled mixed PP Cradle to gate LCA.	Patent process (Rubio-de Hita et al. 2018)
Model B	Specific	Ceramic vaults and hollow blocks. Environmental Product Declaration EN 15804 (2012) 2012+A1:2014	EPD Hyspalit (AENOR 2017)
Model C	Specific	Ceramic vaults and hollow blocks. Environmental Product Declaration EN 15804 (2012) 2012+A1:2014	EPD Hyspalit (AENOR 2017)
Model D	Specific	Concrete vaults and hollow blocks. Environmental Product Declaration EN 15804 (2012) 2012+A1:2014	EPD Andece (ANDECE 2020)



Fig. 5 Recycled mixed PP scales incorporated in model A vault (7.3) as raw material (Rubio-de Hita et al. 2018)

Table 7, impacts for 1 ton of ceramic vault production from cradle to gate are included (stages A1–A3, according to EN 15804 (2012)).

Fig. 6 Model A. System boundaries for recycled mixed PP vault production



Specific data for model D: Precast cement mortar vault model For model D, including precast cement mortar vault model, specific data has been obtained from available Environmental Product Declaration (EPD) (ANDECE 2020), representing a 42.50% of Spain production for this type of products. This EPD has been conducted following UNE-EN 15804 rules. The declared included processes are the acquisition of raw materials, mainly cement and aggregates, transportation to production plant, production on concrete and moulding, and finally, concrete curing and demoulding of pieces, which afterwards are stored ready to be delivered. In Fig. 8, considered system boundaries are represented, and impacts for 1 ton of precast cement mortar vault production, from cradle to gate (A1–A3 stages, according to EN 15804 (2012)), are presented in Table 8.

2.2.6 Impact assessment

As above-mentioned, this study has been conducted following EN 15804, which applies CML 2012 method; consequently, the characterisation factors considered are the following: primary energy depletion (MJ), abiotic resource depletion (kg Sb eq), soil and water acidification AP (kg SO₂ eq), stratospheric ozone depletion potential ODP (kg CFC⁻¹¹ eq), global warming potential GWP (kg CO₂ eq), eutrophication potential EP (kg (PO₄)³-eq) and photochemical ozone formation potential POCP (ethylene kg eq).

Table 5 Reference scenario (model A). LCI for 1 ton of recycled mixed PP vault

	Unit	Elementary flow	Source
Material consumption (kg)			
Cement	1.55E-01	Cement production, Portland, Europe without Switzerland.	Ecoinvent database
Water	1.20E-01	Tap water production, conventional treatment, Europe without Switzerland	Ecoinvent database
Sand	6.24E-01	Sand 0/2, wet and dry quarry, production mix, at plant, undried, EU-27 S System.	ELCD database
Recycled mixed PP	1.02E-01	Obtained according production process information.	Patented product
Transport (ton km)			
Lorry	4.37E-02	market for transport, freight, lorry 16–32 metric ton, EURO5, RER.	Ecoinvent database
Energy consumption (W)			
Electricity	2.03E+00	market for electricity, low voltage, ES.	Ecoinvent database

3 Results and discussion

Cradle to gate LCA calculation results for the four analysed floor systems are presented in Table 9 and represented in the form of bars graph in Fig. 9.

It is noted that model A floor slab (recycled mixed PP vault) impacts bear the lowest values for all impacts categories except for abiotic depletion (AD). Furthermore, in this category, the difference with model bearing lowest score is of 9%.

In Fig. 9, it is observed that the amount of the impact for global warming and abiotic depletion (fossil fuels) is much higher than in the rest of categories. In this regard, it is reminded that scores between different categories cannot be directly compared.

Comparing single scores, Fig. 10, in the assessed four slab systems, we find that both models B and C, with ceramic vaults, present substantial higher values, approximately 30% higher, in GWP100a, and AD fossil fuels, due to the high temperatures needed to produce ceramic materials (Muthukannan and Ganesh 2019). Furthermore, these models bear higher values in photochemical oxidation, acidification, and eutrophication impact categories due to air emissions produced during the production process of ceramics (Muthukannan and Ganesh 2019; Zhang and Biswas 2021). It is noted that in all these impact categories, the least scores are for model A (slab with recycled mixed PP vault).

On the other hand, for photochemical oxidation (PO) impact category, the highest score is for model D, which is the slab with cement mortar vault. In this category, the lowest impacts are also for model A, bearing scores 13% lower than model D.

3.1 Normalisation

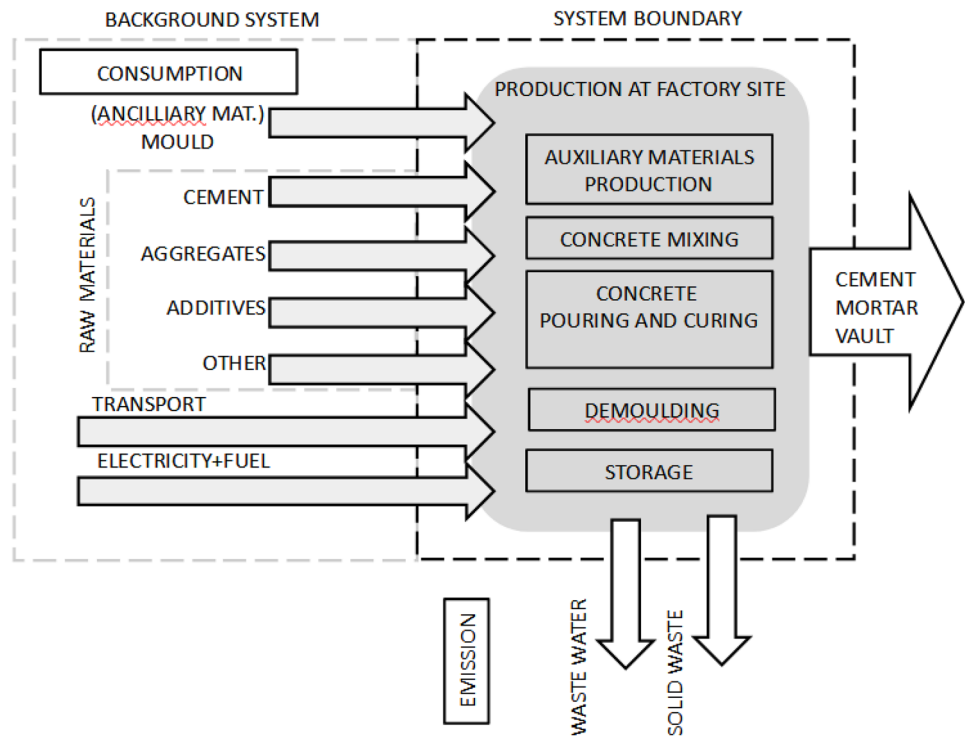
In order to compare the results obtained for different impact categories, the normalisation step of the results is included. Normalisation is an optional step in LCA methodology (ISO 14044) (Sleeswijk et al. 2008). This step shows the relative contribution of the product system score to the impact categories at a regional level. In this study, the scores per impact category are divided by normalisation factors corresponding to CML EU25, which represent the impacts of the year 2000, for the countries included in the European Union in 2006 (PRé Sustainability 2014, 2016). The normalised results cannot be interpreted as a weighting result to compare results between impact categories; they only show to which extent the impacts of the assessed product system contribute to the overall environmental impacts for a region during a year. The normalised scores for each impact category are obtained by dividing obtained results by the normalisation factors (ILCD 2010) (Sleeswijk et al. 2008).

Once analysed the normalised scores represented in Fig. 11, it has to be noted that GWP100a and AD (fossil fuels) are the most important contributors to overall impact,

Table 6 Reference scenario (model A). Impacts for 1 ton of recycled mixed PP vault

Impact category	Units	1 ton recycled mixed PP vault production
Abiotic depletion (ADPE)	kg Sb eq	9.72E-05
Abiotic depletion (fossil fuels) (ADPF)	MJ	5.97E+02
Global warming (GWP100a)	kg CO ₂ eq	9.59E+01
Ozone layer depletion (ODP)	kg CFC-11 eq	5.98E-06
Photochemical oxidation	kg C ₂ H ₄ eq	1.21E-02
Acidification	kg SO ₂ eq	2.81E-01
Eutrophication	kg PO ₄ eq	7.79E-02
Human toxicity	kg 1,4-DB eq	1.67E-02

Fig. 7 Models B and C. System boundaries for ceramic vault production



and in both categories, model A is clearly the system with the lowest score. On the other hand, ozone layer depletion contribution category is of no relevance.

In regard to abiotic depletion category, this is the only category in which model A does not bear the lowest score; it is observed in Fig. 11 that this is the second lowest contributor to EU25 overall impact, and the difference between the score of the four models assessed is within the range of 12%.

Finally, for all impact categories, models with ceramic vaults bear the highest normalised scores, except for abiotic depletion and (ODP), which are the less relevant categories according to CML EU25 normalisation factors.

In conclusion, obtained results show that assessed slab models with ceramic vaults bear the highest scores, and that reference scenario, model A, shows the best environmental performance.

3.2 Contribution analysis

A contribution analysis has been performed to detect the processes with larger impacts in the assessed system according to ISO 14044 (2006) and ILCD Handbook (2010).

This analysis has been performed on the reference scenario, model A, processes. For the rest of the models, impacts have been obtained from the corresponding commercial EPDs; therefore, consumption data is not available.

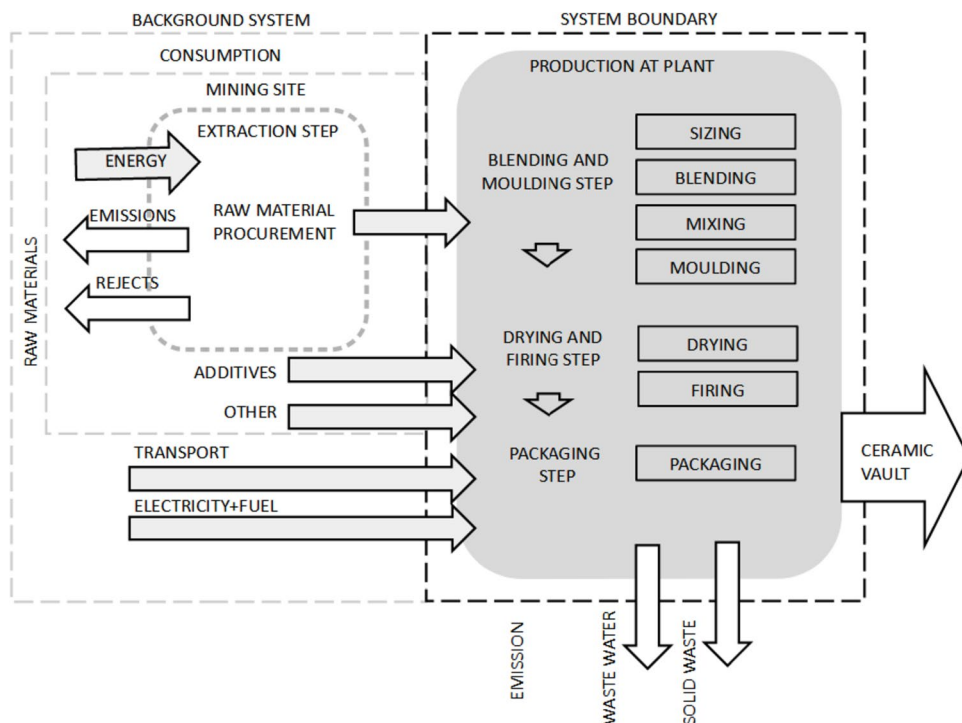
3.2.1 Contribution analysis for model A slab

For model A slab, the relative contribution of each calculated process (see Table 2) to the obtained total impact score is presented in the following Fig. 12.

Table 7 Impacts for 1 ton of ceramic vault (models B and C) (AENOR 2017)

Impact category	Units	1 ton precast cement mortar vault production
Abiotic depletion (ADPE)	kg Sb eq	1.02E-05
Abiotic depletion (fossil fuels) (ADPF)	MJ	2.41E+03
Global warming (GWP100a)	kg CO ₂ eq	2.40+02
Ozone layer depletion (ODP)	kg CFC-11 eq	6.29-08
Photochemical oxidation	kg C ₂ H ₄ eq	9.07E-02
Acidification	kg SO ₂ eq	1.00E-00
Eutrophication	kg PO ₄ eq	6.51E-02

Fig. 8 Model D. System boundaries for precast cement mortar ceramic vault production



It is observed that the main contributor to the obtained impact scores is the use of concrete. The rest of the processes are responsible in different proportions to each impact category score.

When focusing GWP, the second contributor is the use of model A mixed PP vault.

In this study, concrete is considered as a generic process, and therefore, data used has been obtained from a generic database (Ecoinvent database), representing an average production for EU. As a consequence, modifying the flows involved in considered concrete production is out of this study scope. Furthermore, the concrete mass included in model A slab is a fixed data, because it depends on the slab geometry.

On the contrary, the production of mixed PP vault in model A is considered as specific process; consequently,

a contribution analysis can be performed for its production process (ILCD Handbook 2010).

3.2.2 Contribution analysis for model A vault

For model A slab vault, the relative contribution of each calculated process (see Table 6) to the obtained total impact score is presented in the following Fig. 13.

It is observed that the main contributor to the obtained impact scores is the use of cement in the vault production. The second contributor is the use of recycled mixed PP, and the third score is due to the transport. Finally, the impact score due to the rest of processes is negligible.

In this study, cement production is considered as a generic process, and therefore, data used has been obtained from a generic database (Ecoinvent database), representing an average production for EU. As a consequence, modifying

Table 8 Impacts for 1 ton of precast cement mortar vault (model D) (ANDECE 2020)

Impact category	Units	1 ton precast cement mortar vault production
Abiotic depletion (ADPE)	kg Sb eq	9.05E-06
Abiotic depletion (fossil fuels) (ADPF)	MJ	6.20E+02
Global warming (GWP100a)	kg CO ₂ eq	7.68E+01
Ozone layer depletion (ODP)	kg CFC-11 eq	8.46E-06
Photochemical oxidation	kg C ₂ H ₄ eq	1.92E-02
Acidification	kg SO ₂ eq	2.01E-01
Eutrophication	kg PO ₄ eq	4.50E-02

Table 9 LCI for 1 m² floor slab, models A to D. Cradle to gate attributional

Impact category	Units	Model A	Model B	Model C	Model D
Abiotic depletion	kg Sb eq	1.31E-04	1.25E-04	1.34E-04	1.20E-04
Abiotic depletion (fossil fuels)	MJ	3.67E+02	5.13E+02	4.76E+02	4.01E+02
Global warming (GWP100a)	kg CO2 eq	4.81E+01	6.39E+01	6.27E+01	5.12E+01
Ozone layer depletion (ODP)	kg CFC-11 eq	3.25E-06	3.37E-06	3.76E-06	3.85E-06
Photochemical oxidation	kg C2H4 eq	1.16E-02	1.67E-02	1.45E-02	1.31E-02
Acidification	kg SO2 eq	1.52E-01	2.10E-01	1.94E-01	1.57E-01
Eutrophication	kg PO4 eq	4.97E-02	5.48E-02	5.80E-02	5.01E-02

the flows involved in considered cement production is out of this study scope. Moreover, the cement mass included in a vault is a fixed data, as it has been established after an optimisation process to obtain the best mechanical properties for this piece (Rubio-de Hita et al. 2018).

On the contrary, the production of mixed PP vault in model A is considered as specific process; consequently, a contribution analysis can be performed for its production process.

3.2.3 Contribution analysis for recycled mixed PP

For the production of recycled mixed polypropylene, the relative contribution of each calculated process, as shown in Section 2.2.4, to the obtained total impact score is presented in the following Fig. 14.

It is observed that main contributor to the obtained impact scores is the use of electricity, and the second contributor is the transport from the urban waste sorting facility to the recycler factory.

In this regard, it is noted that for electricity consumption, it has been considered Spanish average mix

(Ecoinvent database), and for transport, it has been considered a distance (74.2 Tkm), which is an average of the distances for different potential recycling facilities within a provincial range.

3.3 Sensitivity analysis

As established in Section 3.2, the main contributors to the obtained impact scores for model A slab, throughout the whole assessed system, are the following:

- Model A slab production step: concrete use. Mixed PP vault is the second contributor in GWP impact score
- Model A mixed PP vault production step: use of cement. Use of recycled mixed PP is the second contributor.
- Recycled mixed PP production step: electricity consumption is the largest contributor. Transport process is the second contributor.

As stated in the preceding section, this study utilised average production data for the concrete process. Furthermore, the amount needed to form 1 m² of slab is fixed due to its

Fig. 9 LCI for 1 m² floor slab, models A to D. Cradle to gate attributional

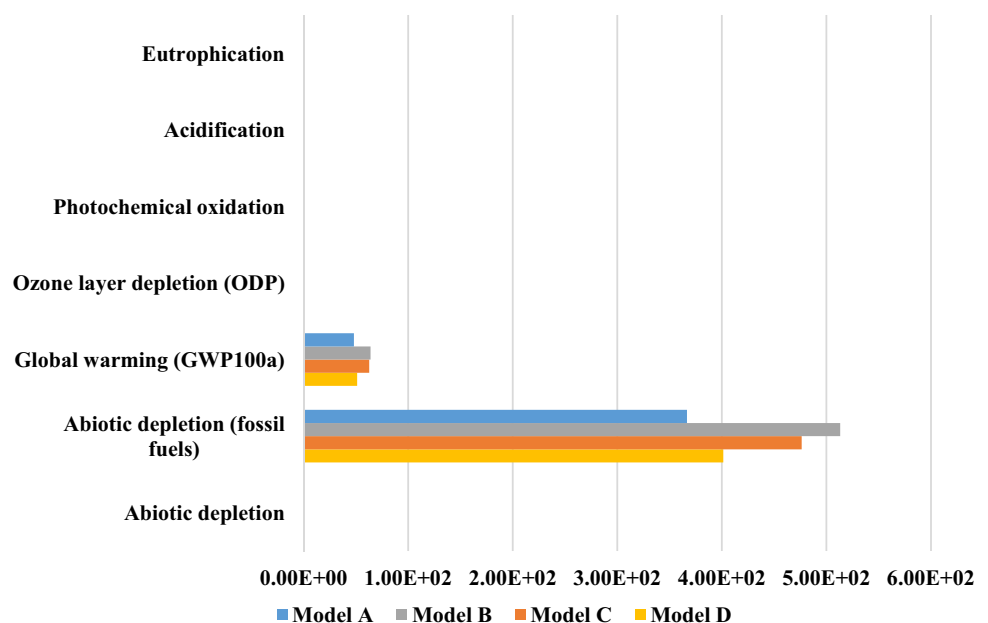
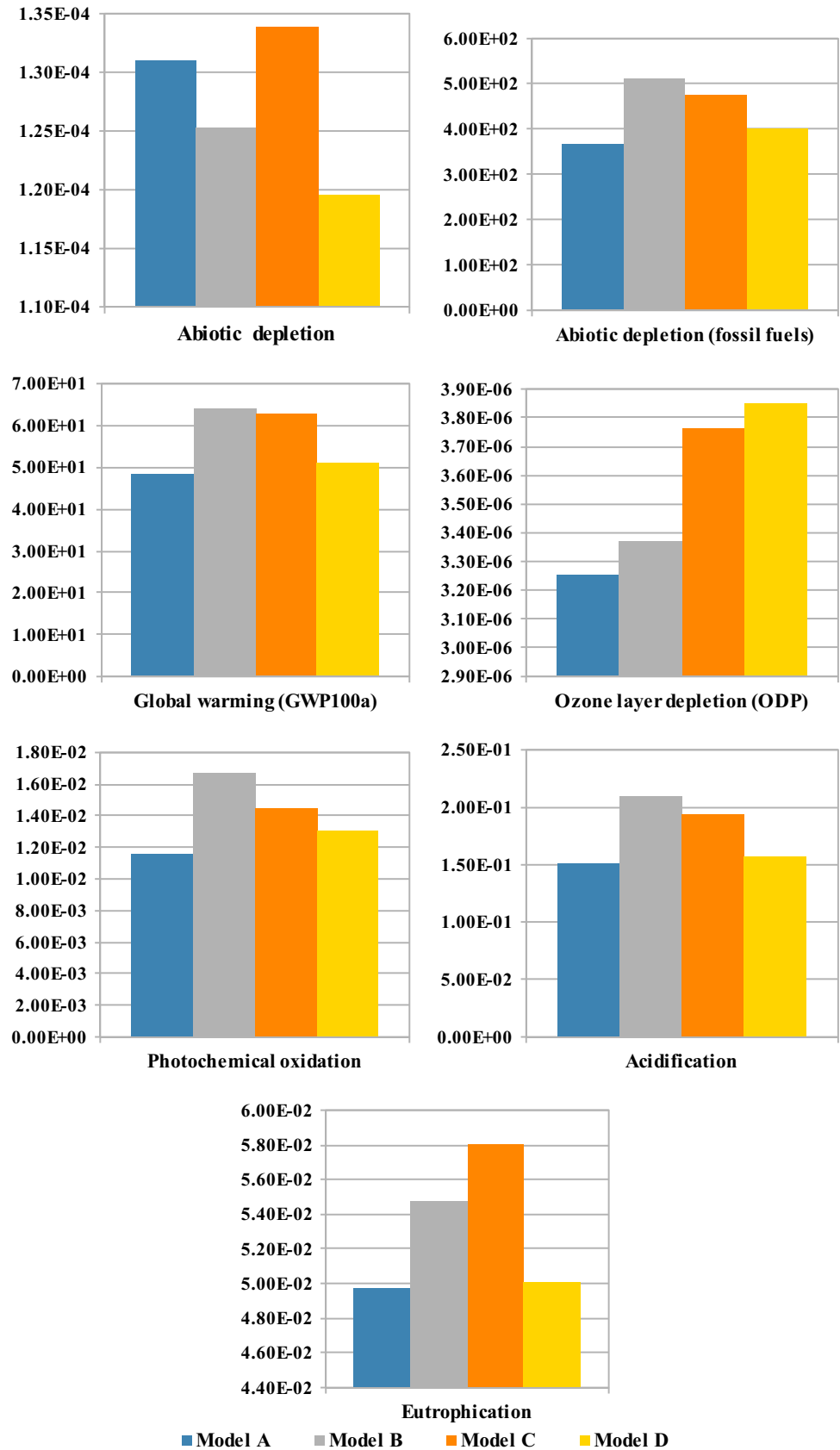


Fig. 10 LCI for 1 m² floor slab models A to D. Single scores



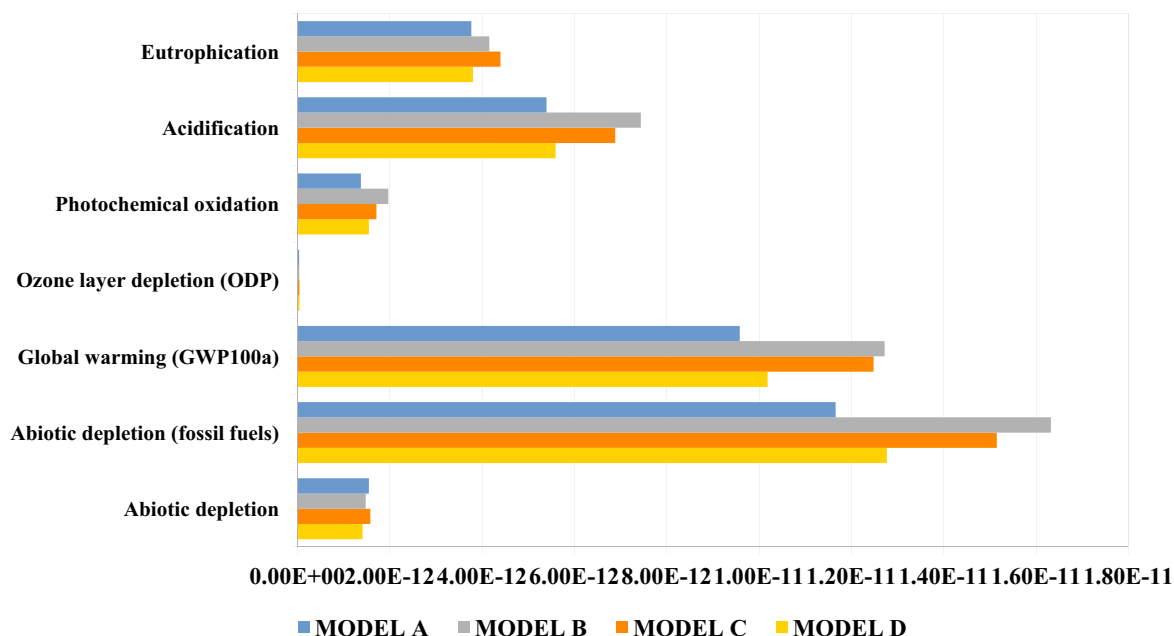


Fig. 11 LCI for 1 m² floor slab models A to D. Normalised scores

geometry. As a result, in spite of its relevance, it is not possible to conduct a sensitivity analysis for this process.

The same circumstances apply in the case of considered cement process.

On the other hand, for the recycled mixed PP production step, we can apply a sensitivity analysis for the transport distance and assess the influence of changes in the electricity used (ISO 14044 2006; ILCD Handbook 2010).

3.3.1 Transport distance sensitivity analysis. Recycled mixed pp production step

The following Table 10 represents the variation of impact scores in different scenarios for the transport from the urban waste sorting facility to the recycler factory.

The reference scenario is defined for a provincial range, with a calculated distance of 74.25 Tkm. The best approach

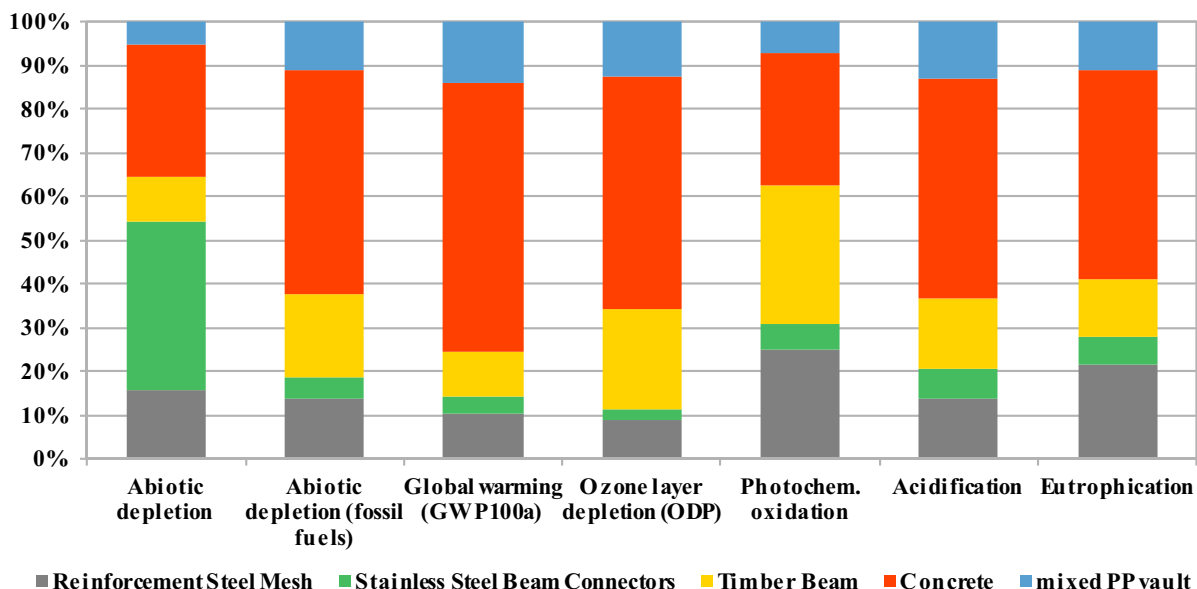


Fig. 12 Model A slab. Process contribution

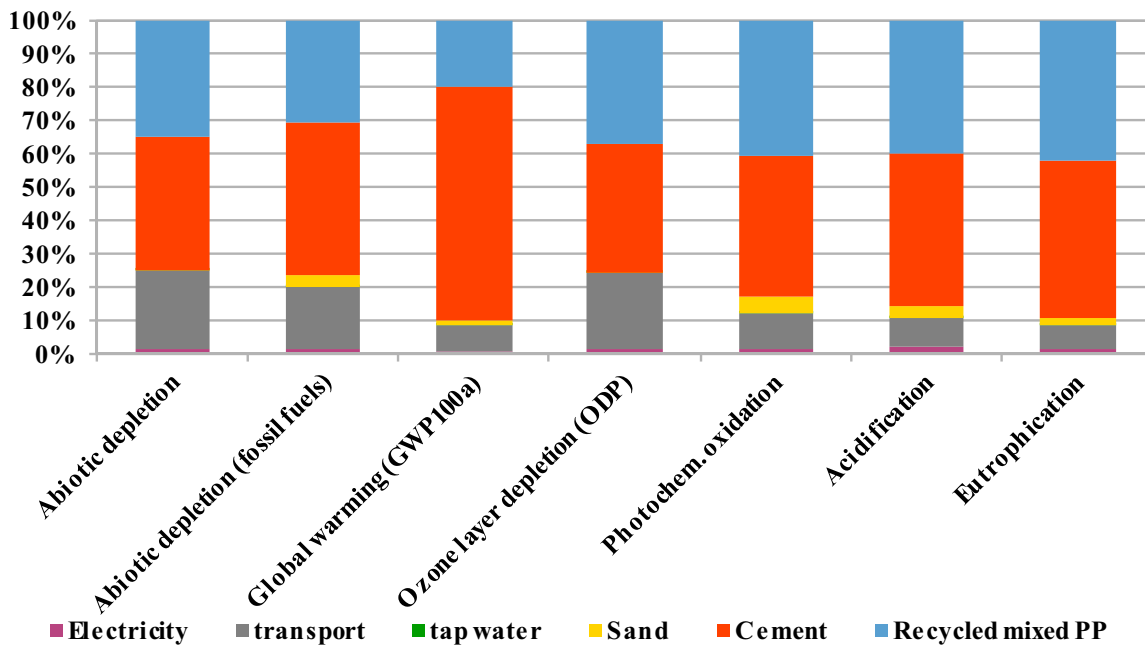


Fig. 13 Model A vault (mixed PP). Process contribution

is defined for a local range, covering 50% less distance, while the worst-case scenario is defined for a regional range, involving a 50% increase in transport distance.

As shown in Table 10, the sensitivity analysis indicates that the different scenarios calculated for the recycled mixed

PP production process are not influential in model A’s total impact score. The variation in impact score between the reference scenario and the defined sensitivity best and worst scenarios is less than 1%. This is due to the low weight of mixed PP included in model A slab.

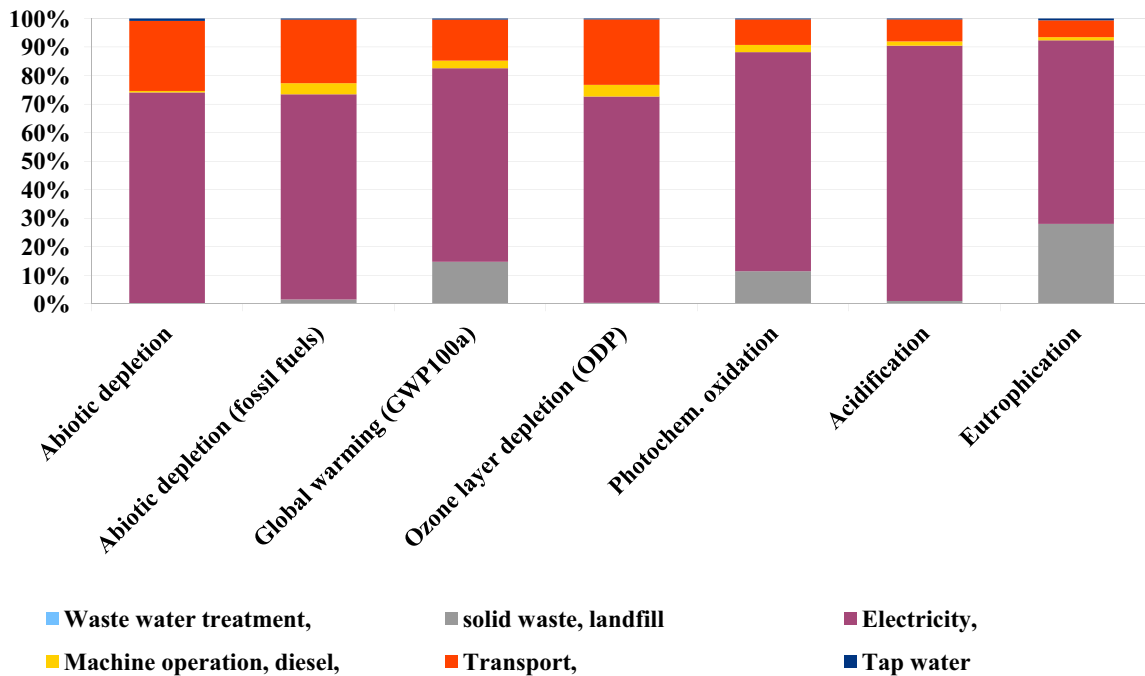


Fig. 14 Recycled mixed PP production. Process contribution

Table 10 Model A. Sensitivity analysis. Recycled mixed PP production. Transport

Transport sensitivity analysis Model A Recycled mixed PP production	Reference scenario transport 74.25 Tkm	Sensitivity (+50%) Transport 37.12 Tkm	Sensitivity (−50%) Transport 111.37 Tkm	Sensitivity (+50%) Transport 111.37 Tkm (%) variation	Sensitivity (−50%) Transport 37.12 Tkm (%) variation
Abiotic depletion	1.29E−04	1.29E−04	1.29E−04	0.21	−0.23
Abiotic depletion (fossil fuels)	3.66E+02	3.67E+02	3.64E+02	0.37	−0.40
Global warming (GWP100a)	4.81E+01	4.82E+01	4.80E+01	0.18	−0.21
Ozone layer depletion (ODP)	3.25E−06	3.26E−06	3.23E−06	0.51	−0.55
Photochemical oxidation	1.16E−02	1.16E−02	1.16E−02	0.12	−0.14
Acidification	1.52E−01	1.52E−01	1.51E−01	0.17	−0.22
Eutrophication	4.96E−02	4.96E−02	4.95E−02	0.12	−0.16

3.3.2 Electricity consumption sensitivity analysis. Recycled mixed pp production step

Similarly to transport process, following recommendations in ISO 14044 (2006) and ILCD Handbook (2010), a sensitivity analysis has been performed on electricity consumption.

The defined best-case scenario includes a reduction of 50% for impacts due to electricity consumption. The improved conditions for recycled mixed PP production step could be achieved in the short term through recycling factory consumption optimisation, production machines renewal, or improving the content of renewable energy use in the Spanish national electricity mix.

The defined worst-case scenario includes an increase of 50% for impacts due to electricity consumption. This worst-case scenario has been established only for this sensitivity analysis purpose, as it does not represent any future trend for the recycling plastic facilities.

The following Table 11 represents the variation of impact scores in different scenarios defined for electricity consumption.

As shown in Table 11, the variation in impact score between the reference scenario and defined sensitivity best and worst scenarios is below 3% for all impact categories. Bearing in mind that the scenarios have been defined for

a variation of 50% of electricity consumption, it can be concluded that the electricity consumption for the recycled mixed PP production process has a low influence in model A slab total impact score. This is due to the low weight of mixed PP included in model A slab.

3.4 Discussion of results

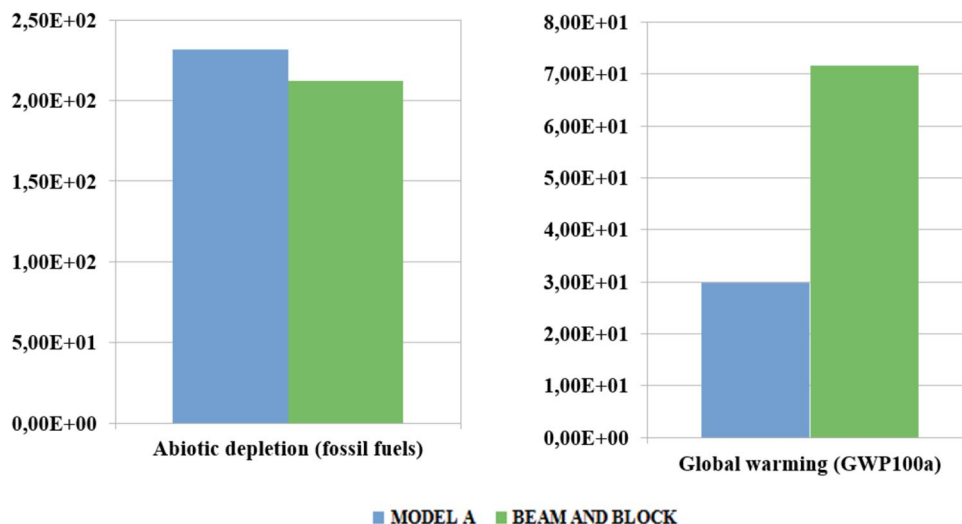
As shown in the contribution analysis included in Section 3.2, the main contributor to the obtained impact scores for model A slab is the use of concrete. In addition to this, the sensitivity analysis performed for specific processes, such as recycled mixed PP production, has resulted in negligible changes in the final impact category scores in the different defined scenarios. The conclusion is that the mass of recycled mixed PP included in model A slab is very low, and therefore, impacts associated to this production step are not relevant in the final impact scores.

On the other hand, bearing in mind that the main purpose of all assessed vault models is to fill slab interjoint spaces, according to Table 2, the most efficient models are the recycled mixed PP vault model A and the cement mortar vault model D, as the concrete content per square metres in these models is lower than in ceramic vault models B and

Table 11 Model A. Recycled mixed PP production. Electricity

Electricity sensitivity analysis Model A Recycled mixed PP production	Reference scenario	Sensitivity electricity (+50%) Increase	Sensitivity electricity (−50%) Reduction	Sensitivity (+50%) Electricity % variation	Sensitivity (−50%) Electricity % variation
Abiotic depletion	1.29E−04	1.30E−04	1.28E−04	0.43	−0.89
Abiotic depletion (fossil fuels)	3.66E+02	3.69E+02	3.60E+02	0.84	−1.64
Global warming (GWP100a)	4.81E+01	4.84E+01	4.75E+01	0.7	−1.12
Ozone layer depletion (ODP)	3.25E−06	3.28E−06	3.17E−06	1.12	−2.24
Photochemical oxidation	1.16E−02	1.17E−02	1.15E−02	0.97	−1.27
Acidification	1.52E−01	1.55E−01	1.48E−01	2.02	−2.5
Eutrophication	4.96E−02	5.02E−02	4.88E−02	1.3	−1.62

Fig. 15 LCI for 1 m² floor slab model A and block and beam slab (Demertzi et al. 2020b). Impact scores



C. Moreover, it can be observed in Table 2 that the weight of recycled mixed PP vault included in model A is 69.33 kg/m², whereas cement mortar vault mass included in 1 m² of model D slab is 105.99 kg/m². This is a 52.8% increase for cement mortar vault mass. This can be explained on the observed reduction of density for recycled mixed PP vaults (Rubio-de Hita et al. 2018).

As a result, it can be concluded that the most efficient assessed slab is model A, with recycled mixed PP vault. The main reason for this outcome is that the content of concrete and cement per square metres for model A slab is lower than in the rest of cases, and therefore, the impact score for this model is lower.

In general, obtained results are in line with recent research. Regarding ceramic industry, published studies stress that the higher impacts for this industry are for categories global warming potential and abiotic depletion (fossil fuels) (Atılgan et al. 2021); furthermore, researches comparing ceramic brick and concrete blocks show that 1 kg of ceramic bricks production bears higher impacts regarding abiotic depletion (fossil fuels) and global warming potential (Muneron et al. 2021) than the same weight of concrete block. This is coherent with obtained results, as ceramic interjoist piece models (model B and model C) bear the higher impacts for these impact categories. Therefore, researches on this issue conclude that ceramic industry future challenges have to do with CO₂ emission reduction and energy efficiency improvement (Gabaldón-Estevan et al. 2014; Silvestri et al. 2021).

On the other hand, for cement mortar vaults slabs (model D), the obtained highest impacts are for ozone layer depletion (ODP), being this category the least contributors to the overall impact. Nevertheless, current research on this field remarks that the main efforts to improve cement production are focused on energy consumption reduction (Maddalena

et al. 2018; Lippiatt et al. 2020), so as to achieve a significant reduction in GWP100a and AD (fossil fuels), as these are the most important contributors to the overall impact.

As a result, scores for model A and model D slab systems are very similar, but model A, including a proportion of recycled mixed PP vault, shows lower scores for most influential impact categories, due to the benefit of using recycled plastic, as it is pointed out in related research (Ersan et al. 2022; Gravina et al. 2021).

Finally, it has to be mentioned that there are only a few studies in the literature focused in LCA of structural floor systems, and furthermore, all existing research is focused in the complete flooring system not specifically in the interjoist piece. The most similar research that has been found is that of Demertzi et al. (2020b), which develops an LCA of five structure flooring systems, which include one reinforced concrete beam and block slab. This is the most similar system to model A, in current research, but it still bears substantial differences, because model A includes timber beams. Furthermore, in Demertzi et al. (2020b), considered systems are not adapted to slab refurbishment. Therefore, specific characteristics related to slab refurbishment, such as timber beam connectors or a minimum of 5 cm thickness for the top layer of reinforced concrete needed to transmit connector tension, are not included. As a consequence, in order to enable the comparison, model A, in current study, has been adapted to a newly built slab system, removing above-mentioned elements. Afterwards, resulting impacts for modified model A slab have been calculated. In the following Fig. 15, the impacts obtained for abiotic depletion (fossil fuel) (ADP), as well as global warming category, are included. It is stressed that these are the most relevant impact categories according CML EU25 normalisation factors, as shown in the preceding section.

These figures show that the score in ADP fuel impact category, for reference scenario (model A), is slightly above beam and block models (which is 8.6% inferior). This is mainly due to transport distances considered for timber beams. On the contrary, for GWP100a category, the score for model A is much lower than block and beam, with the score for model A being roughly 60% lower than the value for beam and block. This difference is due to the content of timber and recycled mixed PP fraction in model A. In conclusion, this comparison shows that results obtained in this research are coherent with recent research.

4 Conclusions

In this paper, the environmental performance of 1 m² of floor slab including a new precast vault piece made of cement mortar with a fraction of recycled mixed polypropylene has been calculated. This new precast vault has been especially designed for traditional joist arch floor slab refurbishment. This slab type is used mainly in historic buildings (Rubio-de Hita et al. 2018; Diodato et al. 2015); therefore, this design is oriented to the building refurbishment sector. The corresponding environmental impacts have been calculated according to LCA methodology, attributional approach, and following core rules for the product category of construction products included in EN 15804 (2012) (AENOR 2017; ANDECE 2020). In addition, we have compared the results with the impacts corresponding to three equivalent flooring systems, which represent current most used technology (models B to D), using the data included in the corresponding Environmental Product Declaration already published. Data for generic flows, such as concrete, steel, timber beams electricity mix and road transport, has been obtained from generic databases (Ecoinvent, ELCD ref) and modelled for Spain and EU-27 area. The results obtained show that the reference scenario, model A flooring, is the system with lower impacts in six out of the seven categories assessed. Furthermore, when adding the LCA normalisation step, the conducted analysis shows that for the most influential impact categories, GWP100a and AD fossil fuels, the reference scenario, model A, bears the lowest scores. On the other hand, the only impact category, where model A is not the lowest score, is abiotic depletion (AD), which is the second least influential in the overall impact. In this impact category, model A shows a difference of only 9% with model D, which bears the lowest score.

As a result, it can be concluded that the new patented vault, made of cement mortar with recycled mixed PP (model A), has a better environmental performance than the other three assessed systems.

In addition to this, the results obtained yield the following:

- The flooring assessed systems incorporating ceramic vaults bear far worse scores in GWP100a and AD fossil fuel categories.
- The conducted contribution and sensitivity analysis conclusion is that the assessed recycled mixed PP vault has a reduced density, and fills the slab interjoist space with less mass consumption per square metre of slab; therefore, the impact score for model A slab is lower than assessed commercial slabs.
- Specific data used, corresponding to ceramic and cement mortar vaults, has been obtained from commercial models representing the current state of the art for Spanish construction market. Specific data for recycled mixed PP vault (model A) has been obtained from prototype production process. Therefore, the results obtained are considered to be representative of Spain current construction market.
- The research has been conducted following EN 15804 (2012) rules; consequently, obtained results can be compared with any other research applying the same standard and dealing with the same functional unit.
- This example shows the benefits of the construction sector to incorporate recycled plastics. This leads to an enhanced environmental performance and to a reduction of plastics waste (da Silva et al. 2021).
- Obtained results can encourage the research in the incorporation of recycled plastics in construction products.
- Bearing in mind that this study assesses the impacts corresponding to a recycled mixed PP vault prototype (model A), it is considered that there is room for further investigation on this new piece production process optimisation and consequently for further environmental impact score reduction.

Funding Funding for open access publishing: Universidad de Sevilla/CBUA The authors received the financial support provided by the VII Research Plan of the University of Seville.

Data availability Data will be made available on reasonable request.

Declarations

Competing interests The authors declare no competing interests.

Open Access This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit <http://creativecommons.org/licenses/by/4.0/>.

References

- AENOR (2017) Global EPD. Bovedillas y casetones cerámicos según la Norma UNE-EN 15037-3. Ceranor SA
- Allacker K, Mathieux F, Pennington D, Pant R (2017) The search for an appropriate end-of-life formula for the purpose of the European Commission Environmental Footprint initiative. *Int J Life Cycle Asses* 22(9):1441–1458
- Almeshal I, Tayeh BA, Alyousef R, Alabduljabbar H, Mohamed AM (2020) Eco-friendly concrete containing recycled plastic as partial replacement for sand. *J Mater Res Technol* 9(3):4631–4643
- ANVIPLAST, DECLARACIÓN AMBIENTAL (2019) Según Reglamento (CE) 1221/2009, Reglamento (UE) 2017/1505 y Reglamento (UE) 2018/2016
- ANDECE (2020) Asociación Nacional de la Industria del Prefabricado de Hormigón. Autodeclaración Ambiental de Producto de elementos ligeros huecos de hormigón prefabricado
- Assefa G, Ambler C (2017) To demolish or not to demolish: life cycle consideration of repurposing buildings. *Sustain Cities Soc* 28:146–153
- Atılğan Türkmen B, Budak Duhbacı T, Karahan Özbilen Ş (2021) Environmental impact assessment of ceramic tile manufacturing: a case study in Turkey. *Clean Technol Environ Policy* 23(4):1295–1310
- CEN/TR 15941:2010. Sustainability of construction works - Environmental product declarations - Methodology for selection and use of generic data
- da Silva TR, de Azevedo ARG, Cecchin D, Marvila MT, Amran M, Fediuk R, Szelag M (2021) Application of plastic wastes in construction materials: a review using the concept of life-cycle assessment in the context of recent research for future perspectives. *Materials* 14(13):3549
- Demertzi M, Silvestre J, Garrido M, Correia JR, Durão V, Proença M (2020b) Life cycle assessment of alternative building floor rehabilitation systems. *Structures* 26:237–246. Elsevier
- Demertzi M, Silvestre JD, Durão V (2020a) Life cycle assessment of the production of composite sandwich panels for structural floor's rehabilitation. *Eng Struct* 221:111060
- Diodato M, Macchioni N, Brunetti M, Pizzo B, Nocetti M, Burato P, Mileto C (2015) Understanding Spanish timber jack arch floors: examples of assessment and conservation issues. *Int J Archit Herit* 9(6):641–654
- ECOEMBES (2016) Plantas de Selección de Envases Ligeros. Depósito Legal M-5527-2016
- Elliott T, Gillie H, Thomson A (2020) European Union's plastic strategy and an impact assessment of the proposed directive on tackling single-use plastics items. In: *Plastic waste and recycling*. Academic Press, pp 601–633
- EN 15804:2012+A2:2019. Sustainability of construction works - Environmental product declarations - Core rules for the product category of construction products
- Eriksen MK, Pivnenko K, Faraca G, Boldrin A, Astrup TF (2020) Dynamic material flow analysis of PET, PE, and PP flows in Europe: evaluation of the potential for circular economy. *Environ Sci Technol* 54(24):16166–16175
- Ersan YC, Gulcimen S, Imis TN, Saygin O, Uzal N (2022) Life cycle assessment of lightweight concrete containing recycled plastics and fly ash. *Eur J Environ Civ Eng* 26(7):2722–2735
- Eurocode. Eurocode 1: Actions on structures. EN 1992-1-1:2004. <https://eurocodes.jrc.ec.europa.eu/EN-Eurocodes/eurocode-1-actions-structures>. Eurocode 2: Design of concrete structures. EN 1995-1-1:2004. <https://eurocodes.jrc.ec.europa.eu/EN-Eurocodes/eurocode-2-design-concrete-structures>. Eurocode 5: Design of timber structures. EN 1995-1-1:2004. <https://eurocodes.jrc.ec.europa.eu/EN-Eurocodes/eurocode-5-design-timber-structures>
- European Union (2018) Official journal of the European union. Directive (EU) 2018/852 of the European parliament and of the council of 30 May 2018 amending Directive 94/62/EC on packaging and packaging waste
- European Union (2019) Official journal of the European union. Directive (EU) 2019/904 of the European parliament and of the council of 5 June 2019 on the reduction of the impact of certain plastic products on the environment
- Eurostat (2021) Statistics explained. Packaging waste statistics. https://ec.europa.eu/eurostat/statistics-explained/index.php?title=packaging_waste_statistics
- Ferreira J, Pinheiro MD, De Brito J (2015) Economic and environmental savings of structural buildings refurbishment with demolition and reconstruction—a Portuguese benchmarking. *J Build Eng* 3:114–126
- Gabaldón-Estevan D, Criado E, Monfort E (2014) The green factor in European manufacturing: a case study of the Spanish ceramic tile industry. *J Clean Prod* 70:242–250
- Gebremariam AT, Di Maio F, Vahidi A, Rem P (2020) Innovative technologies for recycling end-of-life concrete waste in the built environment. *Resour Conserv Recycl* 163:104911
- Gravina RJ, Xie T, Bennett B, Visintin P (2021) HDPE and PET as aggregate replacement in concrete: life-cycle assessment, material development and a case study. *J Build Eng* 44:103329
- Guinée JB, Lindeijer E (eds) (2002) Handbook on life cycle assessment: operational guide to the ISO standards, vol 7. Springer Science & Business Media
- Hahladakis JN, Iacovidou E (2019) An overview of the challenges and trade-offs in closing the loop of post-consumer plastic waste (PCPW): focus on recycling. *J Hazard Mater* 380:120887
- ILCD Handbook (2010) International Reference Life Cycle Data System. EUR 24708 EN- 2010. IES, JRC, European Commission
- INE Instituto Nacional Estadística (Spain) Estadísticas sobre generación de residuos. Últimos datos. https://www.ine.es/dyngs/INEbase/es/operacion.htm?cid=estadistica_C&cid=1254736176841&menu=ultiDatos&idp=1254735976612. Accessed May 2022
- ISO 14044 (2006) Environmental management. Life cycle assessment. Requirements and guidelines
- Kamal MA, Moussa RR, Guirguis MN (2021) Recycled plastic as an aggregate in concrete. *Civ Eng Archit* 9(5):1289–1294
- Lamba P, Kaur DP, Raj S, Sorout J (2021) Recycling/reuse of plastic waste as construction material for sustainable development: a review. *Environ Sci Pollut Res* 1–24
- Lippiatt N, Ling TC, Pan SY (2020) Towards carbon-neutral construction materials: carbonation of cement-based materials and the future perspective. *J Build Eng* 28:101062
- Maddalena R, Roberts JJ, Hamilton A (2018) Can Portland cement be replaced by low-carbon alternative materials? A study on the thermal properties and carbon emissions of innovative cements. *J Cleaner Prod* 186:933–942
- Muneron LM, Hammad AW, Najjar MK, Haddad A, Vazquez EG (2021) Comparison of the environmental performance of ceramic brick and concrete blocks in the vertical seals' subsystem in residential buildings using life cycle assessment. *Clean Eng Technol* 5:100243
- Muthukannan M, Ganesh ASC (2019) The environmental impact caused by the ceramic industries and assessment methodologies. *Int J Qual Res* 13(2):315
- Plastics Europe (2020) Association of plastics manufacturers. “Plastics – the facts 2020. An analysis of European plastics production, demand and waste data”. <https://plasticseurope.org/knowledge-hub/plastics-the-facts-2020/>. Accessed May 2022
- Plastics Europe (2021) Plastics - the facts 2021. An analysis of European plastics production, demand and waste data. <https://plasticseurope.org/knowledge-hub/plastics-the-facts-2021/>. Accessed May 2022

- PRé Sustainability (2014) Tommie Ponsioen. Normalization: new developments in normalization sets. <https://pre-sustainability.com/articles/the-normalisation-step-in-lcia/>. Accessed Oct 2023
- PRé Sustainability (2016) Mark Goedkoop, Michiel Oele, Marisa Vieira, Jorrit Leijting, Tommie Ponsioen, Ellen Meijer. SimaPro Tutorial
- Real Decreto 293/2018, de 18 de mayo, sobre reducción del consumo de bolsas de plástico y por el que se crea el Registro de Productores. «BOE» núm. 122, de 19/05/2018. <https://www.boe.es/eli/es/rd/2018/05/18/293/con>
- Rubio-de Hita P, Pérez-Gálvez F, Morales-Conde MJ, Pedreño-Rojas MA (2018) Reuse of plastic waste of mixed polypropylene as aggregate in mortars for the manufacture of pieces for restoring jack arch floors with timber beams. *J Clean Prod* 198:1515–1525
- Silvestri L, Palumbo E, Traverso M, Forcina A (2021) A comparative LCA as a tool for evaluating existing best available techniques (BATs) in facing brick manufacturing and more eco-sustainable coating solutions. *Int J Life Cycle Assess* 26(4):673–691
- Sleeswijk AW, van Oers LF, Guinée JB, Struijs J, Huijbregts MA (2008) Normalisation in product life cycle assessment: an LCA of the global and European economic systems in the year 2000. *Sci Total Environ* 390(1):227–240
- Starlinger. Recycling Line recoSTAR dynamic. Technical data sheet. https://www.starlinger.com/fileadmin/user_upload/03_recycling_technology/recoSTAR_dynamic/FB_en/2/index.html
- Syberg K, Nielsen MB, Clausen LPW, van Calster G, van Wezel A, Rochman C, Hansen SF (2021) Regulation of plastic from a circular economy perspective. *Curr Opin Green Sustain Chem* 29:100462
- Tam VW (2008) Economic comparison of concrete recycling: A case study approach. *Resour Conserv Recycl* 52:821–828
- UNE-EN 15037-2:2009. Precast concrete products - Beam-and-block floor systems - Part 2: Concrete blocks
- Usman A, Sutanto MH, Napiah M (2018) Effect of recycled plastic in mortar and concrete and the application of gamma irradiation-a review. In: *E3S Web of conferences*, vol 65. EDP Sciences, p 05027
- Wang B, Yan L, Qiuni Fu, Kasal B (2021) A comprehensive review on recycled aggregate and recycled aggregate concrete. *Resour Conserv Recycl* 171:105565
- Zhang X, Biswas WK (2021) Development of eco-efficient bricks—a life cycle assessment approach. *J Build Eng* 42:102429

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.