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Comparative Life Cycle Assessment (LCA) between standard gypsum ceiling tile and polyurethane gypsum ceiling tile

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A B S T R A C T

In this paper, the LCA of two gypsum ceiling tiles is compared, the first one is a traditional gypsum tile and the second is a new eco ceiling tile in which polyurethane foam waste has been incorporated. Both tiles were made at one of the largest gypsum tile factories in Europe. The life cycle assessment has been considered from cradle to grave for which the corresponding production stages have been defined. This includes the extraction and transportation of raw materials, the manufacturing process, transportation to the client, the use of the product and the end of its useful life. The results show that the tile with polyurethane has a better environmental performance than the standard commercial ceiling tile. This is quantified as a 14% reduction in energy consumption, a 14% reduction in CO_2 emissions and a 25% reduction in water consumption compared with the standard tile, all the while maintaining the technical performance. An analysis of the results suggests that the new eco product has a competitive advantage on the market thanks to its environmental improvements and good technical performance.

1. Introduction

Construction which is responsible for 10% of global economic activity, is one of the sectors that uses the most energy and non-renewable natural resources [1,2]. On a global scale, this consumption represents approximately 40% of energy, 30% of raw materials, 25% of manufactured wood and between 17 and 25% water resources [3,4]. On the other hand, the construction sector generates around 40–50% of the greenhouse gases in the world and 36% in Europe [5,6].

The European economy is largely dependent on the plastics industry, however, the amount of waste that it generates has a significantly negative environmental impact [7]. Data shows an increase in plastic production on a global level [8,9], however, despite the fact plastic production in Europe decreased by 6.31% between 2018 and 2019, the recorded demand for PU remained the same at 7.9% each year [10]. Approximately 68% of polyurethane products are rigid and flexible foam, disposal at landfill being the most common form of dealing with this type of plastic waste [11]. In 2018 in European countries (EU28 + NO/CH) a total of 29.1 MT of plastic waste was collected, of which 3.3MT was polyurethane. Of this amount, 24.90% was taken to landfill, which translates as 572 mT of polyurethane waste [10]. Taking this waste to landfill is far from the European strategy on the use of landfill, as the aim is for only 10% of waste to end up at landfill sites by 2035 [12,13]. Moreover, waste production in European Union countries increases each year, in 2016 and 2018 2.500 and 2.600 million tons was generated respectively [14].

The European Union has initiated an industry level action plan which will be the catalyst for change from a linear economy to a circular economy (CE) based on the ecological design of products, consumer behaviour and industrial innovation [15–17]. CE aims to achieve a regenerative model in accordance with basic principles of redesign, reuse, renovate, repair, the recovery of materials and recycling thereby decreasing CO_2 emissions, the production of waste. The consumption of resources is curtailed by using the latter in a more efficient way lengthening its useful life [18,19]. However, circular economy does not always guarantee that environmental impact is diminished, which could be due to environmental rebound effect [20], this is why life cycle assessment (LCA) is a major tool as it allows for the environmental impact of current products to be quantified and to compare them with other similar or equivalent ones in which renewable resources are incorporated [21].

We currently live in a society that is concerned about the environment and has transferred this interest to the economy, encouraging research into different by products [8,21–23].

According to previous research conducted by GIIE at the University of Burgos, within the scope of the LIFE 16 ENV/ES/000254

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REPOLYUSE project, the use of polyurethane (PU) foam waste that comes from different sources has proved to be a suitable material to be used as a load for gypsum ceiling tiles in accordance with the standard and with a good fire reaction classification (A1) [24–28]. However, there are no studies reporting on the environmental impact of the stages involved in the manufacturing of gypsum ceiling tiles with PU waste. The European production of gypsum ceiling tile in 2019 was 4.3 Mm2 [29,30]. Based on the work done during the LIFE 16 ENV/ES/000254 REPOLYUSE project, it is estimated that the new PU product will have 10% of the market share. The fact that a PU-Gypsum ceiling tile consumes 0.35 Kg per square metre, means that a 150 Tn/year of PU waste will be necessary in Europe to produce the PU-ceiling tiles. This means that there is an adequate supply of PU waste to produce the new ceiling tiles.

Due to the fact that the product has a better functional performance (lower weigh and better insulation), plus it is more environmentally friendly, the new product will expected to be priced with a premium price around 7% to 10%, compared to the current products. According with the data obtained from the manufacturer about technology direct costs, the PU-Gypsum Model is 0.33 €/m2 (-9,51%) less than the Standard Gypsum Model costs.

The aim of this study is to assess and compare the environmental performance between two manufactured ceiling tiles: one carried out in a traditional way (standard gypsum tile), and another in which polyurethane foam waste has been incorporated as a raw material (PU-gypsum tile), in order to identify the best environmental performing product.

2. Materials characterization

The two products compared in this comparative statement are two gypsum tiles: Standard gypsum ceiling tile and PU-gypsum ceiling tile. Both gypsum tiles are installed in partitions, linings and interior ceilings, forming systems that provide the acoustic insulation, thermal resistance and fire resistance required in each case. The Fig. 1 shows the appearance of the two types of ceiling tiles.

The polyurethane foam waste comes from the refrigeration industry, specifically, it is generated from the manufacture of insulation slabs, they are those which are rejected at the production line or from those which are used for various manufacturing tests. The type of PU waste used in this research is a rigid polyurethane foam and is made out of two components which are polyol and isocyanate, this has an open cell structure.

In the last years, a variety of climate-friendly blowing agents have been or are being developed for use in building/construction foam applications to replace CFCs, HCFCs, and HFCs. For example, for production of PU rigid foams, low-GWP hydrocarbon (HC) alternatives are being used to produce panels, boardstock, block, and pipe-in-pipe foam [31].

The blowing agent used in the production of polyurethane used in this study has been *n*-pentane (type HC) classified as R601 whit zero ODP and ultra-low GWP (4). This comply with the protocols for the preservation of the atmospheric ozone layer [32].

Regarding volatile compounds, some polyols have anti-flame components that make them flame retardant. In some countries, the use of this component is mandatory and it is classified under safety regulations. For this reason, usually these polymers are very stable products in which the release of dangerous volatiles is not expected in any stages of the LCA [33]. This is the reason because both gypsum ceiling tiles do not contain dangerous substances in their composition that are subject to authorization (Candidate List of Substances of Very High Concern). At the same time, they do not emit harmful substances into the air, water or soil during their use stage.

The main difference between both models of gypsum ceiling tile is the incorporation of polyurethane foam waste in one of them: PU-gypsum ceiling tile. Fig. 2 provides a schematic section which includes a Scanning Electron Microscope and an Axial Computerized Tomography (ACT) of the PU-Gypsum ceiling tile to show the distribution of the PU waste in the matrix of the product. The composition of both gypsum ceiling tiles is shown below (Table 1):

The tiles dimensions and weight are outlined for both models (Table 2).

On the performance of the functional unit, the analysis has been proposed by calculating the different thermal, acoustic and humidity insulation capacities of the two models of gypsum ceiling tiles. For this, the following tests have been carried out and the results obtained in these tests are outlined below (Table 3):

3. LCA methodology

The Life Cycle Assessment (LCA) allows for the environmental ramifications of a product system throughout its life cycle to be

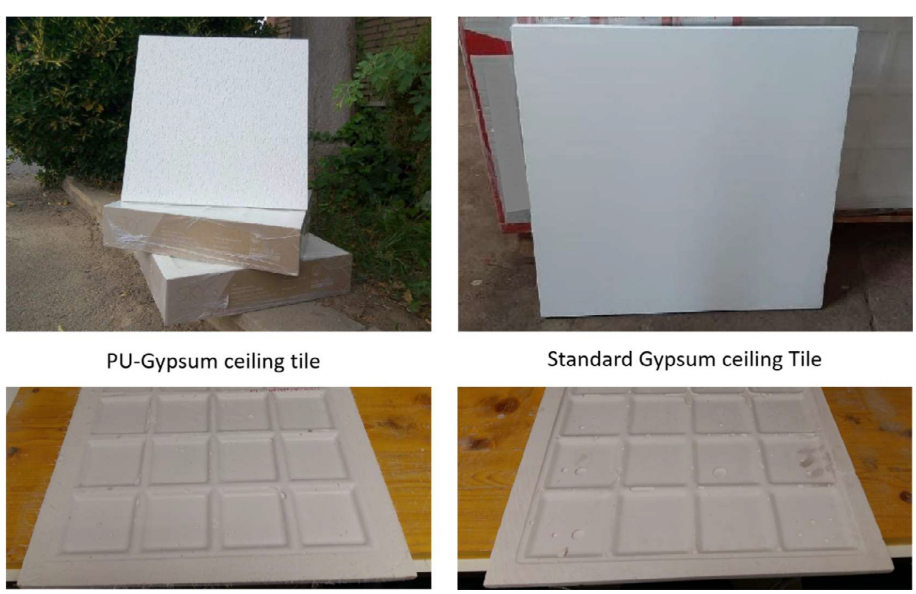

Fig. 1. Superficial appearance of the PU-Gypsum ceiling tile and Standard Gypsum ceiling tile.

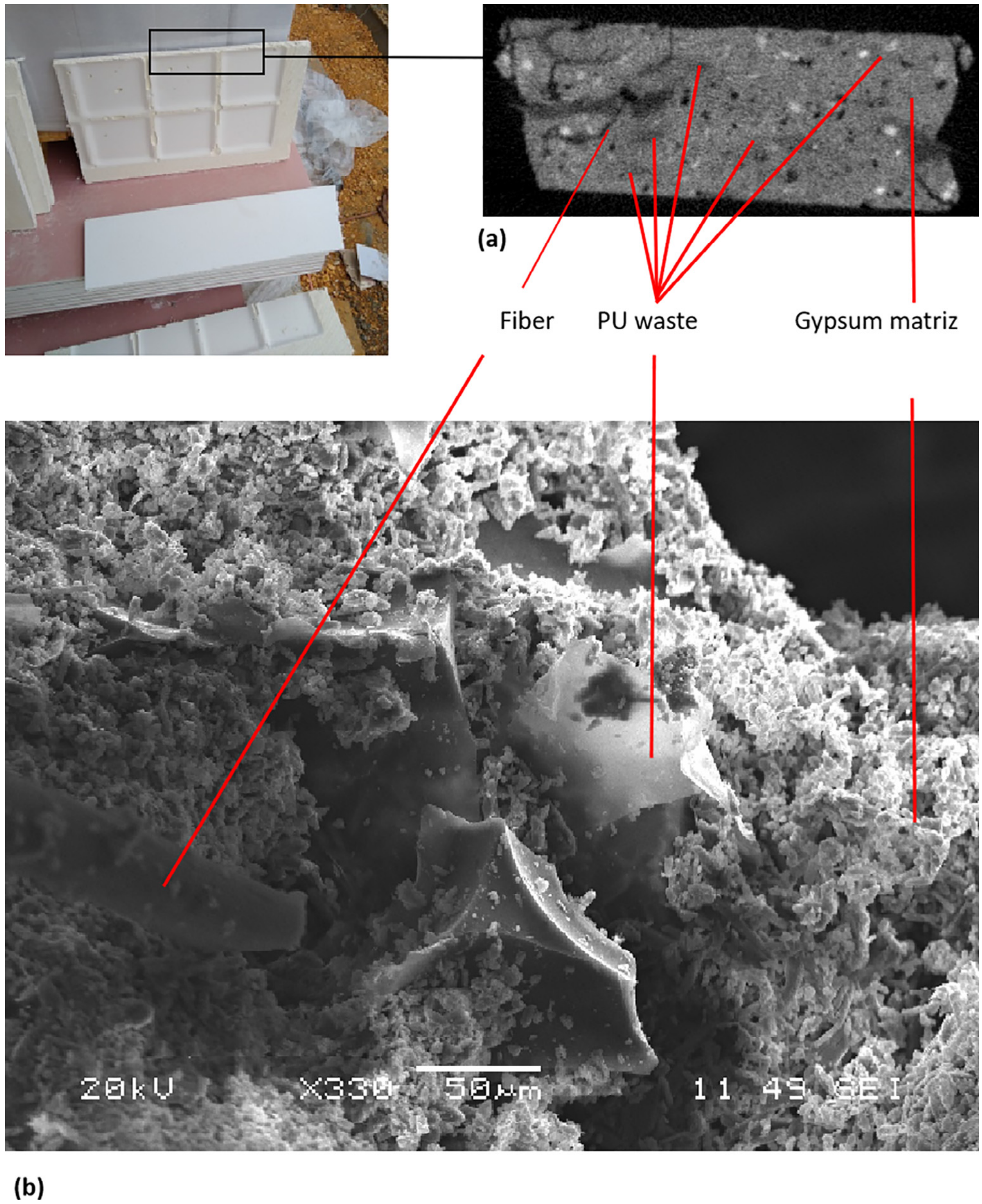

Fig. 2. **(a)** Axial Computerized Tomography and **(b)** a Scanning Electron Microscope of the PU-Gypsum ceiling tile.

Table 1
Ceiling tiles composition.

	Composition per square meter	
Raw materials	**STANDARD GYPSUM CEILING TILE**	**PU-GYPSUM CEILING TILE**
Polyurethane (Kg/m^2)	0.00	0.35
Fluidifying (Kg/m^2)	0.00	0.04
Gypsum (Kg/m^2)	6.19	4.23
Water (Kg/m^2)	8.19	6.09
Fibers (Kg/m^2)	0.06	0.06
Lime (Kg/m^2)	0.06	0.25
Pallet (Kg/m^2)	0.14	0.14
Paperboard packaging (Kg/m^2)	0.04	0.04
Plastic packaging (Kg/m^2)	0.03374	0.03374

Table 2
Ceiling tiles dimensions and weight.

	STANDARD GYPSUM CEILING TILE	PU-GYPSUM CEILING TILE
Nominal dimensions	593 X 593 X 15 mm (±2 mm)	593 X 593 X 15 mm (±2 mm)
Weight per unit	3,49 Kg (±5%)	2,50 Kg (±5%)

evaluated taking into account the different manufacturing workflows that occur at each stage. While carrying this out, the following regulations were used ISO 14040:2006 and ISO 14044:2006 [34,35].

The study includes the goal and scope, inventory analysis (ICV), environmental impact assessment (EICV) and the interpretation of the research. If the events and the contexts of the assessments are similar, these can compare the results of their LCA [35].

Moreover, a LCA is a suitable tool for assessing the environmental impact of gypsum production and its associated supply chains, this has been applied to studies on gypsum and plasterboard production in order to analyse the direct impact from the manufacturing site as well as the indirect impact from mining resources and electricity production. Several publications exist in which, for

Table 3
Results of the thermal, acoustic and humidity insulation capacities test.

	STANDARD GYPSUM CEILING TILE	PU-GYPSUM CEILING TILE
Fire reaction and fire resistance test (UNE-EN ISO 1716:2011)	A1	A1
Thermal conductivity (W/mK) (UNE-EN 12,667 standard)	0.30	0.22
α_m (Average absorption coefficient) (EN ISO 10534–2: 2001)	0.08	0.08
NRC (Noise reduction coefficient) (EN ISO 10534–2: 2001)	0.12	0.12
α_W (Weighted sound absorption coefficient) (EN ISO 10534–2: 2001)	0.10	0.10

example, the environmental advantages of a gypsum tile compared with a standard tile are outlined [36–38], the reduction of the environmental impact of bio-composite boards next to a traditional gypsum board [39,40], the different effects on the environment of a traditional gypsum plasterboard and a phase-change gypsum plasterboard [41] or the environmental improvement that gypsum plasterboards with polycarbonates experience with respect to a traditional plasterboard [42].

3.1. Study goal and scope

The objective of the present study is to be able to establish which of the two models of tiles, the standard gypsum ceiling tile or the PU-gypsum ceiling tile, has a better environmental performance, including an assessment of the components of the tiles, their manufacturing processes, their functional characteristics during the tiles' useful life and even an assessment of the aspects related to their removal and disposal.

3.2. Functional unit

A functional unit is determined as 1 m^2 of gypsum tile of a 15 mm thickness. Based on this referential unit, the input and output flows of the system are quantified. On the other hand, the useful life of the products is estimated as being 30 years.

3.3. System boundaries

A full "cradle to grave" type assessment of the system is carried out in which all stages of the product's life are assessed so that the stages of the system that have a greater environmental impact can be identified. The boundaries of the system studied include the following stages of the life cycle: the supply of raw and auxiliary materials (A1), the transportation of raw material to the manufacturing site (A2), the manufacture and packaging (A3), the transportation of the tiles to client (A4), ceiling tile installation (A5), the client's use of the tile (B1) and the transportation and disposal at landfill (end of life) (C1-C2) (Fig. 3). The geographic limit for the study is Spain.

3.4. Life cycle inventory (LCI) and data modelling parameters

This current inventory includes the entirety of the units' processes along with its elementary and product flows (input and output) in which the product system is divided. Standard ISO 14044:2006 defines the unit process as the *"smallest element considered in the inventory analysis of the life cycle for which the input and output data is quantified"*.

All the information presented was obtained from the producer, Yesyforma Europa SL, a medium-size gypsum manufacturer located in Sástago, Zaragoza (Spain). The life cycle assessment of gypsum ceiling tile manufacturing procedures was carried out on the traditional ceiling tiles and on gypsum ceiling tiles with polyurethane foam waste with the aim of comparing both products in terms of environment impact. This LCA is based on the data obtained during 2018 and 2019, except for the electric mixing which only corresponds to the data from 2018. Secondary data has been obtained using SIMAPRO software [45].

3.5. Life cycle impact assessment (LCIA)

The evaluation of the life cycle impact assessment (LCIA) consists of quantifying the environmental impact applying an impact model on the LCI [46]. There are diverse application methodologies, in this study, the impact model used corresponds to CML 2.001. This model has also been used to carry out the LCA of other building material such as mortars containing mining residues [47], insulation panels made with eucalyptus bark fiber [48] and different types of external walls [49].

In the current LCA study, the following categories of impact per functional unit are analysed: Global Warming Potential (GWP) (kg CO_2 eq/m^2), soil and water Acidification Potential (AP) (kg SO_2 eq/m^2), Eutrophication Potential (EP) (kg $(PO_4)^{3-}$ eq/m^2), photochemical ozone formation (kg C_2H_2 eq/m^2), exhaustion of abiotic resources (ADP – elements) (kg Sb eq/m^2), exhaustion of abiotic resources (ADP – fossil fuels) (MJ/m^2), use of renewable raw energy excluding resources used as raw material (MJ/m^2), use of non-renewable raw energy excluding resources used as raw material (MJ/m^2), net use of running water (L/m^2), hazardous waste disposed/deposited (kg/m^2), non-hazardous waste disposed/deposited (kg/m^2), material for recycling (kg/m^2) and energy exported (MJ/m^2).

The calculation of some categories of impact have been excluded from the current Life Cycle Assessment study as no substance and or product was identified that influence these.

The impact categories excluded in the LCA are ozone layer depletion (kg CFC-11 eq/m^2), use of renewable primary energy used as raw material (MJ/m^2), use of non-renewable primary energy as raw material (MJ/m^2), total use of renewable primary energy (primary energy and renewable primary energy resources used as feedstock) (MJ/m^2), use of secondary materials (kg/m^2), use of renewable secondary fuels (MJ/m^2), use of non-renewable secondary fuels (MJ/m^2), radioactive waste disposed of/dumped (kg/m^2), materials for reuse (kg/m^2) and materials for energy recovery (kg/m^2). Those categories were not included in the LCA due to the fact that no substances were identified that has influence in the study.

4. LCA model description

The LCA was carried out on two products, the standard gypsum ceiling tile and the PU-gypsum ceiling tile, so that the results obtained can be compared and establish in which environmental category the environmental impact of each of the products is greater as well as establishing in which stages of their life cycle they are most harmful for the environment.

The product system has been studied taken directly into the manufacturing plant where the gypsum ceiling tile has been regularly manufactured, which is the same one that has carried out the development of the production process of the PU-gypsum ceiling tile. It represents the set of unit processes with their elemental flows and product flows and will serve as a model for the life cycle

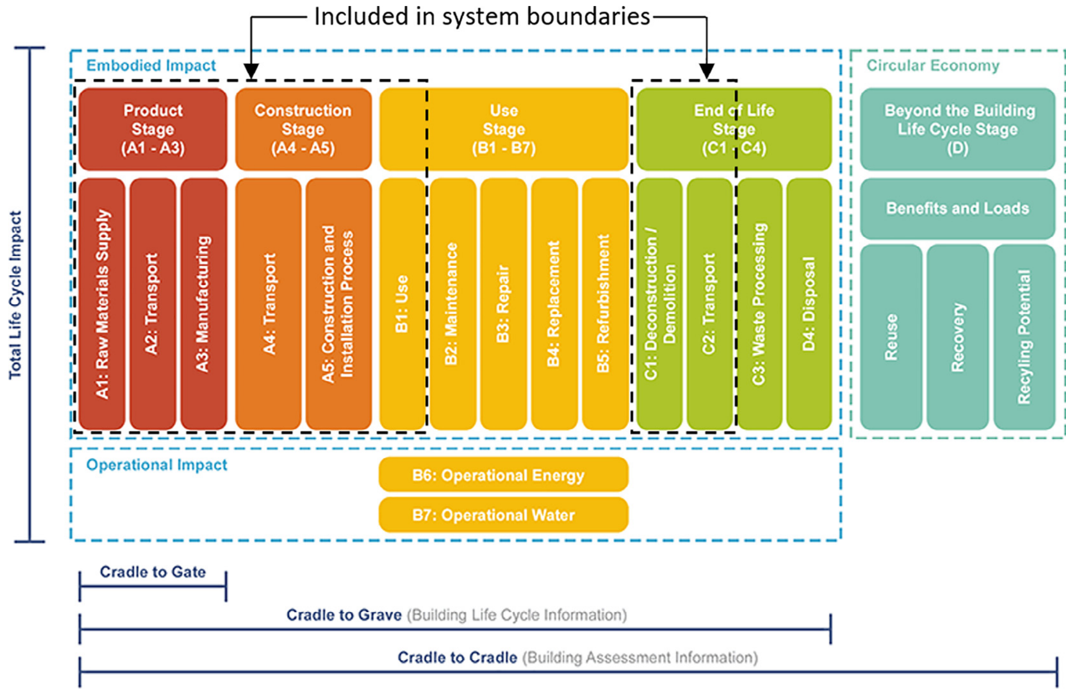

Fig. 3. Stages included in system boundaries [43,44].

of the two gypsum ceiling tiles. Therefore, the diagram of both systems is shown below (Fig. 4).

As shown, the manufacturing stage is quite similar in both tiles, although there are some differences based on the incorporation processes of the recycled materials in the case of the PU-Gypsum ceiling tile. On it's arrival at the manufacturing plant, the PU waste is placed into an industrial shredder. The powder obtained is mixed with gypsum and other components (fiber, gypsum and lime) which are stored in several hoppers. Then, the raw materials go to the mixer where water and other additives are added and it is thoroughly mixed. Later, the mixture is poured into the molds and finally the tiles pass undergo drying to remove the moisture. When the tiles are finished they are packed for transport and ready to install. The PU-Gypsum ceiling tile process differs from the standard gypsum ceiling tile process in that there is one more hopper that contains the polyurethane that has previously been crushed

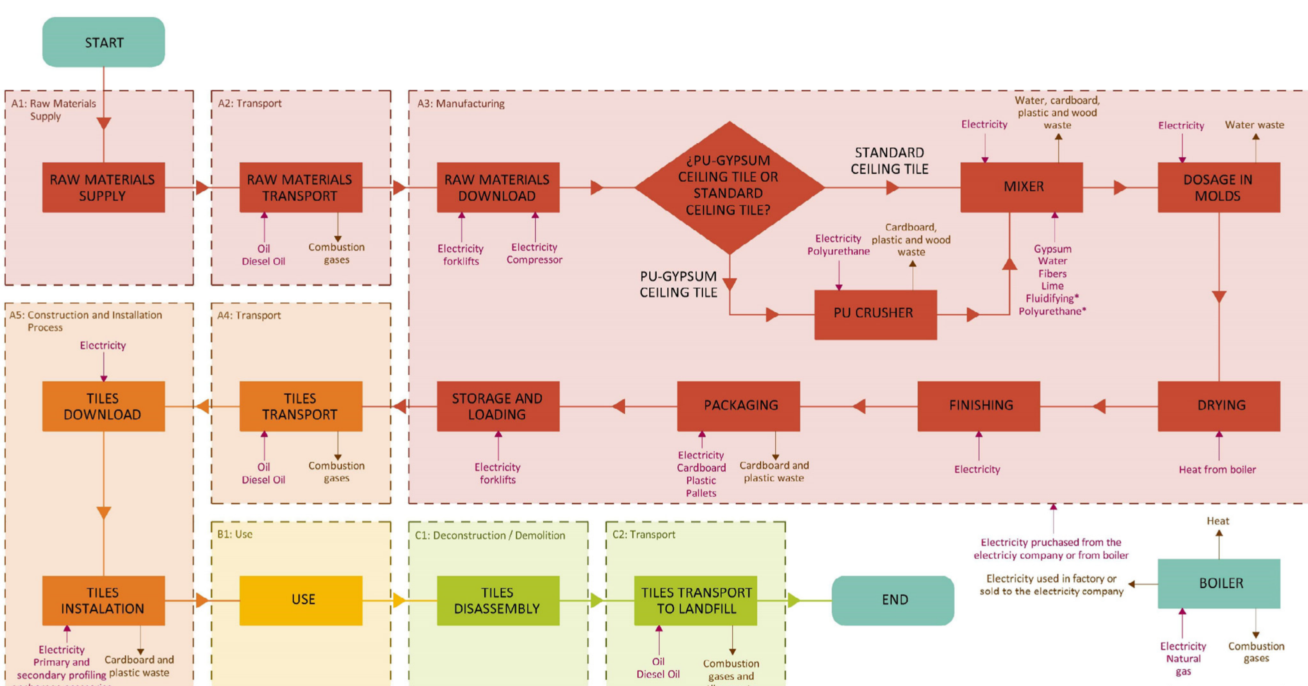

Fig. 4. Standard Gypsum and PU-Gypsum ceiling Tile Product System.

in another part of the factory. In addition, these tiles also contain fluidifying agents. The composition and dosage of both tiles is quite different as can be seen in Table 2.

4.1. Raw materials supply (A1), raw materials transport (A2) and manufacturing (A3)

This process includes the extraction and manufacture of raw materials and energy. Polyurethane waste that is incorporated into the PU-gypsum ceiling tile is considered as a raw material; in this case it is obtained from a polyurethane panel factory in Cuenca (Spain). The transportation of the raw material by road is also included from the extraction or manufacturing site to the gypsum ceiling tile production plant located in Sástago (Zaragoza), the consumption of fuel and auxiliary elements and the emissions into the atmosphere are taken into account.

The suppliers currently used by the company have been considered. The distance between the supplier and the ceiling tile manufacturing plant in terms of the raw material is 468 km for the polyurethane waste, 19 km for the gypsum, 350 km for the fibers, 300 km for the additives, 60 km for the pallets, 300 km for the cardboard packaging, 250 km for the plastic packaging and 19 km for the lime. The water comes from the water supply in situ at the manufacturing plant. This way, it has been confirmed that the raw materials shared by both models of ceiling tiles have identical characteristics and are perfectly equivalent

The manufacturing process of the tiles is divided into the following unit processes: the unloading of raw materials, the shredding of polyurethane waste and its incorporation into the product (solely in the case of the PU-gypsum ceiling tile), the mixing of raw materials, the placement of doses into moulds, drying, finishing, packaging, storage and transportation.

As regarding the finishing process, as there are various possible finishes in terms of the painting of the tiles, for the present study, it was opted to analyse the simplest solution which is the finish that occurs as the final colour of the drying process without being painted afterwards. Within the manufacturing, the "Boiler" process is included in which heat is generated in order to dry the tiles and in which, by means of a concurrent generation process, electric energy is generated which is used in the different manufacturing processes that are carried out at the plant, moreover part of that generated energy is returned to the electric grid.

4.2. Transportation of tiles (A4) and unloading and installation of tiles process (A5)

In this process the transportation of the tiles to the location of use was studied. given the variability of these, category N_3 vehicles according to European Directive 70/156/CEE were considered, with a petrol consumption of 35 L per 100 km and with an average load of 21.560 kg (22 pallets). It is estimated that the vehicle transports 100% of its volume capacity and does not operate empty return journeys as it is a case of transport via an agency.

The unloading of the tiles at the client's premises is included in this process and or at the site where they are used, as well installation work in buildings and work sites where the ceiling tiles will be used.

4.3. Operation phase (use) (B1)

On the other hand, the study of the period of the tile's use in the building in which it is installed is taken into account, including its use, maintenance, repair, substitution, renovation, use of operational energy and the operational use of water.

It has been established that the useful life of the product is 30 years. This assumes that the product can remain in place in the building without needing maintenance, repair, substitution or renovation during this period of time in normal conditions of use. The PU-gypsum ceiling tile and the standard gypsum ceiling tile are a passive product inside a building, which means it does not have any impact on this stage of the life cycle.

At the customer level, and in order to minimize the subjectivity or the variability of the available customers that may be present, as well as their different location and their different choice of a product compared to another that is intended to be compared in this study, a typical client located at a distance of 300 km from the production plant has been assumed. In this way the comparative calculation between both models of ceiling tile can be performed.

4.4. Removal of tiles and transportation to landfill (C1-C2)

In this stage, the removal of the gypsum ceiling tiles from the building where they were installed, the transportation of waste to landfill and depositing this waste at landfill sites is included in the study.

The final possible recycling of the ceiling tiles in order to be reused or of the materials of which they are comprised has been omitted due to it being impossible to have reliable information about this process, since no organization is known of that has carried out this process, especially in the case of PU-gypsum ceiling tiles. As a consequence, it is assumed that 100% of the product is taken to landfill, collected and mixed with other construction waste.

Previous studies have been carried out that demonstrate the possibility of closing the life cycle of this product [50]. This can be carried out by separating the PU from the gypsum and reusing both as raw materials. However, the manufacturer in which the LCA of the tile was carried out, does not currently do so.

However, there are specific LCA studies on the treatment of gypsum waste where the waste management strategy is researched or more efficient recycling is researched and whose results show that the scenario with beneficial environmental improvements is the use of gypsum recycled from the agricultural sector [51].

For the transportation of the waste, an N_3 category vehicle according to European Directive 70/156/CEE was considered, with a petrol consumption of 35 L per 100 km. As regards waste management, in order to guarantee the objectivity of the study, it has been assumed that both models of ceiling tiles are deposited in landfill sites located 50 km from the place where they were installed and the average number of tiles transported as waste being 8.840 units.

5. Results and discussion

The results for the LCA process of the gypsum tiles are shown in Figs. 5-7.

From the data obtained, it can be observed that the impact categories in which production is of great significance both for the PU-gypsum tile and in the standard gypsum tile is that of global warming (GWP), the exhaustion of abiotic resources (ADP - fossil fuels), the use of non-renewable primary energy excluding resources used as raw materials, non-hazardous waste disposed/deposited, released energy and the use of water. Moreover, the greatest environmental impact occurs in the production stage, for the PU-gypsum tile 90.9% of CO_2 (GWP), emissions are produced 84.7% of the contribution to soil and water acidification (AP), 84.7% of the eutrophication potential (EP), 92.7% of abiotic resources consumption (ADP - elements), 91.0% of fossil fuel consumption and the use of non-renewable raw energy and 100% of running water. The impact categories related to the use of renewable primary

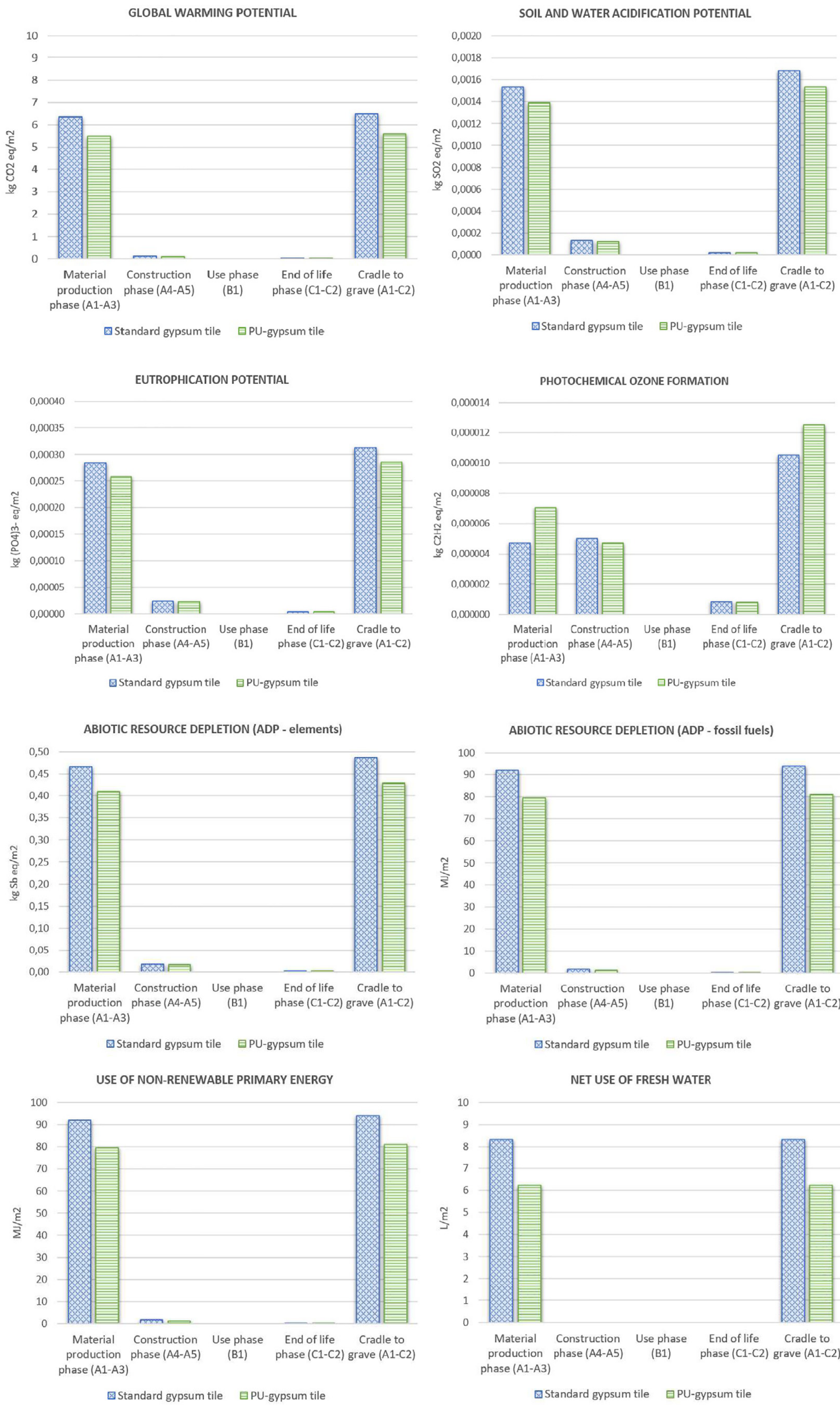

Fig. 5. Impact of the use of resources.

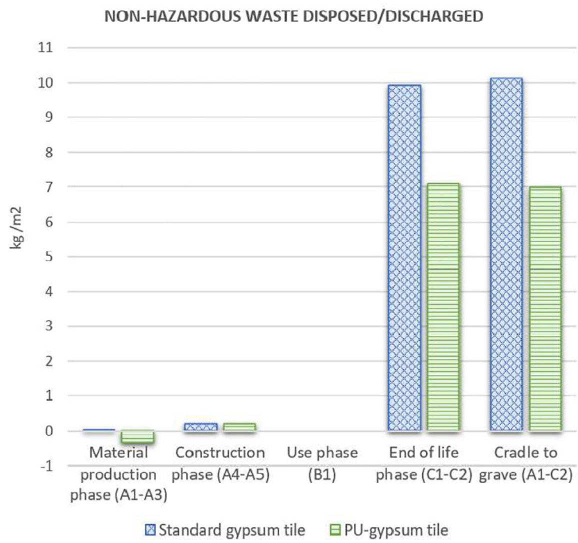

Fig. 6. Impact of waste generated.

energy and the hazardous waste disposed/deposited have also been analysed, however, they have been ignored given their lack of impact on the environment.

The transportation stages, both in raw materials and in the finished product and end waste, in the PU-gypsum tile implies 3,4 % of CO_2 (GWP) emissions, 15.3% of the contribution to soil and water acidification (AP), 15.3% of eutrophication potential (EP), 72.0% of the chemical formation of the ozone, 7.3% of the consumption of abiotic resources (ADP - elements) 3.3% of fossil fuel consumption. The transportation to landfill stage is that which produces the greatest impact in terms of waste management. In the installation stage of the product,3.1% of non-hazardous waste is generated, no other impact was identified, although these may vary depending on the methods used by the companies carrying out the installation.

No impact is produced during the use stage since the tiles are a passive element in the building, given that during the useful life of the tile, no maintenance nor conservation is necessary during this period.

It is notable that polyurethane is used during the manufacture of the product (4.9% in the end product), which reduces the impact of the PU-gypsum ceiling tiles in several of the impact categories studied in the Life Cycle Assessment with respect to their equivalents manufactured without any recycled materials. Thereby, the incorporation of this product, with respect to the standard gypsum tile, means the reduction of the amount of gypsum employed during manufacture, the reduction of the amount of water used in the mixture, the reduction of the consumption of fossil fuels as the amount of water used to dry in the drying process is reduced. The weight of each tile is also reduced, which means the consumption of fuel during transportation and in the final product is also reduced, as well as when the tile is taken to landfill when its useful life ends.

On the contrary, during the manufacture of the PU-gypsum ceiling tile, new aspects are included that have an additional impact such as the transportation of polyurethane waste from the waste management company to the production plant and the shredding of polyurethane waste in order to incorporate it into the production process.

The final comparative balance between the life cycle assessment of the PU-gypsum tile and that of the standard gypsum tile is shown (Fig. 8). The inverse axis radial graph shows a better environmental performance in the variables with the largest polygon area.

Based on these results, and following the directives established in standards UNE-EN ISO 14021:2017, "Environmental labels and declarations. Self-declared environmental statements (Environmental labelling type II)", the following affirmations can be made:

- The PU-gypsum tile contains 4.9% of recycled material (4.9% of recovered polyurethane waste).
- Comparing the life cycle assessment of the PU-gypsum tile with the homogeneous tile manufactured without recycled products, the former uses 25% less water, 32% less gypsum and 14% less energy. In order for this, it is necessary to incorporate 2% of lime and 0.4% of a fluidifying additive in this model.
- Comparing the life cycle assessment of the PU-gypsum tile with that of the standard gypsum tile, the GWP of the former, the exhaustion of abiotic resources (ADP - fossil fuels) and the use of non-renewable raw energy excluding resources used as raw materials, are 14% lower.
- On the other hand, the impact categories AP and EP are reduced by 9% for the PU-gypsum tile.
- The PU-gypsum tile contributes 12% less than the standard gypsum tile to the exhaustion of abiotic resources (ADP - elements).

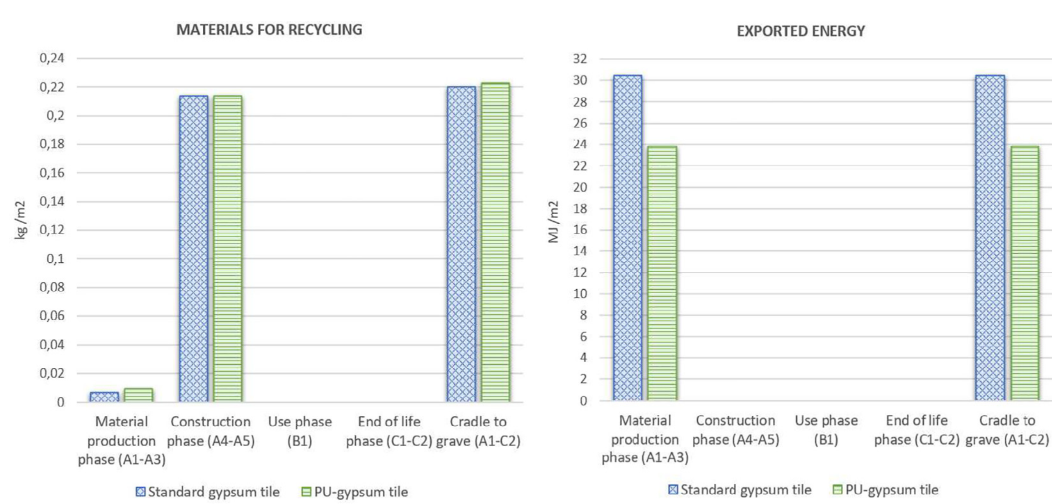

Fig. 7. Impact of other output flows.

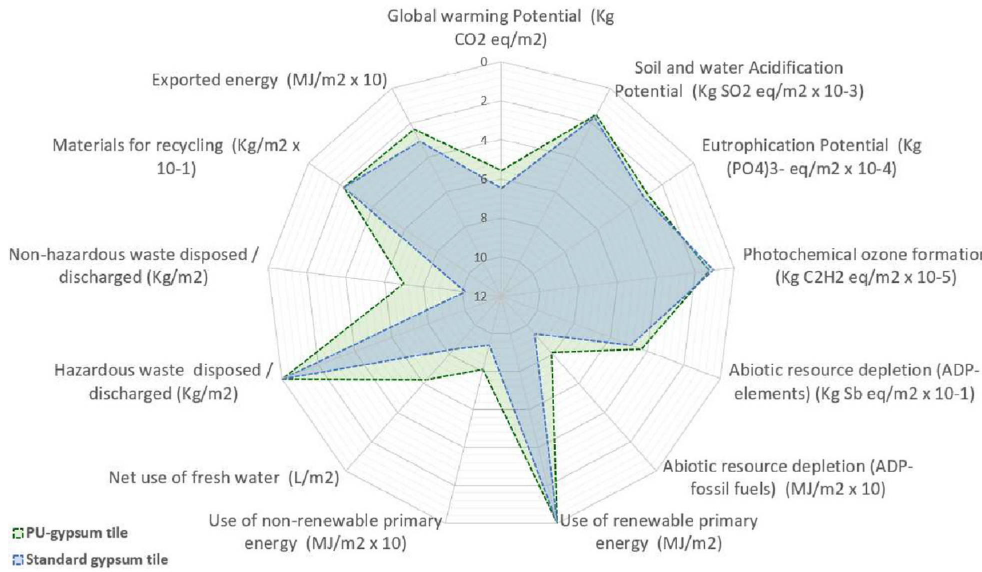

Fig. 8. Cradle to grave environmental impacts.

- Comparing the quantity in mass of non-hazardous waste that the PU-gypsum tile generates on being deposited at landfill with that which is generated by the standard gypsum tile, the former generates 31% less of non-hazardous waste.
- According to the LCA of the PU-gypsum tile and comparing it with the standard gypsum tile, the former releases 22% less energy throughout the whole of its useful life.
- The PU-gypsum tile contributes 19% more photochemical ozone and 1% in materials for recycling.

As well as these results, the results of laboratory tests carried out on the use of the tiles which show a significant 26.7% reduction in conductivity in the PU-gypsum tile compared with the standard tiles should be taken into account. In the rest of the test parameters, no significant differences have been found between both tiles.

6. Conclusions

Global awareness to improve the sustainability of the planet is pushing the industrial sector towards a circular economy, lengthening the useful life of waste and analysing the LCA of several products and systems with the ultimate aim of finding out the environmental impact and commitment to the planet.

After analysing the results of all the impact categories studied, as a final conclusion of the present study of life cycle analysis, it can be established that the environmental behaviour of the PU-gypsum ceiling tile is more favourable than that of the standard gypsum ceiling tile, since it presents improvements in most of the impact categories, some of them substantial and significant; (global warming, depletion of abiotic resources (ADP-elements and ADP-fossil fuels), not use of fresh water and non-hazardous waste eliminated / dumped). Besides, the PU-gypsum ceiling tile has better thermal behaviour.

On the other hand, it can be affirmed that from amongst all the stages of the Life Cycle Assessment of both tiles, the production stage is that which has the greatest environmental impact.

The sustainability and the carbon footprint of this product can be improved by evaluating the PU waste at source and crushing waste prior to transportation. This will mean that a larger amount can be transported at a time thus reducing CO2.

Due to the fact that the manufacturer does not currently recycle the PU-Gypsum product, this means that the product in this study would not be an example of circular economy. The implication of the Authorities would be necessary in order for manufacturers to be incentivized through regulations and legislation.

The technology developed to produce this tile could be transferred to the plasterboard market by also substituting PUW with gypsum. In 2019, in Europe, the plasterboard industry manufactured approximately 1,300.0 Mm^2 as opposed to 4.3 Mm^2 for the gypsum tile ceiling industry. It is clear that the plasterboard market is significantly larger. Hence the adaptation of the product to this market not only would increase the project's general impact but would also reduce the carbon footprint enhancing the environmental impact.

The added value of the proposal is that the new PU gypsum ceiling tile developed gives a competitive edge to companies in the construction sector that opt for the new product due to its environmentally friendly credentials. As consumers are increasingly aware of the need to choose more eco-friendly options and lifestyles, those construction companies that offer such sustainable solutions may have an advantage over those that do not.

This type of products would contribute to policies and standards on sustainable 'green' construction and energy-efficient buildings, by means of offering alternative eco-friendly products with improved properties and lower environmental impact.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

[1] E. Yılmaz, H. Arslan, A. Bideci, Environmental performance analysis of insulated composite facade panels using life cycle assessment (LCA), Constr. Build. Mater. 202 (2019) 806–813.
[2] Y. Chang, R.J. Ries, Y. Wang, Life-cycle energy of residential buildings in china, Energy Policy. 62 (2013) 656–664.
[3] A.F. Abd Rashid, S. Yusoff, A review of life cycle assessment method for building industry, Renew. Sustain. Energy Rev. 45 (2015) 244–248.
[4] UNEP, UNEP SBCI, BUILDINGS AND CLIMATE CHANGE Summary for Decisions Makers, (2009).
[5] M. Jang, T. Hong, C. Ji, Hybrid LCA model for assessing the embodied environmental impacts of buildings in South Korea, Environ. Impact Assess. Rev. 50 (2015) 143–155.
[6] C. Dico, A. Hegyi, G. Călătan, Gypsum plasterboards partition walls behavior, regarding the fire rezistance, in: Int. Multidiscip. Sci. GeoConference SGEM, 2018: pp. 227–334.
[7] A. Di Bartolo, G. Infurna, N.T. Dintcheva, A review of bioplastics and their adoption in the circular economy, Polymers (Basel) 13 (2021) 1229.
[8] C. Moretti, L. Hamelin, L.G. Jakobsen, M.H. Junginger, M.M. Steingrimsdottir, L. Høibye, L. Shen, Cradle-to-grave life cycle assessment of single-use cups made from PLA, PP and PET, Resour. Conserv. Recycl. 169 (2021) 105508.
[9] F.K. Alqahtani, I.S. Abotaleb, M. ElMenshawy, Life cycle cost analysis of lightweight green concrete utilizing recycled plastic aggregates, J. Build. Eng. 40 (2021) 102670.
[10] Association of Plastic Manufacturers (Organization), Plastics – the Facts 2020, PlasticEurope. (2020) 16. https://www.plasticseurope.org/en/resources/publications/4312-plastics-facts-2020 (accessed July 5, 2021).
[11] A. Kemona, M. Piotrowska, Polyurethane recycling and disposal: Methods and prospects, Polymers (Basel) 12 (8) (2020) 1752, https://doi.org/10.3390/polym12081752.
[12] European Council, Directive 1999/31/EC on the landfill of waste, Off. J. Eur. Communities. 182 (1999) 1–19.
[13] European Parliament and Council, Directive (EU) 2018/850 of the European Parliament and of the Council of 30 May 2018 amending Directive 1999/31/EC on the landfill of waste, Off. J. Eur. Union. 2018 (2018) 100–108. https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32018L0850&from=EN.
[14] Eurostat, Gener. Waste by Waste Categ. (n.d.). https://ec.europa.eu/eurostat/databrowser/view/ten00108/default/table?lang=en (accessed July 5, 2021).
[15] European Commission, A new Circular Economy Action Plan For a cleaner and more competitive Europe, Brussels, 2020.
[16] Ellen Macarthur Foundation, (n.d.). https://www.ellenmacarthurfoundation.org/circular-economy/concept (accessed July 5, 2021).
[17] D. Camana, A. Manzardo, S. Toniolo, F. Gallo, A. Scipioni, Assessing environmental sustainability of local waste management policies in Italy from a circular economy perspective. An overview of existing tools, Sustain. Prod. Consum. 27 (2021) 613–629.
[18] N.G. Akhimien, E. Latif, S.S. Hou, Application of circular economy principles in buildings: a systematic review, J. Build. Eng. 38 (2021) 102041, https://doi.org/10.1016/j.jobe.2020.102041.
[19] P. Mhatre, V. Gedam, S. Unnikrishnan, S. Verma, Circular economy in built environment – Literature review and theory development, J. Build. Eng. 35 (2021) 101995, https://doi.org/10.1016/j.jobe.2020.101995.
[20] M. Jaeger-Erben, F. Hofmann, From Take-Mahe-Dispose to a Circular Society, 2019.
[21] L.J. Rodríguez, S. Fabbri, C.E. Orrego, M. Owsianiak, Comparative life cycle assessment of coffee jar lids made from biocomposites containing poly(lactic acid) and banana fiber, J. Environ. Manage. 266 (2020) 110493, https://doi.org/10.1016/j.jenvman.2020.110493.
[22] M. Vidaurre-Arbizu, S. Pérez-Bou, A. Zuazua-Ros, C. Martín-Gómez, From the leather industry to building sector: exploration of potential applications of discarded solid wastes, J. Clean. Prod. 291 (2021) 125960, https://doi.org/10.1016/j.jclepro.2021.125960.
[23] R. Nasser, M. A. Radwan, M. A.Sadek, H. A.Elazab, Preparation of insulating material based on rice straw and inexpensive polymers for different roofs, Int. J. Eng. Technol. 7 (4) (2018) 1989, https://doi.org/10.14419/ijet.v7i4.14082.
[24] S. Gutiérrez-González, J. Gadea, A. Rodríguez, C. Junco, V. Calderón, Lightweight plaster materials with enhanced thermal properties made with polyurethane foam wastes, Constr. Build. Mater. 28 (1) (2012) 653–658.
[25] L. Alameda, V. Calderón, J. Gadea, S. Gutiérrez-Gonzáleza, Recycling of gypsum plasterboard lightened with polyurethane waste, An. Edif. 1 (2015) 33.
[26] L. Alameda, V. Calderón, C. Junco, A. Rodríguez, J. Gadea, S. Gutiérrez-González, Characterization of gypsum plasterboard with polyurethane foam waste reinforced with polypropylene fibers, Mater. Constr. 66 (324) (2016), https://doi.org/10.3989/mc.2016.06015.
[27] R. Gómez-Rojo, L. Alameda, Á. Rodríguez, V. Calderón, S. Gutiérrez-González, Characterization of polyurethane foam waste for reuse in eco-efficient building materials, Polymers (Basel). 11 (2) (2019) 359, https://doi.org/10.3390/polym11020359.
[28] S. Gutiérrez-González, L. Alameda Cuenca-Romero, C. Junco Pretement, V. Calderón Carpintero, A. Rodrigo Bravo, I. Muñiz García, Good practices guide. Recovery of polyurethane for reuse in eco-efficient materials, 2021.
[29] Symposium on availability of raw materials from secondary resources: a key aspect of circular economy. 2018 Eurogypsum. https://iwr.tuwien.ac.at/fileadmin/mediapool-ressourcen/Diverse/2018_Geneva/07_Christine_Marlet.pdf (accessed January 7, 2022).
[30] Critically raw material 2018 Eurogypsum: Gypsum Data; 2009 http://www.eurogypsum.org/wp-content/uploads/2015/05/091109CriticalityGypsumData.pdf (accessed January 7, 2022).
[31] Transitioning to low-GWP alternatives in building/construction foams U.S. February 2011 Environmental Protection Agency EPA-430-F-11-005 https://www.epa.gov/sites/default/files/2015-07/documents/transitioning_to_low-gwp_alternatives_in_building_and_construction_foams.pdf (accessed January 7, 2022).
[32] European Parliament, Council of the European Union. Regulation (EU) No 517/2017 of the European Parliament and of the Council of 16 April 2014 on fluorinated greenhouse gases and repealing Regulation (EC) No 842/2006. 2014.
[33] K. Hillier, D.A. King, A summary of work carried out by EUROPUR into extractable materials from flexible polyurethane foam, Cellular Polymers 27 (4) (2008) 235–249.
[34] International Organisation for Standardisation, ISO 14040:2006, Environmental management — Life cycle assessment — Principles and framework, Geneva, 2006.
[35] International Organisation for Standardisation, ISO 14044:2006, Environmental management — Life cycle assessment — Requirements and guidelines, Geneva, 2006.
[36] K. Weimann, C. Adam, M. Buchert, J. Sutter, Environmental evaluation of gypsum plasterboard recycling, Minerals 11 (2021) 1–13.
[37] M.A. Pedreño-Rojas, J. Fořt, R. Černý, P. Rubio-de-Hita, Life cycle assessment of natural and recycled gypsum production in the Spanish context, J. Clean. Prod. 253 (2020) 120056, https://doi.org/10.1016/j.jclepro.2020.120056.
[38] A. Jiménez Rivero, R. Sathre, J. García Navarro, Life cycle energy and material flow implications of gypsum plasterboard recycling in the European Union, Resour. Conserv. Recycl. 108 (2016) 171–181.
[39] A. Quintana-Gallardo, J. Alba, R. Del Rey, J.E. Crespo-Amorós, I. Guillén-Guillamón, Life-cycle assessment and acoustic simulation of drywall building partitions with bio-based materials, Polymers (Basel) 12 (2020) 1–16.
[40] A. Quintana, J. Alba, R. del Rey, I. Guillén-Guillamón, Comparative Life Cycle Assessment of gypsum plasterboard and a new kind of bio-based epoxy composite containing different natural fibers, J. Clean. Prod. 185 (2018) 408–420.
[41] Y.J. Zhang, L.P. Ma, S.W. Ren, M.C. Huang, Y. Wang, Q.L. Zhang, Comparative life cycle assessment between ordinary gypsum plasterboard and functional phase-change gypsum plasterboard, Mater. Sci. Forum. 993 (2020) 1473–1480.
[42] M.A. Pedreño-Rojas, M.J. Morales-Conde, F. Pérez-Gálvez, P. Rubio-de-Hita, Influence of polycarbonate waste on gypsum composites: mechanical and environmental study, J. Clean. Prod. 218 (2019) 21–37.
[43] Building Enclosure Blog, 29 January 2021. (n.d.). https://www.buildingenclosureonline.com/blogs/14-the-be-blog/post/89547-lca-stages-matter-when-tracking-embodied-carbon (accessed July 8, 2021).
[44] EN 15978:2011 Sustainability of construction works. Assessment of environmental performance of buildings. Calculation method, n.d. https://www.en-standard.eu/bs-en-15978-2011-sustainability-of-construction-works-assessment-of-environmental-performance-of-buildings-calculation-method/?gclid=Cj0KCQjwxJqHBhC4ARIsAChq4as6dr1azoO5Ym47JB1PAfOqA0dvObN30F_759tryOUiMrJLV2bal_0aAgGuEALw_wcB.
[45] Simapro, (n.d.). https://simapro.com/ (accessed July 9, 2021).
[46] P. Li, T.M. Froese, B.T. Cavka, Life cycle assessment of magnesium oxide structural insulated panels for a smart home in Vancouver, Energy Build. 175 (2018) 78–86.
[47] J. Almeida, P. Faria, A.B. Ribeiro, A. Santos Silva, Life cycle assessment of mortars produced partially replacing cement by treated mining residues, Appl. Sci. 11 (17) (2021) 7947, https://doi.org/10.3390/app11177947.
[48] Y. Casas-Ledón, K. Daza Salgado, J. Cea, L.E. Arteaga-Pérez, C. Fuentealba, Life cycle assessment of innovative insulation panels based on eucalyptus bark

fibers, J. Clean. Prod. 249 (2020) 119356, https://doi.org/10.1016/j.jclepro.2019.119356.
[49] D.C. Gámez-García, J.M. Gómez-Soberón, R. Corral-Higuera, H. Saldaña-Márquez, M.C. Gómez-Soberón, S.P. Arredondo-Rea, A cradle to handover life cycle assessment of external walls: choice of materials and prognosis of elements, Sustain. 10 (2018) 10–17.
[50] L. Alameda, V. Calderón, J. Gadea, S. Gutiérrez-González, Recycling of gypsum plasterboard lightened with polyurethane waste, Anales de Edificación 1 (1) (2015) 33–39.
[51] S. Pantini, M. Giurato, L. Rigamonti, A LCA study to investigate resource-efficient strategies for managing post-consumer gypsum waste in Lombardy region (Italy), Resour. Conserv. Recycl. 147 (2019) 157–168.