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Eco-efficiency and economic assessment of gypsum-based precast with polymeric waste: A case study

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ABSTRACT

The adoption of sustainable building policies and the society's increasing emphasis on sustainability underscore the urgent need to evaluate the environmental and economic impact of construction materials. This study examines the effects of incorporating polyurethane foam waste into gypsum-based ceiling tiles. It compares its economic performance and eco-efficiency with conventional alternatives. Methodologically, Life Cycle Cost Analysis (LCCA) quantifies total life cycle costs, followed by Eco-Efficiency Assessment (EE), considering results from both Life Cycle Assessment (LCA) and LCCA. Our findings reveal a compelling 5.91% cost advantage for the novel precast, driven by enhanced production capacity resulting from shorter drying times. The economic benefits of this approach are underscored by a detailed breakdown of cost savings in production phases. Furthermore, the EE remarks a substantial 7.5% boost, emphasizing the positive environmental impact achieved through reduced resource consumption and lower emissions combined with lower life-cycle costs. These results highlight the economic viability and eco-efficiency of polymeric waste-integrated gypsum ceiling tiles for environmental sustainability. The specific percentage improvements in cost and eco-efficiency provide a quantitative basis for understanding the advantages of adopting these innovative materials.

1. Introduction

The current economic system of production and consumption is based on "take, make, use and dispose" [1]. It was seen as a successful model until the unsustainability of this linear economy was demonstrated [2]. The social and environmental damage and loss of value at the end of life of the product or system is greater than the economic value created over its lifetime [3]. Therefore, moving the system towards a circular economy (CE) seems to be the solution to this problem [4]. This new model is a closed system that aims to make efficient use of resources and the promote a sustainable economy, encouraging the reuse and valorisation of waste and avoiding its end in landfills [5].

CE is now a priority objective for most governments, including the European Union (EU), so policies to improve sustainability are being promoted [6,7]. The United Nation' 2030 Agenda is an action plan launched in 2015 that focuses, among other things, on the three fundamental pillars of sustainability: the environment, the economy and the society. It includes 17 Sustainable Development Goals (SDGs), divided into a total of 169 targets, to be achieved by 2030 [8]. Secondly, the Paris Agreement is a multilateral deal

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focused on climate change and signed by 191 countries and the EU [9]. The goal is to prevent global warming from exceeding the barrier of 2 degrees Celsius, for which the progress made by each country is evaluated every 5 years [10]. This agreement led to the European Net Zero Emissions by 2050 Scenario (NZE) initiative, included in the European Green Deal, which sets out the achievable pathway to zero CO_2 emissions by 2050, committing other governments and businesses to climate action [11,12]. Eco-design, closed-loop products and sustainable frameworks are strategies in which the EU is focusing on; in addition, plastics and construction are two of the seven key product value chains identified as urgent [13].

Construction is one of the largest industries. It accounts for the 9% of the EU's Gross Domestic Product (GDP) [14] and the 13% of global GDP [15]. Its ever-expanding size and high environmental impact [16,17] are the reason for the emergence of specific sustainability policies in this sector. Nearly/Net Zero Emissions Buildings (NZEB) is one of them and plays a key role in achieving the targets [18,19].

As for the plastics sector, its production has experienced a great growth since the 56% of the total of polymers ever produced were produced in the first twenty years of this century [20]. The demand for polyurethane in Europe represents the 7.8% in 2020, making it the seventh most requested [21]. The amount of plastic waste increases at the same rate as production due to its short life [22], rising environmental pollution and resulting a risk to human health [23]. Recent studies have demonstrated that degraded plastic releases a wide range of toxic chemicals, including plasticizers, flame retardants, and colorants, which have the potential to leach into the environment, thereby contaminating water and air [24]. Additionally, plastic waste often leads to the release of numerous toxins that have direct and severe health consequences, which include an increased risk of respiratory diseases, neurological disorders, nervous systems, and cardiovascular diseases [25]. Implementing the circular economy in this sector is a priority for the European Commission, which is why the EU Plastics Strategy was launched in 2018 [26]. This was followed by other policies on single-use plastics and bio-based, biodegradable and compostable plastics [27]. Latest data show that only 35% of plastic waste enters the circular economy [28].

The implementation of these agreements and policies requires a major social and economic worldwide transformation, as well as a major effort and cooperation between the main actors. Efficient and reliable analytical tools are emerging to help manage potential, effort, investment and decision-makings in the right direction [29]. Sustainability assessment evaluates and compares the degree of sustainable development of a system, product, strategy, etc., considering its life cycle [30]. It is the result of combining the indicators obtained from the evaluation of environmental, economic and social aspects [31]. Eco-efficiency Assesment (EE) is a methodology for the integration of environmental and economic considerations [32].

Incorporating sustainability criteria into the research and development of innovative products is becoming increasingly important. The Life Cycle Assessment (LCA) methodology is the most widely used in the environmental field. In economics, Life Cycle Cost Analysis (LCCA) is the most common valuation technique. Neverheless, there are a limited number of LCCA studies of building materials that use recycled or waste materials in place of virgin materials. They show a life cycle cost reduction of up to 51%, compared to the cost of conventional materials [33,34]. Others only analyse the production stage, where cost are reduced by 17–35% [35,36]. In several cases, savings are made in transport costs and avoided or reduced landfill fees [37], as well as zero or minimal costs associated with the purchase of these wastes used as raw materials. For eco-efficiency, the number of publications is even lower. Ferrández-Garcia has studied the sustainability of different interior partition walls and found that the most eco-efficient systems are the gypsum plasterboard and the hollow concrete blocks [38].

One area of particular interest is the incorporation of polymer waste into building materials, given the potential to improve the sustainability of both sectors [39]. The technical feasibility of substituting virgin raw materials for industrial polyurethane foam waste (PW) in construction products has been demonstrated in several research [40–47]. However, PW has yet to demonstrate the economic benefits and eco-efficiency of its recovery.

The main objetive of this research is to determine the economic suitability and the economy-environment ratio of a gypsum ceiling tile incorporating polyurethane foam waste recovery in its composition. For this, a financial and eco-efficiency evaluations are conducting as a continuation of this active line research. The LCCA management tool has been used to assess the cost of the products. The EE Assessment evaluates their eco-efficiency. The LCA of the innovative and traditional models have been previously studied to know their degree of environmental sustainability [48]. The results show that the new technology is more environmentally friendly, since the energy consumption and CO_2 emissions are reduced by 14% and it uses 25% less water [48].

2. Materials

The product under investigation is a gypsum ceiling tile containing polyurethane foam waste. In order to know its performance, it is compared with a conventional gypsum ceiling tile. The detailed compositions are included in a previous research [48].

Both precast are manufactured by an industry with extensive experience in the production of ceiling tiles. The implementation of the PW-gypsum model involves several modifications in the plant. Firstly, a polyurethane foam waste management area is set up in the factory, where the polymer is stored and processed. Processing consists of cutting the panels by hand to reduce their size and then crushing these pieces in the grinder installed on the site. The powder obtained, suitable for incorporation into the production line, has a density of between 80 and 100 kg/m^3 and a particle size lower than 2 mm. The second change at the factory is to adapt the normal ceiling tiles production line to include the processed PW as a raw material. For this purpose, two hoppers containing the gypsum and the polyurethane powder are placed at the beginning of the line, and two weight dosing machines pour the raw materials onto an endless screw that guarantees the homogeneity of the dry mixture. Then, the mix is fed into the regular line where it is combined with the other raw materials (lime, water, glass fibre and additive) and the normal manufacturing process continues.

3. Methodology

Life Cycle Cost Analysis (LCCA) and Eco-Efficiency Assessment (EE) are the methods used to assess economical and eco-efficiency performance of the traditional and the innovative ceiling tile.

The methodology of the research consists of first applying LCCA to both product systems and quantifying their total life cycle costs. Then, the EE of the precast is evaluated, for which it is indispensable to take into account the results of the LCCA and the Life Cycle Assessment (LCA) [49]. The LCCA outcomes are from the present study and LCA results are from a previous work [48].

The principles, guidelines and criteria of the LCCA and EE are the same as those considered in LCA to obtain meaningful data, [48] as recommended by other researchers [50]. Based on the same standards, they also share the same functional unit, geographic, temporal and system boundaries, and inventory [51,52].

3.1. Life Cycle Cost Analysis (LCCA)

LCCA analyzes the financial performance of a product or system by looking at the initial and future costs of the product or system over a period of time [53]. It includes the costs associated with the different stages of the life cycle, from the purchase of raw materials, through production, installation and use stages, to the end of the product's life. LCCA is regulated in the standard ISO 15686–5 for buildings and constructed assets [54]. The phases of the process described in the regulation are objective and scope analysis, inventory study, impact assessment and interpretation, in sequential order.

This tool allows to compare the total cost of products and the relative cost of each stage of their life cycle. It shows whether the innovative technology is more cost effective than the traditional specimen, and which phases contribute the most to increasing or decreasing the final cost of the precast.

Currently, there is no specific and unique method that standardises the calculation of life cycle costs, but several methods [55]. In this research, the total cost of the PW-gypsum and standard models is obtained from the sum of the costs of each life cycle stage (Equation 1), which is considered by Hunkeler et al. as the conventional LCCA method [56]. Environmental and social externalities are not considered to avoid double counting.

$$LCCA = VC_{RM} + VC_{M} + FC_{RM\text{-}M} + C_{T\text{-}I} + C_{U} + C_{EOL}$$

Table 1
Inventory and cost data for standard and PW-gypsum ceiling tile [47].

Life cycle stage	Inputs and Outputs		Amount			Cost	
			Unit	Standard	PW-gypsum	Unit	Cost
Raw materials supply and transport	Ceiling tile	Polyurethane supply	(kg/m^2)	0.00	0.35	(€/kg)	-0.16
		Polyurethane transport				(€/kg)	0.219
		Fluidifying	(kg/m^2)	0.00	0.04	(€/kg)	1.0829
		Gypsum	(kg/m^2)	6.19	4.23	(€/kg)	0.04145
		Water	(kg/m^2)	8.19	6.09	(€/kg)	0.00000176
		Fibres	(kg/m^2)	0.059	0.059	(€/kg)	1.55
		Lime	(kg/m^2)	0.06	0.25	(€/kg)	0.00
	Packaging	Paperboard	(kg/m^2)	0.04	0.04	(€/kg)	2.50
		Pallets wood	(kg/m^2)	0.14	0.14	(€/kg)	0.35714
		Plastic (type 1)	(kg/m^2)	0.028	0.028	(€/kg)	1.56
		Plastic (type 2)	(kg/m^2)	0.00574	0.00574	(€/kg)	1.72
Manufacturing	Variable direct cost	Crush process energy	(kWh/m^2)	0.00	0.47	(€/kWh)	0.15
		Crush process labour	(h/m^2)	0.00	0.0014	(€/h)	18.48
		Dryer energy	(kWh /m^2)	25.305	21.709	(€/kWh)	0.01795
		Electrical energy	(kWh /m^2)	0.47244	0.00577	(€/kWh)	0.15
		Labour	(h/m^2)	0.013	0.013	(€/h)	18.48
		Int. Transport energy	(L/m^2)	0.047	0.035	(€/L)	0.39
		Int. Transport service	(€/m^2)	0.1817	0.1817	-	-
	Fix direct cost	Production lines	(€/m^2)	0.362	0.290	-	-
		Crusher/Dosage/Hoper	(€/m^2)	0.000	0.035	-	-
		Other machinery elements	(€/m^2)	0.010	0.008	-	-
		Factory	(€/m^2)	0.046	0.037	-	-
		New buildings	(€/m^2)	0.010	0.008	-	-
		IT	(€/m^2)	0.065	0.052	-	-
		Other assets	(€/m^2)	0.012	0.010	-	-
Installation	-	-	-	-	-	-	-
Use	-	-	-	-	-	-	-
End of life	Removal tiles	Transport energy	(L/m^2)	0.0079	0.0073	(€/L)	0.39
		Transport	(€/m^2)	0.0969	0.0969	-	-

Equation 1. Expression used to calculate the LCCA.

Where:

LCCA is the life cycle cost (€);

VC_{RM} represents raw materials variable costs (€);

VC_{M} includes manufacturing variable costs (€);

$FC_{RM\text{-}M}$ is raw materials and manufacturing direct costs (€);

$C_{T\text{-}I}$ refers to transport and installation costs (€);

C_{U} represents usage costs (€);

C_{EOL} includes end-of-life costs (€).

This phase differs considerably from the one carried out in the LCA. In this assessment, there is no need to characterise the inputs and outputs of the inventory, as currency is the only unit of measurement in this evaluation.

The cost flows for each of the life cycle stages included in the financial study are described below. The unit cost, mentioned throughout the text, refers to the cost of the functional unit.

3.1.1. *Cost data*

All cost inputs and outputs have been obtained directly from the company producing both types of precast. The usual suppliers of raw materials and their distances to the factory, the acquisition cost of the raw materials, the transport routes and the cost of manufacturing, among others, are considered. Inventory and cost data are presented in Table 1.

The raw materials considered are those required to produce both the ceiling tiles and the packaging. LCCA includes the cost of purchasing and transporting raw materials. The water comes from the local municipal network, so there are no transport costs and the recycled polyurethane foam has a no purchase costs. The economic savings from avoiding waste landfill fees are negatively included in the valuation.

At the manufacturing stage, the economic flows of the system are split into variable and fix direct costs, the first being a changeable cost proportional to production, while the second is a firm cost independent of the manufacturing level [57].

3.1.1.1. Variable direct cost. They are related to energy consumption, labour requirements, internal transport and storage of the products. The crush process of the polymer waste is only considered in the study of the new precast. It has been assumed that the cogeneration system would produce the same amount of electrical energy in the production of both tiles models in proportion to the amount of gas used. The reduction in gas consumption is estimated at 14.2%, as the amount of electrical energy required in the dryer is reduced, since the PW-gypsum model requires 20% less drying time.

3.1.1.2. Fix direct cost. Machinery, land and buildings, and other items are included. The method chosen to allocate the fix direct costs to the functional unit "m^{2}" for comparability purposes is to spread the costs of the assets between the maximum production capacity of each ceiling tile model. The difference between the two samples is the additional equipment required for the crushing process of the innovative product.

Establishing an installation cost is complex due to the variety of options available in terms of the commercial process and its unloading and placement by the customer. As this is a comparable assessment and both would have the same commercial and distribution costs, the costs associated with the installation phase are not added to either product. An in-depth study could confirm that the sustainable model requires a lighter structure and has a lower energy consumption during dowloading and installation due to the difference in weight compared to traditional precast. These improvements would imply a lower transportation and installation costs, but have not yet been evaluated as there is no specific data to confirm the difference.

Regarding the use stage, the lifetime of both samples is estimated to be the same. Several laboratory tests have shown that the innovative product has a better hygrothermal behaviour, with a 26.7% reduction in thermal conductivity, so that the building using this eco-product should experience a reduction in energy consumption while maintaining the same desired comfort conditions. However, the estimation of all these parameters also depends on the other materials of the building envelope, the type of fuel used, etc. For all these reasons, it has not been possible to quantify the associated savings and the contribution to the impact category studied has been considered to be zero.

At the EOL stage, it has been established that the average distance for waste transport to the landfill is 50 km. Although previous research supports the possibility of recycling the new product on a laboratory scale [58], the recovery of the final samples has been omitted as there are no known companies that do this on an industrial scale.

3.2. *Eco-Efficiency assessment (EE)*

EE is a method for evaluating the eco-efficiency of a product system considering all the stages of its life. It consists of the ratio between environment and value aspects [59]. Social criteria are not considered in the eco-efficiency perspective. It is a relative concept, the degree of eco-efficiency of a product must be assessed in relation to another product. The methodology followed is contained in ISO 14045:2012 [60].

The process to calculate the eco-efficiency of the products is developed in two steps. The first one is to divide economic performance by environmental behaviour to calculate the different eco-efficiency indicators, according to the equation set out in ISO 14045:2012 (Equation 2). In this case, 11 environmental impact categories and a single economic indicator were considered. Consequently, the first calculation results in a total of 11 eco-efficiency indicators.

$$EE_{e,m} = \frac{LCCA_m}{LCA_{e,m}}$$

Equation 2. Expression used to calculate the eco-efficiency indicators [60].

Where:

$EE_{e,m}$ represents the eco-efficiency for impact "e" and precast "m" (€/impact unit);

$LCCA_m$ is the life cycle cost of precast "m" (€);

$LCA_{e,m}$ refers to the environment impact "e" for precast "m" (impact unit).

The second step determines a global eco-efficiency indicator for each model, by weighting the eco-efficiency indicators and grouping them into a single eco-efficiency score (Equation 3). The same weight or relevance is considered for each eco-efficiency indicator included.

$$EE_m = \frac{\sum EEw_{e,m}}{n}$$

Equation 3. Expression used to calculate the single eco-efficiency indicator.

Where:

EE_m represents the eco-efficiency for precast "m" (-);

$EEw_{e,m}$ is the weighted eco-efficiency for impact "e" and precast "m" (-)

"n" refers to the number of eco-efficiency indicators (-).

Weighting allows a global comparison between precast considering all economic-environmental impacts at the same time. The process is done by giving a value of 1 to the maximum eco-efficiency $EE_{e,m}$ of a product ($EEw_{e,m}$), the weighted value of the other ceiling tile ($EEw_{e,n}$) is equal to the ratio obtained between its eco-efficiency $EE_{e,n}$ and the maximum eco-efficiency $EE_{e,m}$ [61].

The X-Factor is also determined following the recommendations included in ISO 14045:2012. It allows knowing the degree of improvement in eco-efficiency between one precast and the other. The value is obtained linking the normalised economic-environmental ratio of the products.

4. Results and discussion

The results from the LCCA and EE assessment are included and analysed. In addition, a sensitive analysis was performed for the LCCA study.

4.1. LCCA

The results of the financial evaluation of the two samples are shown in Table 2. The costs in each life cycle stage are detailed to identify the system flows where costs vary from one scenario to another.

It is observed that the model with polyurethane foam waste has an economic cost of 2.002 €/m^2, while the cost of the standard model is 2.128 €/m^2 for the whole life cycle, which represents a saving of 5.91%. Another study based on green concrete with recycled polymer reported savings of up to 5.9% over conventional mixes [62]. Sustainable building materials can therefore be economically competitive and viable.

Procuring and transporting raw materials accounts for 33–35% of total life cycle costs. At this stage, there is a cost reduction of 2.98% for the PW-gypsum model. An in-depth study reveals that the raw materials that experience a change in their cost are gypsum, polyurethane foam waste and additive. This is due to the different amounts of raw materials used in the composition of each model. The use of less gypsum (32%) in the innovative ceiling tile is slightly offset by the use of PW and additive, but the final balance represents a cost savings for this model. Both products have the same purchase and transportation costs for packaging raw materials.

Nearly half of life cycle costs are incurred in the manufacturing phase. Compared to the conventional model, the PW gypsum precast is 4.46% cheaper to produce. Other gypsum-based building materials arrive in discounts around 20–31% at this phase adding seashell waste [63]. The crushing process is only required for this sample. However, its cost is offset by the economic savings in the dryer, power consumption and internal transportation. The main difference between the two ceiling tiles in the drying process is due to the drying time. The innovative model takes 20% less time to dry. Consequently, the reduction in gas consumption is 14.21%. The

Table 2
LCCA results for standard and PW-gypsum model.

	Standard ceiling tile Cost (€/m^2)	PW-gypsum ceiling tile Cost (€/m^2)	Difference
Raw Materials supply and transport	0.552	0.535	-2.98%
Manufacturing	0.971	0.928	-4.46%
Fix Direct Cost apply to the product stage	0.505	0.439	-13.01%
Installation Stage	N/A	N/A	N/A
Use Stage	N/A	N/A	N/A
End of life	0.10000	0.09977	-0.23%
Life Cycle Cost	**2.128**	**2.002**	**-5.91%**

decrease in the internal transport costs is due to 28% reduction in weight of the new technology [48]. The purchase cost of the crusher is included in the fix direct costs. Labour costs are the same for both products.

Fix direct costs, applied to the product stage, represent approximately 23% of total costs. The main difference between the two precast is the additional machine required for the crushing process. However, the developed model has 13.01% less fix direct costs. This is due to the fact that the production capacity has a strong influence on the fix direct cost per functional unit. It is known that the bottleneck of the process is the dryer. Therefore, the fabrication capacity for the innovative ceiling tile is 25% higher, since it requires less drying time (20% less). The reason why the fix direct costs in the new sample are lower is that as the production potential increases, the impact of the fix direct cost per m^2 of ceiling tile decreases.

The production phase (raw materials supply and transport, manufacturing and fix direct cost) represents 95% of the total cost in both precast. The production stage is 6.17% more economic for the model that incorporates PW in its composition.

Unfortunately, being conservatives, it has not been possible to consider and include the potential additional cost savings due to the weight reduction of the sustainable model in the installation stage, nor those due to the improved performance of the material as a result of its better thermal and hygrometric behaviour in the use stage.

In the last life cycle stage, it is observed that the new eco-product suffers a slight cost reduction, quantified as 0.23%. Analysing the results, it is concluded that this is due to the fact that this material is lighter, as mentioned above, which implies a small difference in the gas consumption for transport to landfill.

Fig. 1 shows the system flows that modify the functional unit cost of the novel model with respect to the traditional one. The extremes of the graph show the final costs per m^2 of both ceiling tiles. In the middle, the materials or processes that influence the difference in total product costs are included. The data shown correspond to the economic difference between the two samples, with those in red representing an increase in the cost of the innovative product compared to the conventional one and those in green representing a reduction.

Processes that contribute to reducing the cost of the new model prevail. The most significant are the purchase and transport of gypsum, the drying process, electrical energy consumption during manufacture and fix direct cost. Otherwise, only a few processes increase costs, the most significant being the shredding of polyurethane foam waste. The total cost reduction is estimated at 0.13 €/m^2.

4.1.1. Sensitive analysis

Two key variables have been identified as highly sensitive to the economic analysis performed. Their variation can have a significant impact on the result of the cost indicator. On the one hand, there is the cost of the polyurethane foam waste, which is transported 468 km from the waste producer to the ceiling tiles factory. This cost could be significantly modified if a closer waste location could be identified. On the other hand, the production level of ceiling tiles makes the functional unit cost very sensitive. The sensitivity analysis including these two variables is shown in Fig. 2.

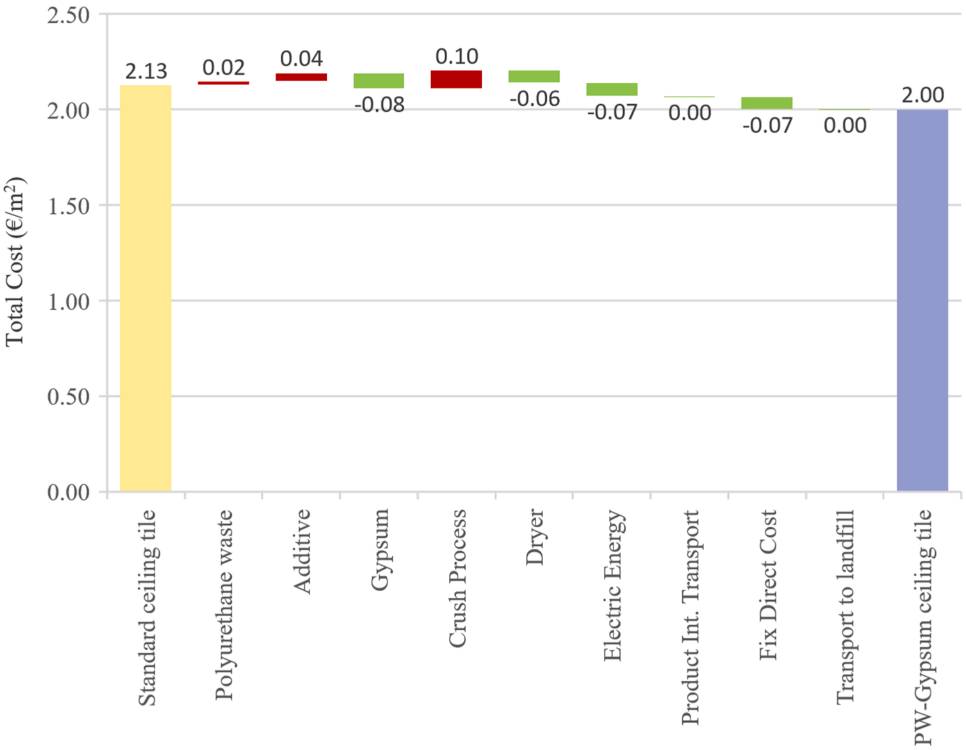

Fig. 1. System inputs and outputs whose cost varies from one model to another.

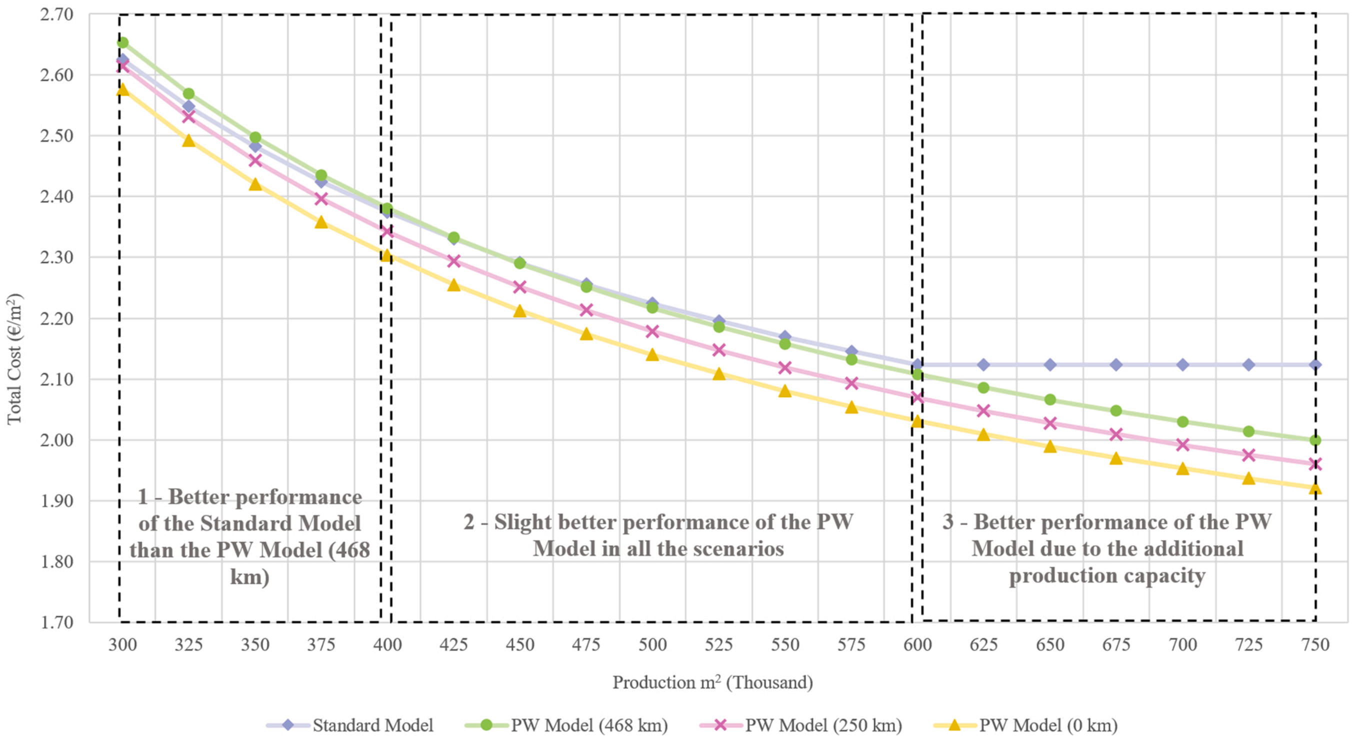

Fig. 2. Evolution of the cost of the functional unit as a function of the distance between the waste producer and the factory, and the level of production.

On the basis of this sensitivity analysis, it is concluded that:

- At low production levels (300.000 m^2/year), the unit cost for the PW-gypsum model is higher than the standard model (2.63 €/m^2 versus 2.60 €/m^2) for the current distance. However, in scenarios with a closer source of PW (0 km), the situation changes and the cost is better for the novel precast (2.58 €/m^2 versus 2.60 €/m^2).
- The functional unit cost is equalised for production level of 400.000 m^2/year. Both models cost 2.36 €/m^2, taking into account the current transport distance of the waste.
- The biggest cost difference occurs at production levels above 600.000 m^2/year, the maximum production level of traditional precast. The new model has an extra production capacity (up to 750.000 m^2/year) with the same assets.

Besides, a further cost sensitivity analysis has been done to evaluate in depth and exclusively the manufacturing stage, where the fix direct costs of the functional unit are very sensitive to the degree of manufacturing. For this reason, the Fig. 3 shows the sensitivity of the functional unit cost to the additional production level of the novel solution compared to the conventional ceiling tile.

From this assessment it can be concluded that, for the same production level up to 53.500 m^2/year additional (9%), the conventional model has a better performance, due to the high cost per m^2 of the additional crushing equipment required for the PW-gypsum model. This changes when the new technology can produce 144.000 m^2/year more (25%), due to the shorter drying process. Therefore, the result is a better cost performance at this higher production level.

4.2. EE assessment

The eco-efficiency of each ceiling tile is analysed and compared. Different scenarios are assessed by combining the economic indicator with eleven environmental impacts. The life cycle cost is the value factor obtained from the LCCA in the financial evaluation. A previous LCA study provides the environmental categories and their results [48]. The environmental categories included are global warming potential (GWP), non-hazardous waste (NHW), eutrophication potential (EP), material for recycling (MR), acidification potential of soil and water (AP), photochemical ozone formation (POF), use of primary non-renewable energy (UPNRE), abiotic resources depletion (ADP-fossil fuels and ADP-elements), use of net freshwater (UNFW) and exported energy (EEN).

Equation 2 has limitations when trying to enhance the eco-efficiency performance of a product. If the economic and environmental impacts (numerator and denominator of the division) decrease proportionally, the final eco-efficiency result will not reflect the change because the proportion remains the same, but the eco-efficiency has actually improved [64]. To avoid these limitations, the two-dimensional chart recommended by Low et al. is considered [65]. The 2D graph makes it possible to observe improvements in both environmental and financial performance, even when they vary by the same ratio. This is because each is displayed on an axis of the chart.

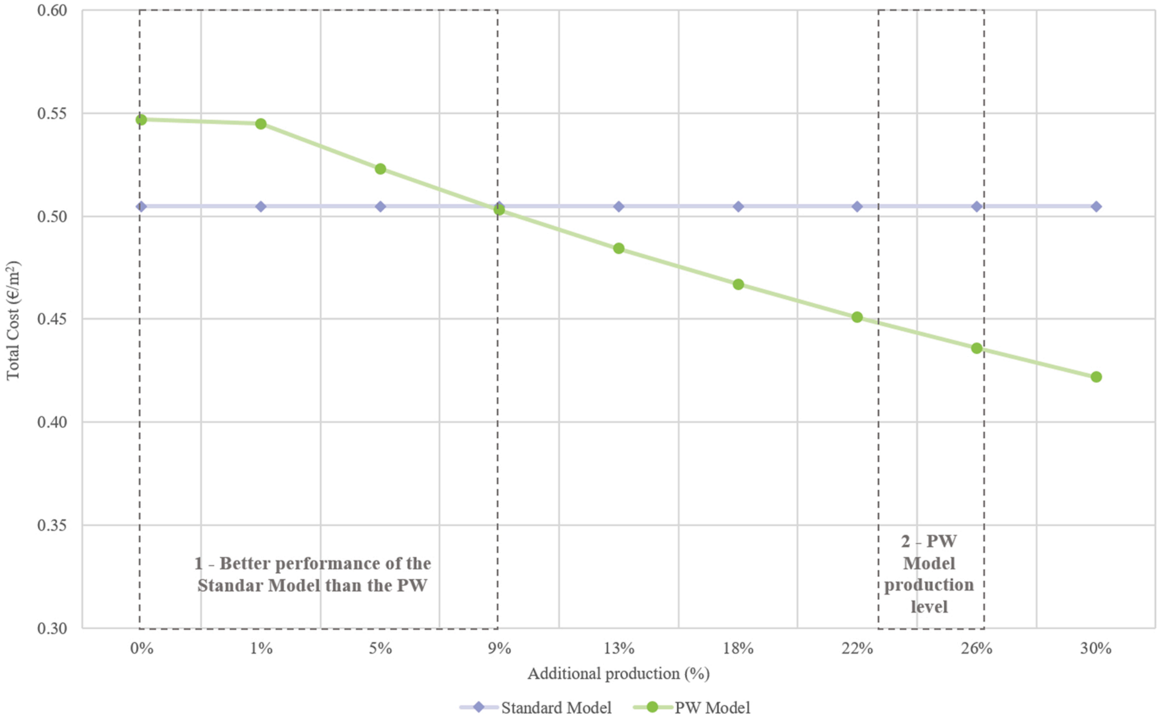

Fig. 3. Progress in the unit cost of the ceiling tiles as the difference in production between both models increases.

Fig. 4 shows the degree of improvement or worsening in each eco-efficiency indicator of the innovative model compared to the traditional precast. The eco-efficiency of the standard model is used as a benchmark against which the performance of the innovative model is displayed. Results are presented as percentages, allowing all indicators to be shown on a single graph despite their different units and magnitudes. "Eco-efficiency" area means that the product performs better in comparison with the reference, both environmentally and economically. "Eco-friendly" seeks improvements in the environmental aspect, while "Profiteering" needs them in the economic domain. Lastly, "Stay clear" means that an improvement is needed in both fields.

The eco-efficiency indicators that take into account the POF and MR environmental impact categories are in the eco-friendly zone, as they improve economically compared to the base case, but not environmentally. For both indicators, PW-gypsum precast EE falls by 26% and 7.5%, respectively. The remaining nine eco-efficiency indicators are in the eco-efficient zone, as they enhance in both fields. The nine EE scores improve by between 3% and 27%.

After the weighting process, the overall eco-efficiency score is 0.97 for the PW-gypsum precast and 0.91 for the standard model, where 1 is the best and maximum score and 0 is the minimum score. The X-Factor is 1.075, which represents a 7.5% improvement in the eco-efficiency of the novel product.

4.3. Potential implications of this research for different stakeholders

There is a current and growing demand for eco-friendly and innovative construction products as well as sustainable housing, driven by social awareness of environmental and energy issues. The development of new "green" certificates and labels is a response to this awareness. Economic estimates predict a 4.2% Compound Annual Growth Rate (CAGR) for the prefabricated gypsum products market from 2022 to 2030 [66]. Despite a limited number of manufacturers, especially for ceiling gypsum boards, the industry is concentrated in a small number of companies. An innovative PW-gypsum ceiling tile offers a lighter alternative with improved performance compared to traditional plaster ceiling boards. The new board demonstrates significant environmental benefits, including reduced energy consumption, CO_2 emissions, water and gypsum usage, and waste generation. Moreover, it presents a 5.91% lower life cycle cost and a 7.5 point improvement in eco-efficiency, both compared to the traditional model.

The findings of this study on incorporating polyurethane foam waste into gypsum-based ceiling tiles have far-reaching implications for the construction industry and sustainability practices. The observed 5.91% cost advantage, driven by enhanced production capacity and shorter drying times, suggests a potential paradigm shift, granting manufacturers a competitive edge. The specific breakdown of cost savings provides actionable insights, allowing companies to strategically optimize production processes. Beyond individual economic benefits, the substantial 7.5% boost in eco-efficiency underscores the broader significance of this research. Adoption of polymeric waste-integrated materials aligns with societal expectations and governmental initiatives for a more sustainable construction sector. Moreover, the study advocates for policy considerations, suggesting incentives or regulations to promote the use of innovative materials. Policymakers could integrate these materials into building codes, fostering a greener construction industry. Additionally, the research opens avenues for further exploration, encouraging future studies on different waste streams, long-term durability, scalability, and societal acceptance of such materials. In essence, the economic viability and eco-efficiency improvements showcased in this study have the potential to reshape industry practices, influence policy decisions, and pave the way for a more sustainable future in construction.

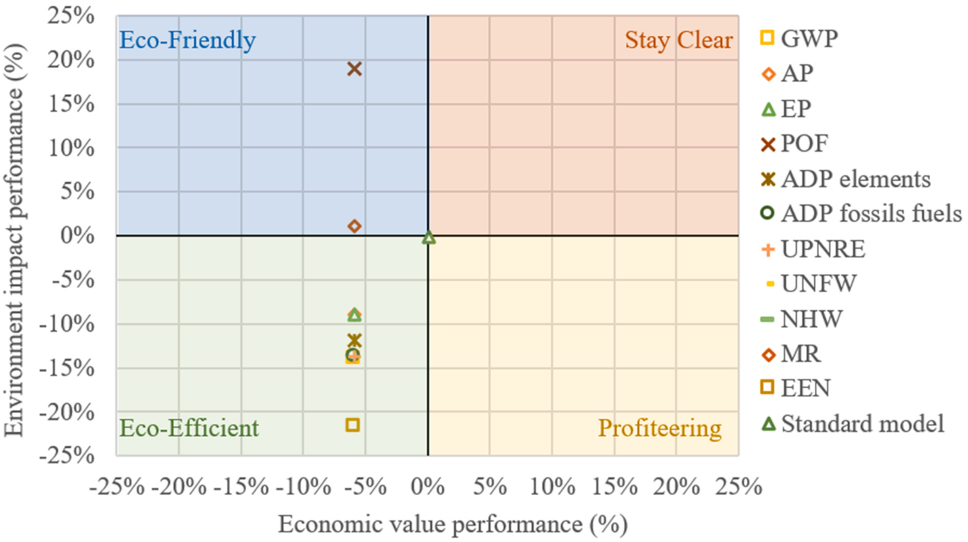

Fig. 4. Eco-efficiency indicators of the PW-gypsum model in comparison with the standard model.

5. Conclusions

The research analyses the financial and eco-efficiency behaviour of a sustainable building material and its traditional alternative. LCCA and EE are the methodologies used, which consider the entire life cycle of the material. The LCCA also includes several sensitivity analyses.

Based on the results of the research, the following conclusions can be drawn:

- The PW-gypsum ceiling tile demonstrates a commendable 5.91% cost advantage over the conventional model, amounting to a life cycle cost reduction of 0.13 €/m^2.
- Key contributors to this financial superiority include reduced gypsum consumption, shortened drying times, increased manufacturing capacity, and lower transportation costs.
- Identified sensitive points in the system, namely the transport of polyurethane foam waste and manufacturing volume, highlight areas for careful consideration in future applications. Challenges faced by the innovative precast, including additional costs for transporting PW and acquiring additives, warrant further exploration for potential optimizations.
- The innovative PW-gypsum technology exhibits a notable 7.5% improvement in eco-efficiency, with nine out of eleven studied indicators showing positive advancements. This underscores the environmental and economic benefits of adopting sustainable building materials.

In conclusion, this study significantly contributes to the understanding of sustainable construction materials, paving the way for informed industrial decisions. The positive indicators in eco-efficiency underscore the potential of the PW-gypsum model to replace conventional materials in a manner that aligns with sustainable development goals.

The new product, a removable suspended ceiling tile, allows for its complete separation from waste (PW-Gypsum-Fibres) at the end of its life cycle or the building in which it has been installed. This approach aims to establish a circular economy for the product, transforming the linear economy model. Looking ahead, the research has the potential to be applied to other construction products, such as concrete, given it is the most widely used building materials [67], plaster acoustic boards or cement boards, which lack ecological considerations. Additionally, there is the possibility of replicating the results in the development of laminated gypsum boards in future studies. An in-depth future research could also focus on quantifying the estimated economic savings during both construction and usage phases. Lastly, a nuanced multicriteria analysis, incorporating environmental (LCA), economic (LCCA) and eco-efficiency (EE assessment) aspects, can contribute to determining the optimal gypsum mortar with polyurethane foam waste.

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CRediT authorship contribution statement

Sara Gutiérrez-González: Conceptualization, Funding acquisition, Methodology, Resources, Supervision, Validation, Visualization, Writing – review & editing. **Raquel Arroyo:** Investigation. **Lourdes Alameda Cuenca-Romero:** Project administration, Visualization. **Verónica Calderón:** Funding acquisition, Supervision. **Alba Rodrigo-Bravo:** Conceptualization, Data curation, Formal analysis, Investigation, Writing – original draft, Writing – review & editing.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Sara Gutiérrez-González reports financial support was provided by University of Burgos. Sara Gutiérrez-González has patent #ES1227514U licensed to Yesyforma Europa, S.A. Nothing more to declare. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

Data will be made available on request.

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