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Combining O-LCA and O-LCC to support circular economy strategies in organizations: Methodology and case study

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ABSTRACT

The pathway to sustainable development requires the transition from a linear economy to a circular economy (CE). For this transition to succeed, it is necessary for all kinds of organizations to participate actively by integrating CE into their daily activities. Today, the identification and selection of possible CE improvements for industrial organizations remains a challenge. The aim of this paper is to propose and apply a methodology capable of evaluating and prioritizing CE strategies at the organizational level based on their environmental and economic performance (eco-efficiency). The methodology was built on the integration of the existing environmental life cycle assessment of organizations (O-LCA) and the proposed life cycle costing of organizations (O-LCC). As a case study, an industrial organization dedicated to the manufacture of construction products was assessed using mainly primary data for the environmental and economic analysis. After an initial diagnosis, ten CE improvement options were selected and arranged into eight alternative scenarios. Their application to the case study showed that although all the alternative scenarios were beneficial from the CE perspective, the environmental and economic effects presented different outcomes. The automation of the curing process was the most eco-efficient scenario, followed by internal material recirculation and energy efficiency. The conclusion was that it was possible to combine environmental and economic assessment with circular indicators to ensure the effective and efficient transition of the organization under study toward circularity.

1. Introduction

Most of the urgent challenges that society has to deal with (social inequality, human health impacts, global warming, loss of biodiversity, resource depletion, supply risk, etc.) are a consequence of the way goods are produced and consumed (European Commission, 2019). Despite the vital importance of targets and arrangements established at the international level to guide different actions carried out by society, such as the Paris Agreement (UN, 2015a) and Sustainable Development Goals (UN, 2015b), there is still a long way to go in this respect. A new production and consumption paradigm, the circular economy (CE), has come to the fore as a possible aid to address these problems. The pathway to cleaner production, waste reduction, and efficient resource use requires the transition from a linear economy to a CE (Geissdoerfer et al., 2017). This transition could also contribute to decoupling economic growth from resource use and achieving sustainable development (European Commission, 2020a). To be successful, the active participation of all kinds of organizations is required, by integrating CE strategies into their daily activities (Geissdoerfer et al., 2018).

Industrial organizations can implement CE strategies and improvements in their operations as a plausible approach to support and encourage the transition to a CE (Pauliuk, 2018). They play a critical role as they represent an important share in value chains and generate important environmental impacts. The European Union, which leads the way in the CE transition, highlights the importance of industrial organizations' circularity to deliver substantial material savings throughout value chains and production processes, generate extra value and unlock economic opportunities, and achieve climate neutrality (European Commission, 2019, 2020b).

Existing literature has outlined the most common CE strategies and future perspectives for industrial organizations. Standard BS 8001 (BSI, 2017) presents a framework to guide organizations in the transition to CE, which provides a list of generic guiding principles for CE and encourages organizations to expand and adapt it. Kalmykova et al. (2018),

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after reviewing more than 100 research articles, developed a database of CE strategies that are useful in the value chain context. Lopes de Sousa Jabbour et al. (2019) reviewed 214 research articles with the aim of identifying changes that are needed in the decision-making processes of organizations in order to achieve circular business models. Similarly, Acerbi and Taisch (2020) identified CE improvements for manufacturing processes from a review of 215 academic publications.

Today, the development of methodologies and tools for identifying CE strategies that are useful for industrial organizations remains a challenge due to the wide variety of approaches to CE (Oliveira et al., 2021) and the extensive range of types of industrial organizations (Kanda et al., 2021). In addition, there is a clear lack of consensus on the method to be applied for selecting the most appropriate CE strategy (Vinante et al., 2021). In recent times, a number of tools to measure the level of circularity of organizations have appeared (CIRCelligence, 2020; Circle Assessment, 2017; Circulytics, 2020; CM-FLAT (Sacco et al., 2021); MATChE, 2021), although they are mostly qualitative methods that are more useful for creating sustainable awareness in companies, their employees, and society than for obtaining information that is useful for making decisions in the process of selecting CE (Valls-Val and Bovea, 2022). Another option is to select CE strategies on the basis of their environmental and economic effects in the organization under study and its stakeholders, as proposed by Corona et al. (2019), Kravchenko et al. (2020) or Vinante et al. (2021).

Life cycle assessment (LCA) can provide a comprehensive and systematic framework (ISO, 2006a; 2006b) for evaluating the environmental effects of CE strategies (Elia et al., 2017), since it is the most internationally accepted tool to support environmental decision-making processes. In addition, the LCA methodology is useful for identifying and managing options for improvement from the point of view of the CE (Peña et al., 2021), as recent studies have shown: van Stijn et al. (2021) and Zimmermann et al. (2020) for the building sector, Schwarz et al. (2021) for the packaging sector, Horodytska et al. (2020) for the plastic sector or Colley et al. (2020) for the food sector, among others. Historically, LCA has been oriented toward evaluating products, services or systems. However, the Organizational Life Cycle Assessment (O-LCA) framework has recently been developed by means of ISO/TS 14072 (ISO, 2014) and the UNEP/SETAC Life Cycle Initiative (2015). O-LCA is interpreted as an alternative to LCA for studying the environmental effects of an entire organization and seems to be an appropriate method for assessing the environmental implications of CE strategies at the organizational level. This methodology complies with the basic structure of LCA, although some of its requirements have had to be adapted (Finkbeiner and König, 2013; Martínez-Blanco et al., 2015). Few studies in the literature apply the O-LCA methodology to evaluate the environmental behavior of organizations (Martínez-Blanco et al., 2020; UN, 2017). Examples include Manzardo et al. (2016) for the beverage sector, Lo-Iacono-Ferreira et al. (2017) for the higher education sector, Manzardo et al. (2018) for the construction sector, Moreira de Camargo et al. (2019) for the cosmetic sector, and Marx et al. (2020) for the sector of renewable energy services. However, to date no application has been developed to evaluate and prioritize CE strategies at the organizational level.

From an economic perspective, the Life Cycle Costing (LCC) methodology can be applied to evaluate the economic performance of systems. The initial methodological framework for LCC (Hunkeler et al., 2008) and the code of practice developed by Swarr et al. (2011), was the basis for the important body of background literature on the application of the LCC methodology, both on its own or combined with the LCA methodology (Alejandrino et al., 2021). Despite this, few studies have focused on evaluating the economic performance of CE strategies, two interesting examples being Wouterszoon Jansen et al. (2020) for the building sector and Albuquerque et al. (2019) for aluminum packaging in the food sector. To date no organizational life cycle costing (O-LCC) framework has been developed. O-LCC could be built on the basis of the LCC framework, by including similar adaptations to the ones required when O-LCA was established from LCA.

Application of LCA and LCC jointly for evaluating the environmental and economic performance of CE strategies is an emerging field of research. The two perspectives, combined in a joint framework, constitute the eco-efficiency analysis (Laso et al., 2018). Dieterle and Viere (2021) and Hummen and Wege (2021) applied it to evaluate the sustainability of CE strategies implemented with products. In relation to organizations, however, the literature has focused on the application of eco-efficiency analyses to prioritize the best techniques available for different industrial sectors, such as the ceramic sector (Ibáñez-Forés et al., 2013) or chemical processing sectors (Mangili and Prata, 2020). Nevertheless, to date, no applications of eco-efficiency for evaluating CE strategies at the organizational level have been found. In addition, although the eco-efficiency of products or processes is standardized (ISO, 2012), eco-efficiency under the organizational life cycle perspective remains a research gap.

Taking this context into account, the aim of this paper is to identify CE strategies at the organizational level and to prioritize them according to the environmental and economic effects that their application could produce. The methodology is built on the integration of CE indicators, O-LCA and the proposed O-LCC. As a case study, an industrial organization located in Argentina dedicated to the manufacture of construction products was assessed. The construction sector consumes large amounts of resources and generates important environmental impacts worldwide, while it has a great potential for transformation to the CE (Hossain et al., 2020).

2. Methodology

To fulfill the objective of this study, the methodology shown in Fig. 1 and described below is proposed. It combines the application of circular indicators, the O-LCA and the novel O-LCC methodologies, and the eco-efficiency analysis of a set of scenarios (current scenario and proposed alternative scenarios).

Main characteristics of the proposed methodology are: 1) It is flexible enough to analyze different CE strategies (including recycling, remanufacturing, sharing, reusing, changing the business model or extend the product life, to name some). 2) It is the first approach that combines the evaluation of CE strategies according to CE indicators and eco-efficiency indicators. 3) It allows the incorporation of the know-how and interests of the organization's stakeholders. 4) It presents the first approach of organizational life cycle costing (O-LCC). 5) It proposes an integrated methodological framework to carry on O-LCA and O-LCC together. 6) It integrates the results of the eco-efficiency analysis through graphic methods oriented to decision making.

2.1. Stage 1. Circularity analysis of the organization: initial diagnosis

The knowledge of the current circularity performance of the organization is the starting point of the study, since it allows the identification of aspects in need of improvement. Taking into account the classification of circular indicators at the micro-level proposed by Vinante et al. (2021) and the categories proposed by EUROSTAT (2021) for monitoring the progress toward a circular economy, the non-exhaustive list of indicators reported in Table 1 were selected as a starting point due to their being easily and routinely quantified by organizations. These indicators should be calculated for the current situation of the organization (baseline scenario, SC0), in order to obtain an initial diagnosis against which the effect of potential circular improvement scenarios can be assessed.

2.2. Stage 2. Proposal and analysis of CE alternative scenarios

Once the circular indicators for the baseline scenario have been calculated, different CE improvement scenarios are suggested with the aim of improving it. For this purpose, a set of 40 CE strategies with

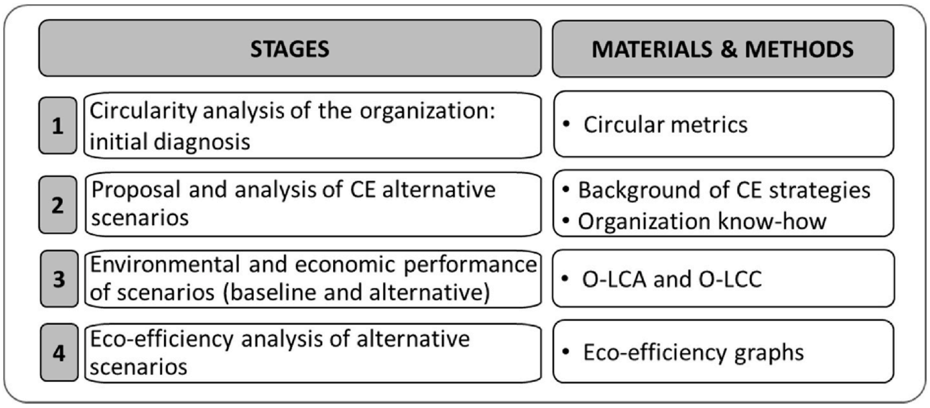


Fig. 1. Methodology.

Table 1
List (non-exhaustive) of indicators for quantifying the circularity at organizational level.

	CE Indicators	Unit
Strategy & vision	1. Circular economy strategies incorporated into other corporate strategies	number (#)
Business model	2. Leasing/renting business models	#
	3. Product lifetime extension initiatives	#
Environmental management	4. Environmental management system	#
	5. Activity reporting on environmental management	#
Industrial symbiosis	6. Collaborations with external partners	#
Design	7. Products recyclable or reusable	#
	8. Products designed for reduced consumption of material/energy	#
	9. Products designed for waste minimization	#
	10. Green packaging initiatives	#
Supplier selection & auditing	11. Supplier selection based on CE performance	#
	12. Environmental purchasing criteria in the selection of suppliers	#
Production and consumption	13. Material consumption	t
	14. Water consumption	m^3
	15. Electric energy consumption	kWh
	16. Renewable electric energy consumption	%
	17. Fuel consumption	m^3
Secondary raw material	18. Recycled content of raw material	%
Waste generation and management	19. Solid waste generated	t
	20. Recycled solid waste	%
	21. Effluents discharged	m^3
	22. Carbon emission generated	t CO_2eq
Competitiveness and innovation	23. CE Investment	ARS
Post-sales services	24. Take back systems for products after their use	#

characteristics that made them suitable for application to industrial organizations were obtained based on a review of strategies proposed in regulatory frameworks (e.g., BSI, 2017; European Commission, 2020a) and the scientific literature (e.g., Acerbi and Taisch, 2020; Kalmykova et al., 2018 or Lopes de Sousa Jabbour et al., 2019). They are shown in Table 2.

The process of preselecting the strategies applicable to each case study should be carried out applying the decision tree shown in Fig. 2. The different departments/areas/stakeholders involved in the organization should participate in this selection process.

The selection of the CE strategies applicable to the case study should be the basis for the definition of circular alternative scenarios. The circularity of each alternative scenario should thus be analyzed by applying the indicators reported in Table 1 to each of them in order to verify they improve organization's circularity.

2.3. *Stage 3. Environmental and economic performance of scenarios (baseline and alternative)*

In order to analyze the baseline scenario defined in stage 1 and the circular alternative scenarios proposed in stage 2 from an environmental and economic perspective, the O-LCA and O-LCC methodologies are applied, respectively, following the stages shown in Fig. 3 and described below. The combined framework proposed follows the requirements of ISO (2014, 2006a, 2006b), Martínez-Blanco et al. (2020, 2015) and UNEP/SETAC Life Cycle Initiative (2015).

Goal and scope definition. The goal of the study is to obtain the environmental and economic performance of the baseline scenario defined in stage 1 and the alternative circular scenarios defined in stage 2. According to Alejandrino et al. (2021), the system boundary should be the same for the environmental and economic analyzes. Finally, this stage also needs to define the reporting unit (UNEP/SETAC Life Cycle Initiative, 2015).

Inventory analysis. Quantitative input and output flows will be determined for the different activities (direct, indirect upstream, and indirect downstream). A differentiated environmental inventory model and an economic inventory model should be developed ensuring they are consistent with the goal and scope of the study. Both inventory models should preferably be obtained from primary data from the organization under study and its suppliers; when this is not possible, it should be completed with secondary data obtained from literature or databases. For the environmental analysis, databases such as Ecoinvent (2020), GABI databases (GaBi, 2021), US-LCI (National Renewable Energy Laboratory, 2012), etc. could be used/adapted. For the economic analysis, data from potential suppliers or material/processes price databases, etc. could be used and/or adapted.

Impact assessment. This stage is used to obtain indicators for the different environmental and economic categories, which together represent, respectively, the environmental and economic performance of the organization under study. For the ***environmental performance***, recognized environmental impact assessment methods can be applied (CML-IA (CML, 2016), ReCiPe (Huijbregts et al., 2017), etc.) and indicators for different impact categories can be obtained, according to their applicability to the case study (global warming, acidification, eutrophication, ozone layer depletion, etc.). For the ***economic performance***, different economic indicators can be applied, although according to Alejandrino et al. (2021), the most common economic indicators are the life cycle cost, which could be interpreted as the total annual cost (TAC) (eq. (1)), for the organizational approach and the payback period (PB) (eq. (2)), which shows the time required to recover the original investment. Both indicators are built on the basis of the net annual saving (NAS) (eq. (3)), which represents the organization's net annual

Table 2
CE strategies applicable to industrial organizations.

Approach	Circular Strategy	References				
		Kalmykova et al. (2018)	European Commission (2020a)	BSI (2017)	Lopes de Sousa Jabbour et al. (2019)	Acerbi and Taisch (2020)
Business model	1 Customization	•	•	•	•	•
	2 Collaborative consumption	•	•	•	•	
	3 Product-service systems	•	•	•	•	•
	4 Dematerialization	•	•	•	•	
	5 Regenerate				•	
Design	6 For disassembly	•	•	•	•	•
	7 For modularity	•	•	•	•	
	8 For durability		•	•	•	
	9 For flexibility				•	
	10 Eco-design	•	•	•	•	•
	11 For reduction	•	•	•		
	12 For recycling			•	•	•
Material sourcing	13 Low impact materials	•	•		•	
	14 Renewable materials	•	•	•	•	
	15 Recycled materials		•	•	•	
	16 Bio-based materials	•	•	•		
	17 Non-harmful substances	•	•	•		
Manufacturing	18 Energy efficiency	•	•	•	•	•
	19 Material efficiency	•	•		•	•
	20 Tracking and mapping of resource		•		•	
	21 Industrial symbiosis	•	•		•	•
Distribution and sale	22 Efficient packaging	•	•			
	23 Product labeling	•	•	•		
	24 Digital information		•			
	25 Efficient surplus management			•		
Consumption and use	26 Resource and energy efficiency		•	•		•
	27 Re-use	•	•	•	•	•
	28 Repurpose			•	•	
	29 Upgrading	•	•	•	•	
	30 Maintenance	•	•	•	•	
	31 Repair	•	•	•	•	•
Reverse logistics	32 Incentivized return	•		•	•	
	33 Infrastructure	•	•	•	•	•
	34 Separate collection	•	•		•	
End of life valorization	35 Refurbishment	•	•	•		•
	36 Remanufacture	•	•	•	•	•
	37 Recycling	•	•	•	•	•
	38 Energy recovery	•		•	•	
	39 Composting	•	•	•		
	40 Extraction of biochemicals	•				

savings once the initial investment has been discounted. TAC and PB can be used to analyze whether the alternative scenarios reduce the costs of the organization and if the initial investment could be recovered (European Commission, 2006; Ibáñez-Forés et al., 2013).

$$TAC_k = I_k\left[\frac{r(1+r)^n}{(1+r)^n-1}\right] + OMC_k[\$/\text{year}] \quad \text{(eq. 1)}$$

$$Payback_k = \frac{I_k}{NAS_k}\ [\text{years}] \quad \text{(eq. 2)}$$

$$NAS_k = TAC_0 - TAC_k\quad [\$/\text{year}] \quad \text{(eq. 3)}$$

where k is the scenario under analysis, I_k is the investment cost in the base year, r is the discount rate, n is the lifetime of the equipment/facility, and OMC_k is the annual operating and maintenance costs.

Interpretation. The results should be analyzed according to the goal of the study. Furthermore, the limitations of those results should be identified.

2.4. Stage 4. Eco-efficiency analysis of alternative scenarios

In order to compare/prioritize the alternative scenarios that improve the circularity of the organization, eco-efficiency graphs are applied. They analyze together both economic and environmental performance (Fig. 4). On the x-axis these graphs present the environmental impact and on the y-axis they show the economic impact, which allows each alternative scenario to be located in one of the four eco-efficiency areas.

3. Case study description

The case study selected is an organization located in Mendoza Province, Argentina, dedicated to the production of precast construction elements. It is a medium-sized privately owned company with 33 employees. Human resources and accounting management activities are outsourced.

Precast construction products are manufactured on demand, so batches of products are generated. The manufacturing process is divided into two production lines: concrete and foamed mortar. The concrete line uses fines and coarse aggregates as one of the main raw materials, while the mortar line only uses fines with a foam-forming additive. Of the total production, concrete products for use as wine vessels account for 80%, the remaining 20% consisting of light and insulating mortar products for use as housing modules and construction panels (Fig. 5).

Unit processes carried out within the organization's facilities are presented in Fig. 6 with bold black boxes numbered from 1 to 9. The production process begins with the cutting and welding of structural

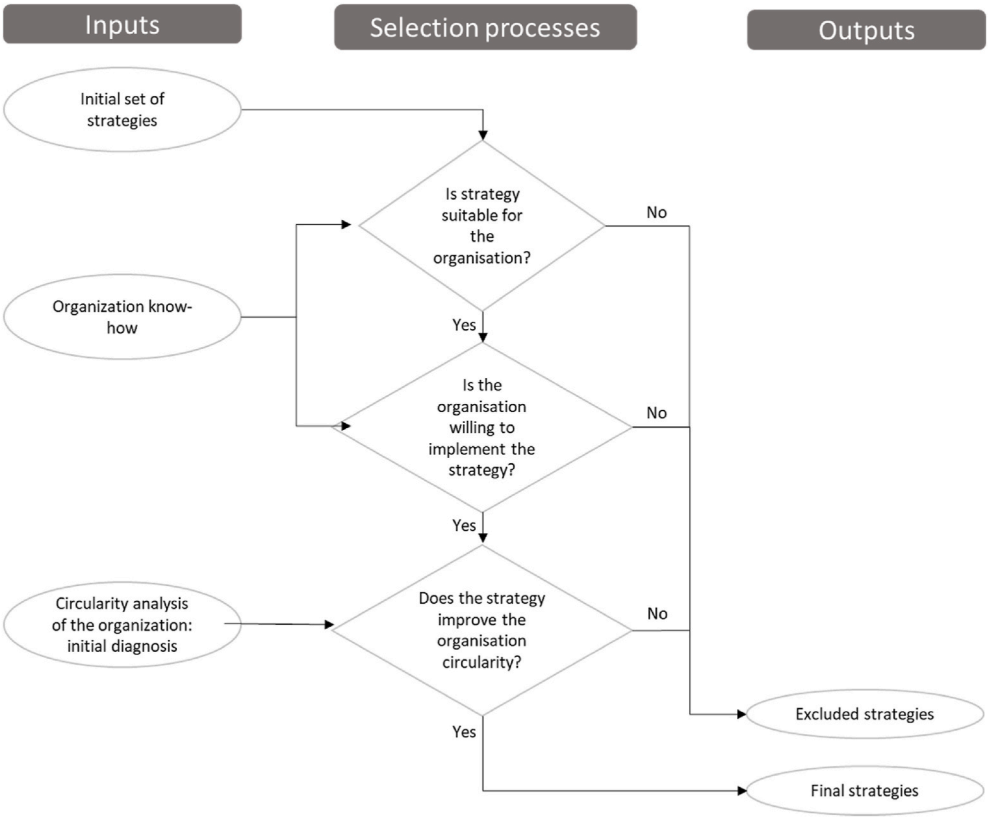


Fig. 2. Decision tree for selecting CE strategies.

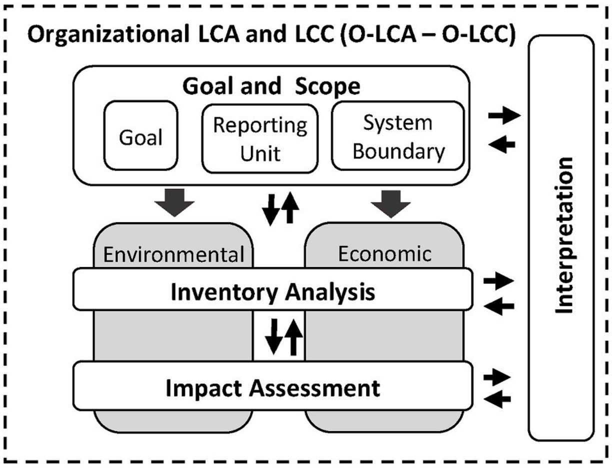


Fig. 3. Proposal of framework combining O-LCA & O-LCC methodologies.

irons (1). Mixture preparation is performed in two different pieces of dosing and mixing equipment – a bigger one for the concrete mixture (2) and a small one for the mortar mixture (3). Once the mixture and irons are ready, the products are built (5) on previously adapted molds (4). Finally, product curing takes place with high humidity and intermediate temperature conditions (6), which are obtained with water sprinklers and combustion heaters. The water consumed for industrial purposes is extracted from a well without any previous treatment. Gantry cranes and forklifts are used to carry out internal movements (7) of products and materials. Two pickups are also used for external movements (8). Finally, administration activities (9) complete the unit processes.

Waste generated by the organization consists of foamed mortar, concrete and iron scrap. Urban solid waste generated by workers was dismissed because it represents a negligible flow. Concrete waste is disposed of in landfill for inert materials. Iron waste is collected and recycled separately. Effluents are treated through a gravity sedimentation facility without any energy consumption and then discharged into the sewage system.

4. Results

4.1. Stage 1. Circularity analysis of the organization: initial diagnosis

The first row of Table 5 presents the results for the initial diagnosis of the organization as regards the circular economy using the indicators presented in Table 1. The baseline scenario (SC0) shows that the organization has initiatives related to industrial symbiosis, products designed for reduced consumption of material/energy and it has already invested in CE. The remaining CE indicators present options for improvement.

4.2. Stage 2. Proposal and analysis of CE alternative scenarios

After applying the decision tree (Fig. 2) to the set of CE strategies applicable to industrial organizations (Table 2), the ten CE strategies applicable to the case study were selected. This decision process is detailed in Supplementary Material. The eight alternative scenarios (SC1, …, SC8) presented in Table 3 and described below were proposed as alternative CE improvement scenarios.

SC1. Use of recycled raw materials. The use of recycled raw materials to manufacture the products was proposed, taking into account that product performance cannot be compromised. This scenario has two sub-scenarios, depending on the type of raw material replaced by recycled (secondary) material:

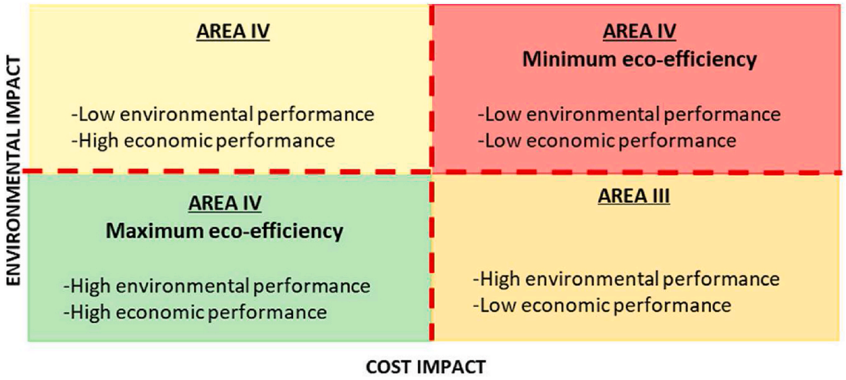


Fig. 4. Example of eco-efficiency graph.

Fig. 5. Example of precast products manufactured by the organization.

- *SC1a. Use of recycled plastic in mortar*. A new dosage for foamed mortar was proposed (Table 4), based on the replacement of fines with crushed plastic waste, which has previously been proven in technical terms (Mercante et al., 2018). According to previous tests, this dosage makes it possible to improve the insulating properties, boost a market for recycled plastics, and achieve a reduction in cement and water consumption (Ojeda et al., 2020). The used recycled plastic (PET) comes from a recycling facility located near the reporting organization (Alejandrino et al., 2019). To implement this scenario, the mixer output needs to be adapted with the installation of a 3″ valve and a matching 20-m long hose.

- *SC1.b. Use of recycled coarse in concrete*. Replacing 20% of virgin coarse with recycled coarse was proposed. This proportion does not reduce the strength of the product (González-Fonteboa and Martínez-Abella, 2005) and satisfies the requirements of the IRAM standard (2016).

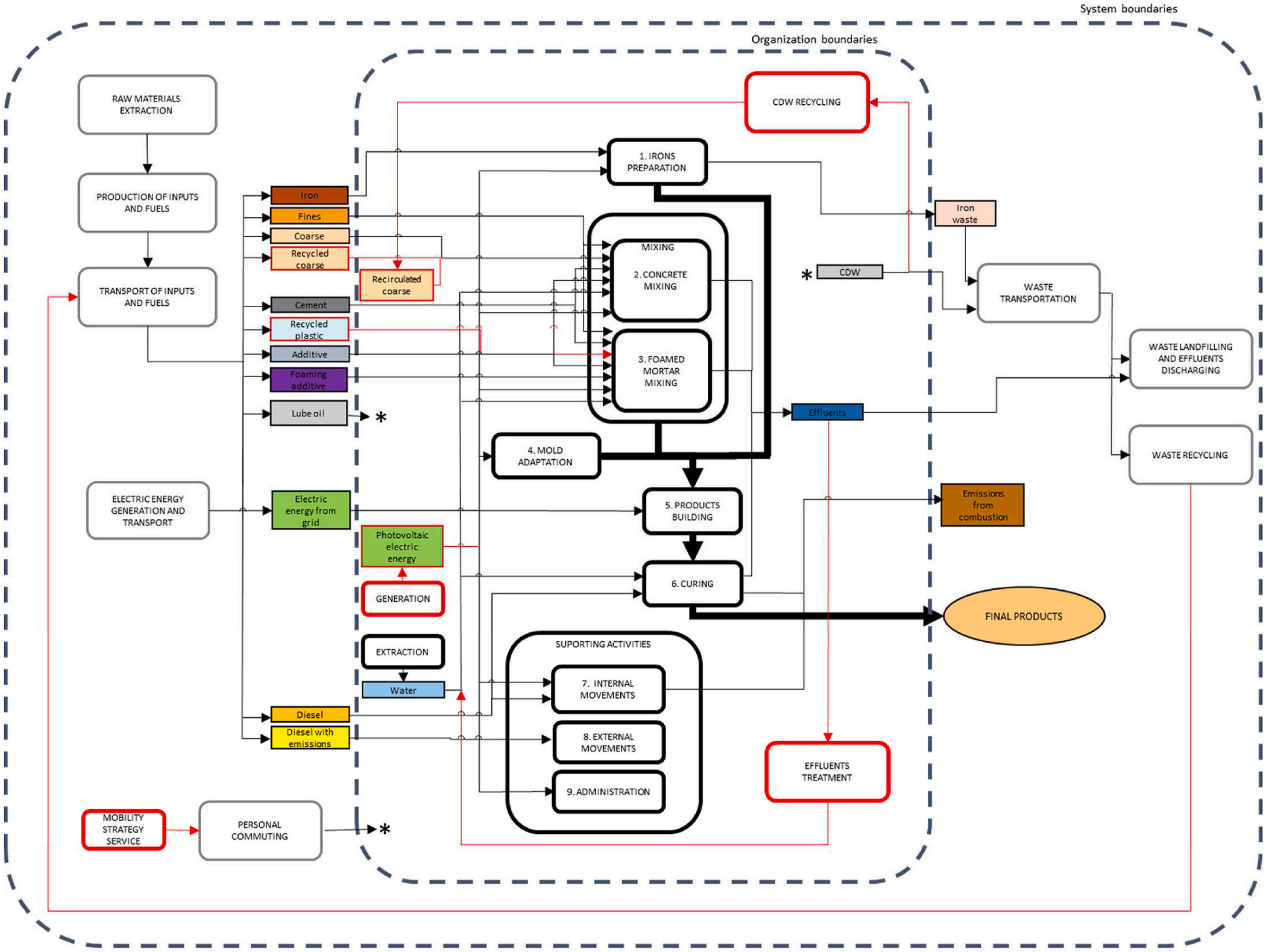
SC2. Waste recycling. Most of the waste derived from the manufacturing process is made up of concrete and mortar, which is currently sent to landfill. However, this waste fraction can be classified as construction and demolition waste (CDW), and taken to an external CDW management facility for recycling. As it is a clean flow, the recycling procedure is simple and only requires a crushing process. A recycling efficiency of 90% and a substitution rate of 1:1 is assumed, in agreement with similar facilities (Mercante, 2014; Mercante et al., 2011).

SC3. Materials recirculation. The in-situ recycling of CDW was proposed. This means that CDW is crushed and used as a secondary coarse to produce new products. Considering the same criteria as in scenario SC1b, only 20% of the total coarse consumption can be replaced by recycled coarse. This amount is significantly lower than the CDW generated, so in any case this scenario needs to send the remaining waste to landfill. A recycling process efficiency of 90% and substitution rate of 1:1 was assumed (Mercante, 2014; Mercante et al., 2011). To carry out this scenario, a small concrete crusher (with a power of 3 HP and a capacity of 2 m^3/h) was assumed to have been acquired.

SC4. Effluent recirculation. Recirculation of effluents from equipment washing and the curing process was proposed. A recovery rate of 50% of water consumed for washing and curing processes was estimated (Sandrolini and Franzoni, 2001). Treated effluents can be employed for the mixing process. A slight reduction in strength and water-cement ratio can be produced due to the use of effluents in the mixing process (Sandrolini and Franzoni, 2001). Both effects were neglected as the volume of recovered effluent is much lower than the water consumed for these processes. To implement this improvement, a channel system for water collection and a treatment facility are required. The curing area already has a slope, and thus only a 20-m channel is necessary for the collection system. The treatment facility was assumed to be composed of a gravitational sedimentation tank with a capacity of 450 l (daily effluent generation) and a pump to transport recovered effluent to the water storage tank of the mixing equipment. A 4″ pump with a power of 4 HP was assumed.

SC5. Curing automation. Today, the curing process is controlled and operated manually. Instead of that, the present scenario suggested an automatic control system. This system uses sensors to acquire humidity and temperature parameters, and activates valves and sprinklers when required. The heaters continue to be activated manually, although the control and alert system is automatic. As a result, a reduction of 50% and 30% of water and fuel consumption, respectively, can be achieved (Yang et al., 2018). The new equipment to implement this improvement is composed of sensors, the circuit board, and a motorized spherical valve.

SC6. Energy efficiency. The present scenario envisages strategies to improve the efficiency of energy consumption and to reduce the use of energy from non-renewable sources. To achieve the first aim, many alternatives for industrial processes (European Comimssion, 2009) and for administration activities (Doty, 2016; Thumann et al., 2003) were analyzed. Improvements to the lighting and cooling systems of the office sector were suggested, since they account for more than 25% of the total energy consumption and also because the industrial equipment already has energy efficiency solutions implemented in it. Installation of photovoltaic sensors for outside lights, replacement of fluorescent lights with LED lights, and replacement of air conditioning equipment with more efficient models were proposed. To reduce non-renewable energy



References
Internal activities and processes of organization are presented in black boxes while external activities and processes that are included in the system boundaries are presented in gray boxes. Input, activities and processes belonging to alternative scenarios are presented in red boxes.
* Input and output not assigned to processes (generic to the complete organization)

Fig. 6. System boundaries.

Table 3
Proposal of alternative CE improvement scenarios.

Alternative scenarios		CE strategies selected
SC1	Use of recycled materials	10 Eco-design.
		11 Design for reduction.
		15 Recycled materials.
		26 Resource and energy efficiency.
SC2	Waste recycling	21 Industrial symbiosis.
		37 Recycling.
SC3	Materials recirculation	19 Material efficiency.
SC4	Effluent recirculation	19 Material efficiency.
SC5	Curing automation	19 Material efficiency.
SC6	Energy efficiency	18 Energy efficiency.
SC7	Nearby suppliers	13 Low impact materials.
SC8	Workers' mobility	2 Collaborative consumption.

consumption, replacing energy provided from the grid (mainly generated from fossil fuels) with energy generated in situ from solar photovoltaic equipment was suggested. It was assumed that 90% of the total consumption would be supplied by solar energy and the remaining 10% from the grid. The equipment needed to achieve this is composed of solar panels, inverters and auxiliary equipment for generating solar energy.

Table 4
New dosage of foamed mortar.

Material	SC0	SC1a
Cement (kg/m3)	350.69	280
Fines (kg/m3)	898.09	815
Water (l/m3)	213	160
Plastic (kg/m3)	0	79.2
Foaming (l/m3)	8.77	7

SC7. Nearby suppliers. In order to reduce raw material transportation in vehicles not owned by the organization, a switch to nearby suppliers was proposed. An alternative cement supplier was suggested. Nearby suppliers of iron, fines and coarse suppliers were not identified in the area.

SC8: Workers' mobility. The present scenario proposed the implementation of a mobility strategy to reduce the effects of employee commuting. To achieve this, alternative methods of transport such as bicycles, public transport and carpooling (Vanoutrive et al., 2012) are encouraged. To put this into practice, the use of a platform to evaluate and distribute incentives according to the reduction in individual commuting was proposed. The platform is based on a cell phone application (Ciclogreen, 2021). A 30% reduction in total employee

Table 5
CE indicator for baseline scenario (SC0) and percentage of improvement of each alternative scenario (SC1 – SC8).

	CE Indicators (Table 1)																							
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
CE indicators for the Baseline scenario (absolute value)																								
SC0	0	0	0	0	0	1	0	1	0	0	0	0	2508 t	432 m^3	40872 kWh	0%	31 m^3	0%	338 t	0.6%	9 m^3	337 t CO_2eq	135000 ARS	0
Percentage of improvement of each CE indicator for each alternative scenario (SC1 – SC8) with respect to the baseline scenario (SC0) (%)																								
SC1a													0.72					0.76				−0.30	26	
SC1b																		7.63				−0.04		
SC1a + SC1b													0.72					8.33				−0.34	26	
SC2						100														100		−0.26		
SC3													7.54		−0.04			7.58	62.43	63.02		0.06	148	
SC4														50	−0.03						100		30	
SC5														25							100	0.05	37	
SC6															10.22	71.83						4.40	2222	
SC7																	3.23					1.34		
SC8																	25.81					7.65		

commuting was estimated, based on similar experiences in other organizations.

The circularity of each alternative scenario was assessed by applying the circular indicators defined in Table 1. Table 5 reports the percentage of improvement of each circular indicator for each alternative scenario (SC1 – SC8) with respect to the baseline scenario (SC0).

4.3. *Stage 3. Environmental and economic performance of scenarios (baseline and alternative)*

Goal and scope. The aim of this stage was to analyze the environmental and economic performance of the baseline scenario (SC0) and those scenarios that incorporate strategies for improving the circularity of the organization (SC1 – SC8). The reporting unit (UNEP/SETAC Life Cycle Initiative, 2015) was defined for the assessment of the whole organization, which consists of a single facility, so no consolidation approach was needed. The reporting flow was the production corresponding to one year (2020), accounting for 980 m^3 of concrete products and 245 m^3 of mortar products. Regarding the system boundary, a cradle-to-gate approach was proposed and indirect downstream activities were excluded. The system boundary is shown in Fig. 6, where organization unit processes (1–9) are presented in bold black boxes, external processes are presented in gray boxes, and processes of alternative scenarios are shown in red boxes. Input and output flows for each process are presented in colored boxes. Dashed lines are used to differentiate the organization boundary from the system boundary.

Inventory analysis. Using primary data from the organization for 2020, Table 6 reports the quantitative input and output flows, transport distances for raw materials for each scenario (baseline and alternatives) and investment for each alternative scenario. In addition, employee commuting and air travel are considered in the inventory model. Table 7 presents the differentiated inventory models for the environmental and economic analysis. For the environmental inventory model, a cut-off of 1% in production volume was considered. SimaPro 9.1.1 software (PRé Sustainability B. V., 2020) was used to model the environmental inventory, and MS Excel (Microsoft, 2021) was employed for the economic inventory.

Impact assessment. For the *environmental impact assessment*, the method CML-IA baseline V3.05 (CML, 2016) was applied to the case study. Recommended environmental impact categories for construction products were selected according to the guidelines EN 15804:2012 + A1:2013 (CEN, 2014). The results of the environmental effects of alternative scenarios compared to the baseline scenario (SC0) are presented in Fig. 7. Scenarios SC1b and SC2 produce slight increases for all the categories assessed. Scenarios SC1a and SC1 present reductions for EP and increases for the rest of the categories. Both scenarios yield similar results, which means that the effect of SC1b is negligible in comparison to SC1a. The increase in the impacts for SC1 and its sub-scenarios is explained by the fact that they use recycled materials that require previous conditioning processes, which generate environmental impacts. The cause of the increased impact for SC2 is the longer distance involved in transport (for the landfill it is 1 km, and for the recycling plant, 12 km). No modifications to environmental impact were identified for SC4 because this scenario only reduces the water consumption (from a well and with no previous treatment), which is not reflected in the impact assessment method that was selected. Scenarios SC3, SC5, SC6, SC7, and SC8 produce less impact for all the categories assessed. Higher reductions with respect to SC0 were observed for SC8, ADP (reduction of 0.002%), GWP (reduction of 7.65%), ODP (reduction of 11.04%), POCP (reduction of 5.45%), AP (reduction of 6.56%) and EP (reduction of 2.78%).

For the *economic impact assessment*, TAC and PB indicators were calculated according to eq 1–eq (3). All costs were considered in the

Table 6
Input and output flows.

Input/output	unit	SC0	SC1a	SC1b	SC1	SC2	SC3	SC4	SC5	SC6	SC7	SC8	Distance (km)
Fines	t	1099	1079	1099	1079	1099	1099	1099	1099	1099	1099	1099	16
Coarse	t	948	948	758	758	948	758	948	948	948	948	948	16
Cement	t	429	412	429	412	429	429	429	429	429	429	429	260[1]
Recycled plastic	t	0	19	0	19	0	0	0	0	0	0	0	15
Recycled coarse	t	0	0	190	190	0	0	0	0	0	0	0	15
Recirculated coarse	t	0	0	0	0	0	190	0	0	0	0	0	-
Iron	t	32	32	32	32	32	32	32	32	32	32	32	860
Foaming	l	2146	1714	2146	1714	2146	2146	2146	2146	2146	2146	2146	[2]
Lube oil	l	120	120	120	120	120	120	120	120	120	120	120	[2]
Additive	l	1980	1980	1980	1980	1980	1980	1980	1980	1980	1980	1980	[2]
Electricity from grid	kWh	40870	40872	40872	40872	40872	40888	40884	40872	7339	40872	40872	
Electricity from photovoltaic in situ generation	kWh	0	0	0	0	0	0	0	0	29357	0	0	
Diesel with emissions	m^3	21	21	21	21	21	21	21	21	21	21	21	
Diesel	m^3	5	5	5	5	5	5	5	4	5	5	5	
Diesel combustion emissions*	m^3	5	5	5	5	5	5	5	4	5	5	5	
Water	m^3	432	432	432	432	432	432	324	324	432	432	432	
Effluents	l	9000	9000	9000	9000	9000	9000	0	0	9000	9000	9000	
Iron waste recycling	t	2	2	2	2	2	2	2	2	2	2	2	
CDW landfilling	t	336	336	336	336	0	125	336	336	336	336	336	1
CDW recycling	t	0	0	0	0	336	0	0	0	0	0	0	12
Investments (ARS*1000)			35	0	35	0	200	40	50	3000	0	0	

[a] 80 km for SC7.
[b] Excluded by cut-off rule.

Argentinian currency [ARS], as the case study is located in Argentina. In accordance with the European Commission (2006), only nominal costs and discount rate were considered. A discount rate of 10%[1] and a lifetime of 20 years for industrial equipment were assumed. A period of 3 years was used as a reference for the PB period because it is the desirable amount of time needed for an investment to be considered profitable (European Commission, 2006). The effect of the problem of inflation that Argentina is currently undergoing is beyond the scope of this study. Results are presented in Fig. 8. Scenarios SC1a, SC1b, SC3, SC4, SC5 and SC6 produce less TAC than SC0, while SC7 and SC8 show higher TAC than SC0. Lower costs were observed for SC6 (2.5% less TAC than SC0) and higher ones for SC8 (2.2% more than SC0). However, in those results none of the alternative scenarios produce important variations for TAC, so every scenario could plausibly be implemented. In reference to the payback period, scenarios SC1, SC1a, SC2, and SC5 present a PB of less than 3 years. Scenarios SC3 and SC6 produce payback in more than 3 years. It was not possible to calculate this indicator for scenarios SC1b, SC4, SC7, and SC8 because they do not generate NAS, and therefore initial investment cannot be recovered.

4.4. Stage 4. Eco-efficiency analysis of alternative scenarios

Eco-efficiency diagrams were built, following the methodology described in section 3 (stage 4 and Fig. 4), for all the alternative scenarios by combining the two economic indicators (TAC and PB) for the seven environmental impact assessment categories. Results are shown in Fig. 9. For the TAC graphs, the position of area division lines was defined using the SC0 position on both axes. This means that an alternative scenario has good environmental and/or economic performance if it improves the SC0 situation and bad performance if it deteriorates the SC0 situation. For the PB graphs, the vertical axis (environmental indicators) is divided in the same way, but the horizontal axis (PB) is divided by the desirable period (3 years).

To facilitate the interpretation of the eco-efficiency graphs, the results are summarized in Table 8, where the scenarios are classified by the four eco-efficiency areas for each combination of indicators. No scenario is located in the lower eco-efficiency area (area IV). Scenarios SC4, SC7, and SC8 are located in the area of good environmental performance but bad economic performance (area III). SC2 is situated in area II, with good economic performance but bad environmental performance. SC1 is located in area II, except for one environmental indicator (EP), which is in area I. Scenarios SC3 and SC6 fluctuate between area I for the TAC graphs and area III for the PB graphs. In other words, these scenarios improve environmental performance and reduce total annual costs, but their payback period is higher than 3 years. Finally, SC5 is situated in the maximum eco-efficiency area, and so it is the best alternative scenario.

5. Discussion

In this section the main contributions, limitations, and future developments of the proposed methodology are discussed, along with the implications of the results obtained from the case study.

The methodology is general and makes it possible to select potential CE strategies that an industrial organization could apply, taking into account its context and stakeholders. In this line, Pauliuk (2018) highlighted the active engagement of industrial organizations as a requirement for the transition toward the CE. In addition, the proposed methodology integrates the joint evaluation of the selected strategies through CE indicators and eco-efficiency indicators. Until now the two approaches were assessed separately, and mainly focused on the environmental performance (Peña et al., 2021).

In addition, the proposed methodology presents the first approach of the O-LCC framework, built on the basis of the LCC framework (Hunkeler et al., 2008; Swarr et al., 2011) and with the inclusion of similar adaptations to those required when the O-LCA framework was established from the LCA framework. As an improvement on the approaches used by Ibáñez-Forés et al. (2013) and Mangili and Prata (2020), the proposed methodology allows the CE strategies in an industrial organization to be evaluated according to eco-efficiency criteria and taking a life cycle perspective through the joint application of the O-LCA and O-LCC frameworks.

The main limitation of the methodology is that social impacts were not included in the assessment. Future work should be carried out to integrate the three pillars of sustainability (environmental, social, and economic) when CE strategies are analyzed and prioritized. For this purpose, partial order algorithms (Arcagni et al., 2021) or operation research methods, such as those identified by Alejandrino et al. (2021), could be applied. Many authors (Acerbi and Taisch, 2020; Moreau et al., 2017; Vinante et al., 2021) agree on the importance of evaluating the

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[1] https://datos.bancomundial.org/indicator/FR.INR.RINR.

Table 7
Environmental and Economic inventory model.

			ENVIRONMENTAL INVENTORY MODEL		ECONOMIC INVENTORY MODEL	
ACTIVITY		INPUT/OUTPUT	Data source	Reference	Cost	Data source
Upstream activities	Raw materials and goods purchased.	Fines	Average measurements from local quarries	Mercante (2014)	0.36 ARS/kg	Suppliers (measure)
		Coarse	Average measurements from local quarries	Mercante (2014)	0.16 ARS/kg	Suppliers (measure)
		Cement	Database. Adapted to Argentinian electric mix	CAMMESA (2020). Ecoinvent (2020)	11.40 ARS/kg	Suppliers (measure)
		Recycled plastic	Direct measurement on supplier facility	Alejandrino et al. (2019)	9.25 ARS/kg	Suppliers (estimate)
		Recycled coarse	Direct measure in similar technology facility	Mercante (2014)	0.16 ARS/kg	Suppliers (estimate)
		Iron	Database. Adapted to Argentinian electric mix	CAMMESA (2020). Ecoinvent (2020)	93.51 ARS/kg	Suppliers (measure)
		Foaming	Excluded by cut-off rule		350.00 ARS/l	Suppliers (measure)
		Lube oil	Excluded by cut-off rule		475.00 ARS/l	Suppliers (measure)
		Additive	Excluded by cut-off rule		66.00 ARS/kg	Suppliers (measure)
	Electric energy purchased.	From grid	Database. Adaptation to Argentinian electric mix	CAMMESA (2020). Ecoinvent (2020)	76888.02 ARS/month	Estimation based on fixed and variable costs
		From grid SC6			61959.42 ARS/month	
		From photovoltaic			Maintenance costs excluded	
	Fuels purchased.	Diesel	Database. Adaptation to Argentinian electric mix	CAMMESA (2020). Ecoinvent (2020)	51.34 ARS/l	Direct measurements from suppliers
	Disposal and treatment of solid waste, outside the organization.	Iron waste recycling	Database	Ecoinvent (2020)	−4.00 ARS/kg	Supplier (measure) Transport included
		CDW landfilling	Average measurements from local landfills	Mercante (2014). Mercante et al. (2011)	0.21 ARS/kg	Supplier (measure) Transport included
		CDW recycling	Direct measurement on similar technology facility	Mercante (2014). Mercante et al. (2011)	0.00 ARS/kg	Estimate from similar facilities in Argentina
	Transportation of materials and waste in vehicles not owned by the organization.	Cement Fines Coarse Iron Recycled plastic Recycled coarse Iron waste recycling CDW landfilling	Direct measurement of suppliers	Mercante (2014). Mercante et al. (2011). Alejandrino et al. (2019)	Transport costs included in materials and goods costs, and in CDW landfilling costs.	
		CDW recycling			0.01 ARS/kg	Suppliers (estimate)
	Employee commuting and organization personnel travel in vehicles not owned by the organization.	Air travel	Database	Ecoinvent (2020)	4000.00 ARS/travel	Suppliers (measure)
		Employee commuting	Database	Ecoinvent (2020)	13.28 ARS/km	Suppliers (measure)
Direct activities	Employee commuting and transportation of materials in vehicles owned by the organization.	Petrol	Database. Adaptation to Argentinian electric mix	CAMMESA (2020). Ecoinvent (2020)	Excluded for O-LCC	
	Generation of energy resulting from combustion of fuels in stationary sources.	Diesel combustion emissions	Database.	Ecoinvent (2020)	Excluded for O-LCC	
	Consumption of natural resources.	Water	Database	Ecoinvent (2020)	60000.00 ARS/month	Supplier (measure) Fixed cost

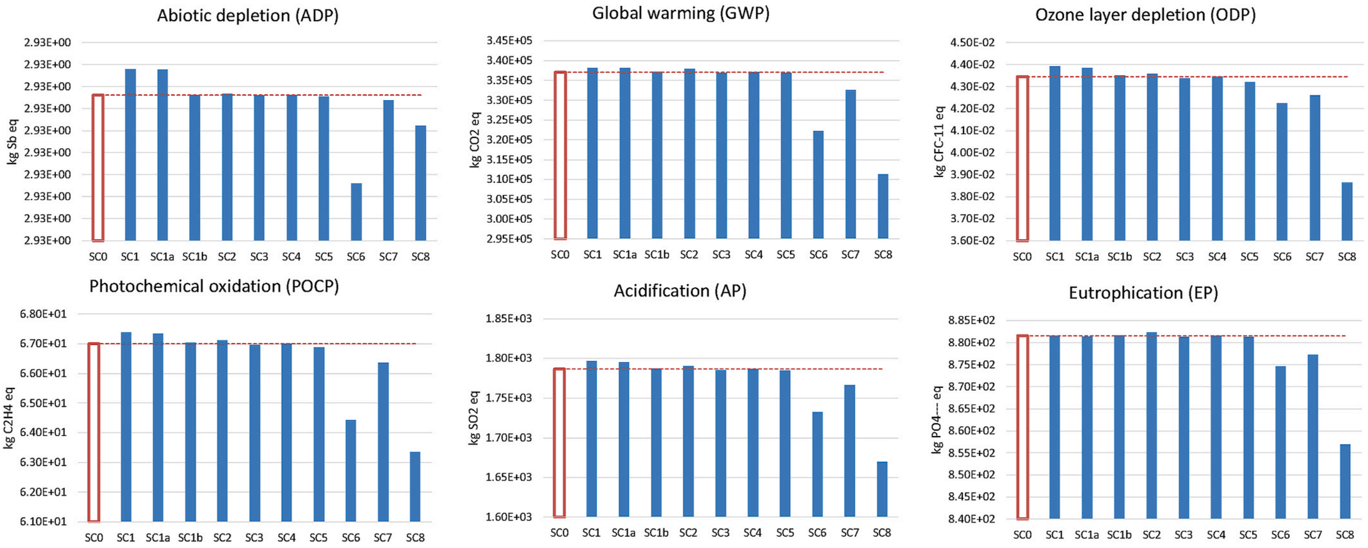

Fig. 7. Comparison of total environmental impacts of the alternative scenarios.

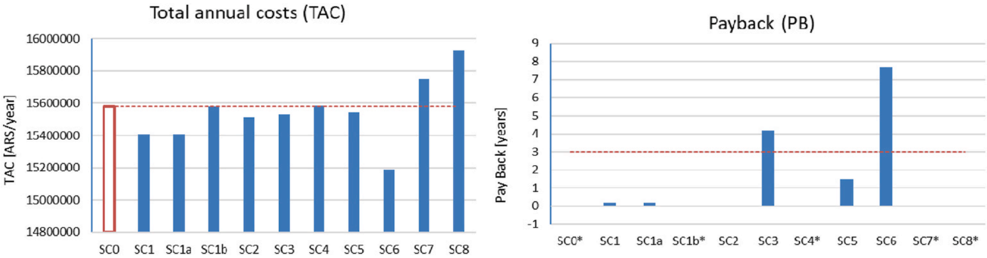

Fig. 8. Comparison of total economic impacts of the alternative scenarios. (*) Not possible to calculate PB.

social impacts that CE strategies could produce on the organization's stakeholders. As an example, certain strategies could reduce the work of some suppliers or increase the workers' labor load. Social life cycle assessments of organizations (SO-LCA) (Martínez-Blanco et al., 2015b; UNEP, 2020) could be combined with the methodology presented in this paper to establish the bases of organizational life cycle sustainability assessment (O-LCSA).

Regarding the results obtained from the case study, the following aspects can be highlighted, depending on the stage of the methodology.

With reference to stage 1, as a recommendation, circular metrics have to be carefully selected taking into account the activity and context of the organization in order to effectively identify the key points of improvements due to the lack of consensus on the CE indicators (Vinante et al., 2021).

The selection of CE strategies (stage 2) is based on four activities: identification of key points for improving the CE performance of the organization, review of high relevance references, participatory procedure for identifying final strategies that are suitable for the organization, and quantitative check that the strategies selected do indeed improve the CE performance of the organization. The authors believe that these dynamic and interactive activities achieve the equilibrium needed to obtain a final set of CE improvements that are complete and well suited to the organization analyzed. In the case study, strategies mainly related to resource efficiency and cleaner production were obtained after the selection process (Table 3). The organization's stakeholders preferred these strategies due to the incipient technology and CE experience of the organization, as well as the characteristics of the products manufactured and the market. The only strategy outside this topic was the collaborative consumption (mobility of workers). The authors believe that future case studies could help to overcome this limitation.

Regarding the combined O-LCA and O-LCC framework (stage 3), environmental indicators were selected due to them having been recommended for the environmental product declaration of construction products (ISO, 2017), although none of them reflect the impact of water consumption from a well and the reduction in the water consumption in alternative scenario SC4 does not affect any environmental indicator. The use of the CE metrics (Table 1) prevents underestimation of the water consumption. Both environmental and economic effects produced by alternative scenarios were quite moderate. The maximum reductions achieved were 11% for ODP (SC8) and 2.5% for TAC (SC6). Yet, these results are meaningful in absolute values because the organizational perspective takes into account all the impacts and costs of the entire organization from a life-cycle perspective. A deeper analysis reveals that of all the alternative scenarios, only the pairs SC2–SC3 and SC4–SC5 are mutually exclusive, while the rest could be implemented at the same time. Combinations of alternative scenarios are possible, and indeed recommended by Acerbi and Taisch (2020). Some combinations could improve environmental and economic performance in a significant way. For example, reductions in environmental impacts of around 15% could be achieved if SC1, SC3, SC5, SC6, SC7, and SC8 were implemented. A saving of around 5% of the total annual costs could be achieved if SC1, SC2, SC3, SC5, and SC6 were combined. However, a complete analysis of the combinations of alternative scenarios is beyond the scope of this paper.

A limitation is identified in the graphical presentation of the eco-efficiency results (stage 4) in Fig. 9 due to the difficulty in interpreting the results of all the impact categories. This fact has been overcome by using the summary presented in Table 8, which allows each scenario to be classified according to the four eco-efficiency areas that have been defined and to present the results in a simplified way. Despite its usefulness, this table does not show any differences between scenarios

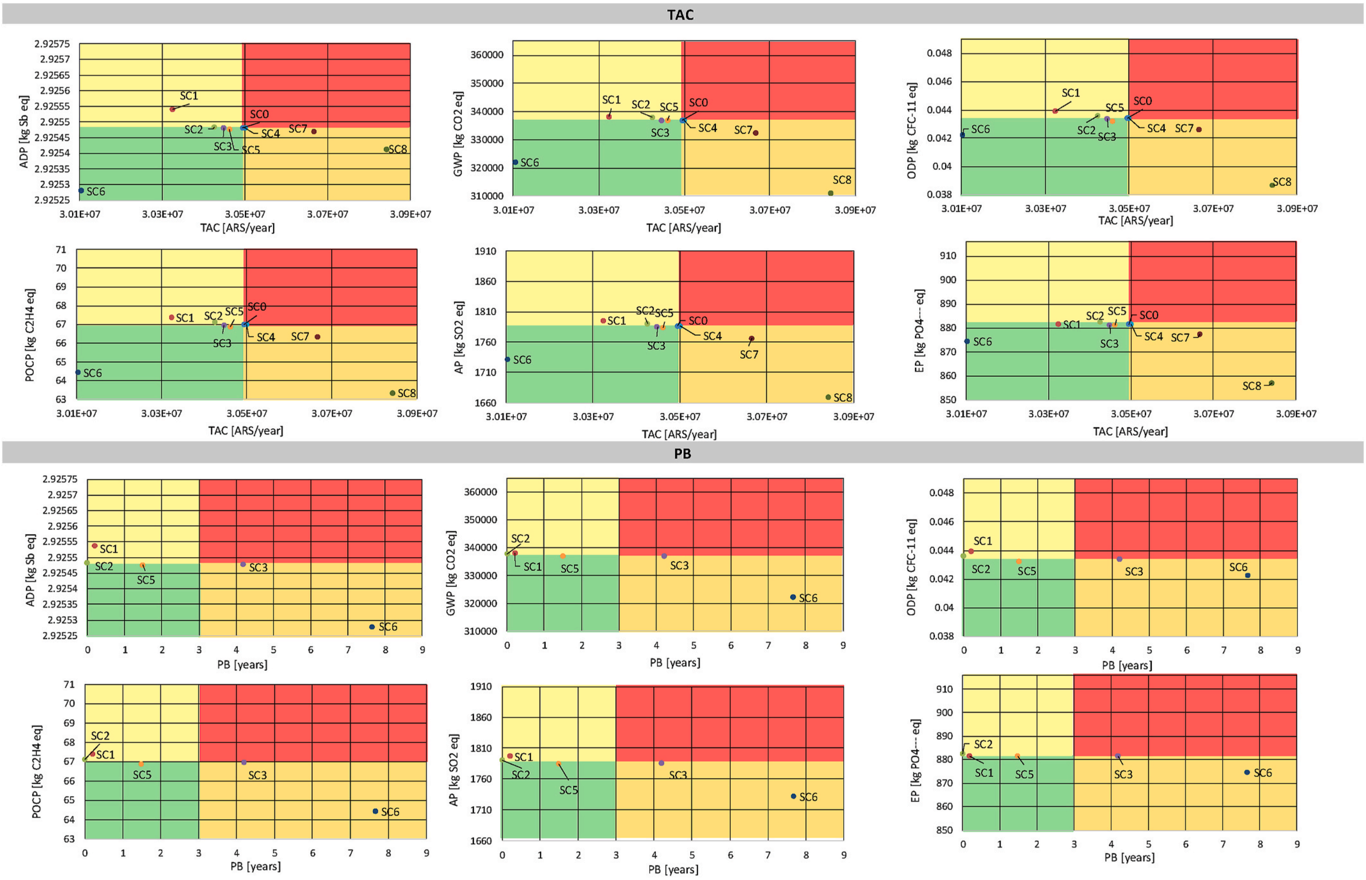

Fig. 9. Eco-efficiency graphs.

Table 8

Summary of eco-efficiency graphs.

CI	EI	SC1	SC2	SC3	SC4	SC5	SC6	SC7	SC8
ADP	TAC	II	II	I	III	I	I	III	III
	PB	II	II	III		I	III		
GWP	TAC	II	II	I	III	I	I	III	III
	PB	II	II	III		I	III		
ODP	TAC	II	II	I	III	I	I	III	III
	PB	II	II	III		I	III		
POCP	TAC	II	II	I	III	I	I	III	III
	PB	II	II	III		I	III		
AP	TAC	II	II	I	III	I	I	III	III
	PB	II	II	III		I	III		
EP	TAC	I	II	I	III	I	I	III	III
	PB	I	II	III		I	III		

located in the same area. Eco-efficiency graphs make it possible to appreciate that information, although they are more difficult to interpret. The use of end-point environmental impact assessment methods, instead of the mid-point method applied (CML, 2016), could facilitate the decision-making process, although it is not recommended by ISO (2006a,b).

6. Conclusions

This study proposes and applies a methodology capable of evaluating and prioritizing CE strategies at the organizational level based on CE indicators and eco-efficiency (environmental and economic) indicators, with the active participation of stakeholders. The main contribution of the present work is the proposal of a methodology built on the integration of the existing O-LCA framework and a proposed O-LCC framework, and its application to the real case study of an industrial organization in the construction materials sector in order to validate its applicability.

The CE indicators made it possible to identify the most suitable strategies for each organization, while the eco-efficiency indicators allowed them to be prioritized. The life cycle perspective of the O-LCA and the O-LCC frameworks proposed herein was essential to extend the assessment along the value chain. The organizational approach selected for the study allowed us to analyze the organization in an integrated way, which is important in CE, as many strategies involve the whole organization and not just the products it manufactures.

It can be concluded that the proposed methodology is a support tool for the effective and efficient transition of industrial organizations toward the CE. A future avenue of research would be to expand the proposed methodology by including the assessment of the social impact of CE strategies, which is essential to achieve sustainable development. The application of the methodology was illustrated by a case study of an Argentinian organization dedicated to manufacturing construction products. Most of the data used were primary data, which is an added value of the present paper. Results showed that all alternative scenarios were beneficial from a CE perspective, but the environmental and economic effects showed mixed outcomes. The authors believe that more case studies could improve the proposed methodology and the knowledge of CE integration into industrial organizations in their daily activities. A large-scale application of the proposed approach to industrial organizations could also contribute to sustainable development.

CRediT authorship contribution statement

Clarisa Alejandrino: Conceptualization, and, Methodology, data acquisition, and, Data curation, Investigation, Formal analysis, Writing – original draft, Writing – review & editing. **Irma T. Mercante:** Conceptualization, and, Methodology, data acquisition, Supervision, Writing – review & editing. **María D. Bovea:** Funding acquisition, Project administration, Conceptualization, and, Methodology, Supervision, Writing – review & editing.

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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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2022.130365.

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