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Prioritising organisational circular economy strategies by applying the partial order set theory: Tool and case study

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ABSTRACT

This study presents a methodology to solve circular economy multiple indicators system decision-making problems by applying the Partial Order Set Theory (POSET). To this end, a user-friendly tool was developed to allow the prioritisation of alternative scenarios or circularity strategies based on the value that each of them takes for different circular economy indicators (both quantitative and qualitative), but avoiding processes involving aggregation and weight among the indicators. The developed tool also makes it possible to model different restrictions that facilitate its adaptation to any case study and the incorporation of the results into the decision-making process. Moreover, it allows a graphical representation of the results to be obtained by using Hasse diagrams. Finally, the developed tool was validated by means of its application to a case study with the aim of prioritising circular economy strategies in an organisation belonging to the construction sector. Specifically, this organisation presented some opportunities for improvement, mainly related to the use of recycled and recirculated materials and effluents, waste recycling, energy efficiency and the proximity of suppliers, among others. The sensitivity analysis of the considered restrictions showed not only the robustness of the results obtained with the tool but also its great influence in circular economy multiple indicators decision-making solutions.

1. Introduction

The transition to a Circular Economy (CE) provides opportunities for a better use of resources and for promoting sustainable growth (The Ellen MacArthur Foundation, 2012). In this framework, organisations play a critical role (Pauliuk, 2018) both in promoting circular and sustainable production that ensures the prevention of waste and the maintenance of resources in the economy for as long as possible and in fostering circular and sustainable consumption (European Commission, 2020). Hence, numerous strategies for industrial organisations have been proposed to achieve a transition to a CE (Acerbi and Taisch, 2020).

However, assessing and prioritising the most suitable CE strategies for each organisation involves complex decision-making processes with numerous indicators that have to be evaluated for each alternative (Vinante et al., 2021). These processes are known as Multiple Indicator Systems (MIS) (Brüggemann and Carlsen, 2014).

The analysis and presentation of the results are essential to facilitate the decision-making process when applying MIS. In this line, the aggregation of the MIS, after normalisation and weighting of indicators, is the most widely disseminated analysis and presentation approach because it is simple to use and easy to understand (Alejandrino et al., 2021). This aggregation approach includes Multi-Criteria Decision-Making (MCDM) methods that make it possible to evaluate a finite set of alternatives based on multiple criteria, which have been widely used in the literature (Thies et al., 2019). MCDM range from the use of weighted averages of indicators to more complex methods such as AHP (Analytic Hierarchy Process) (Saaty, 1980), ELECTRE (ELimination Et Choix Traduisant la REalité) (Gal and Hanne, 1999) or PROMETHEE (Preference Ranking Organization METHod for Enrichment of Evaluations) (Brans and Vincke, 1985). The first, AHP, assigns weights for each element through pairwise comparisons based on quantifying verbal descriptions of preference among alternatives, and the importance among attributes is considered (Simon et al., 2004a). In ELECTRE, concordance and discordance matrices are built to determine the order

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of alternatives, and these matrices determine the strengths and weaknesses of alternatives based on the considered attributes. In PROMETHEE, the order is obtained through the calculation of positive and negative outranking flows (Thies et al., 2019). However, aggregation approaches have been broadly questioned due to the high uncertainty and subjectivity associated to the normalisation and weighting processes (Brüggemann et al., 2006; Badinger and Reuter, 2015; Arcagni et al., 2021).

The Partial Order Set Theory (POSET) presents an alternative approach to solving MIS that avoids the need to apply normalisation and weighting techniques (Fattore et al., 2011). This theory is based on concepts of discrete mathematics (Pavan and Todeschini, 2004) and aims to order elements (alternatives), based on different criteria (indicators), by pair-wise comparison and minimising subjective interventions (Fattore et al., 2012). As a result, it allows a partial order of the alternatives to be obtained instead of a total order of them, since elements that present better values for some indicators but worse for others are considered to be incomparable (Brüggemann and Carlsen, 2014).

The application of POSET presents some important advantages. First, it allows the use of all available information for each alternative. So no alternative has to be excluded if there is a missing value for one indicator (Badinger and Reuter, 2015). Second, it reduces the subjectivity of normalisation and weighting processes (Brüggemann et al., 2008; Alaimo et al., 2020a) and makes it possible to compare indicators of different natures (qualitative or quantitative), different units or with different value scales (Carlsen, 2021). Third, it allows the relationship between two alternatives to be analysed in depth to determine whether they are comparable or incomparable and which indicators cause this relationship (Arcagni et al., 2021).

Numerous studies have compared the use of POSET to other methods of solving MIS aggregation. Beycan et al. (2019) compared POSET with the method proposed by Alkire and Foster (2007) for computing the Multidimensional Poverty Index. Simon et al. (2004b) performed a comparison between PROMETHEE and and Carlsen and Brüggemann (2013) analysed POSET in comparison to weighted aggregation. In general, these studies conclude that POSET allows more information to be obtained from data and solves the main problems of the aggregation approach. This study presents a design tool developed to solve circular economy MIS decision-making problem by applying POSET theory. This tool includes a set of functionalities that allow it to be adapted to the different specificities of any application case. Moreover, it makes it possible to obtain a graphical representation of the results, which facilitates their interpretation and incorporation into the decision-making process. Finally, the tool was applied to a practical case study, where POSET was used to prioritise CE strategies in an organisation belonging to the construction sector.

The paper is arranged as follows. First, section 2 presents the literature review focused on case studies applying and/or prioritising CE strategies in the industrial organisations (IO) context and case studies applying POSET to solve MIS problems. Then, section 3 introduces the methodological process structured in two main blocks (software and the experimental design). Section 4 presents the results that are discussed in section 5. Finally, conclusions are presented in section 6.

2. Background

A literature review was carried out from two different perspectives (Fig. 1). The first focused on studies whose objective was to analyse and/or prioritise CE strategies in the context of IO with the aim of identifying the method applied to prioritise them. And the second focused on studies whose objective was to apply POSET to solve MIS in applied sciences with the aim of identifying the main characteristics and requirements of each case study and the tools applied. This made it possible to identify the research gap developed in this study, as Fig. 1 shows.

Table 1 presents the case studies that analysed CE strategies in the IO context. The 37 CE strategies found were classified according to the categories proposed by Ibáñez-Forés et al. (2022) (business model, design, material sourcing, manufacturing, distribution and sale, consumption and use, reverse logistic and end-of-life valorisation). In addition, the number and type of indicators and the method applied for prioritising the CE strategies was identified. The number of indicators ranged from 1 to 24, depending on the case study, and were mostly qualitative. Only four of the case studies prioritise the CE strategies, the most common techniques applied being MCDM such as AHP. None of them applied POSET for selecting the best CE strategy or for prioritising them.

In addition to these case studies, various reviews can be found in the literature that are also focused on identifying circularity strategies for organisations. Regarding the prioritisation of strategies, Acerbi and Taisch (2020) explored the application of MCDM and Multi objective decision making (MODM), while Diaz et al. (2021) only analysed MCDM. For their part, GitLab (2021) proposed a methodology that combines AHP and Technique for Order of Preference by Similarity to

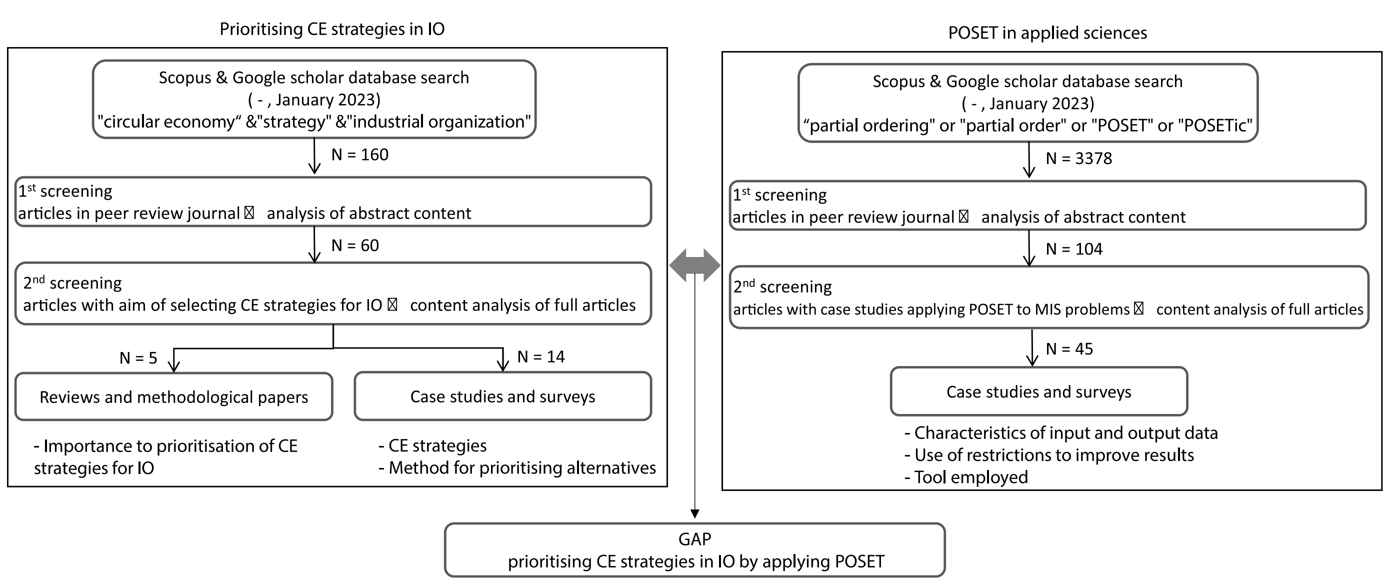


Fig. 1. Literature review procedure.

Table 1
Literature review of case studies analysing and/or prioritising CE strategies in IO (Appolloni et al., 2022; Chowdhury et al., 2022; Kowalski and Makara, 2021; Kristensen et al., 2021; Lahane and Kant, 2022; Nudurupati et al., 2022; Sousa-Zomer et al., 2018; Svensson and Funck, 2019; Trigkas et al., 2020).

Reference	CE strategies																																					Indicators			Method for prioritising strategies
	Design									Inputs					Production				Business				Outputs													Communication					
	Design for disassembly	Design for modularity	Design for durability	Design for flexibility	Eco-design	Design for reduction	Design for repair	Design for recycling	Efficient packaging	Low impact materials	Abundant/renewable	Recycled materials	Bio-based materials	Non-harmful substances	Energy efficiency	Material efficiency	Tracking, tracing and	Industrial symbiosis	Customisation/on demand	Sharing/collaborative	Product-service systems	Dematerialisation	Resource and energy	Re-use	Upgrading	Maintenance	Repair	Incentivised return	Infrastructure	Separate collection	Refurbishment	Remanufacture	Recycling	Energy recovery	Composting	Product labelling	Digital information	#	Quantitative	Qualitative	
(Alejandrino et al., 2022)					•	•				•		•			•	•		•		•			•															24	x		graphical analysis
(Appolloni et al., 2022)												•			•		•		•					•									•					9	x		MCDM
(Chowdhury et al., 2022)					•							•												•														5		•	n/a
(Diaz et al., 2021)	•	•	•				•	•									•				•		•	•		•	•	•			•	•	•	•				10		•	MCDM
(Elia et al., 2020)			•								•				•	•																						3	•		n/a
(Ertz et al., 2019)			•				•													•	•				•	•	•	•	•		•	•					•	n/a			n/a
(Herczeg et al., 2018)																		•																				n/a			n/a
(Kowalski and Makara, 2021)			•				•		•						•	•	•	•			•			•	•	•	•	•	•		•	•	•					3		•	n/a
(Kristensen et al., 2021)	•		•	•			•				•	•		•	•	•	•	•			•	•	•	•				•				•					•	1		•	n/a
(Lahane and Kant, 2022)						•				•								•						•					•		•	•	•			•	•	12		•	PF-AHP[2], PF-CODAS[3]
(Nudurupati et al., 2022)			•		•		•	•		•	•				•	•							•		•													1		•	n/a
(Svensson and Funck, 2019)												•			•	•				•	•				•		•					•	•					n/a			n/a
(Sousa-Zomer et al., 2018)			•		•	•	•	•		•	•		•	•	•	•	•						•						•									15	n/a		n/a
(Trigkas et al., 2020)		•			•					•	•				•	•		•		•				•			•					•	•	•	•			1		•	n/a

Ideal Solution (TOPSIS). The other reviews analysed also agreed on the importance of prioritising CE strategies for industrial organisations, although they did not further analyse any specific method (Kalmykova et al., 2018; Lopes de Sousa Jabbour et al., 2019).

From the perspective of case studies that applied POSET to solve MIS in applied sciences, 45 case studies were identified in the literature, none of them focused on circular economy. Main characteristics and the software applied for the analysis are detailed in Table 2 and described below.

The following aspects were analysed for each case study.

- **Input data.** The number of alternatives to be ordered and the number of indicators for each one of them in each case study were counted. Large variations in the number of alternatives (from 7 to 8000) and the number of indicators (from 2 to 20) were identified, since POSET is a powerful tool for a wide range of problems. In addition, indicators were classified as being either quantitative or qualitative. The majority of indicators identified were quantitative (65%). An analysis was also performed to determine whether the best alternative for all indicators was achieved with the maximum or minimum value for all of them or if, on the contrary, for some indicator it was achieved with the maximum value and with the minimum value for others, which means that there is no common criterion for all the indicators. In this line, a high degree of variability was found, since 38% of the studies used the same criteria (to minimise or to maximise) for all the indicators, 29% did not use any common criteria for all the indicators, while the remaining studies did not specify that fact (33%). It was also seen that when there are no common criteria, some studies needed to perform a previous treatment of the dataset before applying POSET (e.g. Alaimo et al. (2020a), Batunacun et al. (2019), Carlsen and Brüggemann et al. (2021)) in order to unify the criteria for all the indicators in the set, either to minimum or to maximum.
- **Restrictions.** Some of the case studies analysed (22%) applied restrictions to improve the achievement of partial order and to obtain useful information for the decision-making process (Brüggemann and Voigt, 2011). The most common restrictions identified were the use of limit values that prioritise or exclude some alternatives (11%) and the management of data uncertainty in order to dismiss non-significant differences between two alternatives (11%) by applying fuzzy approaches or establishing significant differences (Carlsen et al., 2018).
- **Output.** Most of the case studies analysed presented their results based on graphical representation using Hasse diagrams (82%). The use of sensitivity analysis to study the effect of each indicator in the POSET was also considered in 31% of the studies reviewed. Finally, an assessment to identify the causes of the incomparability of alternatives, which Carlsen and Brüggemann (2017) called peculiarity analysis, was identified in 11% of the case studies analysed.

Regarding the tools/software used to apply POSET, the following were identified: Pyhasse (or Whasse, the previous version) (62%), Parsec (16%), BASIC (2.2%) and Python (2.2%). The remaining case studies did not mention it. Table 3 reports the main characteristics of each tool, in line with the requirements identified from the case studies analysed.

Table 2
Literature review of case studies applying POSET.

Case study	Input data						Restrictions		Output data/Result			Code/package or Tool				
	# elements	# indicators	Indicator Characterisation													
			Quantitative	Qualitative	Uniform best option[a]	Non-uniform best option[b]	Limit value	Data Uncertainty management	Graphic results	Indicator's Sensitivity Analysis	Peculiarity analysis	PyHasse/Whasse	Parsec package	Basic code	Python code	N/A
Halfon and Reggiani (1986)	34	7	●			●			●	●				●		
Brüggemann and Voigt (1995)	15	5	●		●				●							●
Brüggemann et al. (1999)	59	4	●		●		●		●			●				
Brüggemann et al. (2001)	20	5		●	N/A				●	●		●				
Carlsen et al. (2001)	46	3	●		●				●			●				
Lerche et al. (2002)	85	4	●		●				●							●
Voigt et al et al. (2004)	15	5		●	●				●	●		●				
Simon et al. (2004b; 2004a)	9	4	●	●	●				●			●				
Lerche et al. (2004)	107	2		●	N/A				●			●				
Kardaetz et al. (2008)	8	6	●	●		●	●		●			●				
Carlsen et al. (2009)	17	4			N/A				●			●				
Annoni and Brüggemann (2009)	15	18		●	●				●							●
Brüggemann et al. (2011)	18	3	●			●		●	●			●				
Brüggemann and Carlsen (2011)	13	4	●		N/A				●			●				
Brüggemann and Voigt (2011)	19	3		●	●				●			●				
Carlsen et al. (2013)	30	6	●		N/A				●	●		●				
Voigt et al. (2013)	65	20			N/A				●			●				
Carlsen and Brüggemann (2013)	177	12	●		●				●	●		●				
Fattore et al. (2014)	262	5	N/A		N/A				●				●			
Brüggemann and Carlsen (2014)	12	3	●			●			●		●	●				
Annoni et al. (2015)	88	3	●		●			●	●			●				

(continued on next page)

Table 2 (*continued*)

Case study	Input data						Restrictions		Output data/Result			Code/package or Tool				
	# elements	# indicators	Indicator Characterisation													
			Quantitative	Qualitative	Uniform best option[a]	Non-uniform best option[b]	Limit value	Data Uncertainty management	Graphic results	Indicator's Sensitivity Analysis	Peculiarity analysis	PyHasse/ Whasse	Parsec package	Basic code	Python code	N/ A
Badinger and Reuter (2015)	81	7		●	N/A											●
Carlsen (2015)	7	3	●		●				●			●				
Carlsen and Brüggemann (2017	178	12	●		●					●	●	●				
Lenfers et al. (2017)	14	11	●			●	●	●	●	●		●				
Iglesias et al. (2017)	4064	4		●	N/A		●						●			
Carlsen (2017)	28	4	●			●			●	●		●				
Carlsen (2018)	157	7	●		N/A				●	●	●	●				
Carlsen et al. (2018)	20	5	●		●			●	●	●	●	●				
Di Brisco and Farina (2018)	16	3		●	●								●			
Arcagni et al. (2019)	4000	8	●	●	N/A								●			
Beycan et al. (2019)	30	10		●	●		●		●			●				
Batunacun et al. (2019)	12	9	●			●			●						●	
Carlsen and Brüggemann (2020)	33	8	●		N/A				●	●		●				
Carlsen (2020)	162	4	●			●				●	●	●				
Alaimo et al. (2021)	20	4		●	N/A				●							●
Ivaldi et al. (2020)	32	4		●	●				●				●			
Alaimo et al. (2020a)	20	–	●			●			●							●
Alaimo et al. (2020b)	33	4	●	●		●			●				●			
Rimoldi et al. (2020)	8000	7	●		N/A											●
Arcagni et al. (2021)	103	8		●	N/A			●					●			
Carlsen (2021)	27	4	●			●			●	●		●				
Carlsen and Brüggemann (2021a)	27	6	●			●			●	●		●				
Carlsen and Brüggemann (2021b)	29	6	●			●			●			●				
Alaimo et al. (2021)	249	9		●	●				●							●

[a] Different best option criteria (the minimum or maximum) for all the indicators.
[b] At least one different best option criteria (the minimum or maximum) for all the indicators.

Table 3
Tools used in the case studies applying POSET identified in Table 2.

Tools	General		Input		Restrictions		Output			
	# of case studies	Availability	Allows non uniform best option	Allows qualitative variables	Limit values	Data uncertainty	Graphic results	Matrix	Indicators sensitivity analysis	Peculiarity analysis
Web PyHasse version	28	Yes	No	No	No	No	Yes	Yes	Yes	No
Parsec package	7	Yes	No	Yes	No	No	Yes	Yes	No	No
Basic code	1	No	not available							
Python code	1	No								

Pyhasse is a software package that has modules for different functions of POSET. This tool has a reduced web version (Brüggemann et al., 2021) and a full one that has to be requested directly from the developer (Koppatz and Brüggemann, 2017). Parsec (PARtial orders in Socio-EConomics) is a tool for solving MIS problems based on qualitative indicators that allows application of the POSET-based approach and a counting approach through a set of modules. It is available on CRAN (the Comprehensive R Archive Network) (Arcagni and Fattore, 2021). It was not possible to access the BASIC and Python codes.

The main limitations identified in the Pyhasse and Parsec tools were that they do not allow the analysis of datasets with non-uniform criteria in order to identify the best option for each indicator, the definition of limit values to prioritise or exclude some alternatives if they do not fulfil the restriction, the management of data uncertainty through fuzzy approaches or by establishing significant differences, and the possibility of performing peculiarity analyses. An extra limitation of Pyhasse and Parsec is that neither of the tools is user-friendly. This was identified in the assessment of the case studies, since in more of 80% of case studies an expert tools user was needed (Table 2).

On the basis of this background, a research gap was identified, since there were very few studies that prioritised the CE strategies proposed for each case study and, in addition, none of them applied POSET for this end. Taking into account this context, the aim was to design a tool for prioritising organisational circular economy strategies by applying POSET, and to answer the following two main research questions (RQ).

RQ 1. - Is it possible to design an MIS decision-making tool that does not require normalisation and weighting of the CE indicators that is flexible enough to adapt to the idiosyncrasies of different industrial organisations?

RQ 2. - Are the results of the developed MIS decision-making tool robust enough and useful for decision-making processes?

3. Materials and methods

The methodological procedure adopted in this study was based on the four stages shown in Fig. 2 and described below. These stages were grouped into two main blocks: the software and the experimental design.

3.1. Stage I: conceptual design

According to the conclusions from the background, the first stage of the methodology was the conceptual design of the multi-criteria decision tool, in which its requirements and basic characteristics were established. Specifically, the following requirements were defined for the design of the tool.

- Be able to partially order alternatives. To do so, it should be able to compare the alternatives in pairs and consider that one alternative is better than another only if it has a better or equal value in each and every one of the indicators under comparison.
- Allow the use of qualitative and quantitative indicators.
- Allow indication of the best option for each indicator, since the best behaviour for each indicator can be reached at both its maximum and its minimum values.
- Allow the incorporation of the following functionalities in order to obtain useful results for the decision-making process:
  - Be able to specify the significant difference (SD) between the values achieved by each indicator, in order to manage the comparability of alternatives.
  - Be able to enter minimum and/or maximum cut-off values (CuV) to exclude alternatives that do not meet or exceed them.
  - Be able to define critical values (CrV) to consider an alternative as better or worse than the others when they are reached or not exceeded.
  - Be able to specify saturation values (SV) for indicators to consider alternatives that exceed these values as equally good.
- Be capable of obtaining information required to perform peculiarity analyses and to identify which indicators are causing incomparability between alternatives (indicator sensitivity analysis).
- Have a user-friendly interface so that the user can introduce and obtain data in a quick and simple way, without needing to have deep knowledge of POSET or be an expert user of it.
- Allow the creation of an output report that details the output results in a clear and simple way, including matrices and graphic representation of results.

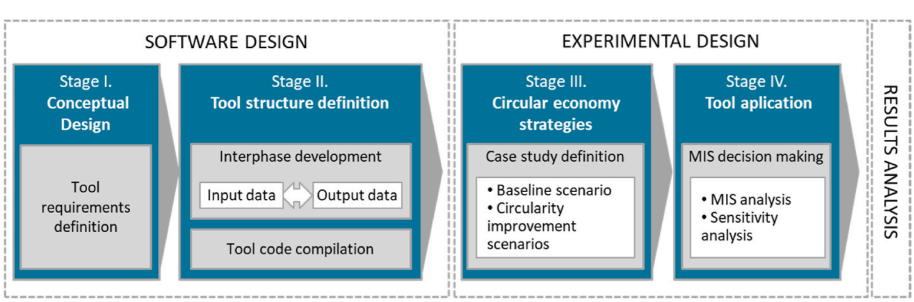


Fig. 2. Methodological process.

3.2. Stage II: tool structure definition

Secondly, the tool structure was developed, in which the overall functioning of the tool was described and compiled, including the establishment of the different modules which make up the tool and the connections between them.

The purpose of the tool was to allow the partial order analyses to be performed using POSET theory and the representation of the results by means of Hasse diagrams. The code was programmed using the interpreter language Python. In addition, the following libraries were used: *Numpy-Pandas* for data reading and processing, *Graphviz* for graphic representation and *Tkinter* for the application interface.

The tool was structured in two main modules, described in detail in the following subsections.

- *Input data*, where the specific information about the value that each alternative takes for each indicator is introduced by the user.
- *Output data*, including a report with two types of output information: *descriptive results* by means of matrices representing the results of the peer comparison of the alternatives, and *graphical results*, represented by means of Hasse diagrams.

As Fig. 3 shows, the tool allows selection of the input data file for each case study and the name of the file including the results after calculation.

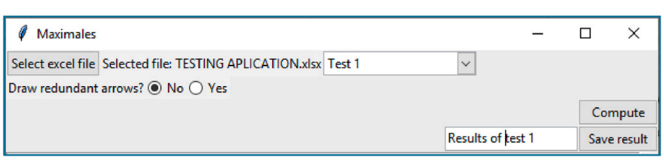


Fig. 3. Screen interface.

3.2.1. Input data

The data entry was made by using an MsExcel file with the template shown in Fig. 4 and described below. This template can be modified by adding/deleting columns, in order to change the number of alternatives to be compared, and by adding/deleting rows to modify the number of indicators for each alternative.

A. Alternatives. Each column represents an element to be compared.
B. Indicators. The following information should be entered:
   . Indicator name
   . **B1.** Unit: unit of measurement of each indicator considered.
   . **B2.** Type: both qualitative (Ql) and quantitative (Qn) indicators are supported by the tool. Qualitative indicators need to be ordinal, otherwise POSET theory cannot be applied and no partial order could be obtained.
   . **B3.** Range: Minimum and maximum values that each indicator can take. They are generally enclosed in square brackets, for example: [-1, 1].
   . **B4.** Best option: It is necessary to specify, for each indicator, whether the best option is reached with its maximum or its minimum value. This feature allows a heterogeneous data input matrix to be analysed without any previous treatment. This was an important gap in the existing tools for solving science-applied MIS problems through POSET theory, as was identified in the background assessment.
C. Functionalities. Optional restrictions/preferences to be established by the user in order to improve the results for decision-making:
   . *Significant difference* (SD). The tool makes it possible to specify, for each indicator, either as an absolute value or as a percentage, the difference in the values that an indicator takes for each alternative above which the alternatives are considered to be the same or different. If the difference between the values that an indicator takes for two alternatives is below this margin, both alternatives are considered equal for the indicator under study.
   . *Cut-off value (CuV)*. The tool allows options that do not reach a given cut-off value to be discarded. This restriction can be for values greater than the value established in indicators to be minimised, or less than the value established in those to be maximised.
   . *Critical value (CrV)*. A critical value (minimum or maximum) can be established and any alternative that does not reach it is considered worse than the rest. This restriction does not rule out alternatives like the previous one, but places them lower in the order of priority.
   . *Saturation value (SV)*. This restriction allows a limit value to be set for an indicator beyond which all alternatives that exceed it will be considered equally good.
D. Value that each indicator takes for each alternative.

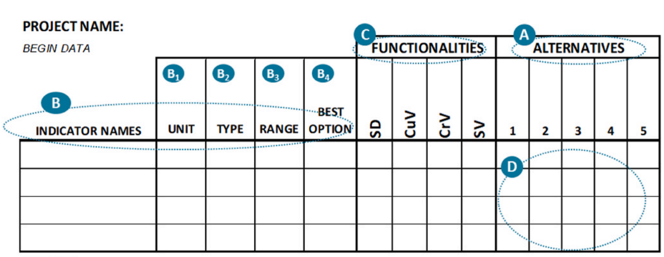


Fig. 4. Data input template.

3.2.2. Output data

The results were planned to be reported by means of an output report that included them in two different formats, as shown in Fig. 5 and described below.

- **Descriptive results.** Matrix representing the results of the peer comparison of the alternatives. Besides, additional information to facilitate the interpretation of the results is also provided.
- **Graphical results.** Hasse diagram representing the comparabilities (alternatives joined by arrows) and incomparabilities (alternatives not joined), but not the magnitude of difference between alternatives. Alternatives appear represented in descending order from worst to best options. Hasse diagrams are drawn based on *Graphviz* library graphics (GitLab, 2021).

3.3. Stage III: circular economy strategies

The third stage was based on defining the circular economy MIS decision-making problem. To this end, the baseline scenario (current scenario) of the organisation under study was assessed and characterised in order to identify opportunities for circularity improvement. Based on the incorporation of those circular economy strategies in the baseline scenario, alternative improvement scenarios were defined and analysed.

3.3.1. Description of the baseline scenario

An organisation located in Mendoza Province, Argentina, and dedicated to the production of precast construction elements was selected as a case study. These products are made up of an iron structure that provides resistance and a concrete or mortar mixture, both the latter based on cement. The first of them includes coarse and fines aggregates whereas the second one has only fines.

As shown in Fig. 6 (grey colour), the current production process (baseline scenario, SC0) starts with four parallel processes: the cutting and welding of structural irons, preparation of the concrete mixture, preparation of the mortar mixture, and adaptation of the mould to the characteristics of the product. Then, the products are built and cured with high humidity and intermediate temperature conditions. The water

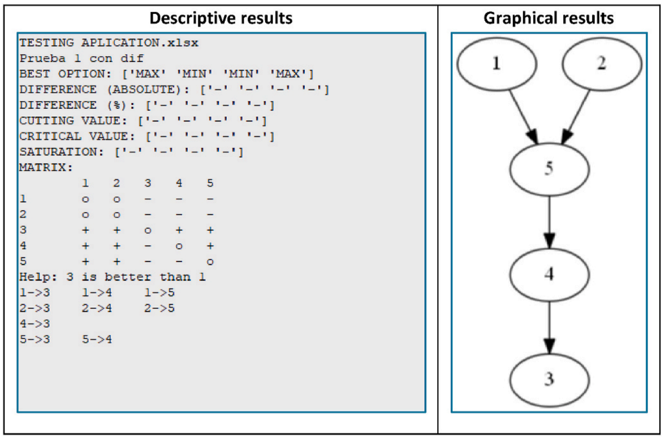


Fig. 5. Example of output information report.

consumed in the process is extracted from a well without any previous treatment. Solid waste produced consists mainly in mortar, concrete and scrap iron. Mortar and concrete waste are disposed of in landfill for inert materials whereas iron waste is collected and recycled separately. The main air emissions are produced by the fuel combustion of engines. Effluents generated have solids in suspension that are treated through gravity sedimentation and then discharged into the sewage system.

3.3.2. *Definition of the circularity improvement scenarios*

From the point of view of the transition towards a CE, this organisation presents some opportunities for improvement mainly related to the use of recycled raw materials, waste recycling, recirculation of materials, recirculation of effluent, curing automation, energy efficiency, nearby suppliers or workers' mobility (Alejandrino et al., 2022). The following alternative scenarios were defined for each of these opportunities (SC1, …, SC8) (orange colour in Fig. 6, processes added/modified with respect to SC0).

- **SC1 Use of recycled raw materials.** In the mortar, some of the fines are replaced by recycled plastic (Mercante et al., 2018), achieving a reduction in the consumption of cement and water (Ojeda et al., 2020). In the concrete, 20% of the coarse is replaced by recycled coarse (González-Fonteboa and Martínez-Abella, 2005).
- **SC2 Waste recycling.** Recycling of the construction and demolition waste (CDW) in an external CDW management facility (Mercante, 2014; Mercante et al., 2011).
- **SC3 Materials recirculation.** In situ recycling of CDW for its utilisation as recycled coarse in a 20% proportion of the consumed coarse (Mercante, 2014; Mercante et al., 2011). The rest of the CDW is sent to landfill, as in the base scenario.
- **SC4 Effluent recirculation.** Recirculation of 50% of effluents from equipment washing and the curing process (Sandrolini and Franzoni, 2001).
- **SC5 Curing automation.** Use of an automatic control system to monitor humidity and temperature and to activate valves and sprinklers when required. As a result, a reduction of 50% of water consumption and 30% of fuel consumption is achieved (Yang et al., 2018).
- **SC6 Energy efficiency.** A 25% reduction in energy consumed through improvements in the illumination and refrigeration systems (Doty, 2016; Thumann et al., 2003) and 90% of the purchased energy being replaced by energy generated in situ with photovoltaic panels.
- **SC7 Nearby suppliers.** Reduction in raw materials transport by the replacement of some suppliers for others that are nearby.
- **SC8 Workers' mobility.** Implementation of a mobility strategy to reduce the effects of employee commuting (Vanoutrive et al., 2012), creating a 30% reduction in the total amount of employee commuting (Ciclogreen, 2021).

Based on the opportunities for circularity improvement identified in the 3.3.1 Stage, eight circularity improvement scenarios were defined for each of these opportunities (SC1, …, SC8) (orange colour in Fig. 6, processes added/modified with respect to SC0).

In order to measure the level of circularity of the baseline scenario (SC0) and each of the circularity improvement scenarios (SC1, …, SC8), the CE indicators proposed by Vinante et al. (2021) were calculated. Table 4 reports the value of each indicator for each alternative scenario. The details of the calculation of each indicator for each alternative scenario are described in full in Alejandrino et al. (2022).

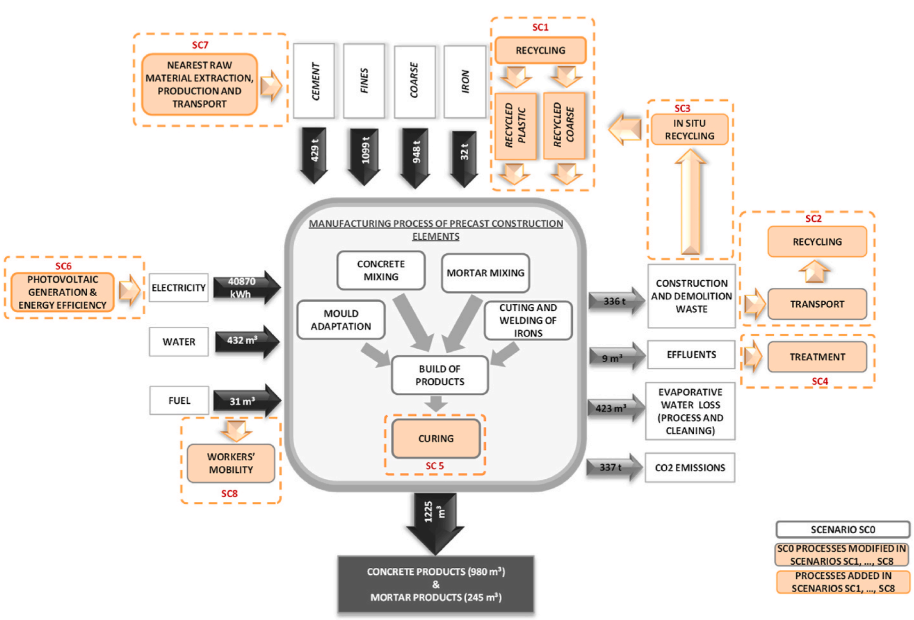


Fig. 6. Flowchart for the baseline scenario (SC0) and alternative improvement scenarios (SC1, …, SC8).

Table 4
Alternative scenarios and CE indicators (corresponding to the annual production).

Scenarios		CE categories	CE Indicators: Material consumption (t)	Recycled raw material (%)	Water consumption (m^3)	Electricity consumption (kWh)	Renewable energy consumption (%)	Generated solid waste (t)	Recycled solid waste (%)	Effluents (m^3)	Fuel consumption (m^3)	Carbon emissions (t CO_2eq)	CE Investment (ARS)
SC0	Baseline scenario	–	2,508.0	0.0	432.0	40,872.0	0.0	336.0	0.0	9.0	31.0	337.0	–
SC1	Use of recycled raw materials	Inputs	2,490.0	8.3	432.0	40,872.0	0.0	336.0	0.0	9.0	31.0	338.2	35,000.0
SC2	Waste recycling	Outputs	2,508.0	0.0	432.0	40,872.0	0.0	0.0	100.0	9.0	31.0	337.9	0.0
SC3	Materials recirculation	Production	2,319.0	7.5	432.0	40,888.0	0.0	125.0	63.0	9.0	31.0	336.8	200,000.0
SC4	Effluent recirculation	Production	2,508.0	0.0	324.0	40,884.0	0.0	336.0	0.0	0.0	31.0	337.0	40,000.0
SC5	Curing automation	Production	2,508.0	0.0	324.0	40,872.0	0.0	336.0	0.0	0.0	31.0	336.9	50,000.0
SC6	Energy efficiency	Production	2,508.0	0.0	432.0	7339.0	71.8	336.0	0.0	9.0	31.0	322.2	3,000,000.0
SC7	Nearby suppliers	Suppliers	2,508.0	0.0	432.0	40,872.0	0.0	336.0	0.0	9.0	30.0	332.5	0.0
SC8	Workers' mobility	Social	2,508.0	0.0	432.0	40,872.0	0.0	336.0	0.0	9.0	23.0	311.2	590,000.0
Indicator to be minimised or maximised (MIN/MAX):			MIN	MAX	MIN	MIN	MAX	MIN	MAX	MIN	MIN	MIN	MIN

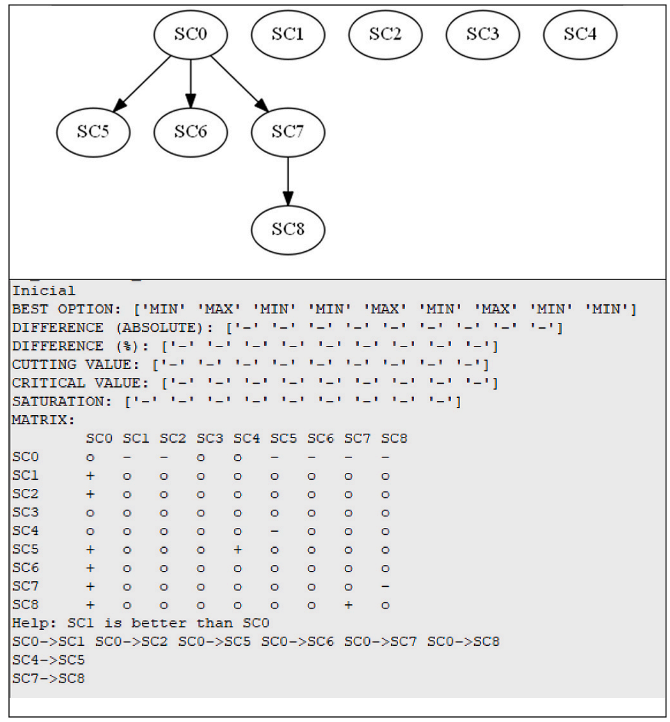


Fig. 7. Output data for the case study, without restrictions.

3.4. *Stage IV: tool application*

The tool developed was used to prioritise the alternative scenarios presented in Table 4 considering all the CE indicators. To do so, data reported in Table 4 were introduced into the input data file and analysed. In the first instance, no restrictions were applied and a Hasse Diagram with a large number of incomparability scenarios was obtained.

Next, in order to improve the results and validate the functionalities of the tool, some restrictions were applied and a new Hasse Diagram was obtained for each one, based on the characteristics and context of the organisation described below.

- The organisation stated that they were interested in major improvements, and hence non-significant differences between scenarios should be dismissed.
- The organisation was located in an area of water scarcity in Argentina, so a restriction related to the maximum water consumption and effluent generation was also considered.
- In Argentina, the legal framework (Ley 27191, 2015) requires that electro-intensive consumers must self-generate 20% of their electricity consumption by 2025. So, the self-generation of renewable energy should be highlighted among the scenarios.
- The company's budget for the implementation of CE strategies, which was limited, was also introduced.

Lastly, the restrictions considered were submitted to a sensitivity analysis. This analysis was performed through an iterative process where different values were tested for each restriction independently, without introducing changes in the other restrictions.

4. Results

4.1. *MIS analysis*

As a result of the research process described in the methodology section, a circular economy MIS decision-making problem based on

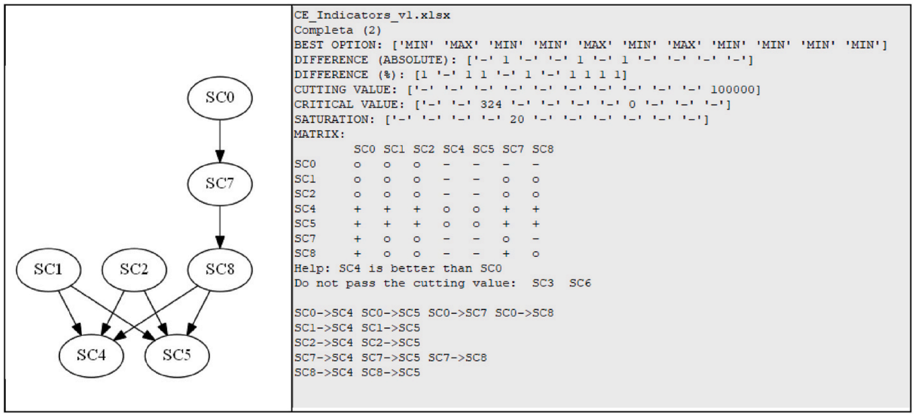
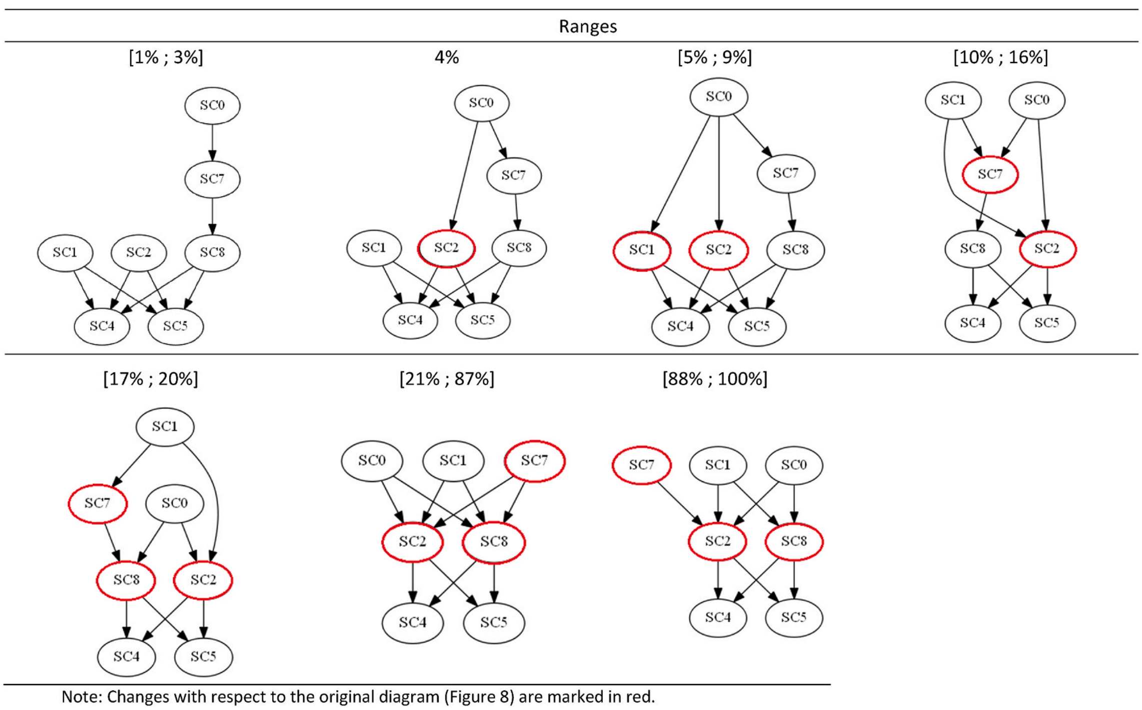


Fig. 8. Data output for case study with restrictions.

Table 5
Sensitivity analysis: Restriction 1 **(SD)**.



Note: Changes with respect to the original diagram (Fig. 8) are marked in red.

comparing eight alternative scenarios for circularity improvement of a baseline scenario was defined (Table 4). In order to solve it, in the first instance, no restrictions were applied, and a Hasse Diagram with many incomparabilities between scenarios was obtained (see Fig. 7).

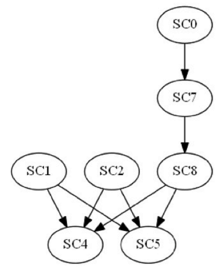
In this instance, SC1, SC2, SC3 and SC4 did not show themselves to be improvements for all the indicators with respect to SC0, while the other alternative scenarios (SC5, SC6, SC7 and SC8) did. Regarding the prioritisation of the alternative scenarios, it was only possible to identify an order relationship between SC7 and SC8. The rest of the alternative scenarios were incomparable with one another.

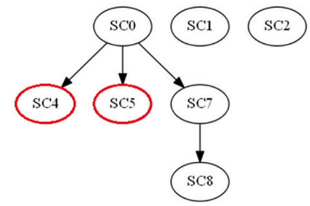
To improve the results, taking into account the characteristics and context of the organisation defined in the methods and materials section, the following four restrictions were incorporated, and the results presented in Fig. 8 were obtained.

- **Restriction 1 (SD = 1% for all indicators).** Under this restriction, two alternative scenarios whose value for a given indicator differs by less than 1% from the maximum value that this indicator takes are considered equal. Note that, for recycled raw material, renewable energy consumption and recycled solid waste indicators, this restriction was defined as an absolute number due to the fact that they are already percentage indicators.
- **Restriction 2 (CrV = 324 m^3 for Water consumption and CrV = 0 m^3 for Effluents).** Water is a critical resource for the location of the case study. So alternative scenarios that exceed the minimum water consumption of 324 m^3 or the null generation of effluents achieved by some scenarios (critical values established) are considered worse than those which do generate them.
- **Restriction 3 (SV = 20% for Renewable energy consumption).** Although the organisation under study is not currently a large energy

Table 6
Sensitivity analysis: Restriction 2 (CrV).

	Ranges	
Water consumption	[324; 432]	[0; 324] & >432
Effluents	[0, 9]	>9





Note: Changes with respect to the original diagram (Figure 8) are marked in red.

Note: Changes with respect to the original diagram (Fig. 8) are marked in red.

user, they have projections for growth in the future and can obtain tax benefits related to the use of renewable energy (Argentina, 2021). Consequently, a value of 20% was established as the saturation value for the percentage of energy from renewable sources used, and so scenarios with more than 20% of renewable energy are all considered equally good.

- **Restriction 4 (CuV = ARS 10,000 for CE Investment).** The organisation has a budget of ARS 100,000 available for the implementation of the alternative scenarios. Thus, scenarios with higher investments are excluded by establishing this amount as a cut-off value.

As Fig. 8 shows, with the exception of SC1 and SC2, all the alternative scenarios show improvements compared to the current scenario (SC0). In addition, a partial order between the alternative scenarios was obtained, which is useful for decision-making. Clearly, SC4 and SC5 present the best alternatives, although it is not possible to choose which is the best of the two. SC8, SC2 and SC1 are worse than the previous two and cannot be compared with each other. SC7 is worse than SC8, but incomparable with SC2 and SC1. Finally, SC3 and SC6 were excluded due to the cut-off value for CE investment.

4.2. Restrictions sensitivity analysis

In order to verify whether the results obtained for the case study were robust, the restrictions considered were submitted to the following sensitivity analysis.

4.2.1. Restriction 1 (SD = 1% for all indicators)

In this restriction, a variation in the significant difference (SD) defined between 1 and 100% was analysed. The results are presented in Table 5, grouped by ranges of SD that present the same behaviour.

Some incompatibilities of alternative scenarios appeared when changing the SD. For values greater than 4%, SC2 is considered better than SC0. SC1 is better than SC0 only for the 5%–9% range. For values greater than 21%, the SC7 starts to be incomparable with the baseline scenario. The prioritisation of alternative scenarios was affected only in the second-best scenarios, and the scenarios SC4 and SC5 remain the best for any value of the SD restriction.

4.2.2. Restriction 2 (CrV = 324 m^3 for water consumption and CrV = 0 m^3 for effluents)

In restriction 2, all values between 0 and the maximum values for each indicator (432 m^3 for water consumption and 9 m^3 for effluents) were analysed as CrV (see Table 4). The results are presented in Table 6, grouped by ranges of CrV with the same behaviour.

In this restriction, no changes in the comparison of the alternative scenarios with the baseline scenario were identified, for example SC1 is incomparable to SC0 and SC4 is better than SC0 in both diagrams in Table 6. Large changes were seen in the prioritisation of the alternative scenarios.

For the extreme CrV, represented in the right-hand column of Table 6 (water consumption <324 m^3 or >432 m^3 and effluents >9 m^3), the graph becomes flat. Here the incompatibilities between the alternative scenarios increase and it is not possible to know which scenarios are better from among SC1, SC2, SC4, SC5 and SC7-SC8. If all scenarios fulfil equally, or do not fulfil, the critical values (see right-hand column of Table 6), the effect of this restriction disappears. In this case the diagram obtained is more similar to that of Fig. 7 (without any restriction) and it is less useful for decision-making. It can be concluded that this restriction is what makes SC4 and SC5 the best scenarios in Fig. 8.

4.2.3. Restriction 3 (SV = 20% for renewable energy consumption)

For this restriction only one scenario has a percentage of renewable energy. Due to this, it is concluded that for any saturation value (from 0 to 100%) for the renewable energy indicator, the order of priority would not be affected, since that scenario would always be the best.

4.2.4. Restriction 4 (CuV = ARS 10,000 for CE investment)

For restriction 4, ranges of cut-off value of the budget available to the organisation were analysed based on the values of the investments of all the alternative scenarios (see Table 4): [0–35,000], [35,000–40,000], [40,000–50,000], [50,000–59,000], [59,000–200,000], [200,000–3,000,000] and more than ARS 3,000,000.

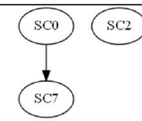
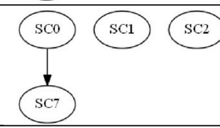
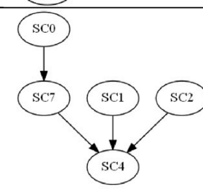
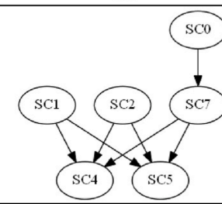
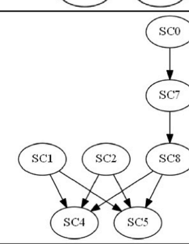
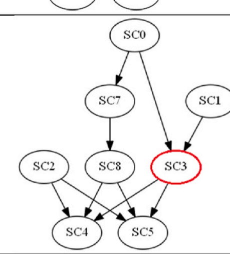
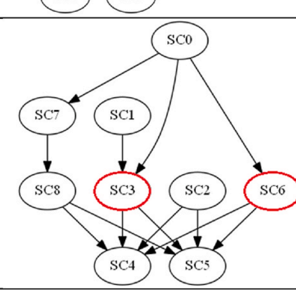
Table 7 shows which scenarios are excluded for each budget CuV range and the diagram. It can be concluded that as the budget increases, more scenarios are included and they intervene in the prioritisation. For a budget lower than ARS 50,000, one of the prioritised scenarios (SC5) in Fig. 8 is excluded and for a budget below ARS 40,000 the two prioritised scenarios are excluded (SC4 and SC5), so SC2 becomes the best scenario.

5. Discussion

To compare the circularity level of different organisational strategies, it is necessary to consider different issues of circularity, which include a broad range of CE indicators of various natures, ranges, metrics, etc. (Welfens et al., 2017; Ibáñez-Forés et al., 2022).

Therefore, regarding **RQ1** (Is it possible to design an MIS decision-making tool without weighting the CE indicators that is flexible enough to adapt to the idiosyncrasies of different industrial organisations?), in this study a tool based on POSET has been proved to be

Table 7
Sensitivity analysis: Restriction 4 (CuV).

CuV range for ARS for CE Investment	Scenarios excluded	Diagram
[0 – 35,000]	SC1, SC3, SC4, SC5, SC6, SC8	
[35,000 – 40,000]	SC3, SC4, SC5, SC6, SC8	
[40,000 – 50,000]	SC3, SC5, SC6, SC8	
[50,000 – 59,000]	SC3, SC6, SC8	
[59,000 – 200,000]	SC3, SC6	
[200,000 – 3,000,000]	SC6	
More than 3,000,000	None	

Note: Changes with respect to the original diagram (Figure 8) are marked in red.

Note: Changes with respect to the original diagram (Fig. 8) are marked in red.

capable of prioritising circularity improvement alternative scenarios based on the value that each of them takes for different CE indicators, while avoiding normalisation and weighting processes among the indicators, which are commonly associated with high uncertainty and subjectivity (Brüggemann et al., 2006; Badinger and Reuter, 2015; Arcagni et al., 2021).

Moreover, a set of functionalities based on the possible restrictions and the preferences of the organisations was incorporated into the tool to enable its adaptation to the different specificities of any application case. These functionalities were mainly based on the consideration of different limit values and the establishment of significant differences for each indicator, which are the most demanded restrictions in decision-making processes (Carlsen et al., 2018).

The adequacy of the proposed functionalities and the robustness of the results obtained with the tool were analysed by applying restrictions and preferences (see section 4.1) and sensitivity analysis (see section 4.2), respectively. The main conclusions were.

- Regarding the ***Restriction 1 (SD = 1% for all indicators)***, the results showed that the prioritisation of alternative scenarios was affected by the variation of this restriction only in the second-best scenarios, so the results obtained were considered robust.
- ***Restriction 2 (CrV = 324 m3 for Water consumption and CrV = 0 m3 for Effluents)*** was shown to have a great influence on the order of preference obtained for the circularity improvement scenarios, since it was responsible for highlighting the best scenarios.
- ***Restriction 3 (SV = 20% for Renewable energy consumption)*** was shown to have no effect on the order of priority of the alternatives in the case study.
- ***Restriction 4 (CuV = ARS 10,000 for CE Investment)*** was shown to have strong effects on the partial order obtained and its adjustment was stated as very useful when critical or essential indicators are assessed in decision-making processes.

According to these conclusions, it can be highlighted that the consideration of restrictions and preferences of the organisation under study (the tool's functionalities) proved to be essential to the prioritisation process, especially the Critical and the Cut-off values (CrV & CuV) functionalities, which seem to have a great influence on the circular economy MIS decision-making solutions.

Additionally, regarding **RQ 2** (Are the results of the developed MIS decision-making tool robust enough and useful for decision-making processes?), the results showed that scenarios SC4 and SC5 were those prioritised by the tool in more than 75% of the realised analyses (see section 4.1 and 4.2). This concords with the results from Alejandrino et al. (2022), who compared the same scenarios thoroughly an eco-efficiency study and obtained the same preferred scenarios. So, the user-friendly tool developed seems to be robust enough and useful for decision-making processes.

6. Conclusions

A tool based on POSET has been designed to prioritise CE alternative scenarios based on the value that each of them takes for different indicators but avoiding aggregation and compensation processes among them. In addition, the tool developed here allows for the option of including organisational restrictions and preferences that facilitate the prioritisation process, in order to improve the usefulness of the results for decision-making processes.

Regarding the case study, the application of the tool has made it possible to identify the prioritisation of different alternatives for improving the level of circularity of the organisation and to do so in a simple way while considering restrictions due to the location and the preferences of the organisation. The prioritised scenarios were SC4 (Effluent recirculation scenario) and SC5 (Curing automation scenario), both related to the control and better management of incoming and outgoing water.

Note that, although the presented tool has been used in this study for the prioritisation of circularity strategies, it has a generic nature and offers functionalities to be adapted to each multiple decision-making processes. Therefore, it could be applied to solve different types of problems with different specificities.

The main limitation of the tool and the POSET method was that the computational capacity required to solve problems with more than 25 scenarios is extremely high. Some researchers have proposed the use of statistics and numerical tools to deal with this difficulty, but these were not considered since the number of alternative circular scenarios is often limited.

As a future development, the intention is to add new functionalities to the tool, such as the calculation of an average ranking, or to expand the case study by increasing the number of indicators and their nature (social and economic in addition to the environmental/circular ones already considered) in order to cover the three pillars of sustainability.

CRediT authorship contribution statement

Valeria Ibáñez-Forés: Conceptualization, Methodology, Formal analysis, Software, Supervision, Software, Validation, Writing – original draft, Writing – review & editing. **Clarisa Alejandrino:** Data curation, Software, Validation, Formal analysis, Writing – original draft, Writing – review & editing. **María D. Bovea:** Funding acquisition, Project administration, Conceptualization, Methodology, Supervision, Writing – review & editing. **Irma Mercante:** data acquisition, 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.

Data availability

Data will be made available on request.

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