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Multi-expert multi-criteria decision analysis model to support the conservation of paramount elements in industrial facilities

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Abstract

The coupling of urban retrofitting with climate change adaptation and environmental conservation is impacting on current industrial activities such as electricity production based on fossil fuels. Therefore, new tools are required to support adaptive reuse towards the conservation of industrial facilities, in order to leave testament of their cultural and industrial heritage once their production activities cease to exist. Multi-Criteria Decision Analysis (MCDA) can help analyse complex interactions between industrial elements, society, culture and nature, providing key benefits when approaching heritage investigations. In this context, this research concerned the design of a Multi-Expert MCDA (ME-MCDA) methodology to support the selection of paramount heritage elements in power plants based on the collection and processing of the views of a panel of experts to result in consensus groups. This approach was tested using a case study in the As Pontes power plant (NW Spain), which will be dismantled in a near future. The results achieved pointed out to cooling towers, boilers, chimney and turbine hall as the fundamental elements to preserve due to their relevance across a set of technical, historical and sociocultural criteria. These outcomes proved the usefulness of the proposed approach in favouring the valorisation of industrial facilities as heritage areas protecting the social and cultural history of a territory.

Keywords: Conservation, Expert elicitation, Industrial heritage, Multi-Criteria decision analysis, Power plant, Technical processes

Introduction

Industrial activity has prompted a wide variety of technical elements over time. However, they were not valued as part of the cultural heritage of a place until the mid-twentieth century [1], as stressed by the International Committee for the Conservation of the Industrial Heritage (TICCIH) [2]. Industrial heritage encompasses the professional and cultural ties of industrial activities, emphasizing the valuation of elements from either a historical, technological, social, architectural or scientific standpoint [3].

However, the presence of industrial heritage in the Spanish governmental agenda is rather recent [4]. The main reference in this sense is the Spanish Industrial Heritage Plan [5], which emphasises the need for heritage conservation to avoid deterioration and the loss of key elements. According to Lin [6], industrial facilities can be converted into tourism assets with educational and heritage values, among others.

The role of fossil fuels as a primary contributor to climate change is preventing their use to generate electricity [7]. In consequence, there is a need for cleaner strategies and technical processes in the production of electricity. Hence, it is of great interest to leave evidence of electricity generation for future industrial heritage purposes, so that governments can design policies to appropriately

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preserve current facilities and machinery used in thermal power plants.

Another significant challenge to consider is to find sustainable new uses for industrial facilities [8]. Multi-Criteria Decision Analysis (MCDA) provides a comprehensive way of addressing the interactions between industrial elements, society and culture, thereby supporting the preservation of original elements of former industrial activities. These methods allow the integration of a wide range of economic, social, historical and environmental concerns, whilst considering the opinion of specialists in the process [9].

Moreover, MCDA-based reuse strategies for industrial heritage allow the preservation of the symbolic value of a place, while adapting former industrial processes towards new uses [10]. In this vein, Langston et al. [11] and Ferretti et al. [12] highlighted adaptive reuse approaches for buildings as key processes to transition towards new uses, incorporating sustainable dimensions related to the environment, society and economy.

Consequently, MCDA tools are useful in developing a methodological framework accounting for varying scenarios, ranging from their historical land use associated to their industrial activity up to their future potential use [13]. Hence, MCDA is suitable to support the selection of heritage elements, since it enables prioritizing their preservation according to a series of criteria. This conceptualization differs from that of machine learning algorithms such as artificial neural networks, which are based on fitting a response variable from a series of explanatory variables. In this case, the aim is rather to produce this response variable by aggregating the ratings of the elements with potential for preservation across the conservation criteria.

MCDA methods have been utilised in recent times in research involving UNESCO's World Heritage places such as the Etna Park, Italy, where sustainable uses and environmental conservation required a robust assessment to guide policy makers [14]. Ferretti and Comino [15] also revealed the importance of developing an integrative framework based on MCDA to deal with the recovery of cultural and natural heritage systems for touristic purposes. Previous studies [13, 16, 17] showed that the Analytic Hierarchy Process (AHP) is one of the preferred MCDA tools for the preservation and adaptive reuse of industrial heritage.

There is an extensive literature in the analysis of MCDA in heritage buildings, which in many cases could be used in informing future heritage sites with strong industrial base. Dutta and Husain [18] used MCDA methods to integrate building heritage in urban planning strategies. Li et al. [19] pointed out that conservation strategies in architectural heritage should be based on minimal interventions, reversible actions, sustainability and liveability, noting that MCDA methods and questionnaires will be key in future research.

Nadkarni & Puthuvayi [20] highlighted the main fields of focus up to date such as adaptive reuse, priority order for renovation, building value, evaluation of alternative solutions, assessment of functional service life and contractor selection. This study marked the need for further development of MCDA in cultural landscapes. Former industrialised areas with high cultural footprint may be liable to be included in this conceptual framework. Morkūnaitė et al. [21] found that a combination of the AHP method and expert's knowledge were the most utilised means to determine the strategies for building heritage. In addition, Pavlovskis et al. [22] concluded that modern technologies such as Building Information Modelling (BIM) should be used in combination with MCDA in the next years to come.

Turskis et al. [23] widened the scope for heritage structures renovation towards economic criteria such as project cost and implementation, as well as historical-cultural and social criteria. Haroun et al. [24] emphasised the importance to identify the strengths and weaknesses of structures to ensure an adequate evaluation of future uses of heritage buildings. Da Silva et al. [25] introduced new concepts and views in the analysis of potential heritage sites including safety features and priority locations, focusing in industrialised areas with long mining history.

Another focus was implemented by Eldiasty et al. [26], who develop a MCDA method which allowed the inclusion of features relevant to potential heritage sites with significant historical commercial activities. Legislative frameworks were also included in MCDA methods by Vehbi et al. [27] in their work to define new uses for an old administrative hospital in Cyprus. Finally, Salerno [28] proposed a method to assess the sustainability of redevelopment projects under examination through sensitivity analysis aiming at increasing heritage values.

These previous investigations focused on industrial and/or cultural heritage assets with a former activity, which is the common place for this sort of studies. However, more research is needed to address scenarios with current industrial activity in place prior to the end of its operational life. In addition, there is a lack of studies associated with power plants as potential heritage places, as well as the use of MCDA techniques to help identify key elements to preserve for future uses. Another gap in the literature lies in the use of MCDA to consider the production process in plants over the years as a potential core element in terms of industrial heritage.

The aim of this paper is to fill these gaps by designing a methodology to support the transformation of industrial facilities into heritage assets through the preservation of their key elements. The prioritization of which elements should be preserved was conducted using a MCDA model based on the collection and processing of the opinions of experts in industrial heritage to produce consensus groups. This approach was tested through the As Pontes case study, a thermal power plant in Galicia (NW Spain) that is in use nowadays but will be dismantled soon.

The use of MCDA is particularly suitable to achieve this aim, since it can structure a decision-making problem according to cognitive and normative dimensions [29], while enabling the involvement of multiple criteria [30] and stakeholders [31] of a different nature and the combination of quantitative and qualitative data [32]. One of the main drawbacks of MCDA relate to their capacity for eliciting the preferences of a reduced group of people [33]. Another problem with MCDA methods refers to their openness, since the criteria and alternatives are commonly pre-established and the role of participants is limited to stating judgments [34]. The persons involved in this study were required to be experts with proven experience in industrial heritage, which is not a very broad area of research. Moreover, the conservation criteria and elements were proposed based on existing governmental plans. As such, the impact of these flaws was expected to be limited.

The rest of the document is structured as follows: Sect. 2 outlines the case study of the As Pontes power plant, which serves to refer the proposed conservation criteria and elements to the description of the methodology to support its preservation in the next section. Section 4 presents and discusses the results achieved, with emphasis on highlighting the most important conservation criteria and the hierarchy of heritage elements recommended for preservation. The document ends by underlining the main findings and conclusions drawn from this study, as well as some lines of research to develop in the future.

Case study

The As Pontes power plant is in As Pontes de García Rodríguez, Galicia, NW Spain. Figure 1 depicts its geographic location and layout. Its aim was to generate electric power using fossil fuels, while establishing a thermodynamic water-steam cycle. It was originally built to make rational use of the lignite extracted from an open pit mine located in its vicinity.

The plant began its activity in 1976 with the start-up of the first electric power generation group. Subsequently, three others were added until reaching a total of four groups in 1978 [35]. The highest rates of exploitation were achieved during the 90s, resulting in great economic impacts, including the generation of 3,000 jobs related to this facility [36]. The emission regulations set in Spain during the next two decades led the plant to use imported low-sulphur coal, causing the termination of all lignite mining activities in 2007.

Endesa, the multinational company the power plant belongs to, presented in 2019 a formal request to the Spanish Ministry of Ecological Transition to close the plant, alleging its lack of competitiveness due to the increased price of CO_2 emissions. Finally, Endesa updated its strategic plan at the end of 2019 to remark that its coal-fired power plants are projected to disappear

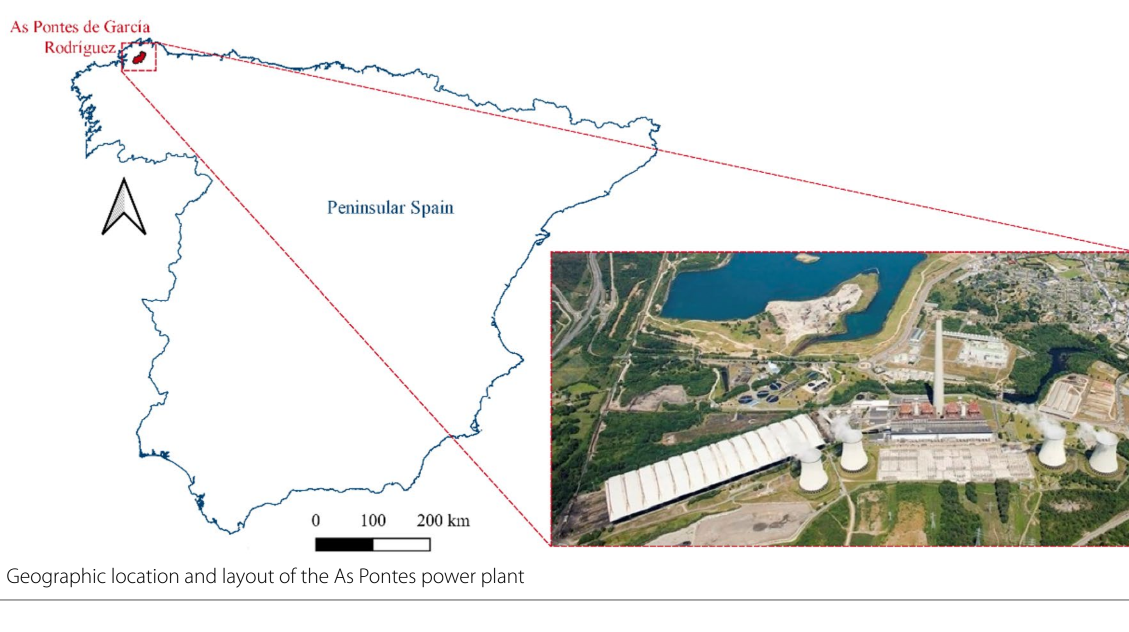

Fig. 1 Geographic location and layout of the As Pontes power plant

as of 2022 [37], which becomes the deadline for the As Pontes power plant.

The methodology explained below can be applied to any industrial facility in the world if it is represented using a series of conservation criteria and elements to preserve. This study is limited to the As Pontes power plant for two reasons: (1) it epitomizes the need to address the dismantling of industrial facilities due to their key contribution to climate change through coal emissions; and (2) there was thorough information available about the history and operation of this power plant, which is required to properly characterize their elements and, therefore, be in a position to invite experts to participate with their opinions about their preservation.

Methodology

The approach taken to conduct this study is depicted in Fig. 2. After introducing the case study of the As Pontes power plant (1), the criteria and elements proposed for its preservation were described (2). Then, a questionnaire was prepared to collect the opinions of a panel of experts in industrial heritage (3). Finally, a Multi-Expert Multi-Criteria Decision Analysis (ME-MCDA) methodology was built to process the judgments of the experts (4), which enabled identifying those elements whose conservation is suggested through their weighted rating (5).

Definition of conservation criteria

Seven criteria as listed in Table 1 were defined to support which elements of the As Pontes power plant deserved to be preserved. These criteria were set to account for all the dimensions encompassed by industrial heritage, including technical, historical, social, practical and visual considerations. They were defined to provide a representative picture of the valuation and selection criteria set in the Spanish Industrial Heritage Plan [5], including testimonial (C_1), uniqueness (C_2), architectural (C_3), viability (C_4 and C_5), social (C_6) and technological (C_7) considerations. Therefore, the original set of fifteen criteria proposed in this Plan was reduced to seven, in order to ease the participation of experts and minimize respondent fatigue [38, 39].

Table 1 Criteria proposed to evaluate the conservation of the As Pontes power plant

C_j	Criterion
C_1	Importance in the electricity generation process
C_2	Singularity
C_3	Aesthetics
C_4	Ease of preservation
C_5	Adaptability to new uses
C_6	Sociocultural interest
C_7	Work and technology testimony

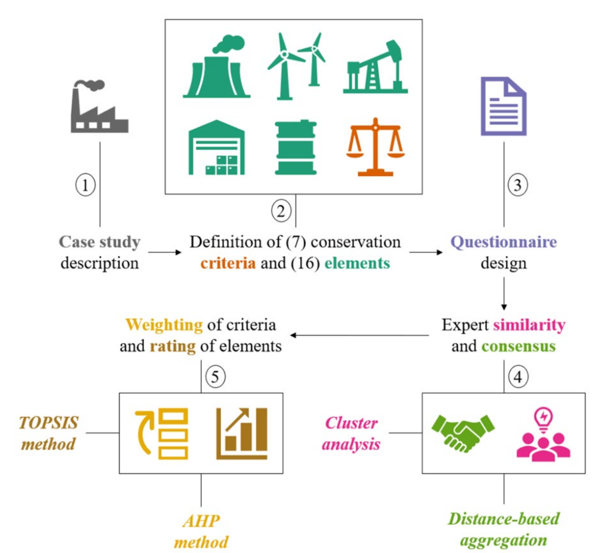

Fig. 2 Diagram of the approach taken for the conservation of the As Pontes power plant

Production is essential in the field of industrial heritage due to its relevance to understand how the plant used to work. As such, C_1 was included in the list of criteria as a representative of the production process, whereby an input (carbon) goes through a boiler where water is transformed into steam, which in turn causes the rotation of a turbine to generate electric power.

Singularity (C_2) stands for those elements whose design can be considered remarkable for different reasons. Hence, it may refer to items involving improvements in terms of production, maximum generation or transformation capacity. Also, this criterion can be related to components of large dimensions or other nonconventional characteristics that might justify the interest in safeguarding them.

Aesthetics (C_3) accounts for factors associated with the aspect of the power plant and its integration in the landscape. Therefore, this criterion values the elements in the context of their surroundings or their mimicry in terms of colour or geometry, as well as the interaction of the facility with the environment in terms of land occupation, visual impact, layout distribution, etc.

The maintenance of the power plant with time is addressed by C_4, whose goal is to prioritise those elements less susceptible to experience degradation. Exposure of these elements to the environmental conditions may result in corrosion and decay depending on the constituent materials. Consequently, preservation must be compatible with new uses, which in turn cannot provoke the deterioration of the elements to be conserved.

New uses must not endanger the patrimonial value of the elements preserved, since this would be against industrial heritage. Thus, adaptability to new uses (C_5) considers positive aspects such as the presence of open spaces or the capacity for coexisting with other activities; instead, complex and large components are difficult to accommodate to different purposes.

The sixth criterion (C_6) values the degree of attraction for the society. It represents the perception of the dwellers in the region in respect of considerations such as the societal modifications in the urban environment entailed by the power plant, the new activities that might be developed once it is decommissioned, their position with regards to the preservation of the facility, etc.

Finally, the last criterion (C_7) appraises the testimony of the activities undertaken in the power plant. On the one hand, it accounts for the evolution of production processes, computing and environmental conservation. On the other hand, this criterion also deals with changes in the daily activities of workpeople, the organization chart of the company, the relationships among the different types of employees, their salary or the existence of subcontractors.

Description of the elements to preserve

Due to the complexity of the process for generating electric power, the elements to be rescued in the As Pontes power plant are numerous and diverse. Their breakdown is also complicated due to the existence of interrelationships among them. Based on their characteristics and importance in terms of industrial heritage, a set of 16 elements as shown in Table 2 were shortlisted as potential candidates.

These elements stand for the thermal processing unit of the As power plant, thereby providing a coherent and representative sample of its industrial activity, as stated in the guidelines on industrial heritage currently in force in Spain [5]. In fact, these elements are included in the governmental resolution published by the Spanish Official State Gazette, whereby the As Pontes power plant is projected to be dismantled throughout 2022 [40].

Multi-Expert Multi-Criteria decision analysis (ME-MCDA)

The prioritisation of the elements to be preserved in the As Pontes power plant was undertaken with the support of ME-MCDA. The data used as inputs stemmed from a questionnaire prepared to gather the views of a panel of international experts in industrial heritage. The responses collected were processed using the Analytic Hierarchy Process (AHP) and the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS), which enabled determining the weights of the criteria and the ranking of elements.

Both methods were selected because of their wide acceptance and use in the field of heritage science [41–44], including applications in which they are coupled with expert elicitation [45, 46]. The AHP method is particularly suitable to capture linguistic judgments as those requested from the experts and transform them into numbers [47], whilst TOPSIS has been argued to outperform other ranking methods due to its capacity for representing the rationale of human choice, accounting for best and worst alternatives simultaneously and ease of computation [48].

These methods were complemented with cluster analysis and a Distance-Based Weighting (DBW) approach, whose combination served to handle the vagueness inherent to the answers provided by the experts. Their use served to adjust their responses in case of inconsistencies and group them systematically to result in a series of scenarios with different values for the weights of the criteria and the ratings of the elements. In this sense, the purpose of cluster analysis and DBW was similar to that of fuzzy logic [49] in other MCDA methodologies, which is often used to deal with uncertainty in decision-making processes [50–52]. All these methods were applied using the open source statistical package R [53].

Preparation of questionnaires

A two-phase questionnaire was elaborated using Google Forms to capture the preferences of a panel of experts (Fig. 3). Invitations were mostly sent to Spanish respondents, since they should have a better understanding of the specifics of the case study. Still, some international experts were addressed too to capture distant views about the preservation of As Pontes power plant. Most of the specialists consulted were academics, since industrial heritage is not a field very prone to technical and/or private work.

To facilitate their completion, both questionnaires were structured in several sections to limit the number of dropouts. All the invitations were sent by email, since there was certainty that this communication channel was regularly used by every potential participant. These emails, which served to briefly introduce the case study and provide the link to access the form, were personalized to each addressee and thus help increase response rates. These introductory and customization actions were aimed at reducing sampling and nonresponse biases, respectively.

The first questionnaire started with a detailed presentation of the case study, including explanations about the situation of the As Pontes power plant and instructions about the other sections in the form. Then, to further

Table 2 Potential elements to be preserved in the As Pontes power plant

E_i	Element	Description
E_1	Coal park	The dimensions of this park, which was devoted to coal storage and homogenization tasks, were 160 m wide by 592 m long. It is formed of a series of prestressed metal arches with circular section, from which the roof cladding is suspended
E_2	External coal park	The coal used in the plant was transported by road and stored temporarily in an external park where it was accumulated in piles. Subsequently, the coal went through a tunnel and was poured it onto a conveyor belt by two machines
E_3	Coal distribution system	The coal passed through other conveyor belts in the distribution system, which also resulted in its magnetic separation and crushing. This element had two independent lines that ensured the continuous fuel supply to the boiler
E_4	Air intake system and precipitators	The gases derived from combustion went through air preheaters that transmitted their thermal energy to the air used for combustion. In turn, these gases were separated from solid particles to prevent their release to the atmosphere by means of electrostatic precipitators
E_5	Boiler	The boiler had a natural circulation system and was prepared for the combustion of lignite and sub-bituminous coal. Its height amounted to 90 m, with a double line of forced and induced draft fans and 6 columns of burners tangentially arranged
E_6	Chimney	The chimney is a unique structural element whose presence allowed the evacuation of combustion gases. It is 356.5 m high and contains four metal conduits in a concrete shaft with diameters of 36.5 m at the base and 18.9 m at the top
E_7	Ash and slag extraction system	Wastes derived from the combustion of coal were collected in the form of slags and fly ash. The extraction system was continuous and discharged into the so-called ashtray, where slags and fly ash were extracted and subsequently evacuated
E_8	Ash and slag landfill	Slags and fly ash were disposed at a non-hazardous waste landfill specifically designed for their elimination. It was in a hillside area within the facilities of the thermal power plant. Until 2011, theses wastes were reused by the cement industry
E_9	Turbine hall	The turbine hall highlights by its occupation and technological complexity, including four turbines and their corresponding alternators. The hall comprises both metal and reinforced concrete frames, which work as a linkage with other areas in the park
E_{10}	Cooling towers	The cooling towers enabled the power plant working according to a closed thermodynamic cycle. The cooling process consisted of releasing water in the form of rain and exposing it to the air current that is inside. The flow processed amounts to 38,000 m^3/h, with a thermal leap of 11 ºC
E_{11}	Transformer substation	There were 4 transformers corresponding to the output of each of the generation groups. These transformers served to change the nominal voltage of the alternators from 18 kV to 410 kV, which corresponds to the voltage of the high-power grid
E_{12}	Sewage treatment plant	The entire plant needed potable water for different general uses, such as production, human consumption, hygienic services, etc. The system had a clarification capacity of around 200 m^3/h, as well as ozonation, demineralization and filtration systems
E_{13}	River water collection station	Water was extracted from the Eume river, which is very close to the power plant. It was collected by means of a pumping machine and then circulated to the water treatment plant
E_{14}	Fuel oil and gas oil storage tanks	There were 2 fuel oil tanks with a capacity of 4000 m^3 and 3 diesel tanks with a capacity of 100 m^3 each. This enabled having sufficient energy available for the complicated start-up processes
E_{15}	Effluent treatment plant	This plant treated effluents between 0.1 and 3.0 m^3/s meeting the regulations in terms of authorization of discharges. The treatment phases included roughing filtration, neutralization, grinding, flocculation, decantation, homogenization and sludge reuse
E_{16}	Environmental monitoring infrastructures	The plant had different monitoring stations for environmental control. These included the analysis of the Eume river water, the evaluation of noise outside the perimeter of the facilities and a temporary deposit for hazardous wastes

put the respondents in context, a detailed briefing on the elements and layout of the plant was provided. Next was asking the experts for setting pairwise comparisons about the relative importance of the conservation criteria (Table 1). Seven levels of importance were established, ranging from "much less important" to "much more important".

Another section was included to collect information about the origins, profile, years of experience and expertise of the respondents. This step was made anonymous and left to the end, which contributed to controlling response and order biases. This form was first sent to a reduced sample of 5 people for pre-testing purposes, including an ending section to ask if the questionnaire was understandable and easy to fill out, while leaving space for making any suggestion to improve the form. Since their definition stemmed from governmental documents, there was not a specific space for proposing the

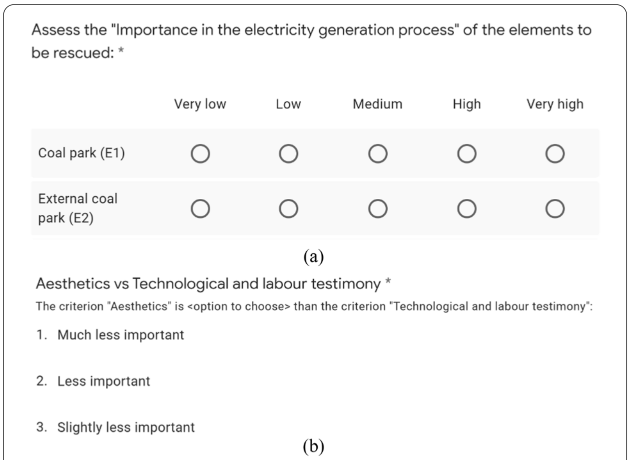

Fig. 3 Excerpts of the questionnaires prepared **a** Conservation criteria **b** Elements to be preserved

Table 3 Reduced comparison scale to set the importance of the conservation criteria

Relative importance of C_{j_1} with respect to C_{j_2}	Value
Much less important	1/7
Less important	1/5
Slightly less important	1/3
Equally important	1
Slightly more important	3
More important	5
Much more important	7

addition or removal of either criteria or elements; however, any comment in this sense could be included in the blank space mentioned above.

The second questionnaire aimed at evaluating the elements described in Table 2 with respect to the conservation criteria. First, there was a section intended to act as a reminder of the purpose of the first questionnaire. Then, a graphical representation of each element was provided to clarify the characteristics of the As Pontes plant. The core of this questionnaire consisted of asking the participants to rate the proposed heritage elements across the conservation criteria.

In this case, the qualitative valuation was carried out according to a Likert-type scale containing the following levels: very low, low, medium, high, and very high. These linguistic judgments were then transformed into semiquantitative values ranging from 1 (very low) to 5 (very high) for subsequent analyses. Again, anonymous information about the respondents was requested as described in the first form.

Weighting of conservation criteria

The criteria in Table 1 were weighted with the support of the AHP method [54], which uses pairwise comparisons to determine the relative importance between two criteria (Table 3). The original scale proposed by Saaty, which consists of nine comparison levels [55], was reduced by removing the most extreme values (1/9 and 9) to facilitate the choice of options by the experts. This modification also helped limit extreme responding bias.

The linguistic comparisons provided by the experts were arranged in the form of a matrix to enable evaluating their coherence using the Consistency Ratio ($C.R.$). This term was computed based on the size and maximum eigenvalue of the matrix and the consistency of a series of random matrices. Hence, comparisons were considered consistent when $C.R. \leq 0.1$.

Those responses resulting in values of $C.R. > 0.1$ were made consistent using the method proposed by Jato-Espino et al. [56], which consists of modifying the values in an inconsistent matrix until $C.R. \leq 0.1$. This is expressed as the minimisation of the Root Mean Square Error (RMSE) of the inconsistent ($x_{j_1j_2}$) and consistent ($x'_{j_1j_2}$) comparison values provided by an expert in relation to criteria j_1 and j_2 (Eq. 1).

$$Minimize\sqrt{\frac{1}{n}\sum_{j=1}^{n}\left(\ln x_{j_1j_2}-\ln x'_{j_1j_2}\right)^2} \quad (1)$$

$$subject\ to: C.R. \leq 0.1$$

$$\ln x^{L.B.}_{j_1j_2} < \ln x'_{j_1j_2} < \ln x^{U.B.}_{j_1j_2}$$

where $x^{L.B.}_{j_1j_2}$ and $x^{U.B.}_{j_1j_2}$ are the lower and upper bounds of $x_{j_1j_2}$ as indicated in Table 3 (e.g., if $x_{j_1j_2} = 3$, then $x^{L.B.}_{j_1j_2} = 1$ and $x^{U.B.}_{j_1j_2} = 5$). Equation (1) was solved using the Generalized Reduced Gradient (GRG) algorithm [57], leading to a consistent comparison matrix whose values were as close as possible to the original responses given by the experts. The inputs provided by an expert were considered invalid if they failed to meet the restrictions set in Eq. (1). This meant that their opinions were too inconsistent to enable solving the minimization problem without introducing substantial variations in their original judgments.

In the end, this adjustment was intended to attenuate the difficulties found by the addressees to choose between similar linguistic terms as those included in Table 3. Equation (1) is an alternative to the traditional solution used to deal with inconsistencies, whereby experts must perform reassessments until the required value of $C.R.$ is met. This process can force the experts to adjust their original judgments for the sole purpose of being consistent, which may lead to important distortions with respect to their initial beliefs [58]. Instead, the proposed approach is much more respectful with the assessments provided by the experts, since its constraints guarantee that the variations in their inputs were reduced at the minimum amount.

Rating of elements to preserve

The rating of heritage elements across the conservation criteria was carried out using the TOPSIS method [59], which helped determine how close the elements under consideration were to be ideal in terms of heritage values. TOPSIS was applied according to the following steps:

- Obtaining consensual ratings r_{ij} for each element E_i across the conservation criteria C_j from the opinions provided by the experts.
- Normalising r_{ij} through vector normalisation to result in n_{ij}.
- Determining the normalised weighted ratings (v_{ij}) by multiplying the normalised ratings n_{ij} by the weights w_{Cj} achieved using the AHP method.
- Calculating the positive (A^+) and negative (A^-) ideal heritage elements as the maximum and minimum values of v_{ij} per criterion.
- Measuring the distances (d_i^+ and d_i^-) from each element under consideration to A^+ and A^-.
- Computing the Relative Closeness ($0 \leq RC_i \leq 1$) from each element to the ideal element in terms of heritage values through Eq. (2). The higher the value of RC_i achieved by an element, the more preferred its conservation was

$$RC_i = \frac{d_i^-}{d_i^+ + d_i^-} \quad (2)$$

Cluster analysis

Cluster analysis was used to partition the opinions provided by the experts according to their similarity. It was applied to the two phases of the questionnaire to demonstrate how sensitive the results achieved were to changes in either the weights of the criteria or the ratings of the elements. This technique has been previously used to group participants based on survey responses [60], due to its capacity for revealing opinion diversity properly and preventing minorities from being lost [61].

This technique was conceived by Tryon [62] based on the idea that the items included in a group are similar to each other and different from those included in the remaining clusters. Its application started by determining the optimal number of clusters (k) from the responses derived from the two phases of the questionnaire. This was double checked with the support of the Elbow criterion and the Calinski-Harabasz index.

The Elbow criterion is based on calculating the sum of squares of the items within each cluster [63]. This is plotted against the number of clusters, so that the amount of information gained as the latter increases drops at certain point, indicating the optimal number of clusters. The Calinski-Harabasz index is measured as a ratio of between-cluster variance and overall within-cluster variance [64]. Suitable numbers of clusters correspond to high values of this ratio.

Knowing the number of clusters is the first requisite to apply the k-means algorithm, which seeks to minimize the sum of squared Euclidean distances between the items and the centroid of their corresponding cluster [65]. This algorithm consists of the following steps:

- Select k random items from the dataset to perform as initial centroids.
- Assign the remaining items to its closest centroid according to their Euclidean distance.
- Update the mean value of each cluster every time a new item is added to it.
- Determine whether some items might need being relocated to a different cluster or not.
- Repeat the last three steps until cluster assignments remain constant.

The resulting clustering combinations for conservation criteria and heritage elements yielded a set of scenarios representing different preservation priorities depending on the highest values of RC_i (Eq. 2). To support the selection of key elements to preserve, the third quartile (Q_3) of these values of RC_i was calculated, serving as a threshold to highlight the most preferred 25% elements under each scenario.

Distance-based aggregation

Although cluster analysis served to partition the opinions received from the experts, there was still a need to aggregate all the responses associated with each group into a single and synthetized view. This was achieved using the DBW method [56], which enabled capturing the consensual perspective of each cluster of experts regarding the conservation criteria and elements.

The DBW method is based on giving more importance to those experts whose responses are more alike to the others. This was accomplished by determining the weight (w_{e_p}) of each expert e_p according to the Euclidean distance ($d_{e_{p_i}e_{p_j}}$) of his/her responses to those provided by the others. For a number of experts q, w_{e_p} can be formulated as shown in Eq. (3).

$$w_{e_p} = \frac{1/\sum_{p=1}^{q} d_{e_{p_i}e_{p_j}}}{\sum_{p=1}^{q}\left(1/\sum_{p=1}^{q} d_{e_{p_i}e_{p_j}}\right)} \tag{3}$$

Then, the geometric mean of the opinions of the experts in a cluster (o_{CL_i}) was calculated according to their weighted responses (Eq. (3)) with respect to a certain criterion or element (x_{e_p}), in order to represent the consensus of such cluster. Hence, Eq. (4) was used to compute the aggregated values obtained for either the conservation criteria or the elements to be preserved.

$$o_{CL_i} = \prod_{p=1}^{q} \ln x_{e_p}{}^{w_{e_p}} \tag{4}$$

Results and discussion

This section summarizes and discusses the main outputs obtained through the application of the proposed ME-MCDA approach to the analysis of the As Pontes power plant. The results are arranged according to the main parts into which the methodology was divided: processing of questionnaires, weighting of conservation criteria and rating of elements to be preserved. The section ends with the discussion of the implications of the results achieved.

Overview of questionnaires

The pre-testing of the first questionnaire was successful, since the five experts involved in this stage valued the understandability of the form positively. Despite there was room for suggesting changes of any kind in the questionnaire, none of the addressees made any specific comment to improve it. Since these experts were selected because the authors were aware of their solid career in the field of industrial heritage, the form was concluded to be ready for further dissemination.

The first phase of the questionnaire was responded by 26 experts, which means a response rate of 54.17% in relation to the original sample of addressees. This figure decreased to 18 in the second phase, a fact that demonstrates the difficulty to maintain cooperation as the number of rounds increases [66]. The correspondence between both phases was not exact, so that some experts only replied to one out of the two questionnaires and some others participated in both. Still, the response rate in the second round (37.5%) was higher than the values commonly found in the literature for email surveys, which are in the range of 25–30% [67].

Considering the participants were limited to experts and the extension of industrial heritage as an area of research, these results were deemed satisfactory. Overall, the number of respondents involved in the investigation amounted to 33. Figure 4 summarizes the characteristics of the participants. Given the location of the power plant, most addressees were from Spain (54.55%). Other regions with more than one participant were United Kingdom (4), Italy (3) and Brazil (2).

The vast majority of respondents belonged to the academia, especially in the role of researchers (almost 70%). Their experience in industrial heritage ranged from 3 to 40 years, with a mean value of 17 years. In line with these values, more than three quarters of experts considered their expertise in the field to be medium-high or high.

The breakdown of the participants according to their profile revealed a predominance of academics. This could result in a more idealistic vision of the problem, compared with the more pragmatic and pressured angles provided by the private industry and governments. However, having a more balanced sample was difficult because of the specifics of industrial heritage. It is not a usual business area in private companies and its inclusion in governmental agendas is still scarce.

Weighting of conservation criteria

The comparisons provided by the experts to evaluate the criteria were transformed into numerical values according to the AHP scale (Table 3). Then, these values were further processed to obtain a vector of weights for each respondent. The validity of these results was checked according to the $C.R.$, which revealed that only 5 out of the 27 experts were consistent ($C.R. \leq 0.1$). This fact supported the simplified scale represented in Table 3, since the consideration of two additional levels would probably have led to greater inconsistency [68].

Those comparisons reaching values of $C.R. > 0.1$ were processed using the GRG algorithm. Thanks to this, all the comparisons were made consistent except for one, whose inconsistency was so high ($C.R = 0.58$) that failed to meet the restrictions of $C.R. \leq 0.1$. Table 4 exemplifies the process whereby an inconsistent comparison matrix ($C.R. = 0.19$) became consistent ($C.R. = 0.1$).

An overview of the consistent vectors of weights revealed that the perspectives of the experts differed notably from one another. In response, cluster analysis was applied to group them according to their similarity. The flattening in the curve in Fig. 5a suggested that the optimal number of clusters might be 3, whereas the highest value according to the Calinski-Harabasz index confirmed this notion (Fig. 5b).

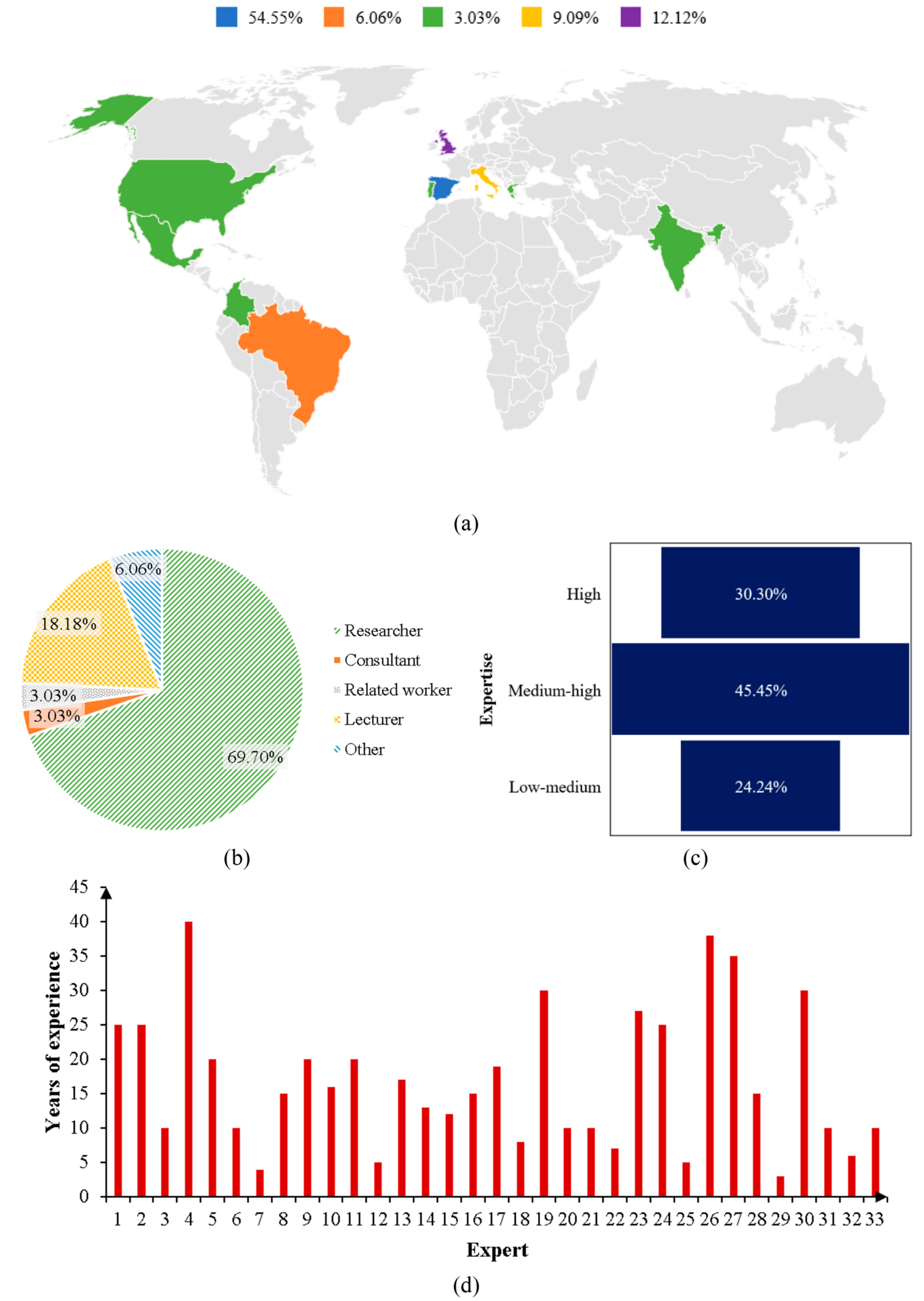

Fig. 4 Summary statistics of the experts addressed **a** Region of origin **b** Profile **c** Degree of expertise **d** Experience (years)

In case of discrepancies between the number of clusters suggested by both methods, the internal logic of the resulting groups should be reasoned to determine a single outcome. A more comprehensive alternative would consist of creating two sub-scenarios, one for each number of clusters suggested by each method. However, this solution might be cumbersome because of the exponential increase in scenarios to consider.

Table 4 Inconsistent and consistent comparison matrices and weights obtained before and after applying the Generalized Reduced Gradient (GRG) algorithm

C_j	Original inconsistent comparison matrix							Consistent comparison matrix (after GRG)						
	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_1	C_2	C_3	C_4	C_5	C_6	C_7
C_1	1	1.000	5.000	5.000	0.333	1.000	0.333	1	1.053	4.422	4.634	0.361	0.928	0.374
C_2		1	3.000	5.000	0.333	0.333	0.200		1	2.765	4.354	0.344	0.353	0.233
C_3			1	5.000	0.200	0.200	0.200			1	3.649	0.201	0.206	0.207
C_4				1	0.200	0.200	1.000				1	0.189	0.194	0.643
C_5					1	1.000	1.000					1	1.025	1.030
C_6						1	1.000						1	1.003
C_7							1							1
W	0.136	0.099	0.060	0.056	0.227	0.199	0.223	0.136	0.099	0.056	0.047	0.235	0.206	0.222

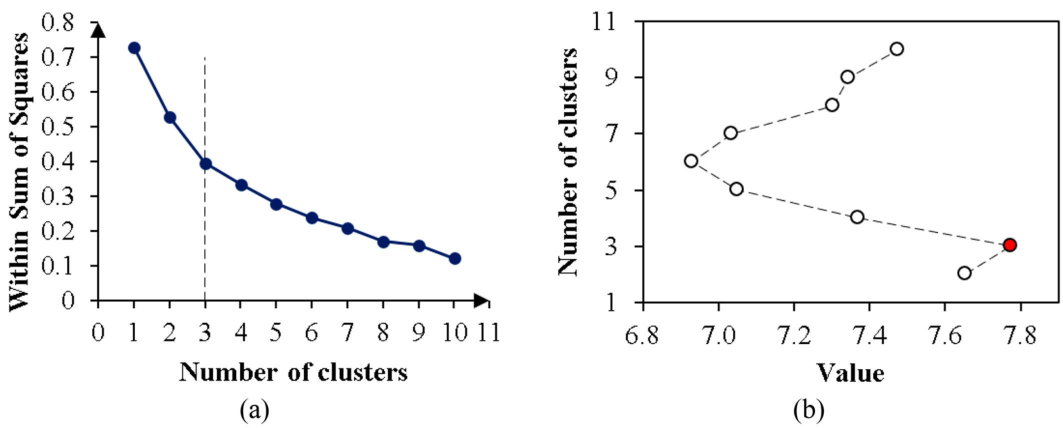

Fig. 5 Optimal number of clusters to group the opinions of the experts regarding the conservation criteria **a** Elbow criterion **b** Calinski-Harabasz index

Table 5 Weighting clusters obtained after aggregating the comparisons provided by the experts

Cluster	Criterion						
	C_1	C_2	C_3	C_4	C_5	C_6	C_7
1 (n = 11)	0.105	0.146	0.057	0.085	0.171	0.204	0.177
2 (n = 6)	0.182	0.144	0.054	0.230	0.138	0.071	0.122
3 (n = 8)	0.229	0.217	0.085	0.075	0.074	0.105	0.159

The three groups obtained using the k-means algorithm were rather balanced in size, since they were formed by 11, 6 and 8 experts, respectively. The aggregation of weights for these groups using the DBW approach led to the values contained in Table 5. The first cluster (CL) focused on the attractiveness of the elements, emphasizing their reusability (C_5), sociocultural interest (C_6) and preservation of the testimony of the power plant (C_7). This is in line with the main trends found in the literature, in which industrial landscapes are deemed to constitute a testimony of the cultural, social and economic conception of a place [69, 70].

Other authors coincide with the second cluster of experts in preferring a more pragmatic angle to address industrial heritage, pointing out to the importance of production processes (C_1) in comparison with modern practices [71] and ease of conservation (C_4) [72]. The relevance of the operation in the plant (C_1) was also underlined by the third cluster, whose other main priority laid on the uniqueness of the elements

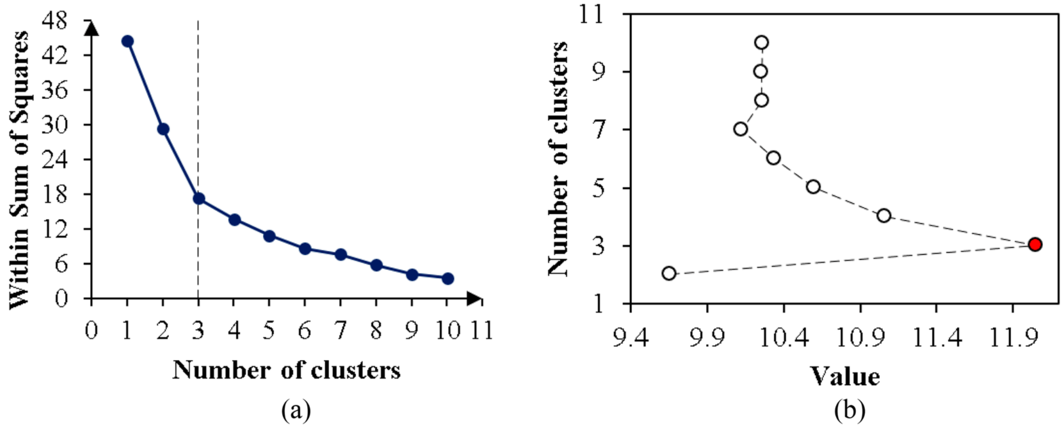

Fig. 6 Optimal number of clusters to group the opinions of the experts regarding the elements to be preserved **a** Elbow criterion **b** Calinski-Harabasz index

Table 6 Weighted ratings per cluster obtained after aggregating the comparisons provided by the experts

Element	Criterion / Cluster ($CL_1 \rightarrow n=5$; $CL_2 \rightarrow n=12$; $CL_3 \rightarrow n=1$)																				
	C_1			C_2			C_3			C_4			C_5			C_6			C_7		
	CL_1	CL_2	CL_3	CL_1	CL_2	CL_3	CL_1	CL_2	CL_3	CL_1	CL_2	CL_3	CL_1	CL_2	CL_3	CL_1	CL_2	CL_3	CL_1	CL_2	CL_3
E_1	3.7	3.0	1.0	3.6	2.8	1.0	3.6	2.3	1.0	3.6	2.4	1.0	3.6	3.3	1.0	4.1	2.8	2.0	4.0	2.9	2.0
E_2	3.4	2.4	1.0	2.9	2.4	1.0	2.7	1.8	1.0	3.7	2.2	1.0	3.0	2.3	1.0	3.7	2.2	2.0	3.7	2.4	2.0
E_3	4.3	3.0	2.0	3.3	3.0	1.0	3.1	2.8	1.0	3.2	2.4	2.0	2.6	2.0	1.0	4.1	2.6	2.0	4.5	3.2	2.0
E_4	3.9	2.8	2.0	2.9	2.7	1.0	2.7	2.9	1.0	3.0	2.5	2.0	2.3	1.8	1.0	3.8	2.4	1.0	4.0	2.6	2.0
E_5	4.8	3.4	3.0	4.0	3.0	1.0	3.9	3.1	2.0	3.2	2.5	3.0	3.5	2.3	2.0	4.6	2.8	2.0	4.8	3.3	3.0
E_6	4.8	3.8	3.0	4.2	3.4	1.0	4.6	3.5	1.0	3.7	2.9	3.0	3.2	1.9	3.0	4.6	3.2	3.0	4.6	3.1	3.0
E_7	3.7	2.9	2.0	2.9	2.2	1.0	2.7	2.2	1.0	3.2	2.2	2.0	1.9	1.6	2.0	3.9	2.2	2.0	4.1	2.8	2.0
E_8	3.3	2.1	1.0	2.7	2.0	1.0	2.5	1.9	1.0	3.5	2.3	1.0	3.1	1.7	1.0	3.5	2.2	2.0	3.3	2.4	2.0
E_9	4.8	4.0	2.0	4.2	3.3	1.0	4.4	3.6	1.0	3.7	2.8	2.0	4.5	3.0	2.0	4.6	3.2	3.0	4.8	3.6	3.0
E_{10}	4.8	3.7	3.0	4.3	3.3	1.0	4.8	3.6	3.0	3.4	2.8	2.0	3.7	3.0	3.0	4.8	3.2	3.0	4.4	3.6	3.0
E_{11}	4.4	2.9	2.0	3.4	2.8	1.0	3.1	2.7	1.0	4.2	2.3	2.0	1.9	1.9	3.0	3.9	2.4	2.0	4.6	2.8	3.0
E_{12}	3.2	2.6	1.0	2.7	2.4	1.0	2.6	2.0	1.0	3.3	2.2	1.0	2.0	1.8	1.0	3.0	2.2	1.0	3.4	2.9	2.0
E_{13}	3.9	3.1	1.0	2.5	2.8	1.0	3.4	2.7	1.0	3.2	2.7	1.0	2.8	2.3	1.0	3.3	2.8	1.0	3.9	3.1	2.0
E_{14}	4.0	2.7	1.0	3.3	2.2	1.0	3.5	2.5	2.0	4.0	2.3	2.0	3.1	2.0	2.0	3.8	2.3	1.0	4.0	2.7	2.0
E_{15}	3.0	2.7	1.0	2.6	2.2	1.0	2.8	2.2	1.0	3.6	2.1	1.0	2.1	2.0	1.0	3.2	2.5	1.0	3.4	2.9	2.0
E_{16}	2.7	2.2	1.0	2.4	2.2	1.0	2.6	2.1	1.0	3.2	2.4	2.0	3.1	2.4	1.0	2.9	2.2	1.0	3.9	2.4	2.0

(C_2). The singularity and representativeness of industrial elements as an indicator of scientific and technological progress has also been considered a priority in some recent investigations in the field [73, 74].

Rating of potential elements to preserve

The responses received to the second questionnaire resulted in 18 matrices including the rating of the 16 elements considered (Table 2) across the 7 criteria (Table 1). Hence, cluster analysis could not be applied straightforwardly in this case. Instead, the mean ratings allocated by the experts to each element were determined as a previous step. Then, the optimal number of clusters was calculated from these mean values. Again, both the Elbow criterion and the Calinski-Harabasz index indicated that this number was 3, as depicted in Fig. 6.

The resulting groups obtained by applying the k-means algorithm were unevenly distributed, to the extent that the third cluster was formed by only one expert. These groups were arranged depending on how the experts

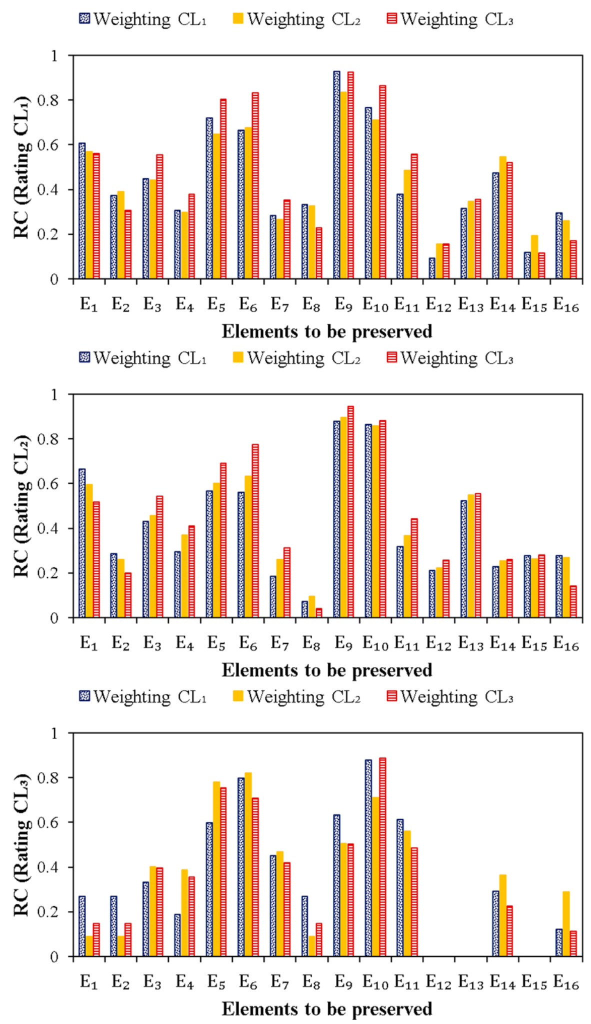

Fig. 7 Values of Relative Closeness (***RC$_i$***) achieved for each rating and weighting cluster (CL) under consideration

rated the contribution of the elements to fulfilling each criterion, from high (CL_1) to low (CL_3). Table 6 compiles the weighted values corresponding to each cluster after aggregating the original ratings provided by the experts using the DBW method.

The joint consideration of weighting and rating clustering yielded 3 groups each, leading to 9 scenarios of results (3 * 3) that stemmed from applying the TOPSIS method from the values in Table 6. Then, each normalized weighted matrix was multiplied by the 3 vectors of weights shown in Table 5. Finally, after the calculation of the distances to the ideal solutions, Eq. (2) was applied to determine the relative closeness (RC_i) of the elements. Figure 7 illustrates the results achieved through this process, broken down according to weighting and rating clusters.

Table 7 Key elements to preserve depending on the combination of rating and weighting clusters

Rating CL	Weighting CL	Third quartile (Q_3)	Elements above Q_3
1	1	0.623	E_5, E_6, E_9, E_{10}
	2	0.589	E_5, E_6, E_9, E_{10}
	3	0.620	E_5, E_6, E_9, E_{10}
2	1	0.561	E_1, E_5, E_9, E_{10}
	2	0.596	E_5, E_6, E_9, E_{10}
	3	0.590	E_5, E_6, E_9, E_{10}
3	1	0.603	E_6, E_9, E_{10}, E_{11}
	2	0.519	E_5, E_6, E_{10}, E_{11}
	3	0.489	E_5, E_6, E_9, E_{10}

The calculation of the third quartile (Q_3) of the values of RC_i for each scenario indicated the most preferred 25% elements under all clustering combinations. As shown in Table 7, E_{10} (cooling towers) was the only element above Q_3 in all cases, followed by E_5 (boiler), E_6 (chimney) and E_9 (turbine hall), which were one of the four elements selected in eight out of the nine scenarios under study.

These four elements formed the shortlisted combination of items to be preserved in six scenarios, which highlighted the solidity and convergence of the results achieved. The consideration of the scenarios derived from the clustering of experts was enlightening, since their coincidence guaranteed the robustness of the proposed approach. Potential decisions to be made in relation to the dismantling of the As Pontes power plant could benefit from the convergence of these results, which can support the strategic safeguard of high priority elements under all scenarios. If the results were not so convergent as in Table 7, a solution may consist of circulating a reduced questionnaire where the elements reaching low positions in the different scenarios are removed. This might facilitate achieving consensual responses due to the limited number of options to assess by the experts.

Discussion

The elements obtaining the best ranking were in line with the criteria valued with the highest mean weights by the experts (Table 5), which concerned the technical (C_1) and historical (C_7) importance of the elements, as well as their singularity (C_2). As shown in Fig. 4, most of the experts were academics with extensive experience in industrial heritage. This also supports the ranking of the elements in Table 7, which are of great interest in terms of research because of their complexity and magnitude, as illustrated in Fig. 8. Instead, water treatment plants (E_{15} and E_{17}) were the least valued elements under all scenarios. The low ranking of these elements may lie on

Fig. 8 **a** General view of the As Pontes power plant elements shortlisted for preservation. Details of the **b** boilers and **c** turbine hall

the fact that they are not particularly representative of the operation of a power plant.

The relevance of the four elements depicted in Fig. 8 was also supported by the literature. According to the US Environmental Protection Agency (EPA) [75], thousands of industrial facilities use large volumes of water to control temperature, for which cooling towers provide a cost-effective and energy efficient solution. As in the case of the As Pontes power plant, the size of these elements can make them impactful in visual terms [76], which also justifies their interest for conservation. Landscape, scenery and panorama also play a key role in cultural and industrial heritage through the socio-cultural footprint left by these activities. This research found that visual impact is substantial in the decision-making process, which follows up from Nadkarni and Puthuvayi [20] and Kraetzig et al. [76].

The preponderance of the boiler and turbine hall provide further evidence of the importance of managing the different states of water in thermal power plants, for which safeguarding elements with great value in terms of technological processing and production is crucial [77, 78]. Instead, the ranking achieved by the chimney might be rather justified by its impressive magnitude, which in this case amounted to more than 350 m height. As emphasized by Ali and Al-Kodmany [79], humans have always admired tall structures since ancient times, so that conserving large elements might help attract more visitors [80].

The As Pontes power plant currently has four cooling towers (E_{10}), of which only one is proposed to be preserved. The conservation suggestions for this element concern its use as an exhibition space for culture (high ventilation in summer) or plastic arts (painting, sculpture, etc.). The turbine hall (E_9) may perform as a future interpretation centre, including evidence of the control systems, computers and other relevant devices for the production process of the plant.

The chimney (E_6) could be safeguarded as a heritage icon, such that it might be used as an elevator with panoramic view or an environmental station. E_5 consists of 4 boilers, of which one is proposed to remain in its original condition and the others to be used as a business incubator. This would entail an auxiliary structure to create different floors and opening holes in the walls to be used as windows.

The other elements highlighted in Table 7 were the coal park (E_1) and the substation transformer (E_{11}). The proposed conservation items for E_1 are the suspended structure, a stacker-picker machine and part of the conveyor belts, enabling potential uses such as biomass-related industrial activities or open-space for holding events of great magnitude. As for E_{11}, substation transformers are elements whose adaption to new uses is complicated. As such, their conservation is proposed as a testimony of their contribution to the generation and transmission of electrical energy.

These proposals received the approval of the controller of the city council, who confirmed the interest of the major in safeguarding the As Pontes plant through new uses. Both looked favourably upon the proposed measures due to their potential for developing new activities. In this sense, a few employees of the plant might be relocated to new jobs related to these new uses, serving as tour guides in charge of explaining different parts of the production process in the plant. The involvement of former workers for heritage purposes would entail social benefits by providing visitors with a sense of rootedness with the area and the important role played by the plant in its historic and cultural development.

Although these employments would be limited in number, this approach may work better than dismantling the plant and try attracting new industries, since the main interest of this area has traditionally been a lignite mine that was closed 15 years ago. In this vein, Da silva et al. [25] showed the path towards the cultural exploitation of old mines by implementing other views such as safety features and priority locations.

This research helps in paving the way to further industrial heritage practice by using MCDA questionnaires in order to identify paramount interventions for conservation in industrial heritage, following to this end the suggestions from previous investigations implemented in the affine area of building heritage [18, 19]. These preceding works stressed the need to prioritize minimal interventions, reversible actions, sustainability and liveability [19].

Overall, these results, which stem from expert evaluation and research, provide the first step towards the conversion of engineering-related sites into heritage assets. As such, they can be valuable if adopted by governmental bodies at local, regional and national levels to design developmental strategies and policies for regulating industrial heritage. Otherwise, democratizing the valorisation of industrial facilities would be difficult. Furthermore, previous investigations pointed out that a combination of expert's knowledge and MCDA were the preferred methodology to select the best strategy to follow in building heritage [21]. The implementation of these practices can entail important benefits across the three pillars of sustainability, since the environmental benefits derived from the closure of industrial facilities might be combined with economic and social developments through local employment creation and increased tourism.

Conclusions

The outcomes of this study support the preservation of industrial facilities according to their heritage values. The proposed methodology enabled processing the feedback provided by a panel of international experts regarding the criteria and elements involved in the conservation of the As Pontes power plant, whose closure is forecasted to take place in 2022. The variety of responses received led to a series of conservation scenarios that were evaluated separately to ensure the robustness of the results achieved.

All these scenarios coincided in pointing out to four elements that should be preserved to leave testimony of the As Pontes power plant: cooling towers, turbine hall, chimney and boilers. Their predominance laid on their primary role in the production process of coal-fired electricity generation, ease of conservation, sociocultural interest or potential to be adapted for new uses. In this vein, the potential uses proposed for these elements are as follows: business incubator, exhibition area for cultural or plastic arts, interpretation centre or panoramic elevator. The preponderance of these elements could also be related to the concept of liveability in building heritage, since it can be correlated to building functionality from a social perception.

These results can be helpful for the decision-makers of the region where the As Pontes plant is located. The owner of the plant has presented a demolition project that is currently under review. In view of the difficulties in establishing new industrial activities in this area due to increasing environmental and energy requirements, the potential uses proposed in this investigation provide alternatives for valorising a facility with which the community has a strong sense of connection due to its presence and importance in the region for almost 50 years.

This link with the community goes beyond the importance of the facility in terms of employment and economic activity. The space where the lignite mine used to be has been flooded and converted into a lagoon, whilst its waste dump has been remodelled and revegetated, favouring the presence of a variety of ecosystems in the area. This process of revitalization has contributed to strengthening the bonds of the people with the area. As such, the valorisation of the plant for heritage purposes would further increase the value of the area by combining historical, cultural, industrial and natural values.

Overall, the outputs obtained can aid decision-making processes related to the conservation of industrial assets at an urban planning level. Increasing regulatory demands in terms of CO_2 emissions are leading to the closure of many industrial sites. The adoption of support tools such as the proposed methodology provides an alternative to the dismantling of these facilities. This favours their valorisation in the form of heritage areas intended to leave testimony of the industrial and economic activity of a region, which are in turn linked to its social and cultural history.

Still, the scope of these outputs is narrowed by certain limitations. Although the conservation criteria were set following governmental recommendations, involving the experts in this step too might have been enriching. In fact, participation may have been approached differently to include other stakeholders (authorities, citizens, etc.) and, therefore, have a more representative picture of the interests of all the parties involved. This could also facilitate having a larger sample of participants, which is another aspect with margin for improvement.

Although the mathematical models used were combined to result in a flexible methodology, more emphasis might be placed on handling the opinions collected from participatory processes. In this sense, fuzzy logic might be a useful tool to better capture the vagueness inherent in linguistic opinions. Furthermore, the format of the participatory process may also be revised to explore the inclusion of two or more rounds to facilitate reaching consensus.

In consequence, future efforts to continue this line of research should focus on the refinement of conservation criteria according to the appreciations of experts, whose participation in this step might help better characterize the situation. Another course of action may focus on testing the proposed methodology with other industrial facilities involving different conservation criteria and elements. Its usefulness and applicability might also be enhanced if automated as a web-based tool. In what concerns the case study, future approaches could focus on organizing workshops to share the results of this investigation with the community. This would enable measuring the acceptance of the proposed measures and adapting them according to the public opinion, while collecting ideas regarding their implementation.

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Author contributions
ÁM-R conceived the research; ÁM-R characterised the case study; DJ-E designed and applied the methodology; ÁM-R, DJ-E and LAS-F analysed the results; AM-C, ÁM-R, DJ-E and LAS-F contributed to inviting experts; DJ-E and LAS-F wrote the manuscript; AM-C, ÁM-R, DJ-E and LAS-F revised the manuscript. All authors read and approved the final manuscript.

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Competing interests
The authors declare that they have no competing interests.

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References

1. Wailes R. The Industrial Monuments Survey. Technol Cult. 1967;8:199–203.
2. TICCIH. Guiding Principles & Agreements. The International Committee For The Conservation Of The Industrial Heritage. 2022. https://ticcih.org/about/about-ticcih/.
3. TICCIH. The Nizhny Tagil Charter for the Industrial Heritage. Moscow (Russia): The International Committee For The Conservation Of The Industrial Heritage; 2003 p. 4. https://www.icomos.org/18thapril/2006/nizhny-tagil-charter-e.pdf.
4. del Pozo PB, Calderón Calderón B, Ruiz-Valdepeñas HP. Territorial management of industrial heritage in Castilla y León (Spain): factories and landscapes. Investigaciones Geograficas. 2016;2016:136–54.
5. Spanish Ministry of Education, Culture and Sport. Plan Nacional de Patrimonio Industrial [Spanish Industrial Heritage Plan]. Madrid (Spain): Spanish Ministry of Education, Culture and Sport; 2015 p. 46.
6. Lin C-L. The analysis of sustainable development strategies for industrial tourism based on IOA-NRM approach. J Clean Prod. 2019;241:118281.
7. Gani A. Fossil fuel energy and environmental performance in an extended STIRPAT model. J Clean Prod. 2021;297:126526.
8. Ifko S, Stokin M. Protection and Reuse of Industrial Heritage: Dilemmas, Problems, Examples. Ljubljana (Slovenia): ICOMOS Slovenia; 2018 p. 147. Report No.: 2. http://www.icomos.si/files/2015/06/publication-icomos-slovenia-2.pdf.
9. Śladowski G, Szewczyk B, Barnaś K, Kania O, Barnaś J. The Boyen Fortress: structural analysis of selecting complementary forms of use for a proposed adaptive reuse project. Herit Sci. 2021;9:76.
10. Bottero M, D'Alpaos C, Oppio A. Ranking of adaptive reuse strategies for abandoned industrial heritage in vulnerable contexts: a multiple criteria decision aiding approach. Sustain (Switzerland). 2019;11:785.
11. Langston C, Wong FKW, Hui ECM, Shen L-Y. Strategic assessment of building adaptive reuse opportunities in Hong Kong. Build Environ. 2008;43:1709–18.
12. Ferretti V, Bottero M, Mondini G. Decision making and cultural heritage: an application of the Multi-Attribute Value Theory for the reuse of historical buildings. J Cult Herit. 2014;15:644–55.
13. Bottero M, D'Alpaos C, Marello A. An application of the a'WOT analysis for the management of cultural heritage assets: the case of the historical farmhouses in the aglie castle (Turin). Sustain (Switzerland). 2020;12:1071.
14. Sturiale L, Scuderi A, Timpanaro G, Matarazzo B. Sustainable use and conservation of the environmental resources of the etna park (unesco heritage): evaluation model supporting sustainable local development strategies. Sustain (Switzerland). 2020;12:1453.
15. Ferretti V, Comino E. An integrated framework to assess complex cultural and natural heritage systems with Multi-Attribute Value Theory. J Cult Herit. 2015;16:688–97.
16. Ribera F, Nesticò A, Cucco P, Maselli G. A multicriteria approach to identify the Highest and Best Use for historical buildings. J Cult Herit. 2020;41:166–77.
17. Della Spina L. Adaptive sustainable reuse for cultural heritage: a multiple criteria decision aiding approach supporting urban development processes. Sustain (Switzerland). 2020;12:1363.
18. Dutta M, Husain Z. An application of Multicriteria Decision Making to built heritage. The case of Calcutta. J Cult Herit. 2009;10:237–43.
19. Li Y, Zhao L, Huang J, Law A. Research frameworks, methodologies, and assessment methods concerning the adaptive reuse of architectural heritage: a review. Built Herit. 2021;5:6.
20. Nadkarni RR, Puthuvayi B. A comprehensive literature review of Multi-Criteria Decision Making methods in heritage buildings. J Building Eng. 2020;32:101814.
21. Morkūnaitė Ž, Kalibatas D, Kalibatienė D. A bibliometric data analysis of multi-criteria decision making methods in heritage buildings. J Civil Eng Manage. 2019;25:76–99.
22. Pavlovskis M, Migilinskas D, Antucheviciene J, Kutut V. Ranking of heritage building conversion alternatives by applying BIM and MCDM: A case of Sapieha Palace in Vilnius. Symmetry. 2019;11:973.
23. Turskis Z, Morkunaite Z, Kutut V. A hybrid multiple criteria evaluation method of ranking of cultural heritage structures for renovation projects. Int J Strategic Property Manage. 2017;21:318–29.
24. Haroun H-AAF, Bakr AF, Hasan AE-S. Multi-criteria decision making for adaptive reuse of heritage buildings: Aziza Fahmy Palace, Alexandria, Egypt. Alexandria Eng J. 2019;58:467–78.
25. da Silva Borges Barbosa V, Mota de Lima H, Fonseca BM. Assessing risks of abandoned urban mines in the UNESCO World Heritage City of Ouro Preto, Brazil. Appl Geogr. 2022;139:102648.
26. Eldiasty A, Sabry Hegazi Y, El-Khouly T. Using space syntax and TOPSIS to evaluate the conservation of urban heritage sites for possible UNESCO listing the case study of the historic centre of Rosetta, Egypt. Ain Shams Eng J. 2021;12:4233–45.
27. Vehbi BO, Günçe K, Iranmanesh A. Multi-criteria assessment for defining compatible new use: Old administrative hospital, Kyrenia, Cyprus. Sustainability (Switzerland). 2021;13:1922.
28. Salerno E. Identifying value-increasing actions for cultural heritage assets through sensitivity analysis of multicriteria evaluation results. Sustain (Switzerland). 2020;12:9238.
29. Vatn A. An institutional analysis of methods for environmental appraisal. Ecol Econ. 2009;68:2207–15.
30. Mendoza GA, Martins H. Multi-criteria decision analysis in natural resource management: a critical review of methods and new modelling paradigms. For Ecol Manag. 2006;230:1–22.
31. Keune H, Dendoncker N. Negotiated complexity in ecosystem services science and policy making ecosystem services: global issues, local practices. Amsterdam (The Netherlands): Elsevier; 2013. p. 167–80.
32. Locatelli B, Rojas V, Salinas Z. Impacts of payments for environmental services on local development in northern Costa Rica: a fuzzy multi-criteria analysis. For Policy Econ. 2008;10:275–85.
33. Stirling A. Analysis, participation and power: justification and closure in participatory multi-criteria analysis. Land Use Policy. 2006;23:95–107.
34. Hanley N. Cost—benefit analysis and environmental policy making. Environ Plann C Gov Policy. 2001;19:103–18.
35. Endesa. Declaración ambiental 2015 - UPT, As P. [2015 Environmental declaration - As Pontes power plant]. Madrid (Spain): Endesa; 2015 p. 78. http://multimedia.cmati.xunta.es/Declaracion_Medioambiental_ENDESA_GENERACION_UPT_AS_PONTES_castellano_fi___.pdf.
36. Endesa. Educa As Pontes: La Explotación Minera [Educa As Pontes: Mining Exploitation]. Historia. 2021. https://www.fundacionendesa.orghttps://fundacionendesa.org/es/biodiversidad/educaspontes/as-pontes-historia.
37. El País. Endesa formaliza la petición de cierre de las plantas de As Pontes y Carboneras [Endesa formalizes the request to close the As Pontes and Carboneras plants]. El País. Madrid (Spain); 2019. https://elpais.com/economia/2019/12/27/actualidad/1577456577_638724.html.
38. Kizielewicz B, Dobryakova L. MCDA based approach to sports players' evaluation under incomplete knowledge. Procedia Comput Sci. 2020;176:3524–35.
39. Wahlster P, Goetghebeur M, Kriza C, Niederländer C, Kolominsky-Rabas P. Balancing costs and benefits at different stages of medical innovation: a systematic review of Multi-criteria decision analysis (MCDA). BMC Health Serv Res. 2015;15:262.
40. BOE. Anuncio del Área de Industria y Energía de la Delegación del Gobierno. en Galicia por el que se somete a información pública el proyecto "Desmantelamiento de los grupos 1, 2, 3 y 4 de la central termoeléctrica de As Pontes en el TM de As Pontes de García Rodríguez (A Coruña)", así como su correspondiente Estudio de Impacto Ambiental [Announcement from the Industry and Energy Area of the Government Delegation in Galicia, whereby the project "Dismantling of groups 1, 2, 3 and 4 of the As Pontes thermoelectric plant in the As Pontes de García Rodríguez (A Coruña)" is subject to public information, as well as its corresponding Environmental Impact Study]. BOE-B-2021-34275. Sect. V-B., 34275 Jul 28, 2021 p. 46066–8. https://www.boe.es/diario_boe/txt.php?id=BOE-B-2021-34275.

41. Wang Q, Yang C, Tian L, Lu J, Wu F, An J. Safety risk assessment of heritage buildings in metro construction based on SPA theory: a case study in Zhengzhou, China. Herit Sci. 2020;8:100.
42. Wang X, Wang Y, Guo Q, Pei Q, Zhao G. The history of rescuing reinforcement and the preliminary study of preventive protection system for the cliff of Mogao Grottoes in Dunhuang, China. Herit Sci. 2021;9:58.
43. Cui K, Du Y, Zhang Y, Wu G, Yu L. An evaluation system for the development of scaling off at earthen sites in arid areas in NW China. Herit Sci. 2019;7:14.
44. Li J, Chen Y, Yao X, Chen A. Risk Management Priority Assessment of heritage sites in China Based on Entropy Weight and TOPSIS. J Cult Herit. 2021;49:10–8.
45. Al-Sakkaf A, Bagchi A, Zayed T, Mahmoud S. Sustainability assessment model for heritage buildings. Smart Sustainable Built Environ. 2021;23:89.
46. Mishra PS, Muhuri S. Grading of architectural heritage using AHP and TOPSIS methods: a case of Odishan Temple, India. J Cult Herit Manag Sustain Develop. 2021;74:890.
47. Zhang B, Li C-C, Dong Y, Pedrycz W. A Comparative Study Between Analytic Hierarchy Process and Its Fuzzy Variants: A Perspective Based on Two Linguistic Models. IEEE Trans Fuzzy Syst. 2021;29:3270–9.
48. Shih H-S, Shyur H-J, Lee ES. An extension of TOPSIS for group decision making. Math Comput Model. 2007;45:801–13.
49. Zadeh LA. Fuzzy sets. Inf Control. 1965;8:338–53.
50. Chen L, Duan G, Wang S, Ma J. A Choquet integral based fuzzy logic approach to solve uncertain multi-criteria decision making problem. Expert Syst Appl. 2020;149:113303.
51. Chen Z-S, Yang Y, Wang X-J, Chin K-S, Tsui K-L. Fostering linguistic decision-making under uncertainty: A proportional interval type-2 hesitant fuzzy TOPSIS approach based on Hamacher aggregation operators and andness optimization models. Inf Sci. 2019;500:229–58.
52. Ma J, Harstvedt JD, Jaradat R, Smith B. Sustainability driven multi-criteria project portfolio selection under uncertain decision-making environment. Comput Ind Eng. 2020;140:106236.
53. R Core Team. R: The R Project for Statistical Computing. 2022. https://www.r-project.org/index.html.
54. Saaty TL. The analytic hierarchy process: planning, priority setting, resource allocation. 2nd ed. New York: McGraw-Hill International Book Co.; 1980.
55. Saaty TL. How to make a decision: the analytic hierarchy process. Eur J Oper Res. 1990;48:9–26.
56. Jato-Espino D, Indacoechea-Vega I, Gáspár L, Castro-Fresno D. Decision support model for the selection of asphalt wearing courses in highly trafficked roads. Soft Comput. 2018;22:7407–21.
57. Smeers Y. Generalized reduced gradient method as an extension of feasible direction methods. J Optim Theory Appl. 1977;22:209–26.
58. Jaffray JY. Some experimental findings on decision making under risk and their implications. Eur J Oper Res. 1989;38:301–6.
59. Hwang C-L, Yoon K. Multiple Attribute Decision Making. Berlin: Springer Berlin Heidelberg; 1981.
60. Ehlert KM, Faber CJ, Kennedy MS, Benson L. Utilizing cluster analysis of close-ended survey responses to select participants for qualitative data collection Quantitative Research Methods. Columbus: American Society for Engineering Education (ASEE). 2017. p. 18265.
61. Hassan MM, Blom M. Applying clustering to analyze opinion diversity. In: ACM International Conference Proceeding Series. Nanjing (China); 2015. p. 1–10.
62. Tryon RC. Cluster analysis; correlation profile and orthometric (factor) analysis for the isolation of unities in mind and personality. 1st ed. Ann Arbor: Edwards Brothers, Inc.; 1939.
63. Syakur MA, Khotimah BK, Rochman EMS, Satoto BD. Integration K-Means Clustering Method and Elbow Method for Identification of the Best Customer Profile Cluster. In: IOP Conference Series: Materials Science and Engineering. Surabaya (Indonesia); 2018. p. 012017.
64. Lukasik S, Kowalski PA, Charytanowicz M, Kulczycki P. Clustering using flower pollination algorithm and Calinski-Harabasz index. Vancouver (Canada): IEEE; 2016. p. 2724–8.
65. Steinley D. K-means clustering: a half-century synthesis. Br J Math Stat Psychol. 2006;59:1–34.
66. Beullens K, Loosveldt G, Vandenplas C, Stoop I. Response Rates in the European Social Survey: Increasing, Decreasing, or a Matter of Fieldwork Efforts? Survey Methods, Insights from the Field (SMIF). Survey Methods, Insights from the Field (SMIF); 2018;18:1–10.
67. Menon V, Muraleedharan A. Internet-based surveys: Relevance, methodological considerations and troubleshooting strategies. Gen Psychiatry. 2020;33:e100264.
68. Sato Y. Comparison between multiple-choice and analytic hierarchy process: measuring human perception. Int Trans Oper Res. 2004;11:77–86.
69. Loures L. Industrial heritage: the past in the future of the city. WSEAS Trans Environ Dev. 2008;4:687–96.
70. Xie PF. A life cycle model of industrial heritage development. Ann Tourism Res. 2015;55:141–54.
71. Szromek AR, Herman K, Naramski M. Sustainable development of industrial heritage tourism – A case study of the Industrial Monuments Route in Poland. Tour Manag. 2021;83:104252.
72. Yung EHK, Lai LWC, Yu PLH. Public decision making for heritage conservation: A Hong Kong empirical study. Habitat Int. 2016;53:312–9.
73. Claver J, Sebastián MA, Sanz-Lobera A. Opportunities of the Multicriteria Methods in the Study of Immovable Assets of the Spanish Industrial Heritage. The Manufacturing Engineering Society International Conference, MESIC 2015. Barcelona (Spain): Elsevier; 2015. p. 175–82.
74. Pardo Abad CJ. Valuation of industrial heritage in terms of sustainability: Some cases of tourist reference in spain. Sustain (Switzerland). 2020;12:1–23.
75. US EPA. Cooling Water Intakes. United States Environmental Protection Agency. 2015. https://www.epa.gov/cooling-water-intakes.
76. Kraetzig WB, Harte R, Montag U, Woermann R. From large natural draft cooling tower shells to chimneys of solar upwind power plants. Evolution and Trends in Design, Analysis and Construction of Shell and Spatial Structures: Proceedings. Valencia (Spain): Editorial Universitat Politècnica de València; 2009. p. 2–17.
77. Zhang J, Cenci J, Becue V, Koutra S. The overview of the conservation and renewal of the industrial belgian heritage as a vector for cultural regeneration. Inform (Switzerland). 2021;12:27.
78. Panagopoulou A, Vroom J, Hein A, Kilikoglou V. Production technology of glazed pottery in chalcis, euboea, during the middle byzantine period. Heritage. 2021;4:4473–94.
79. Ali MM, Al-Kodmany K. Tall buildings and Urban habitat of the 21st century: a global perspective. Buildings. 2012;2:384–423.
80. Bleker J. Redevelopment of large-scale industrial heritage. Delft (The Netherlands): Delft University of Technology, Faculty of Architecture and the Built Environment; 2015 p. 37. Report No.: 4022769. https://repository.tudelft.nl/islandora/object/uuid:908accad-460a-4128-8c7d-ce67e85ac448/datastream/OBJ1/download.

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