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Strategies for decommissioning small nuclear reactors in Brazil

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ABSTRACT

The process of decommissioning nuclear reactors is a complex activity that involves various technical and administrative stages. Its main objective is to ensure the safety of the site, workers, the general public, and the environment during the execution of decommissioning activities, aiming for the release of the site from regulatory control. In the Brazilian context, it is essential to develop decommissioning strategies, taking into consideration the established technical and regulatory requirements, as well as following the guidelines of the Brazilian Nuclear Policy (BNP). Eight decommissioning strategies were proposed for small reactors, with different objectives and in different scenarios, encompassing 23 decommissioning approaches, divided into 6 groups: 1) decontamination and dismantling (DD); 2) radioactive waste (RW) management; 3) RW storage management; 4) human resources (HR) and knowledge management; 5) cost estimation; and 6) financial fund management. Additionally, 18 factors affecting the selection of these approaches were considered, taking into account particularities of the Brazilian context. A qualitative risk analysis was conducted using risk assessment techniques from the ABNT NBR ISO/IEC 31,010 standard, with a focus on the Multicriteria Decision Analysis (MCDA) technique. This qualitative analysis allowed for the evaluation of the approaches considering the current scenario and the future scenario, which includes possible changes in the BNP currently under discussion in the National Congress. The observations and results obtained in this study will be useful in guiding future efforts related to nuclear reactor decommissioning projects in Brazil. Based on the proposed strategies and considerations of safety, regulation, and governmental policies, it will be possible to plan and execute decommissioning activities more efficiently and safely.

1. Introduction

The decommissioning project is a complex undertaking that can take decades to plan and execute. It begins with the development of an Initial Decommissioning Plan (IDP) during the facility's construction phase, which accompanies the entire construction and operational phases. At the end of the facility's lifespan, a Final Decommissioning Plan (FDP) is prepared, which must be approved by the relevant regulatory body before decommissioning activities begin. Approval of the FDP is essential to ensure that decommissioning activities are carried out safely. The execution phase of decommissioning begins after the approval of the FDP and concludes when dismantling, decontamination, and cleanup are completed, and the license can be terminated (IAEA, 2019). Fig. 1 illustrates the phases of decommissioning.

The decommissioning project is characterized by a significant amount of uncertainties and challenges that need to be addressed from the early stages of the construction project. The IDP is developed during this initial phase, but little to no detail may be available, such as DD technologies, the availability of RW storage facilities, financial resources, HR, among others. On the other hand, the FDP is associated with the detailed execution of technical and administrative activities and cannot tolerate uncertainties. The FDP is used to dictate the actual execution of decommissioning work and to map the hazards involved in this process. Therefore, both plans are important for the success of the decommissioning project, but in distinct phases and with the same objectives.

The IAEA recommends (IAEA, 2014) that the decommissioning project be conducted in line with the regulatory framework and the country's technical, administrative, social, environmental, and economic considerations. To achieve the desired final state for the facility, the IAEA suggests adopting one of the three decommissioning strategies: immediate dismantling (DECON), deferred dismantling (SAFSTOR), and entombment (ENTOMB). However, only the first two are applicable. The strategy of entombment or leaving the facility in place after operation

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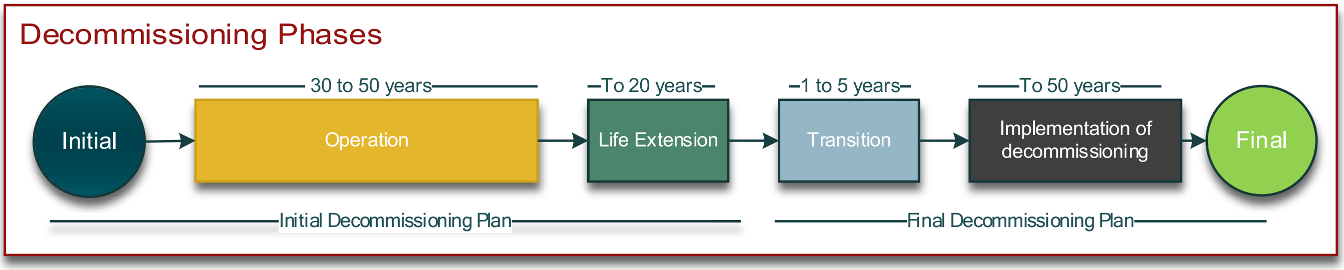

Fig. 1. Decommissioning Phases .
Source: INTERNATIONAL ATOMIC ENERGY AGENCY, 2004

and relying on radioactive decay is not acceptable due to its potential negative impact on future generations (Suh et al., 2018).

In Brazil, there is no experience in implementing nuclear reactor decommissioning projects, which may result in gaps that need to be addressed. With the growth of nuclear activities foreseen in the National Energy Plan 2050 (PNE2050) , the prioritization of small nuclear reactor construction, and considering recent regulatory changes, it becomes important to propose strategies for the future decommissioning activities of these reactors. Among the various aspects to be considered, key areas include DD activities, RW management, HR management, and financial resource management.

In the analysis of the strategies, the risk assessment techniques from the ABNT NBR ISO/IEC 31,010 standard (ABNT, 2012) were employed. The key factors that affect the decision-making in the decommissioning approaches were identified, analyzed, and assessed. Through these techniques, a methodology for the development of nuclear reactor decommissioning strategies in Brazil was devised. Applying this methodology, eight strategies were developed with different objectives, tailored to the Brazilian scenario in the year 2023 and in the future.

2. Methodologies of the work

The process of developing decommissioning strategies involved identifying all the necessary activities for decommissioning and applying the MCDA technique for the selection of approaches.

2.1. *Decommissioning approaches*

In order to develop decommissioning strategies, it is necessary to be familiar with recommended, planned, and proven approaches. Approaches are sets of activities, techniques, and procedures that are used to achieve a specific objective, in this case, decommissioning activities. The optimal selection of approaches will depend on factors such as technology cost, execution time, technical feasibility, radiological conditions, regulatory requirements, radioactive waste management policies, among others (IAEA, 2011).

In the proposed methodology to develop the decommissioning strategy, it was established that the Decision-Making Authority (DMA) should consider all mandatory activities and select one approach within each group of approaches. The selection of approaches in each activity group will collectively form the decommissioning strategy. The MCDA technique was used to indicate approaches based on the priorities of the 18 identified factors. The work was divided into groups of approaches, which are: 1) technical DD approaches; 2) technical RW management approaches; 3) technical storage or repository management approaches; 4) administrative HR and knowledge management approaches; 5) administrative cost estimation approaches; and 6) administrative financial fund management approaches.

Table 1
Factors associated with the approaches and scale.

Approaches	Factors	Score					Source
		1	2	3	4	5	
DD and RW	Time (years)	< 10	10 a 20	20 a 40	40 a 80	> 80	(IAEA, 2014)
	Cost (U.S. million)	< 10	10 a 50	50 a 100	100 a 150	> 150	(NEA, 2016)
	Volume of RW (m^3)	< 3000	3000 a 12,000	12,000 a 30,000	30,000 a 115,000	> 115,000	(NEA, 2016)
	Technical Feasibility	Very High	High	Medium	Low	Very Low	(NEA, 2016)
	Radiological Protection (IOE)	Very High	High	Medium	Low	Very Low	CNEN - IAEA
	Radiological Protection - Public	Very High	High	Medium	Low	Very Low	CNEN - IAEA
	Industrial Risks	Very Low	Low	Medium	High	Very High	(IAEA, 2019)
	Regulatory Uncertainty	Very Low	Low	Medium	High	Very High	CNEN - IAEA
Repository RW	Technical Feasibility	Very High	High	Medium	Low	Very Low	(NEA, 2016)
	Security	Very High	High	Medium	Low	Very Low	CNEN - IAEA
	Regulatory Uncertainty	Very Low	Low	Medium	High	Very High	CNEN - IAEA
HR	Cost	Very Low	Low	Médio	High	Very High	(NEA, 2016)
	Availability of Qualified HR	99%	75	50	25	5	(IAEA. 2005)
	Available Knowledge	99%	75	50	25	5	(IAEA. 2005)
	Intellectual Property Protection	Very High	High	Medium	Low	Very Low	(IAEA. 2005)
Cost Estimation	Time	Very Low	Low	Medium	High	Very High	(IAEA, 2002)
	Cost	Very Low	Low	Medium	High	Very High	(IAEA, 2002)
	Level of Cost Estimation Accuracy	0 a 15%	15 a 30	30 a 60	60 a 80	80 a 100	(IAEA, 2002)
	Difficulty	Very Low	Low	Medium	High	Very High	(IAEA, 2002)
	Regulatory Uncertainty	Very Low	Low	Medium	High	Very High	(IAEA, 2002)
Fund Management	Investment Security	Very High	High	Medium	Low	Very Low	(IAEA, 2002)
	Flexibility in the Use of the Fund	Very High	High	Medium	Low	Very Low	(IAEA, 2002)
	Risks Associated with Premature Shutdown	Very Low	Low	Medium	High	Very High	(IAEA, 2002)
	Transparency	Very High	High	Medium	Low	Very Low	autor
	Regulatory Uncertainty	Very Low	Low	Medium	High	Very High	CNEN - IAEA

Table 2
Factors associated with the approaches and scale.

Group of Approaches	N°	Description of the approach	Example of a reactor that adopted / published	Source
DD	1	Decontaminate and dismantle all reactor components shortly after the transition period and remove them to an off-site RW repository	BR3 (PWR)	(Dadoumont et al., 1999)
	2	Decontaminate and not dismantle the large reactor components, keeping them intact and storing them in off-site RW repositories	Loviisa (VVER) / Trojan (PWR)	(NEA, 2016)
	3	Wait for radioactive decay and then carry out dismantling activities	Dodewaard (BWR)	(NEA, 2016)
	4	Partial (or non) dismantling with intermediate or final “in situ” storage for subsequent removal or disposal	VM-A e VM-4 (PWR)	(IAEA, 2002)
RW	1	Separate, treat, and ’reconcentrate’ all types of waste until it is no longer economically viable	BR3 (PWR)	(Dadoumont et al., 1999)
	2	Separate and treat only low, medium, and high-level RW	Trojan (PWR)	(NEA, 2016)
	3	Transfer RW to be treated, conditioned, and stored in a specialized facility	Jose Cabrera -ESP (PWR)	(NEA, 2016)
	4	Confining RW on-site	Chernobyl	(Suh et al., 2018)
Repository RW	1	Transfer radioactive waste to their respective equivalent repositories	Loviisa (VVER)	(NEA, 2016)
	2	Transfer radioactive waste to an intermediate storage facility	Jose Cabrera -ESP (PWR)	(NEA, 2016)
	3	Transform the initial storage into a repository	VM-A e VM-4 (PWR)	(IAEA, 2002)
HR	1	The operating organization carries out the decommissioning activities	BR3 (PWR)	(Dadoumont et al., 1999)
	2	The operating organization maintains control of the project and delegates activities to third-party companies	Loviisa (VVER)	(NEA, 2016)
	3	The operating organization and contracted company work in partnership	IAEA	(IAEA. 2005)
	4	The operating organization transfers the decommissioning activities to a specialized organization	Jose Cabrera -ESP (PWR)	(NEA, 2016)
Cost Estimation	1	Bottom-up technique based on a Work Breakdown Structure (WBS) with linkage to the items of the ISDC	Nuclear power plants in the USA	(NEA, 2016)
	2	Specific analogy technique based on ISDC	OCDE NEA	(NEA, 2016)
	3	Parametric technique based on statistical data	IAEA	(IAEA, 2002)
	4	Expert Opinion technique	IAEA	(IAEA, 2002)
Fund Management	1	Internal management with resource acquisition through regular fees based on the net present value method and restricted withdrawal mechanisms	IAEA	(IAEA, 2002)
	2	External management with shorter-term financial resource acquisition, maintaining the net present value method without withdrawal mechanism	IAEA	(IAEA, 2002)
	3	Internal or external management, capturing an initial lump sum amount while maintaining the net present value method without a withdrawal mechanism	IAEA	(IAEA, 2002)
	4	Internal management, capturing resources only at the beginning of the decommissioning process	IAEA	(IAEA, 2002)

Table 3
Group of Approaches DD.

Approaches	Time (years)	Cost (U.S. million)	Volume of RW (m^3)	Technical Feasibility	Radiological Protection (IOE)	Radiological Protection - Public	Industrial Risks	Regulatory Uncertainty
N° 1	2	3	2	2	3	2	4	2
N° 2	1	2	3	4	2	4	3	4
N° 3	4	1	3	2	2	2	2	3
N° 4	5	5	4	3	2	5	2	5

Source: Autor.

Table 4
Group of Approaches RW.

Approaches	Time (years)	Cost (U.S. million)	Volume of RW (m^3)	Technical Feasibility	Radiological Protection (IOE)	Radiological Protection - Public	Industrial Risks	Regulatory Uncertainty
N° 1	2	4	2	2	4	2	4	2
N° 2	1	3	4	3	2	4	3	3
N° 3	1	2	3	5	3	3	3	5
N° 4	5	2	4	3	1	5	2	5

Source: Autor.

2.2. Factors associated with the approaches to be analyzed by the MCDA technique

In order to establish a standard for the selection of decommissioning approaches, a scale was developed based on the proposal by the IAEA for risk assessment (IAEA, 2019). This scale considers the relevant factors that should be taken into account in the decision-making process to adopt a specific approach. For each approach, a corresponding score will be assigned to the relevant factors. The scale ranges from a score of 1 to 5, where lower values represent better cases. The factors, their relationships, and their scales are represented in Table 1.

For example, the factor of time was used as a criterion for the selection of technical approaches, indicating the time required for their execution, taking into account decommissioning experience. The scale ranges from less than 10 years (score 1) to over 80 years (score 5). The other scores were assigned using a formula that doubles the time of the previous score. For example, score 2 corresponds to a range of 10 to 20 years, score 3 corresponds to a range of 20 to 40 years, and score 4

Table 5
Group of Approaches Repository RW.

Approaches	Technical Feasibility	Security	Regulatory Uncertainty
N° 1	5	1	5
N° 2	4	2	3
N° 3	3	2	3

Source: Autor.

corresponds to a range of 40 to 80 years. These scores for the time factor can be decisive in determining whether the decommissioning strategy will be DECON, SAFSTOR, or ENTOMB. It is important to mention that ENTOMB-related approaches will only be selected in extreme cases, such as in accidents or technical infeasibility.

Another important factor is cost. The cost of the activity is related to the specific approach and not to the overall decommissioning project. These values were derived from the report costs presented in the ISDC of some power plants from OECD/NEA member countries (NEA, 2016). Therefore, $50 million was added for each score in order to create a scale for cost. In addition to the factors mentioned earlier, other factors were considered to conduct a comprehensive analysis of all approaches. These factors include implementation time and implementation costs at generic levels, risks associated with premature shutdown, and others.

2.3. Multicriteria decision analysis (MCDA)

Analysis MCDA is a technique that enables a systematic evaluation of associated factors to aid in decision-making when selecting one approach instead another. Through this technique, it was possible to consider various factors and assign weights to them, allowing for an analysis in the selection of approaches.

The step-by-step process for using the technique, according to ISO 31010 standard, is as follows: 1) define the approach groups; 2) determine the factors related to each approach group; 3) structure the factors within a hierarchy; 4) identify options to be evaluated regarding the factors; 5) determine the importance of factors in the approaches and assign corresponding weights to them; 6) evaluate the alternatives in relation to the factors, which can be represented as a prioritization matrix; 7) combine multiple scores from individual factors into a single aggregated multi-attribute score; and 8) evaluate the results.

2.4. Group of approaches

In Table 2, the 23 decommissioning approaches are presented, organized into 6 groups. This table provided information related to the reactors that have adopted each approach.

With the aim of analyzing the most suitable approach to be selected within each approach group for developing the strategy across various scenarios (current and future) and established objectives (greenfield and brownfield), it becomes crucial to evaluate the factors influencing the selection of these approaches. Thus, through the implementation of the evaluation scale provided in Table 1, scores were assigned to each of the approaches.

The assignment of scores to each factor was based on information published in research and technical knowledge. For example, the score assigned to the time factor for the technical DD approaches was referenced to the time required for the execute of DD activities. Approach n° 1 was adopted by Reactor BR3, which was deactivated in 1987 and initiated the decommissioning process in 1989, with the final cut of the reactor pressure vessel taking place in 2000 (IAEA, 2002). In this case, an 11-year DD execution period was considered, resulting in a score of 2 (10 to 20 years).

Table 6
Group of Approaches HR.

Approaches	Cost	Availability of qualified HR	Available knowledge	Intellectual Property Protection
N° 1	4	3	2	2
N° 2	2	2	3	4
N° 3	3	4	3	4
N° 4	1	2	3	4

Source: Autor.

Table 7
Group of Approaches Cost estimation.

Approaches	Time	Cost	Level of Cost Estimation Accuracy	Difficulty	Regulatory Uncertainty
N° 1	4	5	1	4	1
N° 2	3	3	2	3	2
N° 3	4	4	3	4	2
N° 4	1	2	5	2	4

Source: Autor.

On the other hand, DD Approach n° 2 was adopted at the Trojan reactor and is outlined in the Loviisa reactor's Decommissioning Plan. The decommissioning of the Trojan reactor took 13 years, including the transition period. As for the Loviisa reactor, a total period of 11 years is projected. Given that the duration of the transition period varies between 2 and 5 years, and furthermore, this entire time frame encompasses activities beyond DD, such as RW activities, Approach n° 2 was assigned a time score of 1. This reflects the fact that the execution time for DD activities will be less than 10 years.

DD approaches n° 3 will require a period of 40 to 80 years, as this technique involves waiting for radioactive decay before beginning the decommissioning activities, which could take anywhere from 40 to 80 years to complete. This led to a time score assignment of 4. Regarding DD Approach n° 4, which is based on confinement, it is anticipated that the process will extend for over 80 years, thus receiving the maximum time score of 5.

In this manner, scores were assigned for all factors in each of the approaches. Considering the current BNP in the scenario of the year 2023, the factor scores assigned to each approach are detailed in Tables 3, 4, 5, 6, 7 and 8. The technical specifics of the all remaining assignments are outlined in the referenced work (CALDAS NETO, 2023).

To perform the analysis in this future scenario, adjustments to the factor scores pre-established in the above tables were necessary. These modifications are based on the aforementioned premises, which aim to anticipate changes in the BNP scenario. Table 9 presents the modified values corresponding to the current and future scenarios, along with the justification for each modification made. These alterations take into account the anticipated changes in the scenario, such as technological advancements, legislative, and other relevant variables.

2.5. Prioritization of factors

To prioritize the factors, the adopted technique was the Priority Matrix (PM). Comparisons are transformed into weights, considering the requirements determined by the DMA. In the PM, each factor is assigned a weight according to its relevance to the decommissioning approach selection process. These weights can be defined by the DMA based on specific criteria such as time, cost, regulatory requirements, project objectives, or strategic preferences.

Once the weights for each factor are established, comparisons are made between the factors, assigning scores that reflect their relative importance in relation to each other. These scores can follow a defined scale, such as 1 to 10, where higher values indicate greater importance. This scale allows for distinguishing importance and assigning objective criteria related to the 18 factors to be considered.

At the end of the comparison and scoring process, the factors are multiplied by the score assigned within the specific approach. This allows for considering the relative importance of each factor within the

Table 8
Group of Approaches Fund Management.

Abordagens	Investment Security	Flexibility in the Use of the Fund	Risks Associated with Premature Shutdown	Transparency	Regulatory Uncertainty
N° 1	3	2	4	4	2
N° 2	2	4	2	2	2
N° 3	4	4	2	2	3
N° 4	5	5	4	4	5

Source: Autor.

context of the analyzed approach. This technique helps identify the most significant factors and make decisions based on the prioritization of these factors according to the requirements and criteria established by the DMA. To exemplify the use of the proposed methodology, let's assume that the DMA has assigned weights to the relevant factors, as presented in Table 10.

2.6. Indication of the approach using the MCDA methodology

The weights established in the PM reflect the relative importance of each factor, as determined by the DMA in the decommissioning approach selection process. In the example of the PM presented in Table 10, the decision was based on assigning the highest priority to the execution time, followed by the available knowledge, and finally, the decommissioning cost.

In a subsequent step, the scores are multiplied by the corresponding weights for each factor. This procedure takes into account both the relative importance assigned to each factor and the weights defined by the DMA. Given a set of 'n' factors to be evaluated within an approach group, with scores S_i and weights W_i assigned to each factor, the formula for calculating the weighted sum is expressed in Equation (1).

$$\sum_{i=1}^{n} S_i x W_i \tag{1}$$

At the end, weighted scores are obtained for each factor, reflecting their relative contribution in the decommissioning approach selection process. These weighted scores can be summed to derive a total score for each approach under analysis. To enhance understanding and streamline the selection process, the criterion of choosing the approach with the lowest total score will be adopted. This criterion is based on the notion that a lower total score indicates a more favorable approach in terms of the considered factors.

As an example, in order to use the MCDA technique to recommend the decommissioning approach, considering the PM from Table 10, the analysis presented in Table 11 is conducted. This table displays the total scores, with the selected approach highlighted in blue.

In this regard, based on the prioritization of factors established in Table 10, DD approach n° 2 was indicated, which is "Decontaminate and not dismantle the large reactor components, keeping them intact and storing them in off-site RW repositories". Thus, the MCDA technique was employed to identify an approach within each group of approach that aligns most closely with the criteria set for assigning weights to the factors in the PM.

Table 10
Example PM for Strategy 1.

Factors	Weights
Time (years)	10
Knowledge Available	9
Cost (in US$ millions)	9
Protection of Intellectual Property	8
Radiological Protection (IOE)	8
Risks associated with premature shutdown	7
Investment Security	7
Level of precision error	6
Industrial risks	6
Physical Security	5
Technical Feasibility	5
Flexibility to invest in R&D and innovation	4
Volume of RW (m3)	4
Availability of qualified human resources	3
Regulatory uncertainty	3
Radiological Protection - Public	3
Difficulty	2
Transparency	2

2.7. Developing decommissioning strategies in Brazil

In the Brazilian context, all decommissioning activities are described in the CNEN NN 9.01 standard, in its Chapter V, which establishes that the operating organization must submit an IDP and a FDP. For the selection of approaches, the MCDA technique was used in conjunction with the PM.

3. Decommissioning strategies

Two scenarios were considered: one based on the current scenario and the other considering possible changes in Brazilian legislation to align it with the development of decommissioning strategies in the future. The changes aim to address relevant nuclear issues that are being discussed in the Brazilian National Congress(Portal da Câmara dos Deputados, 2007; Portal da Câmara dos Deputados, 2007) in planned activities by the nuclear sector (CDTN, 2019) and in ongoing political

Table 9
Modification of factor values corresponding to the current and future scenarios.

Approach	Factor	Current	Future	Justification
RW N° 3	Technical Feasibility	5	2	The premise established for the future scenario considers the existence of a specific company for waste management
RW N° 3	Regulatory Uncertainty	5	2	
Repository N° 1	Technical Feasibility	5	3	The premise established for the future scenario considers the existence of a repository for low and intermediate-level waste; however, the high-level repository does not yet exist
Repository N° 1	Regulatory Uncertainty	4	3	
Repository N° 2	Technical Feasibility	4	2	
Cost estimate N° 1	Implementation Cost	5	4	With the experience gained from decommissioning other Brazilian facilities, cost information will be more accessible, making the estimation easier and with lower execution costs
Cost estimate N° 1	Difficulty	4	3	

Source: autor.

Table 11
Indicate MCDA Highlighting DD approaches.

Approaches	Time (years)			Cost (U.S. million)			Volume of RW (m^3)			Technical Feasibility			Radiological Protection (IOE)			Radiological Protection - Public			Industrial Risks			Regulatory Uncertainty			Sum
Nº 1	2	10	**20**	3	9	**27**	2	4	**8**	2	5	**10**	3	8	**24**	2	3	**6**	4	6	**24**	2	3	**6**	**125**
Nº 2	1	10	**10**	2	9	**18**	3	4	**12**	4	5	**20**	2	8	**16**	4	3	**12**	3	6	**18**	4	3	**12**	**118**
Nº 3	4	10	**40**	1	9	**9**	3	4	**12**	3	5	**15**	2	8	**16**	2	3	**6**	2	6	**12**	3	3	**9**	**119**
Nº 4	5	10	**50**	5	9	**45**	4	4	**16**	3	5	**15**	2	8	**16**	5	3	**15**	2	6	**12**	5	3	**15**	**184**

Source: Autor.

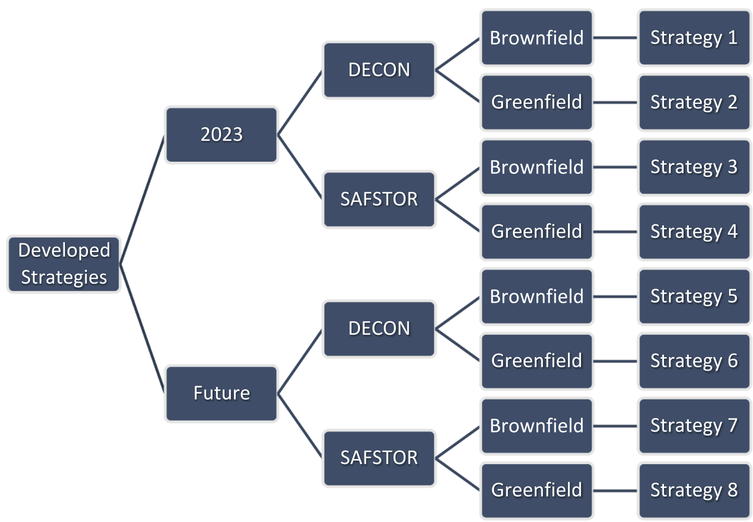

Fig. 2. Decommissioning Strategies Source: autor.

decisions (FRANJNDLICH, 2014; IPEN, 2020). In each scenario, two DECON strategies and two SAFSTOR strategies will be proposed, one to achieve the final state for restricted uses (brownfield) and another for unrestricted uses (greenfield). In total, eight strategies will be developed. A summary is presented in the diagram represented by Fig. 2.

The first scenario was developed based on the current legislation (year 2023) and forecasts the decommissioning with Brazil's current situation, considering the existing legislation, nuclear industries, Institutes of Science and Technology (ICT), regulations, and radioactive waste (RR) management policies (including their sets of regulations). Some premises must be considered, such as: 1) the monopoly of nuclear activities belongs to the Federal Government; 2) there is no repository for low and intermediate-level waste; 3) there is no geological repository for high-level waste; 4) there are few available interim storage facilities, but none of them has the capacity to receive decommissioning waste from nuclear reactors; 5) the policy for spent fuel is not defined. The fuel should be treated as "residue"; 6) there is no specific state-owned company for RW management; 7) there are few professionals and few nuclear universities in the country; 8) Brazilian highways have high accident rates; 9) the CNEN standard defines exemption levels for each radionuclide (CNEN, 2011); 10) CNEN is responsible for the intermediary and final storage (BRASIL, 2001).

The second scenario is developed based on changes in the current Brazilian legislation and improvements in industry aspects and RW management policies. Some premises were considered, such as: 1) there may be a break in the government monopoly; 2) there is a repository for low and intermediate-level waste; 3) there is currently no geological repository for high-level waste; 4) there is a specific company for RW management; 5) there are many professionals and nuclear universities in the country; Brazilian highway conditions have been adapted and improved; 6) the ANSN standard defines exemption levels for each radionuclide; 7) it is possible to transfer the decommissioning responsibility; a specific company can be responsible for the final repository.

3.1. Criteria for prioritizing factors in each strategy

The idea of assigning weights to factors is to emphasize the most concerning aspects within the strategy. For example, if the DMA opts for immediate dismantling, aiming for unrestricted use, it is essential to prioritize the execution speed, the amount of generated radioactive waste, and the industrial risks associated with intense industrial activity at the site. These factors should receive higher weights due to their greater relevance and concern,

In this regard, to adopt the proposed methodology, the following criteria were established to assign relative weights to the associated factors in each approach: 1) Immediate strategies will receive maximum scores in the time factor (weight 10), as the priority is the relatively quick execution of the decommissioning. On the other hand, deferred strategies will have minimum values (weight 1); 2) In the case of strategies for restricted use, the objective is to reuse part of the existing infrastructure at the installation site. In this context, factors such as volume of RW, industrial risks, and others will have relatively lower weights compared to strategies aimed at unrestricted use; 3) The weight of the cost factor will be higher in current scenario strategies and lower in future scenario strategies. This is due to the greater financial concern of the current power plants, where there is little experience in decommissioning, while in future scenarios, after possible reorganizations, this

Table 12
Weights assigned to each factor by strategy.

Factors	Str. 1	Str. 2	Str. 3	Str. 4	Str. 5	Str. 6	Str. 7	Str. 8
Knowledge Available	9	4	2	2	9	4	2	3
Cost (in US$ millions)	9	8	9	9	4	3	4	2
Difficulty	2	2	2	2	2	2	2	2
Availability of qualified human resources	3	8	5	5	3	8	5	5
Flexibility to invest in R&D and innovation	4	9	4	3	4	9	4	3
Regulatory uncertainty	3	6	3	5	9	6	9	9
Level of precision error	6	6	6	3	8	6	6	7
Protection of Intellectual Property	8	9	7	3	8	9	7	3
Radiological Protection (IOE)	8	7	8	8	8	7	8	8
Radiological Protection - Public	3	5	7	7	3	5	7	7
Risks associated with premature shutdown	7	3	7	4	7	3	7	4
Industrial risks	6	8	3	8	6	8	3	8
Physical Security	5	5	5	7	5	5	5	7
Investment Security	7	4	8	8	7	7	8	8
Time (years)	10	10	1	1	10	10	1	1
Transparency	2	3	2	2	2	3	3	2
Technical Feasibility	5	6	5	5	5	6	5	5
Volume of RW (m3)	4	9	3	9	4	9	3	9

Source: autor.

factor may become less concerning; and 4) To establish a ranking among the factors, taking into account the list of 18 factors, each weight will be repeated a maximum of three times, ranging from 2 to 9. The values 1 and 10 will be exclusively reserved for the time factor, which determines the strategy (immediate or deferred).

3.2. Proposed strategies

The summary of the factors considered in each strategy and their respective weights is presented in Table 12. The application of these assigned weights is explained in Appendix A.

For each relevant factor in the approach, a value was assigned, which was subsequently multiplied by their respective weights to indicate the most appropriate approach in the national scenario. In this regard, Table 13 presents the selected approaches in each developed strategy based on the aforementioned factors.

4. Results and discussion

The developed strategies were represented through a flowchart, presented in each analysis within the strategies, encompassing the mandatory activities (gray), the irradiated fuel approach (salmon), and the approaches (white). The activities and approaches are separated into the main periods in which they should be executed.

4.1. Analysis of Strategy 1

The Strategy 1 is represented by the flowchart shown in Fig. 3:

Approach n° 2 was indicated for DD. This approach is more feasible for small reactors, as these reactors have suitable structures to be removed as a whole and transported via highways to an intermediate or final repository. As the country does not yet have intermediate or final repositories for waste storage, approach n° 3 of storage management will be indicated, aiming to transform the initial repository into an intermediate or final repository. This would further facilitate the transportation of the components as a whole and minimize doses to the public during transport. At this stage, it is important for the ownership of the repository to be transferred to CNEN to comply with Brazilian legislation ().

Approach n° 2 of RW management was chosen in accordance with factors related to cost reduction and increased efficiency. Most of the decommissioning RW is of very low level or has a very short half-life, and will be stored only. Since the final repository is located near the facility, transportation costs will be relatively low. Additionally, as no treatment of these RW will be required, radiation doses to the public will be reduced. After radioactive decay, these RW can be disposed in the regular public network, such as landfills, as long as they meet regulatory requirements for radiological safety.

The approach of HR management n° 1 was chosen, in which the personnel of the operating organization themselves are responsible for carrying out the decommissioning activities. In this context, it is appropriate as they have a deeper understanding of the facilities and are more qualified in the nuclear field. These employees will need to be properly trained and replaced when necessary. This consideration can be supported by the fact that most of the dismantling activities will require a high level of nuclear expertise. Additionally, since there won't be a large quantity of structure dismantling, which represents most of the activities, using personnel from the facility itself is the most appropriate and cost-effective option. This consideration is also supported by the need to execute the dismantling quickly, as there would be no need to train external personnel for nuclear activities.

Approach n° 2 for cost estimation, which utilizes the specific analogy

Table 13
Result of the selected approaches in each strategy.

Strategy	Type	Obj. Final	Scen.	DD	RW	Rep.	HR	Cost estimation	Fund management
1	DECON	Brownfield	2023	2	2	3	1	2 > 1	2
2	DECON	Greenfield	2023	1	1	3	2	2 > 1	1
3	SAFSTOR	Brownfield	2023	3	2	3	2	2 > 1	2
4	SAFSTOR	Greenfield	2023	3	1	3	2	2 > 1	2
5	DECON	Brownfield	Future	1	3	2	4	1	2
6	DECON	Greenfield	Future	1	3	2	1	2	1
7	SAFSTOR	Brownfield	Future	3	3	1	4	1	2
8	SAFSTOR	Greenfield	Future	3	3	1	4	1	2

Source: autor.

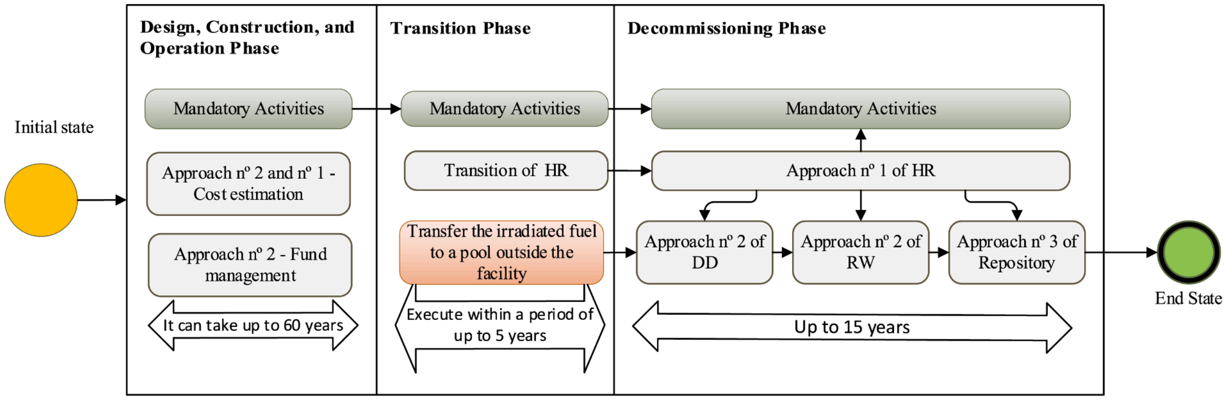

Fig. 3. Flowchart of Strategy 1 Source: autor.

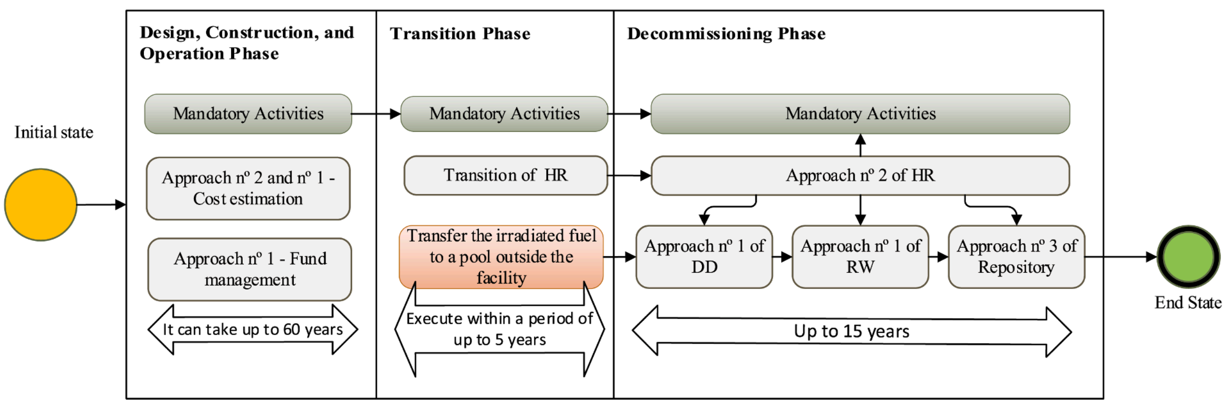

Fig. 4. Flowchart of Strategy 1.

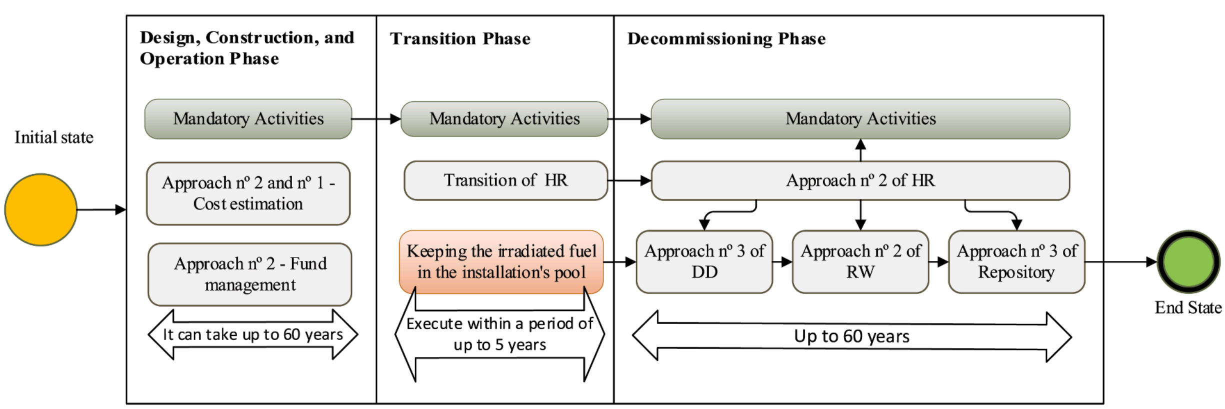

Fig. 5. Flowchart of Strategy 3 Source: autor.

technique based on ISDC, is considered suitable for cost estimation due to the lack of experience in reactor decommissioning in Brazil and the scarcity of information on future costs, which makes it challenging to accurately assess the costs involved in the project. Therefore, one option is to seek cost data and information from countries belonging to the OECD/NEA through ISDC and adapt them to the Brazilian reality. This way, it will be possible to obtain a more accurate estimate of the costs and resources required for the decommissioning of nuclear reactors in the country. In the FDP, it is ideal to adopt approach n° 1, as the information regarding labor, technology costs, and others will be closer to reality.

Approach n° 2 for fund management, which involves external management with the collection of financial resources for a shorter period while maintaining the present value method without a withdrawal mechanism, was indicated by the MCDA technique. This option is favorable as external management carried out by a specialized financial investment organization offers greater financial security compared to internal management, in line with what was established in the prioritization of factors.

The irradiated fuel approach is a determining factor in the selection of decommissioning strategies. Although it is not directly part of the scope of this work, some details have been addressed in previous chapters. To manage irradiated fuel, the adopted strategy consists of constructing a pool outside the facility where the fuel can be temporarily

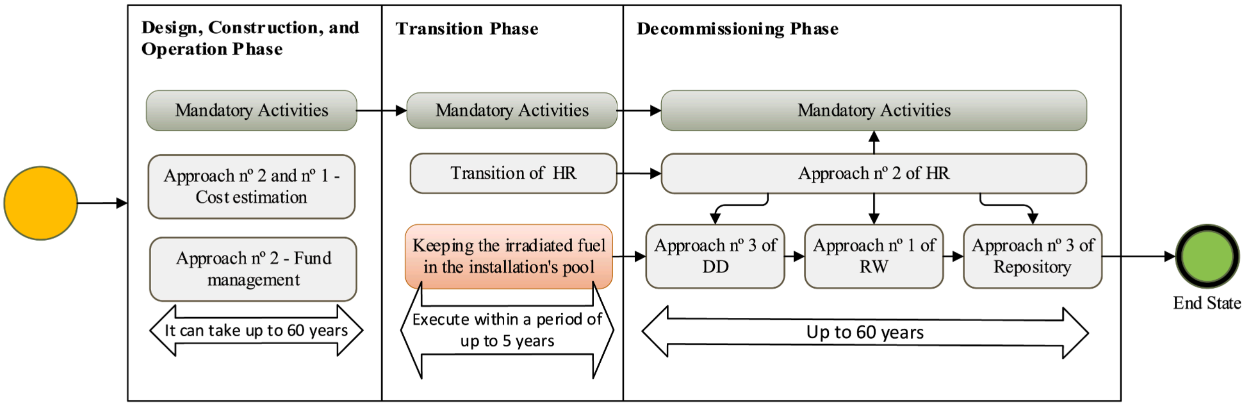

Fig. 6. Flowchart of Strategy 4 Source: autor.

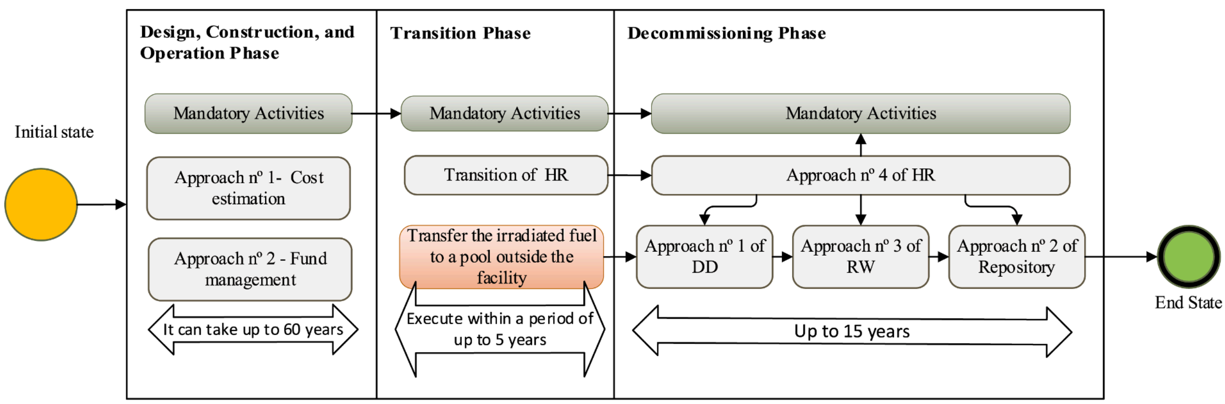

Fig. 7. Flowchart of Strategy 5 Source: autor.

stored until a decision is made by the country regarding its fate. This approach will allow for a safer management during the decommissioning process.

4.2. Analysis of Strategy 2

The Strategy 2 is represented by the flowchart shown in Fig. 4:

Approach n° 1, which involves DD of all reactor components shortly after the transition period, followed by removal to an off-site radioactive waste repository, was indicated by the MCDA technique. This approach aims to minimize the volume of RW as much as possible, seeking to recycle and reuse these materials whenever feasible. The management of RW can be intensified according to approach n° 1 of DD. Emphasis can be placed on the recycling and reuse of RW, especially those derived from the building structure, which represent the largest quantity. Through these approachs, it will be possible to optimize the management of RW, reducing its volume and mitigating the associated environmental impacts. The storage management approach will be the same as in Strategy 1.

Approach n° 2 for HR can be adopted in accordance with the legislation that establishes the responsibility of the facility in the decommissioning process. In this sense, it was chosen to combine the knowledge of facility employees with the outsourcing of specific activities to leverage the expertise of specialized professionals and incorporate new experiences and knowledge into the project. Although the protection of intellectual property is considered more favorable in

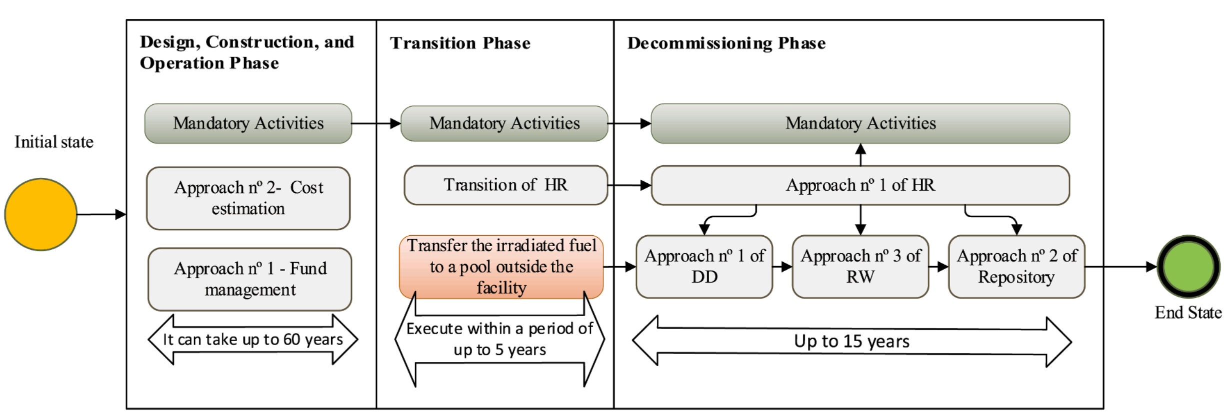

Fig. 8. Flowchart of Strategy 6 Source: autor.

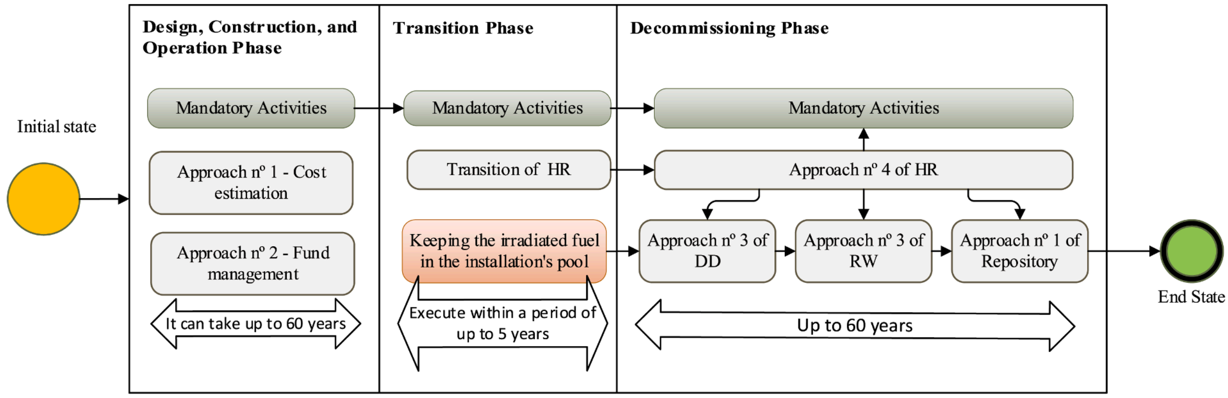

Fig. 9. Flowchart of Strategy 7 and 8 Source: autor.

option n° 1, the MCDA analysis indicates that due to the associated costs and the availability of HR required for the large-scale execution of dismantling tasks and processing of RW, these factors carry more weight than the issue of intellectual property protection. Therefore, the selected option is considered more appropriate.

Approach n° 2 for cost estimation, which utilizes the specific analogy technique based on the ISDC, has been indicated and can be adopted and modified for the same reasons mentioned in Strategy 1. Approach n° 1 for fund management has been indicated and can be selected due to its lower annual funding and independent management. Therefore, the facility will be able to invest a percentage, in case of surplus, in research and innovation projects in decommissioning, in partnerships with ICTs (Institutes of Science and Technology), as the country does not have much experience in this area.

4.3. Analysis of Strategy 3

The Strategy 3 is represented by the flowchart shown in Fig. 5. Approach DD n° 3, which involves placing the facility in a safe condition, allowing for radioactive decay before carrying out dismantling activities and removing the waste to a designated repository, can be selected as an approach for the delayed decommissioning of nuclear reactors. This approach requires investments to improve the infrastructure of the site, reinforce existing structures, enhance biological shielding, and implement monitoring and security systems over an extended period.

Approach RW n° 2 can be recommended to be adopted in cases where restricted uses of nuclear reactors are desired. This approach can be beneficial in conjunction with the restoration of structures, as the waste generated there is of very low level, taking advantage of natural radioactive decay over time. One of the main advantages is that most of the waste will be below the clearance limit, due to the radioactive decay process.

Initially, the selected storage management approach will be n° 03, as there are no other viable options available. However, it is important to consider that, due to the long periods required for safe storage, it is possible that the repository may already be in operation when dismantling activities commence. In this regard, it is recommended that the IDP include a provision for the possibility of changing the storage management approach if an appropriate repository becomes available and the conditions for safe transportation of the waste to the destination are ensured.

The HR management approach n° 2 is highly recommended, considering the characteristics of the HR currently involved in the nuclear field. Currently, these professionals are civil servants who have undergone competitive exams and are highly skilled, possessing specialized knowledge in the operation of the facility. After the shutdown of the facility, there is a possibility that the workforce may remain idle for long periods, especially when considering the safe storage period of up to 40 years. In this regard, it is important to recommend the reassignment of personnel to other nuclear facilities or related activities, in order to make use of and maintain the knowledge and experience of these professionals.

Additionally, it is possible to allocate a small fraction of this personnel to carry out the safe monitoring of the facility during the storage period. This team would be responsible for ensuring the integrity of the infrastructure, monitoring the safety systems, and conducting regular inspections, thereby ensuring the safety of the facility throughout the storage period. When the time comes to initiate the dismantling activities, it is recommended to hire mostly specialized outsourced personnel. These professionals would be responsible for carrying out the dismantling activities of the components and performing the restoration of the structure, following the procedures and guidelines established in the FDP.

The cost estimation approach follows the same principles as Strategies 1 and 2. Approach n° 2 for fund management can be safely selected and adopted. This option is more favorable considering the long periods of fund administration and greater investment security.

To manage the irradiated fuel, the adopted approach can make use of the existing pool in the facility, closely following the country's decision regarding the management policy of this fuel. If a decision is made regarding its disposal during the safe storage period, this action can be carried out according to the established guidelines.

4.4. Analysis of Strategy 4

The Strategy 4 is represented by the flowchart shown in Fig. 6.

The approach for decommissioning, storage management, HR management, fund management, and irradiated fuel management are similar and have the same objectives as the approaches selected in Strategy 3. However, based on the conducted MCDA analysis, it is suggested to make a change in the RW management approach, switching to option n° 1, as it reduces the significant volume of waste that would need to be treated. This approach aims to optimize the management of waste by promoting recycling and reuse, especially regarding the waste generated from the building structure, which constitutes most of the volume.

Another point identified was that, in comparison to Strategy 2, which aimed to prioritize R&D projects, apart from the DD approach indicating the execution time, there was only a change in the fund management approach. Thus, it was identified that in order to prioritize R&D, it is important for the fund management to be internal, adopting the approach n° 1 for fund management.

4.5. Analysis of Strategy 5

The Strategy 5 is represented by the flowchart shown in Fig. 7.

Table A1
Groups of factors to be assigned high or low weights.

Strategy 1		Strategy 2		Strategy 3		Strategy 4	
Higher	Lower	Higher	Lower	Higher	Lower	Higher	Lower
Time (years)	Flexibility to invest in R&D and innovation	Time (years)	Physical Security	Cost (in US$ millions)	Availability of qualified human resources	Cost (in US$ millions)	Risks associated with premature shutdown
Cost (in US$ millions)	Volume of RW (m3)	Protection of Intellectual Property	Radiological Protection - Public	Radiological Protection (IOE)	Technical Feasibility	Volume of RW (m3)	Protection of Intellectual Property
Knowledge Available	Availability of qualified human resources	Flexibility to invest in R&D and innovation	Knowledge Available	Investment Security	Physical Security	Radiological Protection (IOE)	Level of precision error
Protection of Intellectual Property	Radiological Protection - Public	Volume of RW (m3)	Investment Security	Protection of Intellectual Property	Flexibility to invest in R&D and innovation	Investment Security	Flexibility to invest in R&D and innovation
Radiological Protection (IOE)	Regulatory uncertainty	Cost (in US$ millions)	Risks associated with premature shutdown	Radiological Protection - Public	Volume of RW (m3)	Industrial risks	Knowledge Available
Investment Security	Difficulty	Industrial risks	Transparency	Risks associated with premature shutdown	Industrial risks	Radiological Protection - Public	Transparency
Risks associated with premature shutdown	Transparency	Availability of qualified human resources	Difficulty	Level of precision error	Regulatory uncertainty	Physical Security	Difficulty
Industrial risks		Radiological Protection (IOE)			Knowledge Available		Time (years)
Level of precision error		Level of precision error			Transparency		
		Technical Feasibility			Difficulty		
		Regulatory uncertainty			Time (years)		

Unlike the strategy in the current scenario, the DD approach n° 1 was indicated and can be adopted for small reactors. It can be combined with the RW approach n° 3, which involves the treatment of waste in a specialized facility. The specialized company should have the expertise and appropriate equipment for waste minimization and segregation, and it will be possible to recycle the waste as much as possible. The MCDA technique indicates that storage option n° 2 is the most suitable based on the priority list, so the waste will be transferred to intermediate storage facilities.

In this context, the HR management approach n° 4 is also aligned with the other approaches as it involves hiring a specialized decommissioning company to perform the necessary activities. Therefore, Strategy 5 is based on the premise that in the future there will be a specialized company for waste management, and it will be possible to transfer the responsibility of decommissioning.

The cost estimate of approach n° 1 is the most suitable option in the future scenario, considering the potential experience already gained in decommissioning and the availability of more accurate information databases.

With the change in activities, which may no longer be a monopoly of the Union, it is necessary to be careful to ensure that resources are available in case of premature shutdown. Therefore, fundraising will be expedited to ensure that funds are available as soon as possible. In addition, the management will be outsourced, as the specialized company will be responsible for administering the funds. Thus, approach n° 2 has been selected.

4.6. Analysis of Strategy 6

The Strategy 6 is represented by the flowchart shown in Fig. 8.

Approach n° 1 for DD was indicated to carry out the complete dismantling of the facility, aiming to achieve a state for unrestricted use. On the other hand, the waste management approach aims to transfer the waste to a specialized facility, where it will be treated and properly stored. In this context, it is necessary to establish an interface between the human resources of the main facility (HR approach n° 1), responsible for the dismantling, and the HR of the specialized facility, who will handle the waste. This way, the two HR teams work together ensure a more appropriate waste management.

The indicated storage approach is n° 2, although the values in the MCDA analysis were close to approach n° 1. It is important to note that if the geological repository were fully operational, option n° 1 could be considered more viable.

The selected fund management approach is n° 1, in which the facility itself will be responsible for managing the financial resources. The flexibility to invest in R&D and innovation was a determining factor for this indication. Under this approach, the facility will assume the costs related to the RW management activities, which will be paid to the specialized company contracted to carry out these activities.

4.7. Analysis of Strategy 7

The Strategy 7 is represented by the flowchart shown in Fig. 9. When analyzing the set of approaches indicated by the MCDA technique, this strategy involves transferring the responsibility for decommissioning to a specialized company after the operation phase of the facility. This company would be responsible for the dismantling after the period of safe storage, the RW management activities, and the transportation of these wastes to their respective repositories. It could employ its own personnel or outsource the necessary services.

The strategy of this approach aims to transfer all decommissioning activities to a specialized company that would centralize the decommissioning activities. This company would be responsible for managing the decommissioning funds (approach n° 2), hiring specialized personnel for technical activities, and utilizing decommissioning equipment from various facilities, among other benefits. This specialized company would oversee all stages of decommissioning, acquiring expertise, and continuously improving the techniques employed.

Furthermore, the external management of the fund could be carried out by the specialized company from the initial phase, allowing for a

Table A2
Assignment of weights to the factors included in the criteria.

Factor	Condition	Applied weight	Justification
Time (years)	DECON	10	Established criterion
Time (years)	SAFSTOR	1	Established criterion
Cost	Year 2023	9	Established criterion
Cost	Future	3	Established criterion
Volume of RW (m3)	Brownfield	3	Established criterion
Volume of RW (m3)	Greenfield	9	Established criterion
Industrial risks	Greenfield	8	Established criterion
Flexibility to invest in R&D and innovation	Strategy 2 and 6	9	Strategic Option
Flexibility to invest in R&D and innovation	Strategy 4 and 8	3	Strategic Option
Protection of Intellectual Property	Strategy 2 and 6	9	Strategic Option
Protection of Intellectual Property	Strategy 4 and 8	3	Strategic Option

Table A3
Weight Application by Criteria in Strategy 2.

Factors	Weights
Time (years)	10
Cost (in US$ millions)	9
Protection of Intellectual Property	9
Industrial risks	8
Flexibility to invest in R&D and innovation	9
Volume of RW (m3)	9

more comprehensive cost estimate, and the acquisition of necessary resources would be conducted by this company, which would act as the manager of the decommissioning fund. Considering the trend of constructing multiple SMRs starting from 2030 to meet the energy demand, a viable solution would be to apply the same concepts of construction and serial modularization to create dismantling and decommissioning processes in series. In this way, a specialized decommissioning center could be built by the specialized company.

4.8. Analysis of Strategy 8

Despite the change in the values of the considered factors, the MCDA technique indicated the same approaches that were proposed in Strategy 7. This means that the delayed strategies for the future scenario will not have significant differences in the indication of decommissioning approaches. Therefore, the indicated approaches will be the same, regardless of the perspective of the final use.

4.9. Non-selected or non-indicated approaches

The approach of DD n° 4 and the approach of RW n° 4, which consider confinement strategy (encapsulating the facility), as well as the approach of cost estimation n° 4, which defines cost estimation based on expert opinions, and the approach of fund management n° 4, which foresees payment for decommissioning only at the end, were not selected as they are not recommended by the IAEA. However, they may be useful in case of accidents or premature shutdown. Among them, only the approach of RW n° 4 was indicated by the MCDA technique in Strategy 3 and was changed to the approach of RW n° 2.

Other approaches were also not indicated, such as the approach of HR n° 3, where a partnership between the operating organization and an ICT could be established to jointly carry out the decommissioning. Although not indicated by the MCDA technique, it was understood that this approach could be more suitable for decommissioning research reactors that aim to leverage the decommissioning activities to develop new processes or products in order to provide future services in the field of decommissioning.

The approach of cost estimation n° 3 and fund management n° 3 were also not indicated by the MCDA technique. These approaches may only be adopted if imposed by the regulatory body or due to specific needs.

Table A4
Reduction of the “cost” weight in Strategy 2.

Factors	Previous Weights	Actual Weights
Cost (in US$ millions)	9	8

4.10. Changes in strategies during operation

The development of strategies is intrinsically linked to various factors, such as technical feasibility, government policies, and decisions from competent authorities. For example, if there are no intermediate or final repositories available for the storage of RW during operation, the only viable solution for the facility is to convert its initial repository into a final repository. On the other hand, if the repository is operational, the facility will have two options to choose from. Another example is when a country has not yet adopted a policy for the management of spent fuel and there are no plans to construct a facility to receive such fuels. In this case, the only option is to postpone the decommissioning until a solution

Table A5
Assignment of weights for the other factors in Strategy 2.

Strategy 2			
Higher		Lower	
Time (years)	10	Physical Security	5
Protection of Intellectual Property	9	Radiological Protection - Public	5
Flexibility to invest in R&D and innovation	9	Knowledge Available	4
Volume of RW (m3)	9	Investment Security	4
Cost (in US$ millions)	8	Risks associated with premature shutdown	3
Industrial risks	8	Transparency	3
Availability of qualified human resources	8	Difficulty	2
Radiological Protection (IOE)	7		
Level of precision error	6		

Table A6
Assignment of weights for the other factors in Strategy 2.

Factors	Weights Str. 2
Time (years)	10
Flexibility to invest in R&D and innovation	9
Protection of Intellectual Property	9
Volume of RW (m3)	9
Cost (in US$ millions)	8
Availability of qualified human resources	8
Industrial risks	8
Radiological Protection (IOE)	7
Regulatory uncertainty	6
Level of precision error	6
Technical Feasibility	6
Radiological Protection - Public	5
Physical Security	5
Knowledge Available	4
Investment Security	4
Risks associated with premature shutdown	3
Transparency	3
Difficulty	2

is decided upon in the future.

Therefore, a strategy should be developed already in the initial phase of the project in order to consider these possibilities and plan ahead before they occur. In different scenarios, other approaches can be considered after a proper evaluation. For example, it may be initially decided not to dismantle the main components and remove them entirely (DD approach n° 2). However, it is essential to conduct a thorough analysis of the technical feasibility of this option and implement it appropriately. It is important to note that the facility should be prepared for possible changes, such as regulatory alterations throughout the operational lifecycle, which may prohibit this approach. In such cases, the strategy should be adjusted and adopted in accordance with the prevailing requirements.

5. Conclusion

To develop the decommissioning strategies, this study adopted the risk assessment techniques as established in the ABNT ISO/IEC 31,010 standard. In this regard, the main factors influencing the decision-making process regarding the decommissioning strategy were identified, analyzed, and qualified. Based on this analysis, a methodology was developed for the selection of decommissioning approaches, considering the factors that impact the strategy.

By applying the developed methodology to the development of decommissioning strategies for small reactors, success was achieved in creating eight strategies. These strategies were developed based on a prioritized list of relevant factors and were grounded in a risk analysis, providing a solid foundation for decision-making in the decommissioning project.

Furthermore, this study also identified some gaps in the Brazilian scenario that need to be further analyzed for the robust elaboration of plans for nuclear reactor decommissioning projects. These gaps include: 1) the creation of a document for the national policy on radioactive waste management, including the strategy to be adopted, especially for irradiated nuclear fuel; 2) regulation of decommissioning for small reactors; 3) adoption of regulations to ensure that nuclear facilities secure the financial resources to be used in decommissioning and, if insufficient, provide support mechanisms to prevent the interruption of decommissioning activities; 4) adoption of HR and knowledge management policies in nuclear facilities to incentivize employees to remain in the facility and promote appropriate career plans; 5) implementation of mechanisms to encourage science, research, and innovation in the field of decommissioning and protect technological knowledge; and 6) establishment of a robust awareness and communication system with the Brazilian population to clarify the benefits and limitations of nuclear technology.

Furthermore, this study also identified some gaps in the Brazilian scenario that need to be further analyzed for the robust elaboration of plans for nuclear reactor decommissioning projects. These gaps include: 1) the creation of a document for the national policy on radioactive waste management, including the strategy to be adopted, especially for irradiated nuclear fuel; 2) regulation of decommissioning for small reactors; 3) adoption of regulations to ensure that nuclear facilities secure the financial resources to be used in decommissioning and, if insufficient, provide support mechanisms to prevent the interruption of decommissioning activities; 4) adoption of personnel management and knowledge management policies in nuclear facilities to incentivize employees to remain in the facility and promote appropriate career plans; 5) implementation of mechanisms to encourage science, research, and innovation in the field of decommissioning and protect technological knowledge; and 6) establishment of a robust awareness and communication system with the Brazilian population to clarify the benefits and limitations of nuclear technology.

In light of the aforementioned, given the projected demand starting from 2030, small reactor decommissioning projects should be established even before the construction of the facility begins. At this point, this study provides an overview of the main decommissioning activities and how to develop preliminary and final Plans based on appropriate strategies.

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

No data was used for the research described in the article.

Appendix A. Weight application methodology for factors in the prioritization matrix (PM) used in this study

A.1. Methodology

The purpose of applying weights in this study was primarily to simulate the prioritization matrix (PM) that the Decision-Making Authority (DMA) could employ in strategic planning, considering the Brazilian Nuclear Policy (BNP) and the regulatory requirements of the country. For this purpose, specific criteria were outlined for assigning weights to each scenario and objective in question. For instance, in the DECON strategy, to achieve the greenfield uses objective in the 2023 scenario, factors such as time, cost, volume of radioactive waste, industrial risks, among others, would receive higher scores than other factors. It was understood that due to the execution time, the quantity of generated RW volume, and the risks associated with the high number of RW management processes, these factors should be considered as priorities in this specific example.

Therefore, the starting point for the weight application involved establishing the hierarchy among the factors to be considered for each of the four strategies, initially for the year 2023. In order to simplify the weight allocation, the division into two distinct groups was carried out: those factors to which higher weights would be assigned (ranging from 6 to 10), and those that would receive lower weights (ranging from 1 to 5). Thus, Table A1 presents the clear grouping of scores, both higher and lower, related to the strategies in the 2023 scenario.

The second step involved inputting the weights to meet the criteria established in section 3.1 of this work. For example, the weight of time (receiving values of 1 or 10), the weight of cost (receiving values of 3 or 9), and the weight of volume RW (receiving values of 3 or 9). In addition to the established criteria, strategies 2 and 4 had R&D factors with high weights (receiving a value of 9) due to a potential strategic option that could be taken by the DMA. Table A2 shows the assignment of weights for the factors included in the criteria. The other weights for the factors were randomly assigned within their respective score group (high or low).

It's important to highlight that, according to the established criterion, the weights were subject to a restriction of limited repetition, with a maximum of three occurrences. With this consideration, manual adjustments were made involving increasing or decreasing specific weights in order to ensure compliance with this criterion. This process encompassed potential adjustments to the weights mentioned earlier in the preceding criteria. It's worth mentioning that the selection of the involved factors was conducted randomly.

For the strategies outlined in the future scenario, the process involved replicating the weights assigned in the context of 2023, with adjustments made according to the criteria established for the future scenario. With this approach, several weights that had been allocated to factors in the 2023 scenario remained unchanged in the future scenario. This approach allowed for a more concise evaluation, focusing exclusively on variations in the scores that were modified and on the criteria projected for this new scenario. The factors that remained constant in both the 2023 and future scenarios were: Difficulty; Availability of qualified human resources; Flexibility to invest in R&D and innovation; Protection of Intellectual Property; Radiological Protection (IOE); Radiological Protection – Public; Industrial risks; Physical Security; and Technical Feasibility.

A.2. Practical example

To exemplify the weight application, we will demonstrate the weight assignment for Strategy 2, considering the 18 factors to be assigned weights. Thus, the first step was to assign the weights based on the established criteria as presented in Table A2. In Table A3, the initial step of weight application is shown. The weights in red indicate the insertion of the weight value for the factor within the step.

In this step, there were 4 instances where the weight 9 was assigned, creating an inconsistency. In response, a random draw was conducted to determine which factor would have a reduction of 1 in its weight. It's important to note that adding 1 more to the weight wasn't a viable option since the criterion had exclusively designated a weight of 10 to the "time" factor. Therefore, the choice fell on the "cost" factor, which was adjusted to a weight of 8. Table A4 illustrates the reduction in weight for the "cost" factor.

The subsequent step involved the random draw of a weight from each corresponding weight group, as illustrated in Table A1. Consequently, the assigned weights are presented in Table A5.

In the scenario where the presence of more than three factors with identical weights was a possibility, a random selection of one of those factors would be carried out for the application of an adjustment in its weight, either through an increase or decrease. In this manner, the adopted PM for Strategy 2 is shown in Table A6.

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