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Preliminary Analysis on Decommissioning Strategies for Fukushima Daiichi Nuclear Power Station From Waste Management Perspective

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In this study, basic strategies for the decommissioning and site remediation of the Fukushima Daiichi Nuclear Power Station (FDNPS) were investigated. Six scenarios were formulated based on two of the three decommissioning strategies of nuclear power plants defined by the International Atomic Energy Agency (IAEA): immediate dismantling and deferred dismantling. A multicriteria decision analysis was performed to analyze the preferences of the options from the viewpoints of the timeframe to complete decommissioning, the resulting waste, the site usability, and the availability of the radioactive waste disposal route. The same six scenarios were applied to both the FDNPS and the nuclear power plants that ceased operation after a normal plant life cycle for comparison. For the FDNPS, the decommissioning project involved fuel debris retrieval, dismantling, and site remediation. The analysis results suggest that the balance between the amount of waste and the time to achieve the end state may be one of the most critical factors to consider when planning the decommissioning and site remediation of the FDNPS.

Keywords: Fukushima Daiichi Nuclear Power Station, Site remediation, Multi-criteria decision analysis, Radioactive waste, End state, Decommissioning scenario

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1. Introduction

After the accident at Fukushima Daiichi Nuclear Power Station (FDNPS), decommissioning activities are conducted along “Mid-and-long-term roadmap toward the decommissioning of TEPCO’s Fukushima Daiichi Nuclear Power Station [1]” established by the Inter-Ministerial Council for Contaminated Water and Decommissioning Issues of Japanese Government. The Roadmap defines three phases toward the end state of the decommissioning project. The first phase is for preparation of spent fuel removal from spent fuel pools in all of the Units from 1 to 6. The second phase is to remove spent fuels from spent fuel pools, and to prepare for retrieval of fuel debris from Units 1 to 3. The third phase is retrieval of fuel debris, followed by decommissioning of facilities. The decommissioning project is planned to be completed in thirty to forty years after the accident.

Currently, the second phase activities are ongoing, and removal of spent fuels has been completed for Unit 3 and 4, while preparation for spent fuel removal in Unit 1 and 2 is continuing. Preparation for fuel debris retrieval is also in progress, however, the start of the fuel debris retrieval is expected to be delayed for about a year to begin in 2022 due to Covid-19 pandemic. The third phase is planned to start with fuel debris retrieval from Unit 2, and the activities in this phase include fuel debris retrieval from Unit 1 and 3, as well as dismantling of the components and structures in all of the facilities, and management of waste that arises from these activities. In addition, site remediation will likely be necessary to achieve an end state, which will also generate a large volume of radioactive waste.

Radioactive waste management is a critical, but often overlooked, or undervalued part of decommissioning. It is necessary to establish routes to reuse/recycle material and dispose of radioactive waste before material/waste is generated in order for decommissioning activities to proceed [2]. There can be cases where the availability and the capacity of waste treatment and disposal facilities limit the progress of decommissioning activities, especially when the waste volume is significant as in the case of decommissioning of facilities after accidents. Decommissioning and site remediation plans need to be integrated with waste management plans. It is beneficial for decommissioning plans for FDNPS to be re-examined from the perspective of radioactive waste management.

In addition, defining the end state, whether it is a “greenfield” or a “brownfield”, can have significant impacts on overall decommissioning planning, including schedules, cost, and waste management. To achieve the greenfield end state, it is necessary to completely remove of all equipment and structures, and remediate contaminated site to a level that allows unrestricted use for any purpose. If the goal is the brownfield, parts of equipment and/or structures such as underground structures and piping may be left at the site, and remediation may be necessary only to a certain contamination level, as the site may be re-used with restrictions, or stay under the institutional control after decommissioning. However, the end state of FDNPS decommissioning project is not described in the “Roadmap”. It will be important to start discussing potential end states for FDNPS to reach an agreement on shared goals with stakeholders, and for that purpose, it is important to consider a wide range of potential end states in relation to decommissioning, site remediation, and waste management planning.

On the other hand, the atomic energy society of Japan has organized a committee to study on the decommissioning of the FDNPS. A subcommittee organized under the main committee has been discussing on the management of radioactive waste arising from a series of decommissioning and site remediation activities of FDNPS. An interim report “Waste management from international perspectives” was published in 2020 [3]. The report pointed out that defining the final endpoint and determining the strategy toward the goal are essential in considering waste management options. In addition, as examples of endpoint and strategies toward them, four simplified decommissioning scenarios were compared in terms of radioactive waste management with timeframe and amount of waste that will be generated, in order to initiate discussions on decommissioning strategies including the end states.

Discussions need to be started to determine the end state of the Third Phase as decommissioning activities at FDNPS approach the end of the Second Phase. Defining the end state of the FDNPS will be a very complex problem and there may be multiple and conflicting goals that different stakeholders envision. We have analyzed and compared basic strategies for decommissioning in order to identify important issues in this decision making. In this study, potential scenarios were formulated with two possible alternative end states of complete dismantling and demolition (greenfield), or partial dismantling and safe storage with care and maintenance (one of the brownfield options). A multi-criteria decision analysis (MCDA) has been adopted to analyze the preferences of these scenarios, considering the scope of waste management and the timeframe of the activities, which may be of social concerns. Our preliminary study suggests that balance between the amount of waste and the time to achieve the end state may be one of the major discussions in the decision making of the FDNPS decommissioning scenarios.

2. Methods

2.1 Decommissioning Scenarios

Three basic scenarios were considered based on the IAEA report [2], which are immediate dismantling scenario (ID), deferred dismantling, or dismantling after safe storage scenario (SD), and deferred dismantling with long-term safe storage scenario (LSD). LSD scenario is an extreme case of deferred dismantling with very long storage period. In SD and LSD scenarios, 30 years or 100 years were assumed for the safe storage period, respectively. The end states were defined either as greenfield (1) or brownfield (2). In the case of brownfield, "in-situ decommissioning" of leaving the underground structure without dismantling was considered as a measure to reduce the amount of very low-level radioactive waste. The total of these six scenario options were applied to both normally operated nuclear power plant (NPP) without accident and FDNPS, as depicted in Fig.1, and were compared using MCDA.

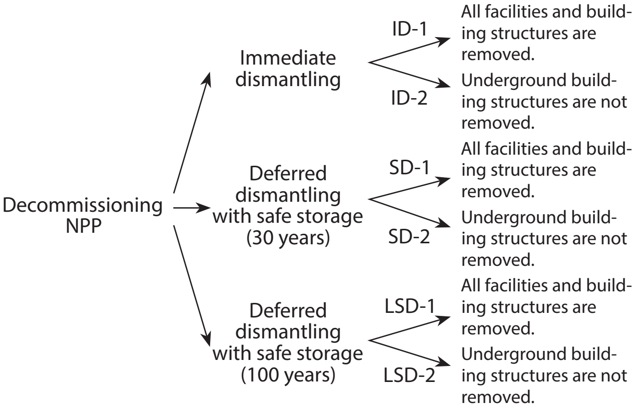
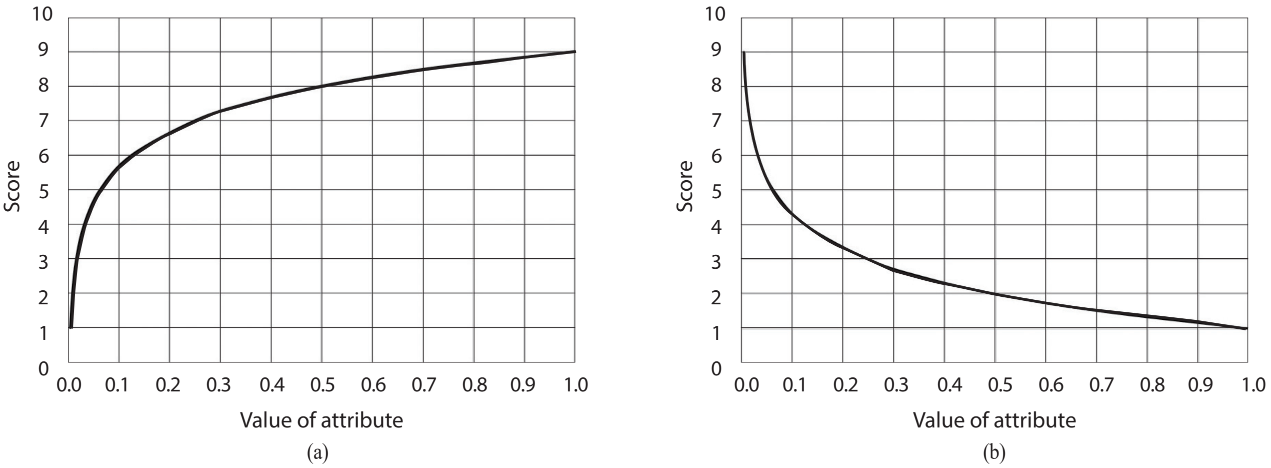


Fig. 1. Six options of decommissioning scenarios.

2.2 Multi Criteria Decision Analysis

Multi-criteria decision analysis is a tool that supports decision-making in complex situations with multiple and often conflicting objectives. MCDA was applied in our study to compare potential decommissioning scenarios of nuclear facilities after accidents, as well as of the ones that ceased normal planned operation. Four attributes were chosen for the analysis: the amount of radioactive waste, availability of waste disposal facilities, area of the site which is usable at the end state, and the time necessary to achieve the end states.

Value ranges of attributes were defined to determine scoring curves for each attribute. The value range of each attribute ($P_{\min}$, $P_{\max}$) was divided into a number of subintervals between the maximum and the minimum values. Grid points, $P_{\min}, P_{\min} + e_0, P_{\min} + e_1 \cdots\cdots$, were determined to denote the attribute score levels, which demarcate these subintervals. The increments of the attribute values, e_0, e_1, e_2, $e_3 \cdots\cdots$, form the scoring scale, and can be set as;



(a)

(b)

Fig. 2. Scoring curves in geometric progression. Greater scores show higher preferences: (a) Scores increasing with an increase in attribute values, (b) Scores decreasing with an increase in attribute values.

$$e_u - e_{u-1} = \varepsilon e_{u-1} \quad \text{……………………………………} \quad (1)$$

$$e_u = (1+\varepsilon)\, e_{u-1} = (1+\varepsilon)^2\, e_{u-2} = \cdots\cdots = (1+\varepsilon)^u\, e_0 \quad \ldots \quad (2)$$

where u is increments (1, 2, 3, ⋯ 9), and ε is the progression factor.

Certain human perception is expressed as geometrical progression [4], the echelons were assumed to constitute a sequence with geometric progression. The valued score (v) is chosen to designate the order of magnitude of the echelons. Subintervals were demarcated by a geometric sequence of nine points corresponding to maximum and minimum attribute values, and the progression factor is set to be 2. The scoring curves were expressed as the following equation.

$$v = \log_2 \left\{ \frac{(P_v - P_{\min})}{(P_{max} - P_{min})} \times 512 \right\} \quad \text{………………………} \quad (3)$$

Two kinds of curves were prepared according to the values of attributes. One curve shows the increasing preference with an increase in the attribute values, and the other curve show the decreasing preference with an increase in the attribute values. Fig. 2 shows the shapes of these scoring curves.

2.3 Values of Attribute for Scoring

The timeframe, and the processes of decommissioning and site remediation activities were schematically shown in Fig. 3. In terms of NPP with normal life cycle (case (a)), decommissioning activities are divided into three phases: preparation/removal of peripheral components, dismantlement of core components, and demolishing structures. In SD and LSD scenarios, a safe storage period of 30 years and 100 years, respectively, was placed before dismantlement of components. Total durations to achieve the end state are 30, 60, and 130 years for scenarios ID, SD, LSD, respectively.

The decommissioning project at FDNPS consists of three activities: fuel debris retrieval, dismantling of the components and building structures, and site remediation. The following two cases were considered: case (b); decommissioning of Unit 1-4 which goes through fuel debris retrieval and decommissioning, and case (c); decommissioning of the entire site which involves fuel debris retrieval, decommissioning and site remediation. Similar to case (a), SD and LSD scenarios for cases (b) and (c) include a safe storage period of 30 years and 100 years, respectively. Three different site-remediation periods were assumed in case (c): 10 years for ID, 40 years for SD, and 170 years for LSD, making the

Table 1. Values of attribute set for scoring

Options	Min/Max	Amount of waste (ton)	Usable site area (grade)	Time to achive the end state (years)	Availability of disposal facility (grade)
(a) NPP with normal life cycle	Minimum	0	1	25	1
	Maximum	6,340	10	150	10
	Max. - Min.	6,340	9	125	9
(b) FDNPS (Decommissioning)	Minimum	2,700	1	25	1
	Maximum	860,000	10	150	10
	Max. - Min.	857,300	9	125	9
(c) FDNPS (Decommissioning & site remediation)	Minimum	2,700	1	25	1
	Maximum	7,600,000	10	350	10
	Max. - Min.	7,597,300	9	325	9

Table 2. Values of attributes for scoring

(a) Decommissioning of NPP with normal cycle (Smallsize)

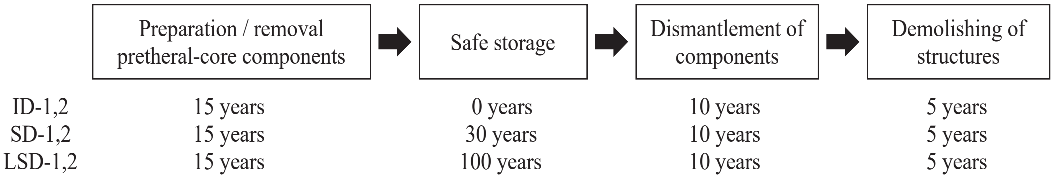
	Immediate dismantling		Differed dismantling (30 years safe storage)		Differed dismantling (100 years safe storage)	
Attribute item	Values (grade)		Values (grade)		Values (grade)	
	Greenfield ID-1	Brownfield ID-2	Greenfield SD-1	Brownfield SD-2	Greenfield LSD-1	Brownfield LSD-2
Radioactive waste arising (ton)	6,340	2,700	4,340	810	810	810
Area of facility usable %	very high	medium	very high	low	very high	very high
Time to end state (years)	30	30	60	60	130	130
Availability of waste disposal site (grade)	medium/ low	medium/ low	medium/ high	medium/ high	very high	very high

(b) Decommissioning of FDNPS Unit 1-4

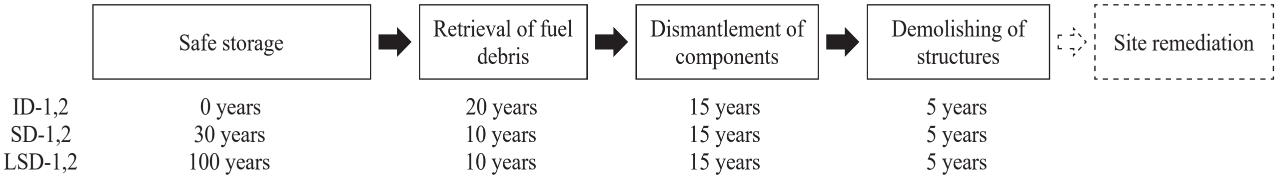
	Immediate dismantling		Differed dismantling (30 years safe storage)		Differed dismantling (100 years safe storage)	
Attribute item	Values (grade)		Values (grade)		Values (grade)	
	Greenfield ID-1	Brownfield ID-2	Greenfield SD-1	Brownfield SD-2	Greenfield LSD-1	Brownfield LSD-2
Radioactive waste arising (ton)	860,000	452,000	860,000	452,000	315,000	158,000
Area of facility usable %	very high	low	very high	low	very high	low
Time to end state (years)	40	40	60	60	130	130
Availability of waste disposal site (grade)	medium/ low	medium/ low	medium/ high	medium/ high	very high	very high

(c) Decommissioning and site remediation of FDNPS

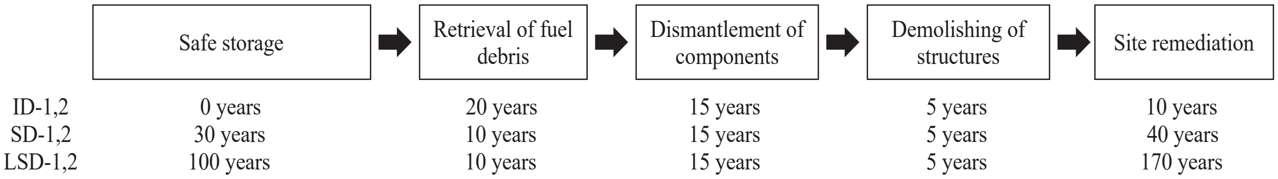
	Immediate dismantling (50 years to end state)		Differed dismantling (100 years to end state)		Differed dismantling (300 years to end state)	
Attribute item	Values (grade)		Values (grade)		Values (grade)	
	Greenfield ID-1	Brownfield ID-2	Greenfield SD-1	Brownfield SD-2	Greenfield LSD-1	Brownfield LSD-2
Radioactive waste arising (ton)	7,600,000	4,400,000	4,000,000	500,000	100,000	50,000
Area of facility usable %	very high	medium	very high	medium	very high	medium
Time to end state (years)	50	50	100	100	300	300
Availability of waste disposal site (grade)	medium/ low	medium/ low	medium/ high	medium/ high	very high	very high



(a) Decommissioning of NPP with normal cycle



(b) Decommissioning of FDNPS Unit 1-4



(c) Decommissioning and site remediation of FDNPS

Fig. 3. Timeframe and process of activities to achieve the end state: (a) Decommissioning of NPP with normal cycle, (b) Decommissioning of FDNPS Unit 1-4, and (c) Decommissioning and site remediation of FDNPS.

total periods to be 50, 100, and 300 years, respectively.

Scores were calculated for the six scenarios by applying the minimum and maximum values for the four attributes: the amount of radioactive waste, areas usable after decommissioning, time necessary to achieve the end state, and availability of waste disposal routes/facilities. The site usability at the end state, and the availability of waste disposal route/facilities were set qualitatively from three to nine ranks; very high (9), high (8), medium/high (7), medium (6), medium/low (5), low (4), and very low (3), with the numbers in the parentheses express their grades. The minimum and maximum values of attribute are listed in Table 1.

The scores were calculated using the data listed in Table 2. The amount of radioactive waste arising from each decommissioning scenario was referred from previous studies [5], [6]. Briefly, the total amount for case (a) was assumed to be 6,340 tons for a small sized BWR [5]. The amount of radioactive waste for case (b) was estimated as the sum of all components and structures of one small-sized and three medium-sized NPPs to be 860 thousand tons [5]. In case (c), it was estimated to be 7,600 thousand tons [6], excluding the waste from decommissioning of contaminated water treatment facilities as it may be necessary to continue treating groundwater after dismantling other facilities. The decrease in the amount due to radioactive decay was estimated assuming uniform distribution of the concentration of major radionuclide, ^{60}Co for case (a), and ^{137}Cs for cases (b) and (c). When the end state is brownfield, a half of the materials was assumed to remain on-site underground without being dismantled. In case (b), 5% of the materials was assumed to be metal and 95% to be concrete. In the LSD scenario of case (b), it was assumed that half of the amount of radioactive concrete waste can be reduced by decontamination process. In the LSD scenario of case (c),

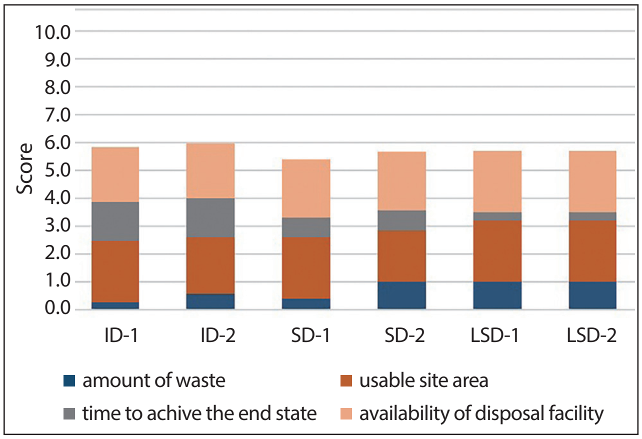


Fig. 4. Scores of six scenarios: Decommissioning of NPP with normal cycle (case (a)).

it was assumed that the waste classified as low and very low-level radioactive waste in [6] would not be considered as radioactive waste after 300 years.

3. Results and Discussion

3.1 Scores of NPP

The attribute scores of the MCDA are shown in Fig. 4 for small-sized NPP which ceased normal operation (case (a)). The scores varied between 5.4 and 6.0 and there were not significant differences between the scores of the six scenarios as shown in Fig. 4. ID scenarios showed the highest scores, followed by LSD scenarios, and SD scenarios. Differences in scores among different scenarios were mainly seen in the amount of waste and the time to achieve the end state. When the time to achieve the end state increases, the amount of radioactive waste decreases due to radioactive decay, mainly of ^{60}Co in the case of plants with normal operation history. As a result, the scores for the amount of waste and the scores for the time to achieve the end state cancel each other, making the overall scores to be within a small variation.

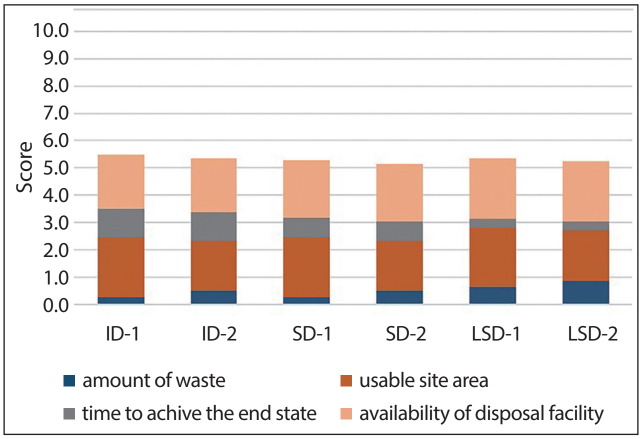
Comparing the extent of removal of building structures between both above- and below-ground (greenfield options: ID-1, SD-1, and LSD-1) and the only above-ground (brownfield options: ID-2, SD-2, and LSD-2), the latter options showed a slight advantage over the former. This is because the reduction in the amount of waste outweighs the reduction in usable site areas after decommissioning.

3.2 Scores of FDNPS

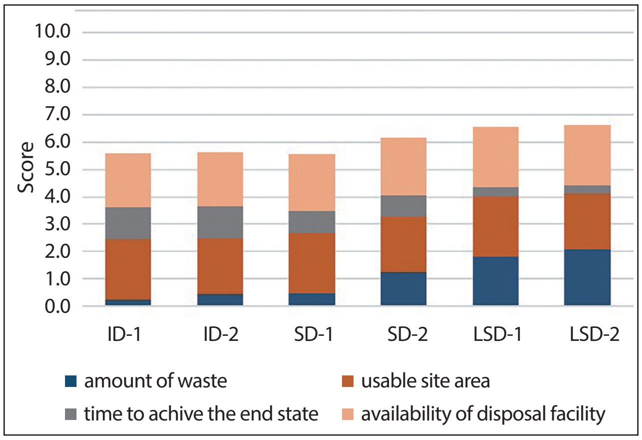
The scores were calculated for decommissioning and site-remediation scenarios of FDNPS. The scores for decommissioning of nuclear facilities (case (b)) are shown in Fig. 5(a), and the scores for decommissioning and site remediation (case (c)) are shown in Fig. 5(b).

The range of the score among six scenarios in case (b) is between 5.1 to 5.5, and the difference in scores among the scenarios is relatively small. ID scenarios are the most preferable options. Similar to case (a) of the NPPs with normal operation history shown in Fig. 4, differences in scores among different scenarios mainly originate from the amount of waste and the time to achieve the end state. The benefits of waste reduction and the effect of extending the timeframe to complete decommissioning are similar, making scores of all of the scenarios to be similar. One reason for the differences between cases (a) and (b) is the half-lives of major nuclides in relation to decommissioning timeframe; the major radionuclide for case (b) is ^{137}Cs, which has a longer half-life of approximately 30 years, and the timeframe considered is relatively similar for cases (a) and (b), thus less reduction in waste volume is expected for case (b).

Comparing between removal of all structures (greenfield options: ID-1, SD-1, and LSD-1) and above-ground structures (brownfield options: ID-2, SD-2, and LSD-2), the former showed a very slight advantage over the latter, which was also opposite of case (a). The balance was perceived to be different between the reduction of the amount of waste and the reduction of the usable areas. Because the amount of waste is too substantial, the reduction in the amount of waste by “in-situ decommissioning” is not



(a) Decommissioning of FDNPS Unit 1-4 (case (b))



(b) Decommissioning and site remediation of FDNPS (case (c))

Fig. 5. Scores of six scenarios in FDNPS: (a) Decommissioning of FDNPS Unit 1-4 (case (b)), and (b) Decommissioning and site remediation of FDNPS (case (c)).

enough to significantly affect the scores.

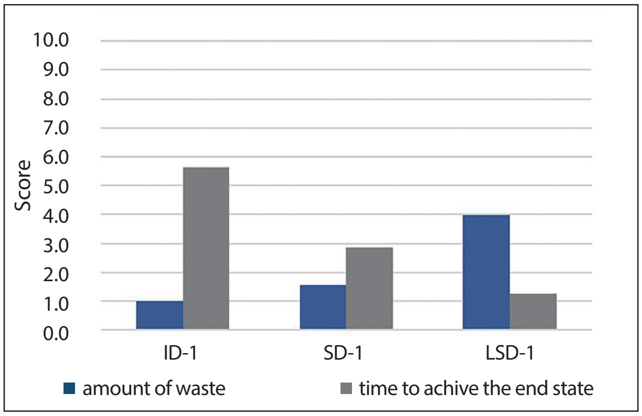
When site remediation was included in consideration (case (c)), the scores differed from cases (a) and (b) (Fig. 5(b)). The range of scores varied between 5.6 and 6.6, which was the greatest of all the cases. Unlike cases (a) and (b), ID scenarios were least preferable, and LSD scenarios showed highest scores. This is due to the significance in the effects of waste reduction over other attributes, because the amount of waste generated, especially from site remediation, is extremely large. Although LSD has a very low score for the time to achieve the end state, its effect is small compared to the effect of waste reduction.

In-situ decommissioning options (ID-2, SD-2, and LSD-2) are preferable for SD-2 and LSD-2, but not for ID-2. In the case of ID scenarios, the amount of waste including site remediation is so significant that the effects of waste reduction from not removing underground structure and contaminated soil become small, making the scores of ID-1 and ID-2 the same. In the case of SD scenarios, in a timeframe which allows a certain degree of radioactive decay, the effects of not removing underground structures and contaminated soil show prominent effect in scores. In the case of LSD scenarios, because the reduction in site remediation waste due to radioactive decay over the 300-year period is significant, the effects of not removing underground structures and contaminated soil becomes negligible.

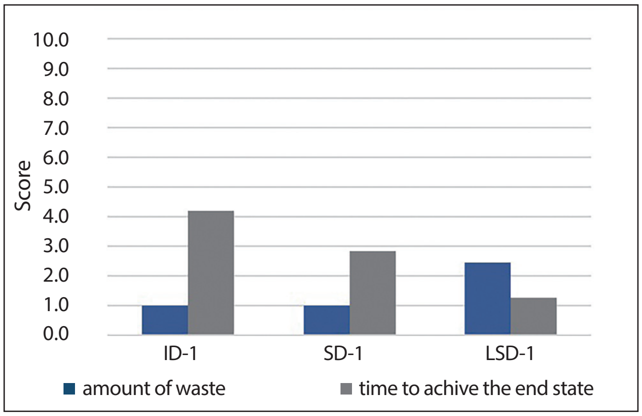
3.3 Comparison of Attribute Scores

When comparing the scenarios, the difference in scores was not very significant for the cases (a) and (b), whereas the scores varied for case (c). The difference in scores mainly originated from two of the four attributes considered: the amount of waste, and the time to achieve the end state. The maximum amount of waste was assumed to be about six thousand tons for case (a), 860 thousand tons for case (b), and 7,600 thousand tons for case (c). In cases (a) and (b), the amount of waste decreased with increasing time due to radioactive decay, and the scores associated with these two attributes almost canceled with each other to make the overall score differences small. However, in case (c), the effect of the reduction in the amount of waste was so significant, partly because the sheer amount was so great, that it overweighed the negative impact on the score from the longer time necessary to achieve the end state (Fig. 6).

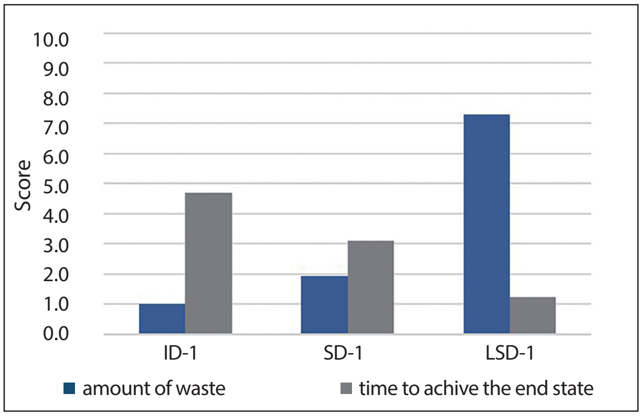
In addition, a relatively significant increase in the scores from SD-1 to SD-2 in cases (a) and (c) was also caused by the increase in the score from the reduction of waste under the assumptions of this study. This was not seen in ID scenarios or LSD scenarios in cases (a) and (c), or in all of the



case (a)



case (b)



case (c)

Fig. 6. Comparison of attribute scores in NPP (case (a)) and FDNPS (case (b), (c)).

scenarios in case (b). The amount of waste decreased with time, making corresponding scores higher, but the degree of reduction was related to the duration of time as well as the half-lives of the major radionuclides. Thus, the changes in the scores from SD-1 to SD-2 were caused by the combination of how much waste and/or contamination is present underground, time of safe storage, and the half-lives of the major radionuclides.

In the decision-making process of practical plans, there are many other important attributes to consider including cost, technical feasibility, project risk, and site-use plan after decommissioning. It may also be necessary to consider weighting factors on attributes when using MCDA to support decision making. However, our preliminary study suggests that balance between the amount of waste and the time to achieve the end state may be one of the major discussions in the decision making of the FDNPS decommissioning scenarios. Completing the decommissioning project in shorter period of time requires establishing radioactive waste disposal facilities with very large capacities, whereas longer storage period means handing down the responsibilities to the future generations to maintain the site, pursue the decommissioning activities and dispose of the radioactive waste, which will have smaller volume due to decay. The trade-offs between these two attributes require considerations on environmental benefits and impacts, the social and economic benefits and costs, as well as on the impacts on natural resources and climate change. Our preliminary study helps to outline the discussion that may be necessary in the future to determine the end state and the strategy toward achieving the end state.

4. Conclusions

Six scenarios were evaluated by using MCDA with geometrical progression curve. From the study, important attributes are shown to be the amount of waste and the time to achieve the end state when evaluating decommissioning scenarios. The duration of safe storage needs to be considered in relation to the concentrations and half-lives of the major radionuclides. Effectiveness of the waste-reducing measures such as in-situ decommissioning may also be influenced by the timing that it is implemented. It may be possible to optimize the timeframe of decommissioning scenarios as more information on the concentrations of major radionuclides in the facilities and in the site environment becomes available.

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