Development of Accident Consequence Assessment Scheme using Accident Cost and Consideration of Decontamination Model

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Abstract: Severe accident at nuclear power plants, including the Fukushima accident in March 2011, wreak various kinds of consequences, including health effects, economic, social and environmental impacts. The authors developed the scheme of the accident consequence assessment using "accident cost", aiming for it to be an index that is as comprehensive as possible. Normalized accident costs of all accident sequences along with their breakdowns, and the breakdown of the average accident cost are presented. The radiation effect cost, the decontamination cost and the relocation cost are the three major components that dominate the accident cost. The decontamination model was reconsidered since decontamination effects were taken into account by very simple assumptions and decontamination cost was estimated by a rough calculation scheme in the former model. 99 decontamination-related parameters were selected and the model is formed. A sensitivity analysis was performed to identify parameters with large influence on accident cost calculation and large extent of interactions with other parameters. Parameters with high importance tend to have large extent of interactions with other parameters. Parameters influential to accident cost, e.g., the dose of setting decontamination target area, a number of waste management-related parameters, are identified.

Keywords: Consequence Assessment, Accident Cost, Decontamination Model, Sensitivity Analysis

1. INTRODUCTION

Severe accident at nuclear power plants, including the Fukushima accident in March 2011, wreak various kinds of consequences, including health effects, economic, social and environmental impacts. Earlier studies [such as 1-3] on severe accident consequence assessment concentrated on mostly health effects as one of indices of consequences. This maybe because the probabilistic safety criteria or goals related to the consequence of severe accidents which were (and still are) commonly used by the regulatory bodies and utilities in several countries are the acute and the chronic doses [4], thus it was necessary to conduct a research that enable to evaluate the doses and propose measures to achieve the goals and fulfill the criteria.

As an index of consequences is assessed, countermeasures are usually proposed to minimize those particular consequences. Minimization of an index of consequences, however, does not necessarily minimize other consequences, in some cases it even increases other consequences. For example, decontamination which is a measure to reduce the dose received by the public may increase the economic impact of the accident as it may cost a great deal. A common index that can take into account various consequences is therefore needed to enable minimization of overall consequences. "Accident cost" (also called "cost per severe accident) has been used for this purpose as it can cover a large scope of consequences and it is simple to understand. In ExternE [5], Hirschberg et al. [6] and IAEA technical reports series no. 394 [7], many kinds of consequences are evaluated in terms of monetary value, referring to the consequences of the Chernobyl accident. As the objective of these studies was to perform a comparative accident consequence assessment among the electricity generation systems, the consequences selected are those can be commonly evaluated in all systems, and there is a possibility for consequences particular to nuclear severe accidents to be overlooked. Park [8] also estimated the total damage cost of severe accidents in particular conditions, but the assumption was way too conservative and the cost associated with decontamination is not included.

The authors have been developing the scheme of the accident consequence assessment using “accident cost”, aiming for it to be an index that is as comprehensive as possible [9-11]. We have modified the accident cost calculation scheme based on the updates of the Fukushima accident in March 2011, and comments from experts who associate with recovery after the accident. The latest version of the accident cost calculation scheme and its results will be introduced in the Section 2.

Though our previous studies on estimation of accident cost [9-11] provide significant insights, which would help to comprehensively assess the consequence of severe accident and to optimize the radiation protection and severe accident management countermeasures, there is still room for improvement. Since the formulation of the assessment scheme was the primary objective, the values of the parameters are determined without adequate data collection and enough consideration, which may crucially affect the results. Although a sensitivity analysis was performed in order to check the validity of the values selected for parameters that are believed important, ceteris paribus technique, where a single parameter is varied at a time while all other parameters are fixed to a constant, was used to perform the sensitivity analysis. As all other parameters are constant when a parameter is examined, the sensitivity of the parameters cannot be systematically evaluated. This makes it difficult to consider the interaction among the parameters which is very important in a non-linear system like severe accident consequence assessment.

A global sensitivity analysis which can take into account the changes of many parameters at a time is therefore needed for this accident cost calculation model. Values of all important parameters must also be reconsidered based on information obtained from review of literatures related severe accidents in the past and updates from the Fukushima accident, in order to get a more realistic consequence assessment. However, if the scope of the sensitivity analysis and the number of parameters incorporated are too large, the uncertainty of the model maybe too large which may obstruct identification of important parameters from non-important ones, and the model itself maybe too complicate to comprehend.

The authors finally decided to focus on decontamination model in this study. This is because: (1) the decontamination cost is one of the three important cost components of the accident cost, i.e., radiation effect cost, relocation cost and decontamination cost, and, (2) decontamination is currently one of the most important the Fukushima accident-related issues, and the insights from this study may help identify the factors that need careful consideration during the decision making process.

The objectives of this study are: (1) to select parameters that are necessary for evaluation of decontamination cost, and formulate the decontamination model for accident cost calculation (Section 3), and, (2) to collect adequate data to set the distribution of each parameter, and perform a sensitivity analysis to identify parameters with large influence on accident cost calculation and large extent of interactions with other parameters which require careful attention, and parameters with negligible influence of which the value can by fixed to constant (Section 4).

2. OVERVIEW OF ACCIDENT COST AND OBJECTIVES OF STUDY ON DECONTAMINATION MODEL

2.1. Methodology

This section shows the overview of calculation of accident cost. Detail of the calculation methodology is provided in K. Silva et al. [9] First of all, the type of the nuclear reactor and its location are determined. Severe accident sequences are defined in a manner that can cover all conceivable severe accidents. Then only accident sequences that lead to release of radioactive materials from the containment vessel are selected. After that, the source term data of each sequence, including the release time, release duration and the amount of the released radionuclides, are taken from the level 2 PRA results. Also the radiation protection scenario is set. This includes the conditions of sheltering, evacuation, relocation and restriction of food intake. At this stage, containment failure frequencies (CFFs) of representative accident sequences are taken from the level 2 PRA results. The CFFs are used to weight the accident sequences in the calculation of the average accident cost in order to prioritize the accident sequences according to their probabilities of occurrence (see Equation (1)). The reason that the CFFs are used to represent the accident occurrence probabilities is that the CFFs are the probabilities that the containment fails to confine the radioactive materials. They have stronger relations than the core damage frequencies (CDFs) with the probability of release of radioactive material to the environment which could determine the extent of the consequences of the accidents.

In the next step, the consequence analysis is performed using the level 3 PRA code, OSCAAR (Off-Site Consequence Analysis of Atmospheric Releases of radionuclides) [12], which was developed by the Japan Atomic Energy Agency (JAEA). OSCAAR estimates the periods of the radiation protection countermeasures, i.e., sheltering, evacuation, relocation and restriction of food intake, and the area and the numbers of people associated with each countermeasure. Also it calculates the individual early (or acute) and chronic doses, the collective dose, and the health effects regarding the radiation exposure.

Before holding accident cost calculation of each accident sequence, the consequences which are able to be quantified and to be taken into consideration are determined. Consequences of the severe accidents to people can be divided into health effects, economic impacts and social impacts. Health effects include the health effects from radiation exposure and the psychological effects. Costs resulting from the radiation protection countermeasures are taken into account as economic impacts. The social impacts are difficult to deal with because they involve the responses of the human-being which make them specific to the accidents. In addition, it is very difficult to convert them to monetary values. The author decided to include only the cost resulting from harmful rumor as quantitative data of other social impacts is not available. Consequences of the severe accidents to the environment can be divided into on-site and off-site consequences. The on-site consequences can be represented by the increase in decommissioning cost and the off-site consequences can be quantified by summing up the costs for decontamination of the land contaminated by the released radioactive materials.

Then the results from the consequence analysis by OSCAAR, i.e., the expected values of the periods and the numbers of people involved in the radiation protection countermeasures and the collective dose of each severe accident sequence, are used as the input data to perform the calculation of the accident cost of each accident consequence. The ways to estimate the monetary values of each consequence are briefly explained below. The equations and the values of the parameters used for the calculation can be found in K Silva et al. [9].

<u>*Health Effects*</u> The cost regarding health effects from radiation exposure is estimated by a simple multiplication of the collective dose and the willingness to pay (WTP) per unit exposure. This is because the stochastic effects from the radiation exposure are supposed to be in linear relationship with the exposure dose according to the linear non-threshold hypothesis of ICRP [13]. The deterministic effects from the radiation exposure is not included because it is internationally recognized that full effort must be made to prevent the deterministic effects even though those measures can significantly increase other consequences (e.g. economic impacts) of the accident [14]. Therefore, there is no point to consider the deterministic effects together with other consequences. The psychological effect cost is estimated by summing up the compensations regarding psychological effects resulting from sheltering, evacuation and relocation. The unit value of the compensation [JPY/person-year] refers to the compensation in the Fukushima accident [15].

<u>*Economic Impacts*</u> Income losses, transportation costs, accommodation costs and capital utility losses of the sheltered, evacuated and relocated population are used to estimate the economic impacts of those countermeasures. Losses of income of people who could not work during the implementation of sheltering, evacuation and relocation are included into the cost estimations of all countermeasures. Transportation costs and accommodation costs are included in the case of evacuation and relocation. Capital utility losses are considered only in the relocation cost calculation. Food intake restriction cost is estimated by summing the losses of the agricultural and livestock products the six types of the agricultural and livestock products: milk, dairy products, meat, leaf vegetables, root vegetables and grains and the cost of waste management

Social Impacts The approximate value of the cost regarding damages by harmful rumor was taken from the report of the commission of management and financial survey of TEPCO [16].

Environmental Impacts The increase in decommissioning cost is estimated by multiplying the total electric power of the target reactor by the increase of decommissioning cost per unit electric power obtained from the report of the commission of management and financial survey of TEPCO [16]. The decontamination of the released radioactive materials is supposed to be done in the entire relocated area. Different decontamination techniques are chosen to suit different land use types. The decontamination cost consists of the total cost generated during the implementation of all decontamination techniques and the summation of the management cost of waste generated. The former is obtained by multiplying the target area of each decontamination technique by the costs generated during the implementation of the technique per unit area which includes the costs of the materials, equipment and labors spent, and sum them up. The latter is the product of the mass of waste generated (volume reduction by incineration is taken into account for burnable waste) and the unit cost for the radiation waste disposal.

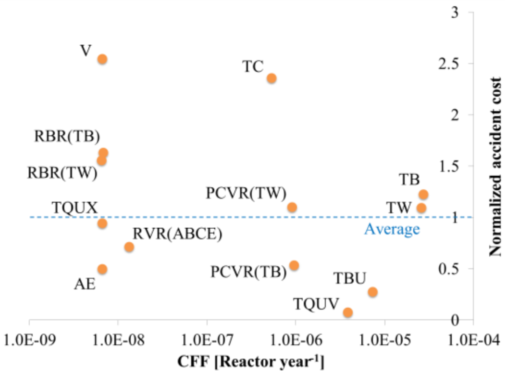
All costs stated above are summed up to form the accident cost of each accident consequences, Finally, calculated accident cost of each accident sequence is averaged using their CFFs as a weighting factor.

$$AC = \frac{\sum_{p} AC_p \times CFF_p}{\sum_{p} CFF_p} \tag{1}$$

where AC_p and CFF_p represent the accident cost and the CFF of the pth accident sequence, and AC represents the average accident cost.

2.2. Calculation Conditions

The methodology was applied to a virtual 1100 MWe boiling water reactor (BWR-5) which is located at the center of Tokai Research and Development Center (TRDC) of JAEA. Dominant severe accident sequences were selected, and the CFFs, release times, release duration times, and release ratios of those accident sequences were taken from the results of an open document of level 2 seismic PRA [17]. The radiation protection scenario was selected based on the recommendations of IAEA, ICRP and Nuclear Safety Commission of Japan (NSC) [18-20]. As TRDC is in Ibaraki Prefecture, the data of population, agricultural and livestock products and land use types were taken from the statistical data of Ibaraki Prefecture [21].



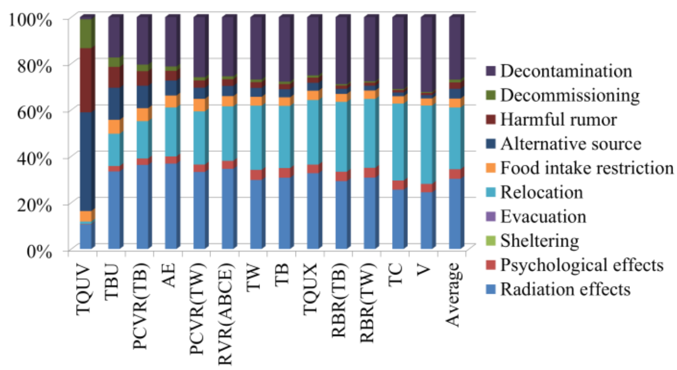


Fig. 1 (left) Normalized accident cost of each accident sequence [9]
Fig. 2 (right) Breakdowns of accident cost of all accident sequences and breakdown of average accident cost [9]

2.3. Results and Discussion

The normalized accident costs NAC_p of each accident sequence are shown with their CFFs in Fig. 1.

$$NAC_p = \frac{AC_p}{AC} \tag{2}$$

Abbreviations, e.g., TB, TW, represent the accident sequences*. This figure shows both the occurrence probabilities (CFFs) and the consequences (accident costs) which are significant indicators to assess the risk of severe accidents in nuclear power plants. Many accident sequences with small CFFs, i.e., V, RBR(TB), RBR(TW), gave large accident costs. If only the CFF (or CDF) is used to indicate the risk, these accident sequences might be considered as insignificant due to their small CFFs. This implies that assessing only one indicator without assessing another may provide misleading information on risk of severe accidents.

Fig. 2 shows the breakdowns of accident costs of each accident sequence and of average accident cost which represent the relative sizes of each component of the accident costs. Accident sequences were sorted by their total accident cost in ascending order, and the breakdown of average accident cost is on the last bar. When the release is very small, e.g., TQUV, all components using constant values, i.e., alternative source cost, harmful rumor cost and decommissioning cost, dominate the accident cost. When the release is relatively small, e.g., PCVR(TB), AE, PCVR(TW) and RVR(ABCE), the radiation effect cost dominates the accident cost because the annual dose rates in most area are not high enough to trigger the relocation, and thus only limited area needs decontamination since the decontamination is assumed to be done only in the relocated area. When the release is moderate (TW, TB, TQUX, RBR(TB) and RBR(TW)), the radiation effect cost, the relocation cost and the decontamination cost are almost the same and dominate the accident cost since the relocated area (= decontamination target area) and the relocation period increase with the amount of source term. When the release is relatively large (TC, V), the relocation cost and the decontamination cost dominate the accident cost because the relocated area and the decontamination target area are significantly enlarged according to the increase of amount of source term while the increase of collective dose which determines the radiation effect cost is rather moderate. Breakdown of the average accident cost shows the similar trend to the accident sequences with moderate release. It can be concluded that the radiation effect cost, the decontamination cost and the relocation cost are the three components that dominate the accident cost. Therefore, measures to minimize these three costs without increasing one another or other costs have to be carefully considered in the decision makings in severe accident consequence management.

3. DISCUSSION ON DECONTAMINATION MODEL

3.1. Parameter Selection

First, All factors related to decontamination cost and the effects of decontamination, that may affect the accident cost were listed. These factors are qualitatively screened by selecting only factors that directly affect the three important cost components of the accident cost, i.e., radiation effect cost, relocation cost and decontamination cost. Selected factors are listed in Table 1. Then the authors carefully examined OSCAAR and identified 99 parameters, also listed in Table 1, to incorporate all selected factors into the accident cost calculation scheme.

* TB: Long-term loss of all AC power; TW: Loss of all decay heat removal function; TBU: Short-term loss of all AC power;
TQUV: Transient with loss of ECCS function; PCVR: Primary containment vessel rupture; TC: ATWS events
RBR: Reactor building rupture; RVR: Reactor vessel rupture; TQUX: Transient with loss of Depressurization
AE: LOCA with loss of ECCS injection; V: LOCA with loss of water injection

Table 1 Decontamination-related factors and parameters that affect the accident cost[1]

Factor	Parameter	Parameter No.
Factors/parameters that affect decontamination cost		
Determination of decontamination target area	Dose for decontamination target area setting [mSv/year]	1
Decontamination techniques used in each land use type	Fraction for application of each decontamination technique on roofs and walls of houses and buildings[2] [%] (2: B, 3: HPW)	2-3
	Fraction for application of each decontamination technique on gardens and playgrounds[2] [%] (4: RL, 5: RSS, 6: WLM, 7: RS, 8: CL)	4-8
	Fraction for application of each decontamination technique on agricultural areas[2] [%] (9: P, 10: RSS, 11: RS)	9-11
	Fraction for application of each decontamination technique on forests[2] [%] (12: RSF, 13: RS, 14: CL)	12-14
	Fraction for application of each decontamination technique on roads[2] [%] (15: SB, 16: CS, 17: W)	15-17
Unit cost of each decontamination technique	Unit costs of 12 decontamination techniques [JPY/m^2] (18: Determination of random number(s) used to determine the unit cost[3], 19: Random number to determine the unit cost for the case of same random number, 20: HPW, 21: B, 22: RS, 23: RL, 24: CL, 25: RSS, 26: WLM, 27: P, 28: RSF, 29: W, 30: SB, 31: CS)	18-31
Waste generated by each decontamination technique	Liquid and solid waste generated by each decontamination techniques[4] [m^3/m^2] (32: HPW (s), 33: HPW (l), 34: B (s), 35: B (l), 36: RS (s), 37: RL (s), 38: CL (s), 39: WLM (s), 40: RSF (s), 41: W (s), 42: W (l), 43: SB (s), 44: CS (s))	32-44
Waste management	Determination whether or not to include cost due to: Temporary waste storage (45), Waste transportation (47), Waste treatment (49), Interim storage (53), Waste disposal (55)	45, 47, 49, 53, 55
	Unit costs of: Temporary waste storage (46), Waste transportation (48), Liquid waste treatment (50), Solid waste treatment (incineration) (51), Solid waste treatment (classification and chemical process) (52), Interim storage (54), high level radioactive waste disposal (56), Disposal of controlled type waste (57) [JPY/m^3]	46, 48, 50-52, 54, 56-57
	Volume reduction rates for: Non-burnable solid waste (58), Burnable solid waste (59)	58-59
Factors/parameters that affect relocation cost		
Determination of decontamination target area	Dose for decontamination target area setting [mSv/year]	1
Determination of way of implication of each decontamination technique	Number of workers that can be involved in the decontamination work [man-year/year]	60
	Work speed of each decontamination technique [m^2/man-day] (61: HPW, 62: B, 63: RS, 64: RL, 65: CL, 66: RSS, 67: WLM, 68: P, 69: RSF, 70: W, 71: SB, 72: CS)	61-72
Dose reduction factors	Selection of data set of dose reduction factors	73
	Dose reduction factors for each decontamination technique [-] (74: HPW, 75: B, 76: RS, 77: RL, 78: CL, 79: RSS, 80: WLM, 81: P, 82: RSF, 83: W, 84: SB, 85: CS)	74-85
	Dose reduction factors for each land use type [-] (86: Houses, 87: Buildings, 88: Agricultural areas[5], 89: Forests, 90: Roads)	86-90
Occupational dose for workers involved with decontamination	Selection of range for calculation of occupational dose	91
	Ranges of average (92) and maximum (93) occupational dose calculation factors [-]	92-93
Period of staying in specific areas per day[6]	Period of staying in each land use type per day [hr] (94: Houses, 95: Buildings, 96: Gardens and playgrounds, 97: Agricultural areas, 98: Forests, 99: Roads)	94-99

[1] Following abbreviations represent 12 decontamination techniques, where HPW = High pressure (HP) water, B = Brushing, RS = Removing soil or covering with soil, RL = Removing, covering or harvesting lawn, CL = Cutting leaves and shrubs, RSS = Replacing soil with subsoil, WLM = Weeding or lawn mowing, P = Ploughing, RSF = Removing sediments and fallen leaves, W = Water, HP water or very HP water, SB = Sandblast or shotblast, CS = Cutting surface or resurfacing.
[2] The sums of the fractions of land use types are normalized to 100%, except for CL which can be applied in the area where other decontamination techniques has already been applied.
[3] Using same random number for all decontamination techniques or different random numbers for each decontamination techniques.
[4] (s) stands for solid waste and (l) stands for liquid waste.
[5] The same dose reduction factor is also used for gardens and playgrounds due to absence of data.
[6] The sum of periods of staying is normalized to 24 hours.

3.2. Model Description

3.2.1 Changes in decontamination cost estimation scheme

The decontamination cost is obtained by adding the total cost generated during the implementation of all decontamination techniques, to the summation of the management cost of waste generated, as is the case with Section 2. The author has improved the decontamination cost estimation scheme in order to include 99 parameters stated in Section 3.1 using information obtained from literatures and updates from the Fukushima accident [such as 22-24]. The detail of improvements of the decontamination cost estimation scheme is as follow:

(1) Decontamination target area is not the same as the relocated area, but is set based on the dose for target area setting,
(2) Decontamination techniques of each land use types are changed to match with the techniques selected in the Fukushima accident and in literatures,
(3) Distributions of fractions for application of each decontamination technique, unit costs of each decontamination technique, waste generated by each decontamination techniques, unit costs of each waste management step and, volume reduction rates are determined, and their values for each run are randomly selected from respective distributions,
(4) Costs from the entire procedure of waste management can be taken into account, and the inclusions of costs associated with respective steps of waste management to the accident cost calculation model are randomly determined,
(5) Volume reduction rate for non-burnable waste is also taken into account.

The total cost generated during the implementation of each decontamination technique for each land use type $DI_{l,t}$ [JPY] is calculated by

$$DI_{l,t} = F_{l,t} \times A_l \times U_{DI,t}, \text{ where } \sum_t F_{l,t} = 1. \tag{3}$$

$F_{l,t}$ stands for the fraction for application of the tth decontamination technique for the lth land use type [-], A_l for the total area of the lth land use type [m^2], and $U_{DI,t}$ for the unit implementation cost of the tth decontamination technique [JPY/m^2]. $F_{l,t}$s that possess no distribution, i.e., $F_{l,t}$s that do not appear in Table 2 as parameter number 2-17, are set to zero. On the other hand, the waste management cost of each decontamination technique for each land use types $WM_{l,t}$ [JPY] is estimated by

$$\begin{aligned} WM_{l,t} = F_{l,t} \times A_l \times \big[&\{(WS_t + WL_t) \times X_{TS} \times U_{TS}\} + \{(WS_t + WL_t) \times X_{TR} \times U_{TR}\} + \\ &\{X_{WT} \times (WS_t \times U_{WT,WS_t} + WL_t \times U_{WT,WL_t})\} + \{X_{IS} \times VR_t \times WS_t \times U_{IS}\} + \\ &\{X_{WD} \times (WS_t \times VR_t \times U_{WD} + WS_t \times (1 - VR_t) \times U_{CWD})\}\big]. \end{aligned} \tag{4}$$

Here, WS_t and WL_t are solid and liquid wastes generated by the tth decontamination technique per unit area [m^3/m^2] and VR_t is volume reduction rate for the tth decontamination technique. X is used to determine whether or not to include the respective step into the waste management cost (If yes, X = 1, if no X = 0.). U represents the unit cost of the respective waste management steps. Subscripts *TS*, *TR*, *WT*, *IS*, *WD* and *CWD* stand for temporary waste storage, waste transportation, waste treatment (volume reduction), waste interim storage, high level radioactive waste disposal and disposal of controlled type waste, respectively. The total decontamination cost is

$$DC = \sum_l \sum_t \left(DI_{l,t} + WM_{l,t} \right). \tag{5}$$

3.2.2 Changes in relocation cost estimation scheme

Relocation cost is estimated by summing the income losses, transportation costs, accommodation costs and capital utility losses, which is also the same as in section 2. The only difference is the estimation of relocation period. In previous studies, decontamination are supposed to be immediately done in the entire area where the dose is above the dose for decontamination target area setting (= dose level for the decision of return home), regardless the decontamination capacity. However, decontamination capacity can be limited by the number of workers that are prepared for the decontamination work. The number of workers that can be involved in the decontamination work N_{WK} [man-year/year] and the work speed of each decontamination technique WSP_t [m^2/man-day] are thus taken into account. The decontamination capacity DCP [m^2/year] can be estimated by

$$DCP = \sum_l \sum_t F_{l,t} \times F_l \times N_{WK} \times WSP_t \times 365 \text{, where } \sum_l \sum_t \left(F_{l,t} + F_l \right) = 1. \tag{6}$$

F_l is the share of the lth area from the entire decontamination target area [-]. The values of $F_{l,t}$, N_{WK} and WSP_ts are randomly selected from respective distributions for each run. If the area where the dose is above the dose for decontamination target area setting is larger than the decontamination capacity, it will be reduced to the decontamination capacity. This will lengthen the relocation period and increase the relocation period, but will in turn reduce the radiation effect cost as the population is kept from the contaminated area for a longer time. Detail on calculation methodology is omitted as it is the same as in previous studies.

3.2.3 Changes in radiation effect cost estimation scheme

Radiation effect cost is the product of the collective dose (the sum of the collective dose of the population and that of the decontamination workers) and the WTP per unit exposure. As the dose reduction factors for each decontamination technique and for each land use type are introduced, the collective dose CD can be calculated by

$$CD = DR \times \left(CD_{POP,B} + CD_{OCP,B} \right), \tag{7}$$

$$DR = \sum_l \sum_t F_{l,t} \times F_l \times DR_t \text{, where } \sum_l \sum_t \left(F_{l,t} + F_l \right) = 1 \tag{8}$$

when the set of dose reduction factors for each decontamination technique is used, and

$$DR = \sum_l F_l \times DR_l \text{, where} \sum_l F_l = 1 \tag{9}$$

when the set of dose reduction factors for each land use type is used. $CD_{POP,B}$ and $CD_{OCP,B}$ are the collective doses of the population and the decontamination workers before consideration of dose reduction factor [Sv], and DR is the average dose reduction factor [-]. The values of $F_{l,t}$, DR_ts and DR_ls are randomly selected from respective distributions for each run. In regard to the dose of decontamination workers, the occupational dose calculation factor OD [-] is introduced. The collective dose of decontamination workers before consideration of dose reduction factor can be estimated by

$$CD_{OCP,B} = \sum_d \sum_r \sum_y X_{DC,d,r,y} \times OD \times D_{d,r,y} \times N_{WK,d,r,y}. \tag{10}$$

Here, $X_{DC,d,r,y}$ is used to indicate whether or not decontamination is done in the area represented by mesh (d,r) in the yth year (If yes, X = 1, if no X = 0.). $D_{d,r,y}$ and $N_{WK,d,r}$ are the annual dose and the number of decontamination workers in the area represented by mesh (d,r) in the yth year, respectively.

4. SENSITIVITY ANALYSIS

4.1. Elementary Effects Method

The authors performed a sensitivity analysis using the elementary effects method proposed by Morris [25] and revised by Campolongo et al. [26]. This method can identify: (1) parameters with large influence to the output and large extent of interactions with other parameters which require careful attention, and, (2) parameters with negligible influence of which the value can be fixed to constant.

In this method, we assume that the k-dimensional vector **X** of the model input has components X_i each of which can assume integer values in the set $\{0, 1/(p-1), 2/(p-1), \ldots, (p-2)/(p-1), 1\}$. This forms a k-dimensional p-level experimental region Ω ($k \times p$ matrix). For a given value **x** of **X**, the elementary effect of the ith input parameter is defined as

$$d_i(\mathbf{x}) = \frac{y(x_1, \ldots, x_{i-1}, x_i + \Delta, x_{i+1}, \ldots, x_k) - y(\mathbf{x})}{\Delta} \tag{11}$$

where Δ is a predetermined multiple of $1/(p-1)$, and $\mathbf{x} = (x_1, x_2, \ldots, x_k)$ is any selected value in Ω such that the transformed point $(\mathbf{x} + \mathbf{e}_i\Delta)$, where $\mathbf{e}_i$ is a vector of zeros but with one as its ith component, is still in Ω for each index $i = 1, \ldots, k$. In this study, accident cost y is the output of the model. The input is a 99-dimensional vector (k = 99), since there are 99 decontamination-related parameters to be examined. The number of levels p and Δ are set to 10 and 5/9, respectively. The number of runs r for each component X_i is set to 20. The way to determine p, Δ and r can be referred to in Saltelli et al. [27].

In each run, **x** is randomly selected from **X**, $y(x_1, \ldots, x_{i-1}, x_i + \Delta, x_{i+1}, \ldots, x_k)$ and $y(\mathbf{x})$ are then estimated, and the elementary effect $d_i(\mathbf{x})$ is consequently calculated. To calculate the accident cost y, all x_is are used as the percentile to pick up a value from the distribution of the ith parameter (the sequence of the parameters is defined in Table 1). After the rth run of the kth component X_k, the average of the absolute values of the elementary effects μ^*, and the standard deviation of the elementary effects σ, of each component X_i are calculated using

$$\mu^* = \sum_{i=1}^{r} |d_i| / r \text{ , and} \tag{12}$$

$$\sigma = \sqrt{\sum_{i=1}^{r} (d_i - \mu)^2 / r} \text{ , where } \mu = \sum_{i=1}^{r} d_i / r \text{ .} \tag{13}$$

Both μ and μ^* can be used as an indicator of the importance of the parameter. μ^* is preferable to μ because di(x)s can give negative value and some effects may thus cancel each other out when computing the average if μ is used [22]. σ can be used to indicate the extent of interactions of the parameter with other parameters.

4.2. Determination of parameter distributions

Distributions of 99 parameters are formed base on the information obtained from literatures and updates from the Fukushima accident [such as 22-24]. Distributions of parameters of high importance

Table 2 Distributions of important parameters

No.	Parameter	Type of Distribution	Min.	Max.	Remarks
1	Dose of setting decontamination target area [mSv/year]	Discrete	1	20	4 annual dose rates (1, 5, 10 and 20) with same probability density (P(x) = 0.25).
55	Determination whether or not to include cost due to waste disposal	Discrete	0	1	[0, 0.5) = no/[0.5, 1) = yes.
60	Number of workers that can be involved in the decontamination work [man-year/year]	Uniform	5000	50000	Determined by the evaluator.
56	Unit cost of waste disposal [JPY/m^3]	Uniform	650000	3018000	
36	Waste generated by removing soil or covering with soil [m^3/m^2]	Uniform	0.000	0.079	

(parameters of which μ*s shown in Fig. 3a are the first to the fifth largest) are presented in Table 2 as examples.

4.3. Results & Discussion

The results of the sensitivity analysis, i.e., the μ*s and the σs of each parameter, are shown in Fig. 3a and 3b. Fig. 3a shows the overview for all parameters, where the graph is zoomed in in Fig. 3b to visualize parameters with small μ^* and σ. The numbers in the graphs correspond to the parameter numbers in Table 1. It is observable from the figure that μ^* correlates strongly with the σ, i.e., parameters with high importance tend to have large extent of interactions with other parameters. In this paper, the discussion will be done based only on μ^* as it may be able to roughly represent the discussion on σ.

It is obvious from Fig. 3a that the dose of setting decontamination target area (1) is very influential to the accident cost as it determines the size of the decontamination target area. Fig. 3a also shows that parameters related to waste management also have very high importance since there are four waste management-related parameters (53, 55, 56 and 58) of which the μ*s and the σs are over 0.20. Very high μ*s and σs of 55 and 56 emphasize the importance of consideration of costs due to waste disposal

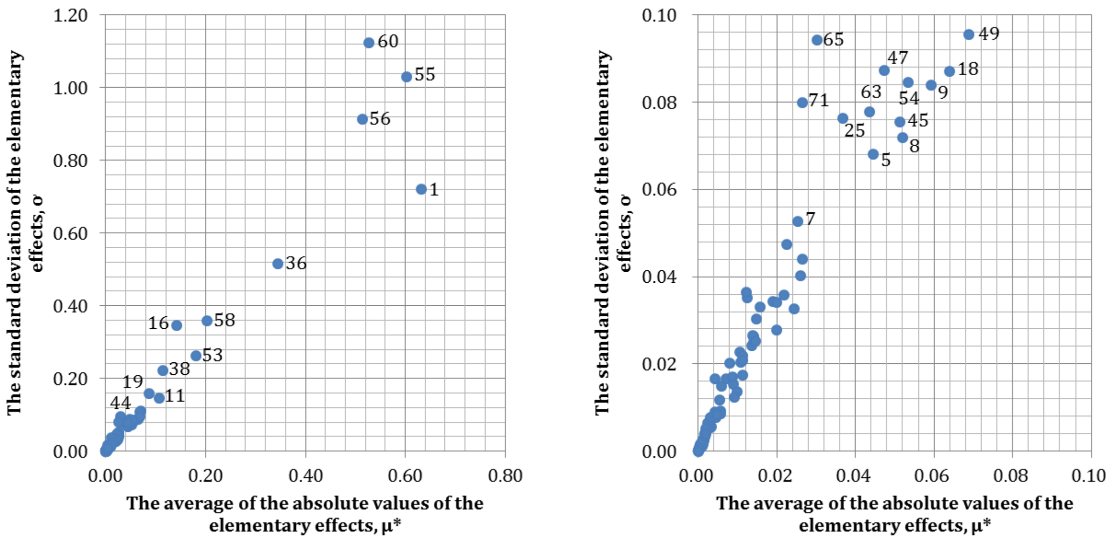


Fig. 3a (left) μ*s and σs of all parameters
Fig. 3b (right) Zoomed-up version of Fig. 3a to the region where $0 \leq \mu^* \leq 0.10$ and $0 \leq \sigma \leq 0.10$
This figure shows all non-negligible parameters other than those shown in Fig. 3a

which is omitted in many earlier studies. This implies that in spite of inadequate information on accurate parameter values, it is important to consider the costs due to waste disposal in the estimation of accident cost, i.e., the estimation of the accident consequences. Another very important parameter is the number of workers that can be involved in decontamination work (60) as it directly affects the relocation period. The volumes of waste generated per unit area by decontamination techniques which generate a lot of waste (36, 38 and 44) also seem to be important as it influence the total amount of the waste. It is also observed that fractions for application of decontamination techniques with high unit cost (11 and 16) can be quite influential to the output. Lastly, the large $\mu*$ of the parameter 19 implies that when the distributions of unit costs of all decontamination techniques are taken into account simultaneously, they may have large effect on accident cost. As for these parameters, more raw data collection is needed for parameters of which distributions are formed by limited number of data points. Further discussion on quality of the data collected or consultation with stake holders to determine the distributions on the specific values to represent the respective parameters may also be needed.

Fig. 3b shows that the influences of: fractions for application of many decontamination techniques (5, 7, 8 and 9), parameters that determine the unit cost of some decontamination techniques (18 and 25), waste management-related parameters other those stated above (45, 47, 49 and 54), and, work speeds of some decontamination techniques (63, 65 and 71), are not negligible (both $\mu*$ and σ are over 0.05). Parameters that did not appear above are theoretically negligible, and can be fixed to constants in order to simplify the model and to reduce the calculation time. It is interesting that none of parameters that affect radiation effect cost, which was the largest component of accident cost in Section 2, are influential to accident cost. One possible reason is that much larger waste management cost and longer relocation period significantly increased the decontamination cost and the relocation cost, respectively, and the radiation effect cost became relatively smaller. However, it is to be noted that distributions of many radiation effect cost-related parameters, e.g., WTP per unit exposure, were not taken into account. Taking them into account may significantly increase the importance of radiation effect cost-related parameters to the accident cost. Similarly, other parameters with low $\mu*$s and σs must be carefully examined before fixing to a constant.

5. CONCLUSION

The calculation scheme of the accident cost, which is an index for severe accident consequence assessment, was introduced. The authors pointed out the needs of improvements of the calculation scheme, including data collection and further consideration of important parameters, and a global sensitivity analysis of the model. This study focused on the consideration of decontamination model. The decontamination model was formulated using decontamination-related parameters that directly affect the three important cost components: the decontamination cost, the relocation cost and the radiation effect cost. Distributions of all parameters were set, and a sensitivity analysis was performed to identify parameters with large influence to accident cost calculation and large extent of interactions with other parameters. Parameters with high importance tend to have large extent of interactions with other parameters. Parameters that are influential to the accident cost are: the dose of setting decontamination target area, a number of waste management-related parameters, the number of workers that can be involved in decontamination work, the volumes of waste generated per unit area by decontamination techniques which generate a lot of waste, the fractions for application of decontamination techniques with high unit cost, and the common random number when the same random number is used for calculation of unit costs for all decontamination techniques. Further studies, e.g., more raw data collection for some parameters, further discussion on quality of the data collected, or consultation with stake holders, may be needed for these parameters.

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