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IFAC PapersOnLine 51-32 (2018) 125–129

Decision-making in waste management: scenarios evaluation

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Abstract: This paper suggests a methodological approach to the problem of waste management. Scenarios evaluation of waste disposal landfills is proposed. Integral index of ecological hazard based on the number of initial landfill indicators is used for decision-making. So one can calculate the value of integral index due to different waste disposal scenarios and choose the most optimal one. Our approach is illustrated by calculation of scenarios for three landfills of one city in the Russia Arctic Zone for 4 years.

Keywords: Rational Use of Natural Resources, Decision-making, Optimization, Waste Management, Waste Disposal, Summary Indices, Scenarios Evaluation, Arctic Zone.

1. INTRODUCTION

Anthropogenic impact to the environment is a natural consequence of economic activities that is a prerequisite of the very existence of human society. Given the current level of technology and economic development this impact often makes a considerable damage to the environment and necessitates corresponding reclamation works. Waste is significant part of anthropogenic impact. Waste management calls for quantitative evaluation of the damage and assessment of reclamation efficiency. Traditionally used financial estimates are insufficient due to versatility of anthropogenic impact to the environment that is an interrelated complex of natural environments (water, air, soil) with their wildlife.

Decision-making in waste management is rather complicated procedure: one has to consider both impact and financial reasons. It comes clear that traditionally used separate evaluation of environmental and economic factors is insufficient due to their versatility and incomparability. Anthropogenic load is presently assessed by each pollutant based on a corresponding qualitative indicator. These indicators are often consolidated in indices to be used in integrated evaluation of the magnitude of adverse impact or, alternatively, of the environment quality.

This work is aimed at the development of methodology for evaluation of waste management scenarios based on computation of integral index reflecting potential environmental hazard. This work utilizes actual data on a number of localities in the Yamalo-Nenets Autonomous Territory of Russian North and can be of interest for the countries of the international arctic zone.

2. METHODOLOGY FOR COMPUTATION OF POTENTIAL ENVIRONMENTAL HAZARD INDICATOR

The well-known recommendations on selection of key indicators and development of summary indices in various areas of human activities (see Handbook on Constructing Composite Indicators: Methodology and user guide (2008) suggest the following general procedure:

1) development of theoretical basis for index formation;
2) selection of indicators-datasets used to compute the indicator;
3) recovery of missing values in the data;
4) multi-factor analysis of the dataset in order to identify its internal structure and interrelationships between the indicators;
5) representation of values of initial indicators in comparable forms through data normalization;
6) selection of weight factors and aggregation of individual indicators into a summary index;
7) evaluation of sensitivity of the obtained index to selection of the normalization scheme, recovery of missing data, selection of weights and indicators aggregation method, removal/addition of an indicator to the initial data and to other factors;
8) identification of relative importance of individual indicators that determine the summary index value;
9) determination of correlation between the obtained summary index and other indicators that characterize the objects in question;
10) visual representation of the obtained results.

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Peer review under responsibility of International Federation of Automatic Control.
10.1016/j.ifacol.2018.11.366

When developing summary indices the most critical are the procedures responsible for initial data (primary indicators) normalization, selection of weights and aggregation. These are the procedures that make the greatest impact on the absolute value of the resulting summary index and on the results of ranking of objects in question.

Data normalization shall be done prior to their aggregation, since the indicators that are part of the initial datasets are usually measured in different units. The most popular normalization methods are shown in Table 1.

also hide the lack of statistical or empirical basis for selection of weights, i.e. when the knowledge about relations between the components is insufficient or when experts cannot reach a consensus. In any case, this approach does not mean abandoning the weighting procedure, but rather assumes that all weights are equal.

The aggregation methods most often used in development of summary indices include linear aggregation method and geometric aggregation. At both linear and geometric aggregation the weights reflect the results of compromise between the indicators.

Table 1. The most common normalization methods

Method/*example of application*	Formula
1. Ranking / *Information and Communications Technology Index* (see J. Fagerberg, B. Lundvall and D. Archibugi (eds.) (2001), *Medicare Study on Healthcare Performance across the United State* (see S.F. Jencks, E.D. Huff and T. Cuerdon (2003)	$I^t_{q,c} = \text{Rank}(x^t_{q,c})$
2. Standardization	$I^t_{q,c} = \dfrac{x^t_{q,c} - x^t_{q,c=\bar{c}}}{\sigma^t_{q,c=\bar{c}}}$
3. Min-max / *Human Development Index* (see Human Development Report (2011).	$I^t_{q,c} = \dfrac{x^t_{q,c} - \min_c(x^{t_0}_q)}{\max_c(x^{t_0}_q) - \min_c(x^{t_0}_q)}$
4. Distance to the base (reference) landfill	$I^t_{q,c} = \dfrac{x^t_{q,c}}{x^{t_0}_{q,c=\bar{c}}}$ or $I^t_{q,c} = \dfrac{x^t_{q,c} - x^{t_0}_{q,c=\bar{c}}}{x^{t_0}_{q,c=\bar{c}}}$
5. Categorical scale	$I^t_{q,c} = \begin{cases} 0 & \text{if } x^t_{q,c} < P^{15} \\ 20 & \text{if } P^{15} \le x^t_{q,c} < P^{25} \\ 40 & \text{if } P^{25} \le x^t_{q,c} < P^{65} \\ 60 & \text{if } P^{65} \le x^t_{q,c} < P^{85} \\ 80 & \text{if } P^{85} \le x^t_{q,c} < P^{95} \\ 100 & \text{if } P^{95} \le x^t_{q,c} \end{cases}$
6. Normalization based on deviation from the average / *Summary Innovation Index* (see European Commission. Summary Innovation Index (2014).	$I^t_{q,c} = \begin{cases} 1 & \text{if } w > (1+p) \\ 0 & \text{if } (1-p) \le w \le (1+p) \\ -1 & \text{if } w < (1-p) \end{cases}$ where $w = x^t_{q,c} / x^{t_0}_{q,c=\bar{c}}$

Note: here – value of a partial indicator q for landfill c at time t; – partial indicator value for the landfill selected as a reference. Pi – i-th percentile of distribution of the indicator , p – arbitrarily select-ed allowable deviation from the average.

Selection of the best normalization method is a non-trivial problem. When selecting a normalization method one should pay attention to the properties of initial data and to the purpose of development of the summary index. Stability tests should be run in order to determine how the properties of the initial data and selection of the normalization procedure impact the final result.

Most summary indices are developed using equal weights, when all the same weight factor is assigned to the indicators-variables. This approach assumes that all variables used to build a summary index are of equal significance, but it can

The absence of "unbiased" methods for selection of weights and a method of aggregation does not necessarily result in failure to justify summary indices, at least as long as this process remains transparent. Goals pursued by the developer shall be clearly stated at the initial phase and selected methods should be tested to find out to what extent these goals have been achieved.

The opportunities for using the summary indices in the environmental protection area are shown in this work through the example of waste management problem. It is known that non-recyclable solid domestic waste are disposed in special landfills that cause damages to the environment. Types and potential magnitude of damage can differ and therefore for evaluation of environmental hazard each landfill poses to the environment a corresponding integral index shall be introduced. It is formed based on the initial indicators, each corresponding to one of the types of potential adverse impact the landfill makes to the environment.

In this work the integral index of potential environmental hazard is computed based on the following set of initial indicators of potential environmental hazard Ii obtained through the expert method using results published in the papers O.M. Guman (2009) and Volynkina E.P. (2011):

I1: landfill area, ha;
I2: sanitary protection zone width, m;
I3: landfill capacity, t;
I4: annual capacity of the landfill, t/year;
I5: amount of accumulated waste, t;
I6: number of environmental protection systems at the landfill, ea.;
I7: number of environment monitoring systems at the landfill, ea.;
I8: distance to the nearest water body, km;
I9: distance to the nearest locality, km.
I10: anticipated time to complete filling of the landfill, years (I10 = (I3 – I5) / I4).

The following methods were used for computation of potential environmental hazard index J:

index J1(LA) – normalization by the standardization method, linear aggregation at equal weights;
index J2a(LA) – normalization using the standardization method without correction of outliers, linear aggregation at equal weights;
index J2b(LA) – normalization by the standardization method with correction of outliers, linear aggregation at equal weights;
index J3a(LA) – normalization by minimax method without correction of outliers, linear aggregation at equal weights;
index J3b(LA) – normalization by minimax method with correction of outliers, linear aggregation at equal weights;
index J3a(GA) – normalization by minimax method without correction of outliers, geometric aggregation at equal weights;
index J4(LA) – normalization using a categorical scale based on distribution percentiles, linear aggregation at equal weights;
index J5(LA) – normalization based on deviation from the average at equal weights.

The indices can assume values in the range of 0 to 1 with greater index meaning a greater potential hazard of the disposal site. Upon computing the potential environmental hazard indices for each landfill located within a specific municipal locality or an autonomous territory as a whole, waste disposal sites can be subjected to ranking by the degree of their potential environmental hazard.

3. EVALUATING POTENTIAL ENVIRONMENTAL HAZARD POSED BY WASTE LANDFILLS

Table 2. Ranking of landfills of municipal localities of Yamalo-Nenets Autonomous Territory by potential environmental hazard index computed using different methods

Municipal locality	Landfill No.	Rank of the landfill determined based on the value of potential environmental hazard index							
		J1(LA)	*J2a(LA)*	*J2b(LA)*	*J3a(LA)*	*J3b(LA)*	*J3a(GA)*	*J4(LA)*	*J5(LA)*
Nadymsky district	**80**	2	7	7	8	9	1	2	4-6
Tazovsky district	**8**	5.5	9	9	7	10	7	6	9-15
Krasnoselskupsky district	**367**	1	1	1	1	1	5	1	2
Tazovsky district	**366**	3	5	5	5	3	6	5	4-6
Yamalsky district	**362**	7	4	4	4	5	8	8	3
the city of Noyabrsk	**92**	13	12	11	13	14	16	13	9-15
Purovsky district	**133**	11	6	6	6	7	10	10	4-6
Tazovsky district	**9**	5.5	11	8	10	8	3	7	9-15
Yamalsky district	**363**	9	13	13	12	16	4	12	9-15
Nadymsky district	**81**	8	2	2	2	4	9	3	7-8
Tazovsky district	**102**	15	16	12	16	15	17	15	9-15
Nadymsky district	**93**	4	10	14	9	12	2	4	9-15
Purovsky district	**364**	10	3	3	3	2	13	11	1
New Urengoy city	**126**	19	19	19	19	19	19	19	17
Purovsky district	**132**	12	8	10	11	11	12	9	7-8
Purovsky district	**131**	14	18	15	14	6	14	14	9-15
Tazovsky district	**365**	18	17	16	15	13	15	17	16
the city of Noyabrsk	**83**	20	21	21	21	21	21	20	20-22
the city of Noyabrsk	**82**	16	15	17	17	18	18	16	18-19
the city of Gybkinsky	**27**	17	14	18	18	17	11	18	18-19
Tazovsky district	**23**	21	20	20	20	20	20	22	20-22
New Urengoy city	**48**	22	22	22	22	22	22	21	20-22

Table 2 shows results of ranking of a number of landfills where waste generated in municipal localities of Yamalo-Nenets Autonomous Territory is deposited. The ranking is done using the aforementioned methods. High rank corresponds to greater potential hazard.

Results of ranking indicate that variation of ranks determined using different indices can be very significant, however an apparent trend is observed, allowing for distinction between most and less hazardous landfills. All methods are equally reliable and free of contradictions in identification of landfills that pose the greatest potential hazard for the environmental and health of residents (see Fig. 1). On that figure ranks, computed using different methods, are shown for landfills located in the bottom third of the list, i.e. those possessing the greatest rank and posing the greatest potential threat. Therefore, any of these methods can be used to identify landfills that have the greatest hazard potential for the environment and health of the residents.

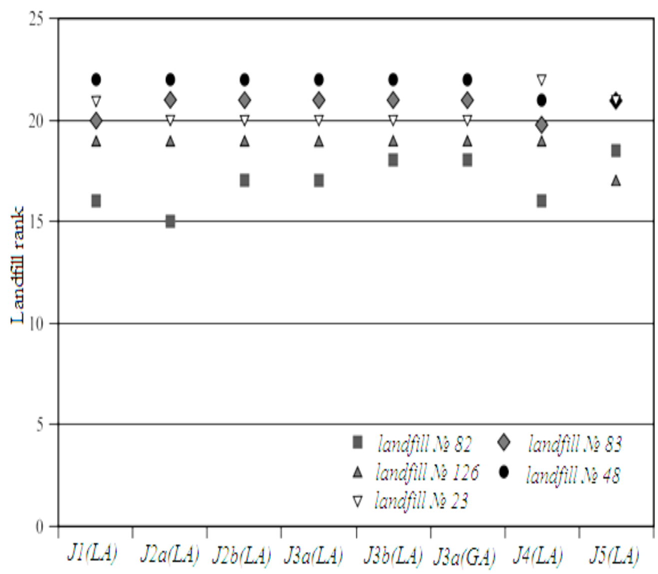

Fig. 1. Ranks computed using different methods, are shown for landfills located in the bottom third of the list, i.e. those possessing the greatest rank and posing the greatest potential threat.

Taking into account drawbacks of each of the ranking methods (ranking normalization and normalization based on categorical scale result in loss of information on absolute values of the initial indicators; values of indices developed using geometric aggregation are very sensitive to near-zero indicators) the most suitable method for landfill ranking is the one based on the potential hazard index J3a(LA). This index should be calculated by minimax normalization method with linear aggregation at equal weights without removal of outliers.

As can be seen from Fig. 1 this method produces results that fit well the ones obtained through other methods. Besides, it does not generate distant outliers or results that differ greatly from the primary trend. Another advantage of this method is its capability to 'disintegrate' the summary index by decomposing it into the initial components and identify factors that make the greatest impact to its absolute value..

4. APPLICATION OF POTENTIAL ENVIRONMENTAL HAZARD INDEX FOR OPTIMIZATION OF WASTE DISPOSAL

Let's discuss the problem of waste disposal of a municipal locality in the course of 5 years using the city of Noyabrsk as an example. This locality with a population of about 110,000 has to dispose about 30,000 tons of solid domestic waste at three available landfills: Nos. 82, 83 and 92 (see Table 2). Values of initial indicators of these landfills are shown in Table 3.

Table 3: Potential environmental hazard indicators for landfills of the city of Noyabrsk, YNAT (as of 2011)

Indicator	Landfill		
	82	**83**	**92**
I_1: landfill area, ha;	14.59	26.82	6.21
I_2: sanitary protection zone width, m;	50	500	500
I_3: landfill capacity, t;	525,780	959,570	171,090
I_4: annual capacity of the landfill, t/year;	29,210	47,979	30,150
I_5: amount of accumulated waste, t;	469,598	152,212	50,497
I_6: number of environmental protection systems at the landfill, ea.;	6	5	6
I_7: number of environment monitoring systems at the landfill, ea.;	3	3	3
I_8: distance to the nearest water body, km;	9	1.25	3.0
I_9: distance to the nearest locality, km.	3.5	2.4	1.3
I_{10}: anticipated time to complete filling of the landfill, years	1.9	16.8	4.0

For further study we used the potential environmental hazard index J3b(LA) - minmax normalization with correction of outliers, linear aggregation at equal weights of 0.1:

$$J3b(LA) = \frac{1}{10}\sum_{j=1}^{j=10} I_j \qquad (1)$$

This index values were forecasted for each of the three disposal sites for a 4-year period by incrementing I5 indicator (amount of accumulated waste) by 30,000 annually and making corresponding changes of the indicator I10 (expected time to complete filling of the landfill). Values of indices were computed both for each disposal site in question iJ3b(LA) and their summary value ∑J3b(LA) in order to obtain an integrated evaluation of environmental hazard of all landfills of the municipal locality (Fig. 2):

$$\sum J3b(LA) = 82J3b(LA) + 83J3b(LA) + 92J3b(LA) \qquad (2)$$

Forecasted values of the summary index ∑J3b(LA) (Fig. 2) calculated for three different scenarios, each assuming that the waste is disposed in one of the landfills while the two others stay unchanged. It can be seen that if the waste is disposed only to the disposal site No. 92, the annual increment of the summary index ∑J3b(LA) is the greatest, so this scenario shall be screened out as the one that creates the greatest potential environmental hazard.

At disposal of the waste in the landfills Nos. 82 and 83 separately, the increment of the summary index ∑J3b(LA) is basically the same, however, after the first two years the site No. 82 is completely filled. Further disposal at this site is not possible and it shall be subjected to land reclamation. After the reclamation the site No. 82 is not a threat to the environment any more, so the value of index 82J3b(LA) comes to zero and the total value of the summary index ∑J3b(LA), computed using the formula (2), should drop considerably. However, the reclamation calls for significant additional financial investments, which does not provide for equal conditions in execution and comparison of these scenarios.

Therefore, given the other conditions equal, the best case will be to dispose waste only in the site No. 83. Inclusion of financial indicators into the problem variables (the cost of reclamation, the cost of waste disposal in each of the sites and the cost of their handling, finances available to the municipal authorities for these purposes) can change the proposed optimal solution.

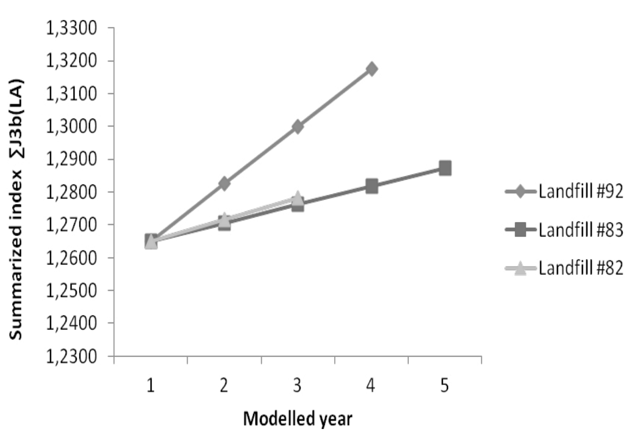

Fig. 2: Expected values of the summary potential environmental hazard index ∑*J3b(LA)* for landfills of the city of Noyabrsk for a 4-year period given that only one of the three landfills will be used.

6. CONCLUSIONS

This paper presents the following outcome of the studies:

1) the main mathematical methods for normalization of initial data are shown and briefly discussed, allowing for development of summary indicators by aggregation of the initial ones;
2) a list of initial potential environmental hazard indicators is presented for landfills in Yamalo-Nenets Autonomous Territory (as of 2011) for computation of the summary index;
3) the paper presents a comparison of calculated values of the summary index of potential environmental hazard using five different normalization methods in a few modifications and two aggregation methods, showing stability of obtained results for the most hazardous landfills (located in the bottom third of the list) regardless of the method used;
4) present study shows the possibility of using the integrated potential environmental hazard index for selection of optimal scenario for disposal of the waste generated by the municipal locality.

Further development of the present study will be focused on landfill life cycle concept de-sign. Such concept will make it possible to calculate the total anthropogenic impact as well as total costs of landfill ownership.

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