# THE CHOISE OF SOIL REMEDIATION METHODS IN BRAUNFILD REGENERATION PROCESS BY MCDA

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***Summary:*** *Architectural practice is actively focused on brownfield sites issues and opportunities for their regeneration and re-use. Given that contemporary science offers a wide range of remediation technologies, in the process of brownfield regeneration is necessary to choose the most optimal one. The research is based on the application of multi-criteria analysis by ranking all possible alternatives in order to simplify decision-makers choose of the appropriate method, taking into account their impact on the environment.*

***Keywords:*** *Brownfield regeneration, soil remediation technologies, MCDA*

## 1. INTRODUCTION

Viewed from economic, social and environmental aspects, the concept of sustainability is one of the key principles in the planning and design process of architectural buildings. Although contemporary trends primarily promote the construction of new ecological and energy-efficient objects, intensive construction processes have led to the lack of free land [1]. In order to achieve sustainability, the stance on minimizing demolition and orientation towards adapting abandoned and devastated buildings and spaces, has been actively represent in recent years. These areas are known as brownfields and special attention is paid to the process of their renewal and finding appropriate ways for their re-use. Taking into account the fact that brownfield areas include former industries and landfills, these locations are considered to be one of the leading pollutants of the environment which directly affect people's health. Therefore, the decontamination of polluted soil is an indispensable step in the process of brownfield regeneration.

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In order to completely remove or reduce pollution from brownfield land, to a level that will not pose a threat to the environment and human beings, it is necessary to implement some of decontamination methods, that have been marked as soil remediation technologies [2]. Nowadays, contemporary science and technology offer a wide range of different types of soil remediation methods, and in the process of specific brownfield regeneration is indispensable to identify the most optimal, single one method. The choice of remediation technology mostly depends on the degree and nature of soil contamination, then the price, the complexity of the proceedings, as well as the time available for decontamination. Bearing in mind that some remediation methods produce harmful by-products, which remain in the soil or are emitted into the atmosphere, the question of the selection of soil remediation method, in the terms of their impact on the environment, arises. In the process of making these complex decisions, multi-criteria analysis can be of great benefit.
The work examines the issues for multi-criteria decision making in the brownfield regeneration process from the point of poluuted soil decontamination, as well as the possibilities of selecting the optimal remediation method. The research is based on the ranking of alternatives by applying mathematical method of Analytic Hierarchy Process (AHP). The aim of the paper is to enable decision makers, using AHP method, to rank alternatives and choose the most optimal solution in terms of soil remediation technologies for brownfield location, taking into account their impact on the environment.

## 2. IMPLEMENTATION OF SOIL REMEDIATION METHODS IN BROWNFIELD REGENERATION PROCESS

Complex processes of transition and urban agglomeration, which swept the whole world in the late 80s and early 90s, have influenced the changes in urban structures. Due to the phenomenon of deindustrialization, suburbanization and the continuous cities expansion, the abandoned spaces and buildings of the former military complex, industry and others, known as brownfield areas, have been formed [3]. Although the interpretation and definition of the term „brownfield“ varies between states, brownfields represent locations that are, due to their former purpose, neglected and underutilized, and which need to be restored in order of their reuse [4,5]. Brownfield sites occur as a former industrial and military objects, warehouses, traffic services and agricultural goods, and they also include landfills, disorganized settlements and coastlines. Regardless of shape, these spatial areas represent negative phenomena in cities and degrade the environment in visual, social, ecological and economic terms. Thus, the issue of sustainable brownfield regeneration is of great importance in contemporary architectural practice.
Given the previous purposes, a certain degree of environmental pollution always follows brownfield locations. Land in these areas suffer from the greatest pollution and is often contaminated with pesticides, poisons, heavy metals and other toxic organic compounds that are falling due to the level of groundwater. Therefore, the soil remediation must be carried out as part of the brownfield regeneration process. Under the remediation we assume a collection of different interventions in term of land treating and polluntants removal, all in order to meet environmental standards and to create adequate conditions for re-use of the space. Although the development of science has enabled application of different types of remediation methods, according to character they can be classified into

three basic groups: biological, physico-chemical and thermal methods [6]. Each of these groups includes more particular technologies. Some of them are performed on the site, while others require soil transport to another location. The identification of contaminants in soil and determination of environmental hazards, precede the selection of appropriate remediation method. When a character of pollutants is found, the methods, as alternatives which have ability to remove present contaminants, are determined. Subsequently, only one of them have to be selected for implementation. The choice of the method mostly depends on the price and duration of the procedure, whereby a negative impact of remediation on the environment is ignored. In this way, in an effort to remediate brownfield, the site become additionally polluted. Therefore, the question of the impact of remediation technologies on the environment is of great importance.

Biological methods of soil remediation are based on the implementation of natural biological processes within the soil structure, with the support of plants, oxygen and microorganisms. As a result of their application, the pollutants are transformed into substances of reduced or completely destroyed toxicity. Bearing in mind that nowadays the architectural practise actively tends to restore brownfields in the context of sustainable development, biological methods are considered to be the most rewarding for use in the term of environmental impact, as they create by-products of low danger group. In the process of brownfield regeneration are mostly used: phytoremediation, bioremediation, bioventilation, bio-piles, slurry bioreactor and landfarming. Bioremediation and phytoremediation have been increasing in the rehabilitation of brownfield sites, because their use has no harmful effects on the environment and human health. Method of phytoremediation uses plants, fungi and algae as agens for absorbing and removing pollution. On the other hand, bioremediation is defined as the process by which microorganisms are stimulated to degrade organic contaminants in soil to a level safe for the environment [7]. Bioventilation process is based on the introduction of air into the soil in order to accelerate the activity of microorganisms. Bio-piles application is the technology based on mixing the excavated soil with a soil of good quality, but unlike previous methods, it produces certain amount of dust which pollutes the air. Landfarming biological method represent mixing the excavated brownfield soil by agricultural activities, whereby harmful vapors occur as a result of the aeration process. The implementation of bioreactor is similar to the landfarming, but it takes place under strictly controlled conditions in closed chamber, where the land is mixed with water to the separation of sand and slurry [8]. Due to the harmful vapor and contaminants that are partially retained in the soil, this method is not suitable for use.

Physico-chemical remediation methods use physical and chemical laws to transform toxic compounds into non-toxic. Unlike biological methods, these technologies in a greater extent create by-products that have a harmful impact on the environment. In the process of brownfield regeneration are applied: chemical extraction, chemical oxidation, soil washing, electrokinetic remediation, solidification and stabilization, as well as the extraction by vapor. Chemical extraction and chemical oxidation represent remediation methods which by adding certain organic compounds and oxidants effectively remove toxic substances from the soil through chemical reactions. A similar method is soil washing, which is based on the addition of water into the soil. All of these methods have a negative impact because, by their use, there is a risk of retaining contamination in the soil. Electrokinetic remediation is a method by which the contamination is removed using electricity. Although it shows successful results, its long-term application changes the pH value and increases soil acidity [9]. Solidification and stabilization represent processes that immobilize contamination by adding the appropriate mineral or cement, where pollution is not always removed successfully and completely [10]. The most harmful physico-chemical method of remediation is extraction by steam, because the vacuum pressure that is used can often increase the level of groundwater.

Thermal remediation methods are considered to be the most efficient methods for short-term treatment, and they use the principles and procedures of the thermal heating, burning and melting. Due to its character, they also represent methods that largely pollute environment by thermal processes by-products. In the process of brownfield regeneration mostly are used: thermal desorption, thermal extraction by vapor, pyrolysis, burning, gas decontamination and vitrification. Thermal desorption is a process of heat using in order to increase the instability of pollutants and to remove them [9]. On the other hand, the thermal extraction by vapor represent an improved physical method of extraction by vapor. Since these methods do not involve burning, they are considered to be most suitable thermal methods in the term of environmental impact. Using pyrolysis and burning, complex compounds are broken down into simpler one or are completely destroyed by heat. However, as a harmful by-product, a smoke and fumes that pollute the air occure. The most damaging thermal remediation methods are gas decontamination and vitrification. Decontamination by gas is based on injecting hot gas in the excavated soil, while the vitrification is based on heat use to melt pollutants.

## 3. MODEL OF MULTI-CRITERIA DECISION MAKING

Multi-criteria decision making is one of the best known branches in the decision making process with a wide application in solving real problems. Models of multi-criteria decision making facilitate the decision-makers adopting optimal decision in situations where there are a large number of diverse criteria, which can often be conflicting, by criteria ranking. Solution of the model of multi-criteria decision making is usually implemented through the following four stages: problem identification; problem defining; analysis of possible alternatives for goal achieving and results defining; selection of optimal alternative for problem solution.

The mathematical basis of the multi-criteria analysis method algorithm can be described as a selection of one alternative from the final set of m alternatives $A_i$ (i = 1, 2, ..., m) based on the n criteria $X_j$ (j = 1, 2, ..., n). Each of the alternatives represent the vector Ai = ($x_{i1}$, $x_{i2}$, ...., $x_{ij}$, ..., $x_{in}$), where $x_{ij}$ is a value of j-th attribute for the i-th alternative. In order to mathematically formulate model of multi-criteria decision making we need the information about all the alternative realizations of the process for which the decision is made, and about the goals that the decision maker wants to achieve. Also, it is necessary to identify in which way each alternative contributes to set goal achivement.

### 3.1. METHODOLOGICAL ASSUMPTIONS OF AHP METHOD FOR MULTI-CRITERIA DECISION MAKING

Analytic Hierarchy Process (AHP) is one of the most popular method for multi-criteria decision making, which is usually used in cases where there is a possibility of hierarchical structuring of relevant criteria [11]. Algorithm of AHP method can be described as an analysis of the complex decision making problem structure, which can contain multiple criteria, multiple alternatives, determining the relative weights of criteria and alternatives by levels and ranking of alternatives. Phases of AHP method can be presented as follows: a) decomposition of the problem, b) data collection and comparison of alternatives pairs, c) determining the relative importance of the criteria, and d) synthesis and solution determination. If we assume that the problem is represented by matrix with dimensions mxn, where it is necessary to carry out assessment of m alternatives based on n relevant criteria, then the process of AHP method can be described as follows. The first phase, problem decomposition, involves creating a hierarchical structure which has the goal at the top, while at the lower levels of the hierarchy are the criteria with sub-criteria. At the lowest level there are the alternatives that need to be evaluated. The second phase, besides data collecting, includes the comparison of pairs of hierarchical structure, formed in the first stage. Comparison of alternatives pairs is primarily carried out at a given level of the hierarchy, and in relation to the criterion of the immediately higher level. Preferences of the decision maker are expressed using the Saaty 's 9-point scale.
Any comparison between two elements of the hierarchy is done using Saaty 's scale [12]:

$$S = \left\{ \frac{1}{9}, \frac{1}{8}, \frac{1}{7}, \frac{1}{6}, \frac{1}{5}, \frac{1}{4}, \frac{1}{3}, \frac{1}{2}, 1,2,3,4,5,6,7,8,9 \right\} \tag{1}$$

Preferential level 1 shows that two alternatives are completely identical, while the absolute preference of one alternative over another alternative is expressed by adding number 9 to a pair. In the third phase, the matrix A with dimensions nxn on the level of criteria, or mxm on the level of alternatives, is formed, in which the elements $a_{ii} = 1$ (the matrix elements on the main diagonal are 1) and $a_{ji}$ elements are reciprocal values $a_{ij}$, $i \neq j$, i, j = 1,2, ..., n

$$A = \begin{bmatrix} 1 & a_{12} & \cdots & a_{1n} \\ 1/a_{12} & 1 & \cdots & a_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ 1/a_{1n} & 1/a_{2n} & \cdots & 1 \end{bmatrix} \tag{2}$$

In the first column of the comparison matrix A there are coefficients of the relative importance of the criteria 2, 3, ..., n in relation to the criteria 1. In the case that the assessment of decision-makers is fully consistent, the remaining columns of the matrix are calculated automatically. However, AHP method does not imply consistency, so the comparison process is repeated for each column of the matrix, making an independent assessment by decision-maker. At the end of the comparison, matrix A is formed which, multiplied by the relative weight vector $\mathbf{w} = (\mathbf{w_1}, \mathbf{w_2}, , \ldots, \mathbf{w_n})$, provides $\mathbf{Aw} = \mathbf{nw}$.

The weight vector w can be obtained by solving the equation $Aw = \lambda_{max}w$, provided that the sum of the weights is 1, and $\lambda_{max}$ represent the largest ownvalue of the matrix A (due to the properties of the matrix $\lambda_{max} \geq n$, n is the dimension of the comparison matrix.).

Consistency index - CI is a measure of the deviation n from $\lambda_{max}$ and can be presented by the following formula:

$$CI = \frac{\lambda_{max} - n}{n - 1}, \quad CR = \frac{CI}{RI} \tag{3}$$

where: CR is the ratio of consistency, RI is random index. If for the comparison matrix is true that the CR < 0.10, alternatives priorities are counted as acceptable [13], [14].

*Table 1. Random consistency index RI*

| n | 1 | 2 | 3 | 4 | 5 | 6 |
|---|---|---|---|---|---|---|
| RI | 0.00 | 0.00 | 0.58 | 0.9 | 1.12 | 1.24 |

Ranking list of alternatives is obtained by multiplying the participation of each alternative with relative weight of the observed criterion, and then all these values are summed for each alternative separately. The data we get on that way represent the weight of observed alternative in the model. The procedure is repeated for each alternative until we get complete order of all alternatives. After receiving the ranking list of alternatives analysis of results sensitivity is carried out.

## 4. CASE STUDY

The research focused on the ranking of the three groups of criteria that represent the three main types of soil remediation methods: B - Biological; F - Physico-chemical; T - Thermal methods.

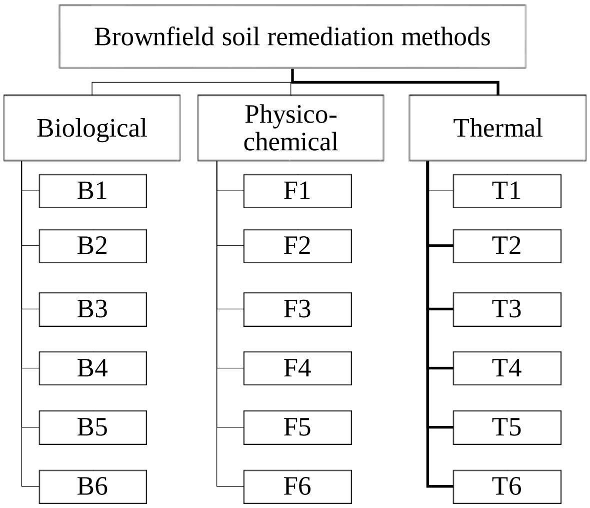

*Figure 1. The hierarchical structure of methods for brownfield soil remediation*

Sub-criteria relating to the biological, physio-chemical and thermal methods represent alternatives that are mostly used in the process of brownfield regeneration, and are marked as follows: B1 - Phytoremediation; B2 - Bioremediation; B3 - Bioventilation; B4 - Bio-piles; B5 - Lanfarming; B6 - Application of a bioreactor; F1 - Chemical extraction; F2 - Chemical oxidation; F3 - Soil washing; F4 - Electrokinetic remediation; F5 - Solidification and stabilization; F6 - The extraction by vapor; T1 - Thermal desorption; T2 - Thermal extraction by vapor; T3 - Pyrolysis; T4 - Burning; T5 - Gas decontamination; T6 - Vitrification. Table 2. represents the evaluation dependence of three main criteria groups and has been formed as a matrix of comparison. Biological remediation methods are more suitable for the implementation in terms of environmental impact in comparison with the physico-chemical methods, with the relevant importance 3, respectively, as compared to thermal methods with the relevant importance 5. Given that CR = 0.0033 < 0.10, comparison matrix is consistent and presents comparison of the criteria on the first level of the hierarchy.

*Table 2. Table of criteria comparation B, F, T*

| | B | F | T | W | CI | CR |
|---|---|---|---|---|---|---|
| B | 1 | 3 | 5 | 0.64 | 0.019 | 0.033 |
| F | 1/3 | 1 | 3 | 0.26 | | |
| T | 1/5 | 1/3 | 1 | 0.10 | | |

Table 3. presents the comparison of sub-criteria relating to biological methods of soil remediation and the appropriate weights are obtained. For example, phytoremediation (B1) is favorable for use in relation to the use of bioreactor (B6) with the relevant importance 6. After CR = 0.030 < 0.10 matrix comparison is consistent.

*Table 3. Comparation table in relation to sub-criteria B*

| | $B_1$ | $B_2$ | $B_3$ | $B_4$ | $B_5$ | $B_6$ | W | CI | CR |
|---|---|---|---|---|---|---|---|---|---|
| $B_1$ | 1 | 2 | 3 | 4 | 4 | 6 | 0.37 | 0.038 | 0.030 |
| $B_2$ | 1/2 | 1 | 2 | 3 | 3 | 5 | 0.24 | | |
| $B_3$ | 1/3 | 1/2 | 1 | 2 | 2 | 4 | 0.15 | | |
| $B_4$ | 1/4 | 1/3 | 1/2 | 1 | 2 | 4 | 0.11 | | |
| $B_5$ | 1/4 | 1/3 | 1/2 | 1/2 | 1 | 3 | 0.08 | | |
| $B_6$ | 1/6 | 1/5 | 1/4 | 1/4 | 1/3 | 1 | 0.04 | | |

Table 4. is the comparison of sub-criteria relating to the application of physico-chemical methods of soil remediation and the appropriate weights are calculated. Given that CR = 0.025 < 0.10 comparison matrix is consistent and represents a comparison of criteria at the second level.

Table 5. represents the comparison of sub-criteria relating to the implementation of thermal methods of soil remediation. For example, thermal desorption (T1) is more suitable for use in relation to vitrification (T6) with the relevant importance 5. Corresponding weights are obtained and matrix comparison is consistent.

*Table 4. Comparation table in relation to sub-criteria F*

| | $F_1$ | $F_2$ | $F_3$ | $F_4$ | $F_5$ | $F_6$ | W | CI | CR |
|---|---|---|---|---|---|---|---|---|---|
| $F_1$ | 1 | 2 | 3 | 3 | 4 | 5 | 0.36 | 0.031 | 0.025 |
| $F_2$ | 1/2 | 1 | 2 | 2 | 3 | 4 | 0.23 | | |
| $F_3$ | 1/3 | 1/2 | 1 | 2 | 3 | 4 | 0.17 | | |
| $F_4$ | 1/3 | 1/2 | 1/2 | 1 | 2 | 3 | 0.12 | | |
| $F_5$ | 1/4 | 1/3 | 1/3 | 1/2 | 1 | 2 | 0.07 | | |
| $F_6$ | 1/5 | 1/4 | 1/4 | 1/3 | 1/2 | 1 | 0.05 | | |

*Table 5. Comparation table in relation to sub-criteria T*

| | $T_1$ | $T_2$ | $T_3$ | $T_4$ | $T_5$ | $T_6$ | W | CI | CR |
|---|---|---|---|---|---|---|---|---|---|
| $T_1$ | 1 | 3 | 4 | 4 | 5 | 5 | 0.43 | 0.04 | 0.033 |
| $T_2$ | 1/3 | 1 | 2 | 2 | 3 | 3 | 0.20 | | |
| $T_3$ | 1/4 | 1/2 | 1 | 2 | 3 | 3 | 0.15 | | |
| $T_4$ | 1/4 | 1/2 | 1/2 | 1 | 2 | 2 | 0.10 | | |
| $T_5$ | 1/5 | 1/3 | 1/3 | 1/2 | 1 | 2 | 0.07 | | |
| $T_6$ | 1/5 | 1/3 | 1/3 | 1/2 | 1/2 | 1 | 0.06 | | |

*Table 6. Ranking alternatives in relation to criteria*

| **Rank** | **Alternative name** | **Wk** | **Wa** | **Wk · Wa** |
|---|---|---|---|---|
| 1. | phytoremediation ($B_1$) | 0.64 | 0.37 | 0.2368 |
| 2. | bioremediation ($B_2$) | 0.64 | 0.24 | 0.1536 |
| 3. | bioventilation ($B_3$) | 0.64 | 0.15 | 0.0960 |
| 4. | chemical extraction ($F_1$) | 0.26 | 0.36 | 0.0936 |
| 5. | bio-piles ($B_4$) | 0.64 | 0.11 | 0.0704 |
| 6. | chemical oxidation ($F_2$) | 0.26 | 0.23 | 0.0598 |
| 7. | landfarming ($B_5$) | 0.64 | 0.08 | 0.0512 |
| 8. | soil washing ($F_3$) | 0.26 | 0.17 | 0.0442 |
| 9. | thermal desorption ($T_1$) | 0.10 | 0.43 | 0.0430 |
| 10. | electrokinetic remediation ($F_4$) | 0.26 | 0.12 | 0.0312 |
| 11. | use of bioreactor ($B_6$) | 0.64 | 0.04 | 0.0256 |
| 12. | thermal extraction by vapor ($T_2$) | 0.10 | 0.20 | 0.0200 |
| 13. | solidification and stabilization ($F_5$) | 0.26 | 0.07 | 0.0182 |
| 14. | pyrolysis ($T_3$) | 0.10 | 0.15 | 0.0150 |
| 15. | extraction by vapor ($F_6$) | 0.26 | 0.05 | 0.0130 |
| 16. | burning ($T_4$) | 0.10 | 0.10 | 0.0100 |
| 17. | gas decontamination ($T_5$) | 0.10 | 0.07 | 0.0070 |
| 18. | vitrification ($T_6$) | 0.10 | 0.06 | 0.0060 |

Results of alternatives ranking, obtained on the basis of weight coefficients from Table 2. to Table 5., by AHP method, are presented in Table 6. The results obtained by calculation of weight coefficients, show the dominant advantage of biological methods phytoremediation, bioremediation and bioventilation, as the technologies with the least harmful impact on the environment and human health. Then, important is the use of chemical extraction, chemical oxidation and bio-piles. The lowest rank have methods burning, gas decontamination and vitrification, because their use creates huge amount of different by-products which greatly pollute the air and threate the health of people.

## 5. CONCLUSION

This study draws attention to the MCDA and analytical processes in clarifying the main features in complicated decisions, in the brownfield regeneration process. The proposed method performs criteria ranking, using all the available information with the aim to find a suitable soil remediation method during the process of brownfield sites restoration, taking into account their impact on the environment and human health. The established order of preferred methods indicates the dominant priority of biological methods - phytoremediation, bioremediation and bio ventilation, as a technology of choice. The development of such methods ranking represents a promising area of future researches for the remediation of brownfield sites in order to achieve sustainability. The proposed method can be successfully applied in decision making in various segments as support the promotion of sustainable development.

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# ВКА КАО ПОДРШКА ИЗБОРУ МЕТОДА РЕМЕДИЈАЦИЈЕ ЗЕМЉИШТА БРАУНФИЛДА

***Резиме:*** *Graditeljska praksa se aktivno bavi rešavanjem problematike braunfild lokacija i stvaranjem mogućnosti za njihovu obnovu i ponovno korišćenje. S obzirom da savremena nauka nudi širok spektar remedijacionih tehnologija, u toku procesa obnove braunfilda potrebno je opredeliti se za najoptimalniju metodu. Istraživanje rada zasniva se na primeni višekriterijumske analize u rangiranju mogućih alternativa sa ciljem da se donosiocima odluke pojednostavi izbor odgovarajuće metode, uzevši u obzir njihov uticaj na životnu sredinu.*

***Кључне речи:*** *Регенерација браунфилда, технологије ремедијације земљишта, вишекритеријумска анализа*