Working Paper

Multi-attribute analysis of the most appropriate flue gas desulfurization (FGD) technologies

N.Roenko

WP-90-72
December 1990

IIASA

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Foreword

Integrated assessment models such as IIASA's Regional Acidification INformation and Simulation (RAINS) model can estimate the country-by-country emission pattern that will meet a specified set of deposition or concentration targets. However, decisions must also be made on a smaller spatial scale such as an individual power plant on the best way of reducing emissions to a specified value. Nikoaj Roenko from the Gluskov Institute of Cybernetics in Kiev USSR took on as a project in the 1990 IIASA Young Summer Scientist Program the application of a software package CHOICE, developed at his institute, that will assist planners in choosing the best flue gas desulfurization technology for a hypothetical power plant. This Working Paper is the result of this application.

Bo R. Döös
Leader
Environment Program

Roderick W. Shaw
Leader
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Contents

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N.Roenko

1 Introduction

The decision maker in environmental planning problems usually faces a complex system of interrelated components, such as resources, objectives, persons or groups of persons, etc.. Often a decision maker has to choose among a finite number of alternatives according to some criteria.

One of the problems in development decision making is to account for the interaction between knowledge and politics. In some circumstances political goals and power rather than knowledge easily dominate development decisions but in other circumstances the reverse may be true. In parallel with quantitative estimations the qualitative and relative estimations of parameters are available for the decision maker. So there is a problem to combine different types of estimations. There is also the problem of missing and uncertain data.

In recent years some approaches were proposed to support the decision making process for such complex problems. We can mention Bayesian decision analysis, fuzzy-set based decision analysis, and the Analytic Hierarchy Process (AHP) as outranking methods. There is corresponding software based on these approaches to support decision making process such as Supertree, COPE, Expert Choice, Rank Master, Trigger, etc..

Here we consider the problem of choosing of the most appropriate flue gas desulfurization (FGD) technologies for implementation on a power plant as a good example of a complex semi-structural problem. The purpose of this work to solve this problem as a test problem using a software package CHOICE [4] designed in the Glushkov Institute of Cybernetics of the Ukrainian Academy of Sciences. This package is intended to analyze the structure of the problem and then present it and support the decision making process. As Kaplan [3] notes: "A theory is not just the discovery of a hidden fact; the theory is a way of looking at the facts, of organizing and representing them".

2 Brief description of the CHOICE package

2.1 The purpose of CHOICE

The CHOICE package is intended to solve multi-objective personal or group decision making problems with hierarchical structure of criteria and with finite set of alternatives.

CHOICE is able to provide a systematic procedure for hierarchically representing the elements of any problem. It organizes the basic rationality by breaking down a problem into its smaller constituent parts. It then guides decision makers through a series of judgements using numerical, graphical, verbal and pairwise comparison modes to express the relative intensity of impact of the elements in the hierarchy. These judgments are then translated to numbers. The CHOICE includes procedures to synthesize the judgments to derive priorities among criteria and subsequently for alternative solutions. The entire process is subject to revision and

*Nikolaj Roenko was a summer student from the Glushkov Institute of Cybernetics in Kiev, Soviet Union was a member of the IIASA Young Summer Scientist's Program in 1990.

re-examination until one is satisfied that he has covered all the important features needed to represent and solve the problem.

CHOICE can be applied to solve the following problems:

- setting priorities;
- choosing a best policy alternative;
- allocating resources;
- designing a system;
- planning;
- conflict resolution.

The CHOICE package is based to a great extent on the Analytic Hierarchy Process (AHP) [9] but it is also based on other theoretical grounds. It runs on IBM-PC, XT, AT and compatibles (with Hercules Graphic Card, Color Graphic Adapter or Enhanced Graphic Adapter) and requires 512K of RAM.

2.2 How to use CHOICE

The process of finding solutions should be carried out in a sequence of the following steps which are reflected in the main menu options of CHOICE.

The general flow-chart of a decision making process implemented in CHOICE is presented in Figure 1.

2.2.1 List of alternatives

The list of alternatives includes the final actions that would contribute positively or negatively to the main objective through their impact on the intermediate criteria.

The name of an alternative is restricted by 12 letters but there is a commentary field to present a more detailed explanation for the alternative.

2.2.2 Structuring of the problem

Planners who use CHOICE to study their problems first define the situation carefully including as many relative details as possible. Then they structure it into a hierarchy of levels of detail. In the most elementary form, a hierarchy is structured from the top (objectives from a managerial stand-point), through intermediate levels (criteria on which subsequent levels depend) to the lowest level (which is usually a list of alternatives). All of nodes of hierarchy tree besides the lowest level (alternatives) are called attributes.

2.2.3 Assessment of persons involved in the decision making process

As a rule, a group of experts take part in the development of a decision making process. They can participate as experts in some particular branch of the problem to estimate corresponding parameters based on their knowledge and experience. However, there are also cases where experts act as members of a planning committee. In this case they have their own view of the problem as a whole and consequently have unique and perhaps conflicting objectives. Within the framework of CHOICE it is possible to integrate the efforts of the corporate planning staff by adding the new level within the hierarchy. To every mode of this level of hierarchy there corresponds an associated member of the committee.

2.2.4 Estimation of attributes

After developing the hierarchy and the list of alternatives, persons involved in the decision making process and the planners judge the relative importance of all the elements. They quantify these judgments by using one of the following modes: graphical, numerical, pairwise comparison, and verbal. Judgments on the relative importance of each element in the hierarchy are made by people who are knowledgeable about the particular problem.

Usually the decision maker who must deal with more than 6 – 7 items makes mistakes. He has an image of an ordered set which has to satisfy the reflexive, antisymmetric and transitive laws. However, in the case of mistakes, the transitive law can be violated. CHOICE generates the confession value of the transitive law and suggests ways to improve estimations.

In general the estimation of attributes take the character of subjective judgments.

2.2.5 Estimations of alternatives

As distinguished from the estimation of attributes, the estimation of alternatives is based on subjective and objective judgments. If some information about alternatives are stored in data bases or spreadsheets, CHOICE supports the compatibility with well-known data bases and spreadsheets through import options of the corresponding submenu.

2.2.6 Synthesis and analysis

To get a global preference order according to the designed hierarchy the user can choose the most appropriate method for multicriteria estimation from the library (maximum method; minimal risk method; permutation method; linear assignment method; hierarchical additive method; ELECTRA ii; ideal point method; reference point method). CHOICE is still under development and for the current version, only the hierarchical additive method is available.

Along with synthesis, the analysis of the problem is of great importance. The user can look at an intermediate preference order setting up the cursor in the corresponding node of the hierarchy.

3 Example application: The problem of choosing the most appropriate FGD technologies

3.1 Problem formulation

In this section we consider the problem of choosing the appropriate technology for controlling sulfur emissions. Although it is possible to reduce sulfur emission using desulfurization before, during and after combustion, here we consider only flue gas desulfurization (FGD) as one of the most important processes presently available for commercial use. FGD has proven to be one of the main sulfur emission control technologies in large installations such as power stations. FGD can at present be applied in new and existing power plants. We will investigate this decision making problem for a single hypothetical 500 MW power plant, operating for 5,250 hours per annum (60 per cent load factor) and burning 3.5 per cent sulfur coal. The main part of the necessary data for this hypothetical power plant is available. For an arbitrary power plant, all figures dependent on power plant capacity, operating time and sulfur content in fuel can be recalculated [6].

Choosing the most economical way to reduce total emissions of sulfur constitutes an important component of the activities within the framework of the Convention of Long-range Transboundary Air-Pollution [5–7].An analysis of the cost-effectiveness of technologies is assumed to use total costs as the main criteria on a macroeconomic level. An example is found in the RAINS model [1]. This approach has been proven for macroeconomic analysis because parameters of technologies are averaged over some region or country. It is quite another matter to analyze this problem for a particular plant. In this case we have to take into account other reasons. As noted in [5], in view of the diversity of the techniques available (e.g. processes using chemical or physical methods, direct conversion into sulfur, absorption) and the wide range of possible applications, the choice of the most appropriate solution is difficult and can only be made after detailed analysis of each individual case, taking into consideration a number of technical and economic variables (composition of the gas to be treated, specification of the final products, local regulation, investment requirements, operating costs, market for extracted products, etc.) as well as social-political and environmental concerns.

Usually experts know the weak and strong points of every technology. For instance, the major disadvantage of the sodium alkali process is that it consumes a relatively expensive Na_2CO_3, without alleviating the problem of liquid waste disposal. This limits the application of the process to geographical areas having a source of low grade carbonate. The main disadvantage of the dual alkali process is the loss of the relatively expensive sodium salts. The main advantage of magnesium oxide is that there is no waste sludge to be disposed of. Advantages of the Wellman-Lord process include scrubbing with a solution rather than slurry, which prevents scaling, and production of marketable material. The disadvantages of high energy consumption and maintenance are due to the relatively complexity of the process. One disadvantage of a spray dryer processes is that, generally, reagent utilization is low because the scrubbing medium is not easily recirculated. The advantages of dry SO_2 removal systems over wet scrubbing systems include: a dry product, lower capital costs, lower energy and water requirements and a more simple design which should be reflected in increased availability and reduced maintenance. This knowledge reflects only some opposite characteristics but here we will try to involve the decision making processes of all factors which more or less influence the result.

The procedure presented in the previous section will be followed to analyze this problem.

3.2 List of alternatives

Several technologies have been developed for reducing emissions of SO_2 generated during the combustion process. Such FGD processes vary according to the type of material used for SO_2 absorption, the nature of the by-products and the ability of the processes to remove other pollutants. These different processes fall into three types:

- Wet scrubbing;
- Spray drying;
- Dry processes.

The most important processes presently available for commercial use are summarized in Table 1 [5]. So we shall consider eleven alternatives:

Wet scrubbing:

- Lime/Limestone;
- Sodium alkali;
- Dual alkali;
- Ammonia absorption (Walther Process);
- Magnesium oxide;
- Sodium sulfite (Wellman-Lord);
- Citrate;

- Aqueous Carbonate;
- Dilute sulfuric acid;

Spray drying:

- Spray dry system;

Dry processes:

- Activated carbon absorption (Bergbau-Forschuing process).

3.3 Structuring of the problem

First we define the main factors which influence the solution. Then we structure them into a hierarchy of levels of details. The highest level is the overall objective.

We consider the following factors:

- **economic**;
- **by-products and wastes**;
- **technical feasibility**;
- **energy and material conservation**;
- **socio-political criteria**.

To begin with we consider **economic factors.**

Investment costs represent the initial investment necessary to install and commission the system. They include materials, equipment and engineering costs, contractors fees, additional infrastructure including transport provision and possibly land requirements.

Operating costs include raw materials, energy, maintenance, overheads, labor and other costs.

Removal costs represent average payment per ton of sulfur reduction taking into account investment costs, operating costs and lifetime of equipment.

The next two factors are by-products and wastes. From the economic point of view we have already taken into account the utilization of by-products and the disposal of waste products in the operating and removal costs but for a particular problem these factors are important. For instance, soluble sodium sulfite and sulfate wastes may create landfill disposal problems in areas of high rainfall; or sulfur is preferable to sulfuric acid as a by-product because it is easier to store and transport.

By-products. The principal by-products generated by various FGD techniques are gypsum, sludge, elemental sulfur, sulfuric acid and ammonium sulfate. This information for each technology are located in Table 1.

Waste products. The principal FGD waste products are waste water, solid and liquid wastes which can be also found in Table 1.

Technical properties. This group of factors concern technical properties which include the following items:

- **removal efficiency** means the greatest level of SO_2 which can be removed;
- **development status** reflects accumulated experience;

- **reliability** assesses risk of failure for installation;
- **potentiality of development** means ability to develop and improve technology;
- **ability to remove other pollutants**, mainly NO_x;
- **simplicity** reflects training requirements for personal.

Energy and material conservation. This group of factors includes:

- **energy consumption;**
- **water consumption;**
- **sorbents consumption;**
- **land requirements for equipment and waste disposal.**

Socio-political factors. This last group of factors considers socio-political concerns such as:

- **public opinion** and
- **created jobs.**

The hierarchy of factors are presented in Figure 2.

3.4 Assessment of persons involved in decision making process

Here we restrict our consideration to the problem to a single decision maker. As mentioned in Section 2.2.3, a corresponding level must be added to the hierarchy if we are required to consider group decision making processes.

3.5 Estimation of attributes

After structuring the problem, we have to estimate the relative importance of each attribute. Clearly only an expert with knowledge about the problem can carry out this work. The preference must depend on a particular problem. If enough money available from local authorities and industry to implement expensive modern FGD technology and the required land for equipment and waste disposal, then the stress would be made on "energy and material conservation" with respect to economic factors. For example, this situation is found in the United Kingdom, where electricity authorities favor sodium sulfate FGD over other systems because of the avoidance of waste disposal problems. For sodium alkali FGD, the liquid waste can be treated by municipal waste treatment facilities. Perhaps then, for some regions, this type of waste disposal would be the most preferable.

3.6 Estimation of alternatives

To estimate alternatives we used references [5],[6] and [7] as sources for necessary data (see Table 2). For some factors such as investment cost, operating cost, removal cost, removal efficiency, and energy consumption we can use the *numerical mode* for estimation (see Table 2). To estimate the next group of factors, such as the potential for development, reliability, development status, simplicity, safety, water consumption and land use we can use the *verbal mode*. For remaining factors we can use the *graphical* or *pairwise comparison mode*. Of course the choice of an appropriate mode for estimation primarily depends on the preference of whoever does it.

There are two main problems in the estimation of alternatives. Firstly, it is necessary to invite an expert or group of experts who are familiar with the particular problem. In advance of their visit we can provide only a pattern based on available data. Then the expert can change this pattern according to his preference and knowledge. In general the estimation of alternatives must be an interactive process. Secondly, there is the problem of unavailable data. Primarily this is the case for technologies which are only at the demonstration/development stage. For empty cells in Table 2 we can also use an expert estimation. An expert can estimate these items with respect to existing ones using graphical or pairwise comparison modes. It might be well to point out that for some factors only a relative estimation is available. One of the advantages of the proposed approach is that, in this case, it is also very easy to take into account this data.

3.7 Test problem

Based on available information for parameters of FGD technologies we can create only a pattern of the problem by the use of CHOICE. Then this pattern has to be operated by experts or group of experts involved in the decision making process.

At first we input data from Table 2 for leaf nodes of a criteria tree (Figure 2). For missing data we input values averaged over existent data. Afterwards these values can be changed by the expert.

The next step includes the assessment of the relative importance of attributes (not-leaf nodes of the criteria tree). This work can be done only by experts because it depends on the particular problem. For a pattern we use uniformly distributed weights for attributes. The global preference of alternatives according to this pattern is presented in Figure 3. Therefore, the initial best alternative is the spray dry system, but we see that the differences between alternatives are not large if we use uniformly distributed weights for attributes.

If, for instance, we add some new information about expert preferences, such as economic factors which are essentialy important in comparison with energy and material conservation for the particular problem, we will get a new preference order for the alternatives (Figure 4). For this case the dual alkali technology would be the best.

4 Conclusions

In CHOICE, the data for an assessment of FGD technology is measured in different scales: numerical and verbal. For some parameters there exist only relative estimations as, for example, in modern technologies for which there are only experimental installations and where it is difficalt to estimate some economic parameters. However in this case it is possible to estimate these parameters with respect to well-known technology such as lime/limestone. Under such varied peculiarities of input data, the advantages of CHOICE have been demonstrated.

The main part of the available parameters for FGD technologies are known with uncertainty. For example, the variance of economic parameters is as great as 20 per cent. For parameters measured by use of the verbal scale the accuracy of estimation may be even less. It is clear that, based on such rough estimates, we can make a decision to get a roughly ordered set of alternatives. CHOICE generates an ordered set of alternatives as a result.

In actuality, the choice of the most appropriate FGD technology requires not only objective estimations but also an accounting for local peculiarities such as existing experience of personnel, acuteness of environmental concerns, availability of sorbents for refining, opportunities of the market for by-products, etc..

The proposed approach offers and supports a sequence for decision making based on existing knowledge and subjective estimation rather than generating automatically a single solution of the problem.

The CHOICE program also supports group decision making which is important in practice.

It is quite clear that this example can only demonstrate the possibile applications of the proposed approach. The CHOICE system is still under development and in the future new options will be available such as: sensitivity analysis, new algorithms for synthesis, logical rules.

References

[1] Alcamo J., Shaw R., Hordijk L., eds., 1990, The RAINS model of Acidification: Science and Strategies in Europe, IIASA, Kluwer Academic Publishers, Dordrecht, Boston, London

[2] Morrison G.F., 1982, Control of sulfur oxides from coal combustion, Report IC-TIS/TR21, IEA Coal Research, London

[3] Kaplan A., 1964, The Conduct of Inquiry: Methodology of Behavioral Science, San Francisco: Chandler

[4] Loskutov V., Roenko N., Rudich A., Nikitenko S., Kozlov A., Decision insight system CHOICE (in russian), Glushkov institute of Cybernatics of the Ukrainian Akademy of Sciences, Kiev. To appear.

[5] UN-ECE, 1984, Air Pollution Studies 1, Air-born Sulphur Pollution: Effects and Control, United Nations, New York, NY, USA

[6] UN-ECE,1985, Air Pollution Studies 2, Air pollution across boundaries, United Nations, New York, NY, USA

[7] UN-ECE, 1986, Air Pollution Studies 3, Transboundary air pollution: effects and control, United Nations, New York, NY, USA

[8] Saaty T.L., Varyas L.G., 1982, The Logic of Priorities, Kluwer-Nijhoff Publishing

[9] Saaty T.L., Kearns K.P., 1985, Analytical Planning: The Organization of Systems, Pergamon Press

Table 1: Schematic summary of commercially available FGD processes [5]

	FGD processes	Operating principles	By-product and waste	Development status
1.	Lime/Limestone	Slurry of lime or limestone absorbs SO_2	Wet sludges or commertial gypsum	Large-scale commertial operation
2.	Sodium alkali	Solution of caustic or soda ash absorbs SO_2	Waste water or waste scrubbing solution	Limited commertial operation
3.	Dual alkali	Sodium based alkali absorbs SO_2, calcium based alkali regenerates absorbent	Wet sludge or commercial gypsum	Commercial operation
4.	Ammonia absorption (Walther Process)	Ammonia-based absorbtion, oxidation to ammonium sulfate	Ammonium sulfate fertilizer	Limited commercial operation
5.	Magnesium oxide	Slury of magnesium oxide/hydroxide reacts with SO_2, subsequantly dewatered and returned to system after regeneration	Elemental sulfur or sulfuric acid	Limited commercial operation
6.	Sodium sulfite (Wellman-Lord)	Solution of sodium sulfite absorbs SO_2 and returned to system after regeneration	Elemental sulfur or sulfuric acid - small amount of sodium sulfate	Commercial operation
7.	Citrate	Solution of sodium citrate absorbs SO_2. The absorbent is regenerated and the SO_2 compounds reduced to elemental sulfur by liquid-phase reduction using H_2S.	Elemental sulfur	Demonstration
8.	Aqueous Carbonate	Solution of sodium carbonate is spray dried to absorb SO_2 and spent absorbent is returned to the system after regeneration.	Elemental sulfur	Demonstration
9.	Spray dry system	Atomized slurry of absorbent reacts with SO_2 while simultaneously dried.	Dry particulate wastes	Commercial operation
10.	Activated carbon absorbation (Bergbau-Forschuing process)	Absorbation and desorption of SO_2 on surface of activated carbon.	Elemental sulfur	Demonstration
11.	Dilute sulfuric acid	SO_2 absorbed by very dilute solution of sulfuric acid containing catalyst, which is then reacted with limestone	Gypsum	Commercial operation

Table 2: Parameters of commercially available FGD processes

	FGD process	investment cost	operating cost	removal cost	removal efficiency	energy consumption
		10^6 $	10^6 $ per annum	$ per tonn SO_2 removed	per cent	per cent of power plant capacity
1	Lime/Limestone	50-60	6-8	470	85-90	3-5
2	Sodium alkali	50-60	12-16	670	95	2-3
3	Dual alkali	57	8.5	580	99	1-2
4	Ammonia absorption (Walther Process)			90		
5	Magnesium oxide	73	9	580	90-95	6-8
6	Sodium sulfite (Wellman-Lord)	73	9	520	90-95	6-8
7	Citrate				90	6-8
8	Aqueous Carbonate					3-4
9	Spray dry system				98	0.5-1
10	Activated Carbon absorption (Bergbou-Forschuing process)	90-100			85-90	0.25-0.5
11	Dilute sulfuric acid					

Table 2 continued: Parameters of commercially available FGD processes.

	FGD process	potentiality of development	ability to remove other pollutant	reliability	development status	simplicity
		verbal	verbal	verbal	verbal	verbal
1	Lime/Limestone	relatively low	no		Large-scale commercial operation	relatively simple
2	Sodium alkali	relatively low	no	average	Limited commercial operation	average
3	Dual alkali	average	no	high	Commercial operation	average
4	Ammonia absorption	average	NO_x	high	Limited commercial operation	
5	Magnesium oxide	average	no		Limited commercial operation	complex
6	Sodium sulfite (Wellman-Lord)	average	no	average	Commercial operation	
7	Citrate		no	average	Demonstration	
8	Aqueous Carbonate		no		Demonstration	
9	Spray dry system		no		Commercial operation	
10	Activated Carbon absorption (Bergbou-Forschuing process)		NO_x		Demonstration	complex
11	Dilute sulfuric acid		no		Commercial operation	

Table 2 continued: Parameters of commercially available FGD processes.

	FGD process	water consumption	material consumption	land use	by-product	waste
		verbal	moles per mole SO_2 removed	verbal	verbal	verbal
1	Lime/Limestone	high	1.2 limestone or 1 lime	required	gypsum	waste water and wet sludge
2	Sodium alkali	high	0.8 caustic ash or 1.4 soda ash	required	sodium sulfate	waste water, scrubbing sollution
3	Dual alkali	high	0.8 lime, 0.07 soda ash	required	no	waste water, wet sludge
4	Ammonia absorption (Walther Process)		ammonia		elemental sulfur	dry product
5	Magnesium oxide	average	0.07 magnesium oxide, 0.02 carbon	not required	elemental sulfur or sulfuric acid	waste water
6	Sodium sulfite (Wellman-Lord)	average	0.11 soda ash, 1 methane	not required	sodium sulfate	no
7	Citrate	low	carbon monoxide, methane, hydrogen, hedrogen sulfide	not required	elemental sulfur	no
8	Aqueous Carbonate	low	0.1 soda ash, 2 carbon	not required	elemental sulfur	no
9	Spray dry system	not used				$CaSO_3/SO_4$, $CaCO_3$
10	Activated Carbon absorption (Bergbou-Forschuing process)	not used	Activated carbon		elemental sulfur	
11	Dilute sulfuric acid	average	limestone		gypsum	

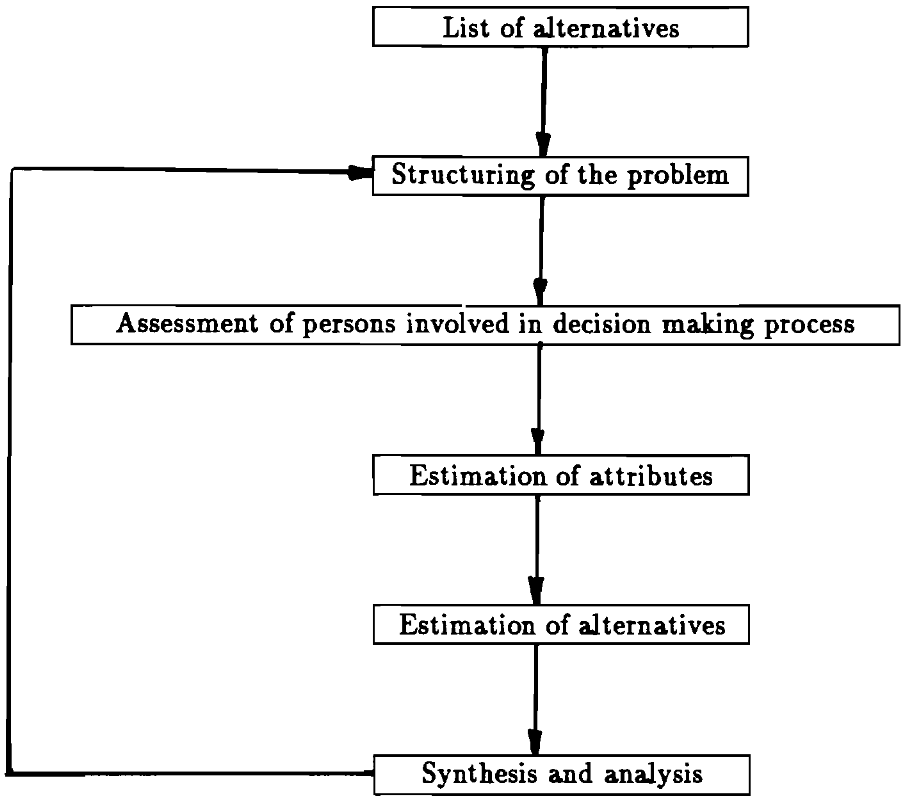
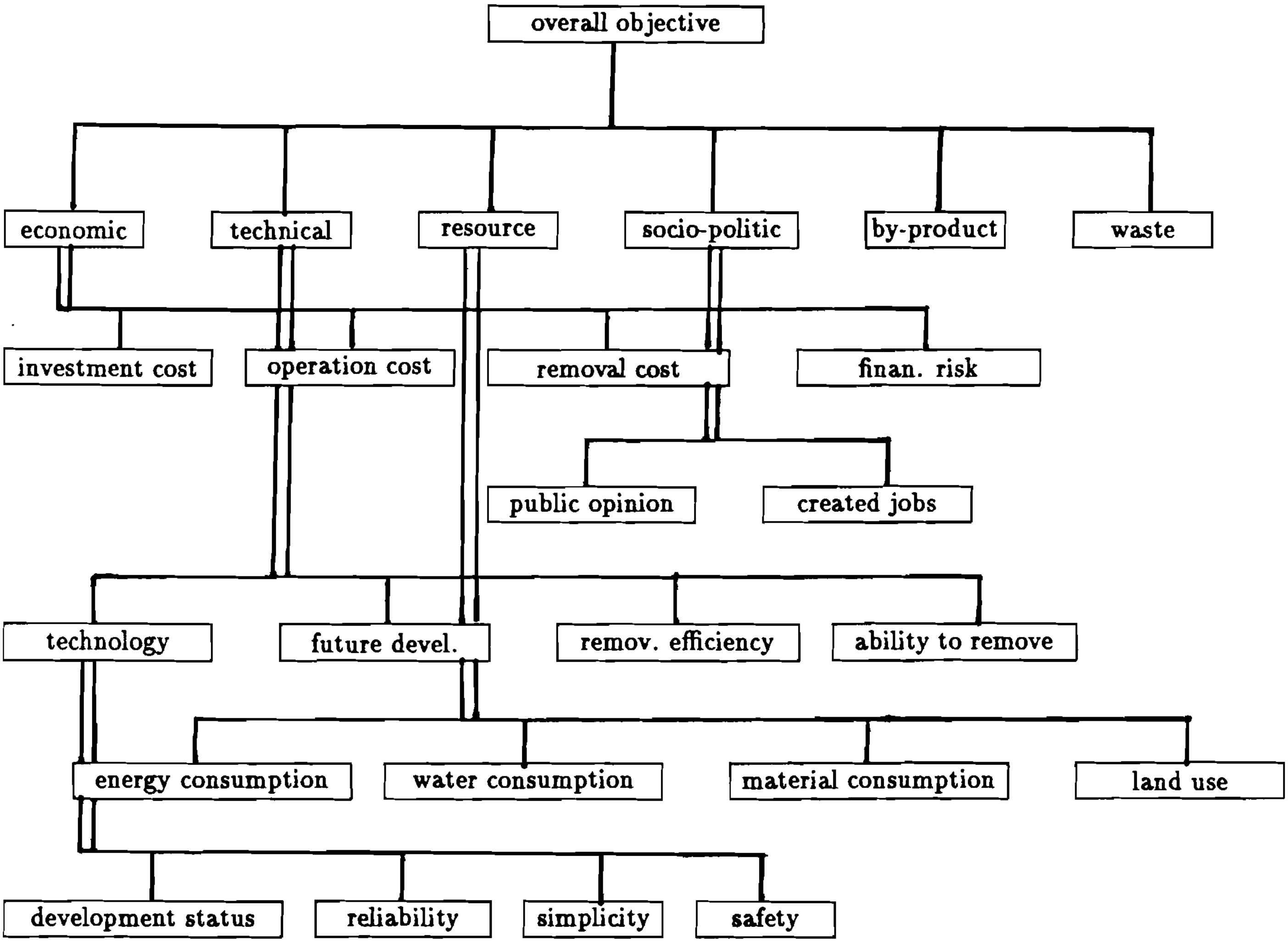

List of alternatives
Structuring of the problem
Assessment of persons involved in decision making process
Estimation of attributes
Estimation of alternatives
Synthesis and analysis

Figure 1


overall objective
economic
technical
resource
socio-politic
by-product
waste
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operation cost
removal cost
finan. risk
public opinion
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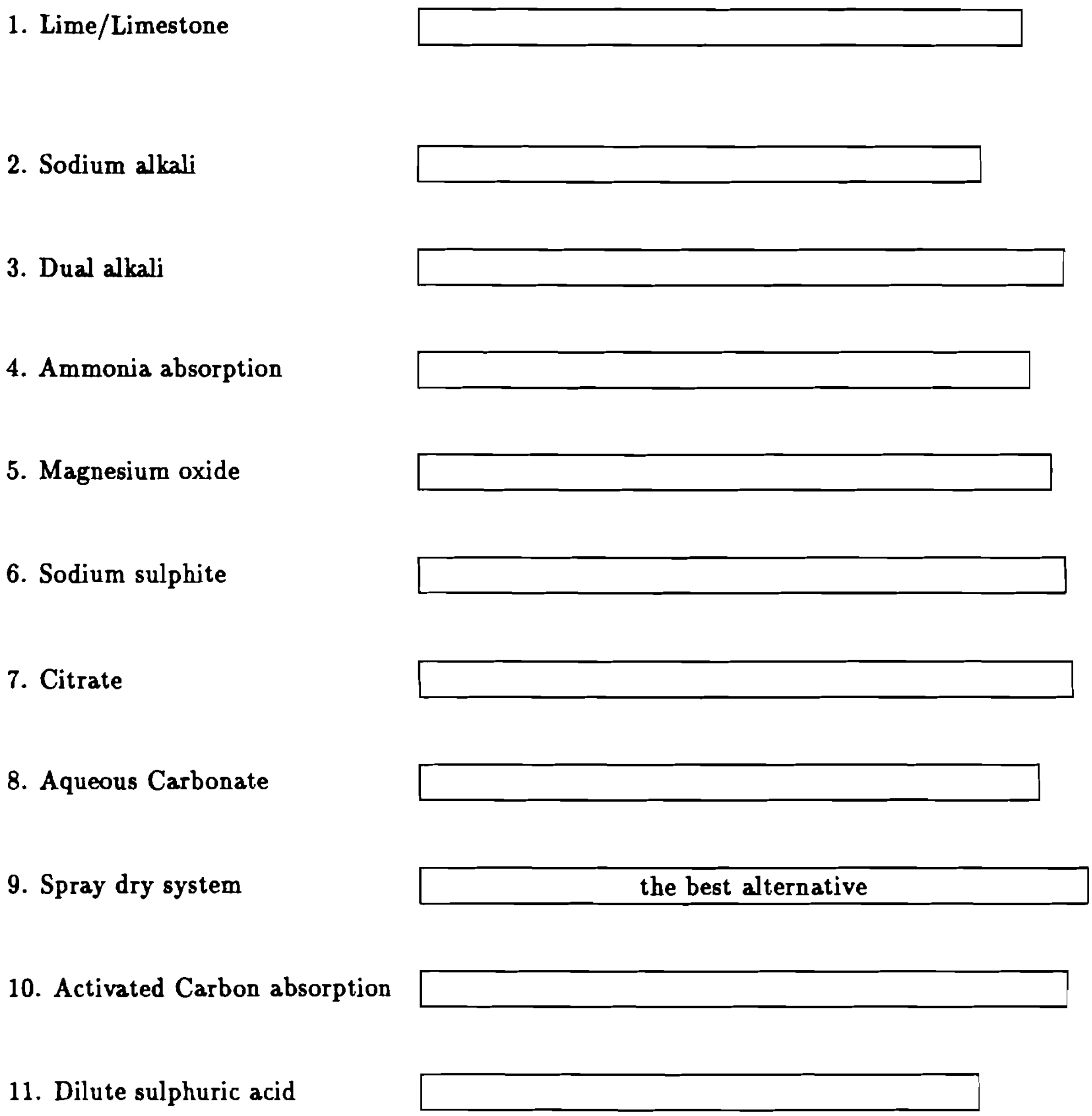
ability to remove
energy consumption
water consumption
material consumption
land use
development status
reliability
simplicity
safety

Figure 2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6. Sodium sulphite
7. Citrate
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the best alternative
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Figure 3

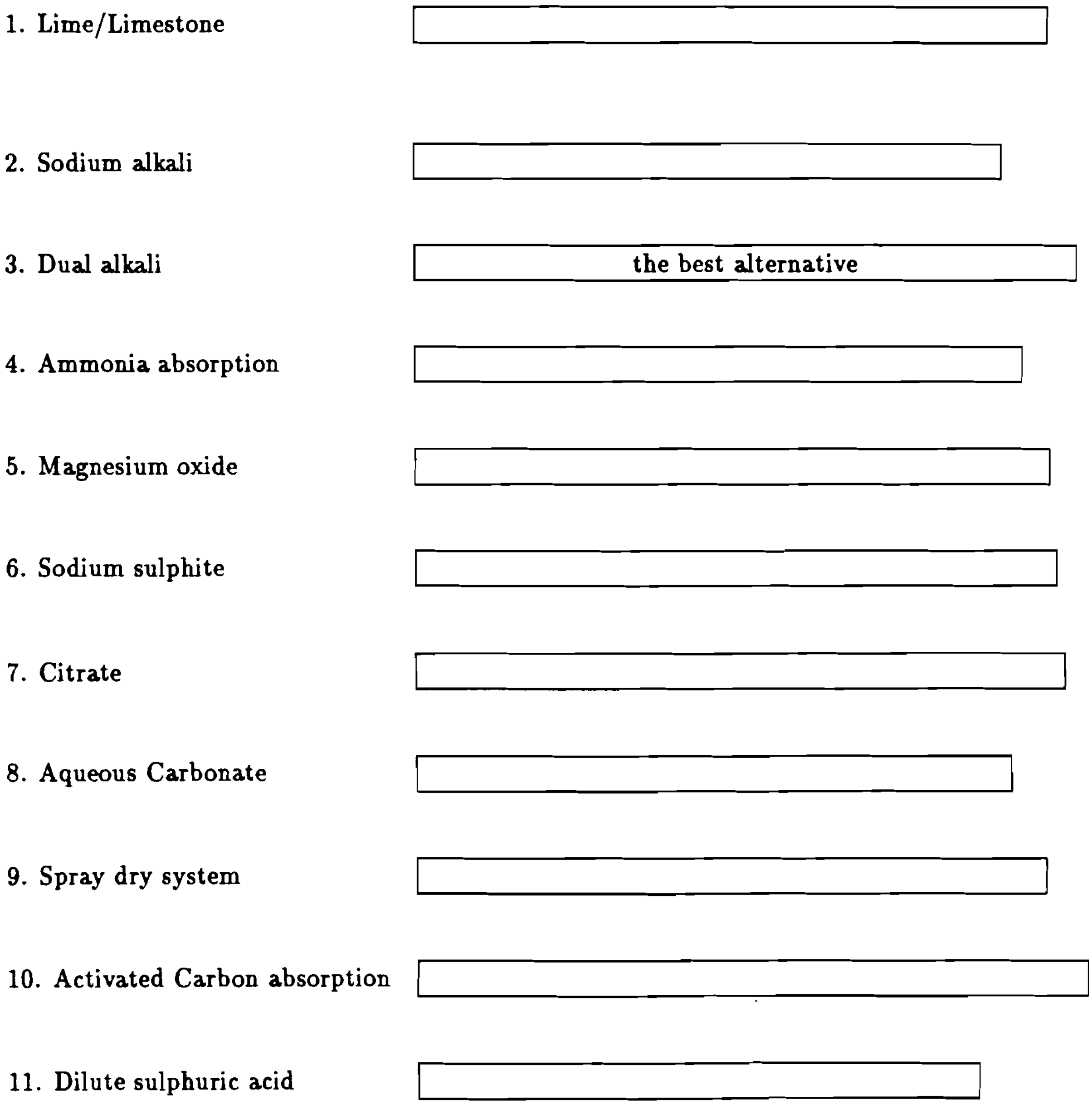
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Figure 4