Environmental factors in optimization of traffic line construction expenses

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Abstract. Environmental politics has got a great impact into many every-day activities with growing importance. The EIA (Environmental Impact Assessment) process, imposed by the European Union laws, is nowadays a standard procedure of evaluation of possible influences of a construction (or, more exactly, a project) to the environment, including the natural, social and economic aspects. In our contribution we present a mathematical optimization model describing the additional expenses spent in order to reduce these (usually negative) impacts. The model considers conditions separated into several categories as standard EIA assumes; some of them depending on technical assumptions, other are based on (abstract) utility terms. Moreover, we search for possible uncertainty sources in model parameters and make suggestions how to deal with them. The resulting stochastic programming model is presented; the different models is constructed with a specific example of line construction (highway) in mind.

Keywords: stochastic programming model, environmental impact assessment, transport line construction

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1 Introduction

The growing economical activity of at least last two decades increase considerably the necessity of government and private investments that support economic development itself, give new opportunities for investors, and, not last, that could assist to increasing number of working positions. The government (or public) part of these investments would be essentially directed to create optimal conditions for subsequent private sector investments; for example, investments in education, science, research, innovation, labour market, support of small and medium-sized enterprised, improvement of legal environment, etc. Actual priorities are declared by government itself, for example by Policy Statement (see e. g. [8]), or Convergence Programme (e. g. [5]). In our contribution we are concentrated on transport line constructions, i. e., part of the transport policy of the government. We describe main ecological factors that enter into the decision process in Section 2. The optimization model with uncertainty and its stochastic programming reformulation is presented in Section 3 and its refinement based on indicators of ecological stability in Section 4.

1.1 Legal environment and motivation

The length of 55,654 km and the density of roads of 0.7 km per 1 km^2 ranks the Czech Republic to the leading position in Europe (see [10]). Worse fact is the structure of the roads; only 2 % of the road kilometers are motorway or expressway type. Rapidly increasing transport intensities, in passenger as well as in freight transportation, is accompanied with growing financial expenses, allocated to the constructions of the new lines on one hand, and to the maintenance and improvement of existing rows (see [10] again). The strategy planning is defined by the Government of the Czech Republic, for example by the government resolution No. 882/2005 concerning Transportation Policy where main purposes are punctuated:

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- construction of motorways and expressways;
- construction of municipality road by-passes;
- modernization of international roads;
- increase of traffic safety;
- quality improvement of the roads.

The main change, in comparison with twenty years old standards, is the actual maximal emphasis on *thriftiness* of the prepared constructions *to the environment*. This have many positive and also negative consequences both of them we describe shortly in the following. Positive factors are obvious:

- protection of the environment;
- sustainable use of the natural resources;
- reduction of the load and enhancement of quality of the life.

The negative impacts are also evident, most important are:

- external force to examine ecologically thrifty but economically and by traffic inappropriate variants;
- long-term and higher expenses to prepare individual constructions;
- big investment expenses to build ecological arrangements and to trace the lines.

We will concentrate on such expenses, and try to design the optimization model incorporating such expenses and other non-financial factors into consideration.

1.2 Environmental Impact Assesment

The legal background for the evaluation of influences of constructions to the environment in European Union is the Council Directive 85/337/EEC of 27 June 1985 on the assessment of the effects of certain public and private projects on the environment [6], with some later complements, and implemented by national rules. The assessment is divided into several phases; we are interested mainly in the so-called process of the *Environmental Impact Assessment* (EIA). It describes most important factors needed in our mathematical model later. The EIA process is obligatory for every big industrial or transport construction. Its main purpose is to determine if negative impacts of the construction are acceptable by society. It is realized before the construction starts and the result of the process is to not realize the project, or to realize the project with prescribed restrictions and compensations.

In the process of the EIA we judge two main classes and several categories of factors:

- influence of the construction to the *human healthy*, for example by noise and air pollution, social and economical impacts, etc.;
- influence of the construction to the *environment*, for example to the animals and plants, ecosystems, areas under organic farming, water, air, landscape, natural resources, but also to the tangible property or cultural heritage, etc.

Each of the factors incorporates many inputs and outputs which will the analyze and modelling process yet more difficult. The EIA takes into account direct as well as indirect influences including that of the construction, working state, and after the end of service (e. g. construction disassembly and reclamation of the area). In the next section we will describe the main categories and factors that enters into consideration during the evaluation of the transport constructions.

2 EIA: the categories of impacts

2.1 Human healthy impacts

1. *Air pollution*, identified by specialized study, is influenced especially by sources of pollution (vehicle emission factors and traffic intensities), and meteorologic and climatic conditions. The air pollution limits, usually given by law, are to be achieved by charging the different categories of roads and vehicle types, forbidden zones or speed reduction.
2. *Noise pollution* is again influenced especially by traffic intensities and vehicle speed. Possible arrangements include special buildings as noise wall, highway tracing or special surface (with many entering parameters as dimensions and material properties).

3. *Social-economic factors (comfort factors)* is purely subjective criterium incorporating such things as better (or worst) life conditions, better transport service, transport loads and emotional factors. These are very hard to quantify and the same is valid for possible arrangements.

2.2 Environment impacts

1. *Air and climate impact* are usually studied together with air pollution.
2. *Water impact*, both surface and groundwater, are assessed by hydrotechnical and hydrological calculations. The possible problems are erosion in time of construction, possibility of accident pollution, service pollution, drainage effect. The compensations include many technical and hydrological elements (retention tanks, dosage and chemical composition of the grit, etc.).
3. *Impact on land and forests.* The main problem is the permanent land take in place of the highway. One of the frequent way of compensating is the replacement planting which also significantly increases costs of the whole construction.
4. *Impact on mineral and natural resources* and other geological factors are rare but sometimes they could occurs, for example as an old contamination (old gallery, etc.).
5. *Impact on flora* and corresponding compensations is usually connected with forests impacts.
6. *Impact on fauna and ecosystems.* The big issue of high capacity line constructions is that they form an impenetrable barrier for a majority of animals. The constructions such as underpasses, culverts, and ecoducts (natural bridges) are the only way to compensate this negative impact. Unfortunately, they are also the most expensive ones, with very difficult and subjective evaluation of benefits to the ecosystem.
7. *Impact on landscape* are not well defined and are usually evaluated by very subjective way (for example, the intensity of intervention in the landscape).
8. *Impact on systems of ecological stability* take into account especially the presence of the bio-corridors and other protected areas and their possible partition. It incorporates also the protection of watercourses, and the compensations are usually prescribed by law.
9. *Impact on tangible property and cultural heritage* resulting in particular by damage or loss of buildings in highway area.

We can see from the above survey, that all the considered factors are of very different nature; also possible compensations are of great number and variations. We have to note also the stochastic (or uncertain) nature of some parameters, for example

- future traffic intensities. They are estimated by prognoses of transportation outputs (see e. g. [2]) but it is also known that the predictions are not very accurate if long-term values are needed. This fact encourages us to use scenario approach to the traffic intensities that allows to incorporate the expected traffic state together with some more extremal situations with lower probability;
- efficiency of the compensating constructions. It is known that some constructions are not functional because of poor design or bad parameters, or just because of inestimable changes in ecosystems;
- subjective criteria and the method of their quantification;
- possibility of an accident.

All these factors will be modeled through the uncertainty parameter in the mathematical formulation of the model presented in the following section.

3 Optimization model

3.1 Characterization of the model

In this section, we start with the characterization of the model, taking into account the information from the previous paragraphs. Denote $x \in X$ the collection of possible compensation and arrangements; $X \subset \mathbb{R}^n$ is the set of all possible combinations of these. The nature of the vector x varies, from 0-1 type (construction build/compensation introduced) by discrete values (variants of different compensations, with associated equivalence and exclusion constraints), to the continuous ones (parameters of the constructions: the dimensions of the wall, quantity of used material, etc.). The very manifold nature of the vector elements will put apparently down a great numerical and computational issue of the problem and is expected to be the subject of possible future research.

The main uncertainty factors was already presented in previous section. We will incorporate the uncertainty to the model through the variable $\xi \in \Xi$ with a predefined (discrete or continuous) support $\Xi \subset \mathbb{R}^s$. For computational reasons we have to suppose that its probability distribution is known in advance.

The cost function $c : X \times \Xi \to \mathbb{R} : (x; \xi) \mapsto c(x; \xi)$ represents the actual expenses on arrangements in place. It is generally non-linear and depends on uncertain factor that is the unknown future cost of the arrangement. If necessary, the cost function is simplified into linear function through $c(x; \xi) = c^T x$, where $c \in \mathbb{R}^n$ is a constant unit cost of the arrangement (usually the expected future cost).

Legislative-nature function $g : X \times \Xi \to \mathbb{R}^G : (x; \xi) \mapsto g(x; \xi)$ is introduced here as a representant for requirements on selected, well defined values, that are measurable, in real-life measured and evaluated. Examples of such typical values are the pollution and noise level, that cannot be exceeded (with prescribed number of exceptions per year). The common (multidimensional) limit to be achieved will be denoted by $L \in \mathbb{R}^G$.

Utility function $u : X \times \Xi \to \mathbb{R}^m : (x; \xi) \mapsto u(x; \xi)$ incorporates all the factors of subjective or evaluative character. The quantification of this function is difficult and it will be subject of the following section.

3.2 Optimization model with uncertainty

We are now ready to formulate the very first optimization model with uncertainty:

$$\text{minimize } c(x; \xi) \text{ subject to } g(x; \xi) \geq L, u(x; \xi) \geq U, x \in X_0 \tag{1}$$

where $X_0 \subset X$ includes deterministic constraints, technical parameters, and 0-1 type constraints, and $U \in \mathbb{R}^m$ is a prescribed minimal level of utility. The usual non-linear nature of utility function would pose a problem so note already here that we could (and will) alternatively work with the second uncertain model

$$\text{maximize } u(x; \xi) \text{ subject to } g(x; \xi) \geq L, c(x; \xi) \leq B, x \in X_0 \tag{2}$$

where $B \in \mathbb{R}$ is prescribed maximal budget of the construction. This second model diverts from the (really?) traditional "cost optimization view" (make the costs as low as possible) in favor of maximizing the utility of the arrangements, limiting only their total expenses.

3.3 Stochastic formulation – two-stage probabilistic model

To deal with uncertainty in models (1) and (2), we now incorporate available information about probability distribution of the uncertain parameters. Moreover, we deal with legislative-type constraint by two ways simultaneously: first, we require the legislative limits to be achieved with sufficiently high probability $1 - \alpha$ (with $\alpha \in (0, 1)$), and second, compensating possible shortcomings of limits (after the random variables are observed or realized), by the second-stage action represented by the recourse function $Q(x; \xi)$ below. The model then falls into the special category of *two-stage stochastic programming models with probabilistic constraints* and reads:

$$\text{minimize } \mathbb{E}c(x; \xi) + Q(x; \xi) \text{ subject to } \mathbb{P}\{g(x; \xi) \geq L\} \geq 1 - \alpha, \mathbb{E}u(x; \xi) \geq U, x \in X_0, \tag{3}$$

where

$$Q(x; \xi) = \inf\{q^T y : W^T y = h([g(x; \xi) - L]^-, [u(x; \xi) - U]^-), y \geq 0\}, \tag{4}$$

W is a recourse matrix, y a recourse (second-stage) action, and h a loss function evaluating both legislative and utility shortcomings; $[\cdot]^-$ denotes the negative part of its argument. The formulation of the model could be also easily modified for other types of recourse functions.

4 Dealing with utility functions

The problem (3) exhibits a shortcoming that one would have to resolve – description and evaluation of the utility function u. The first approach was already outlined – use the uncertain model (2) as the starting point. The resulting model simplifies just to the classical *model with probabilistic constraints* – if we linearize the constructions costs and drop the recourse part of the model (or incorporate it somehow through the utility function), we obtain simply the standard formulation

$$\text{maximize } \mathbb{E}u(x;\xi) \text{ subject to } \mathbb{P}\{g(x;\xi) \geq L\} \geq 1-\alpha, c^T x \leq B, x \in X_0. \tag{5}$$

There are many theoretical and applied results concerning these probabilistic model, we refer the reader to the book [9] as to the starting point. Unfortunately, the issue with not well defined utility function still resists; we will make the aproach more concrete through the concept of *indicators of ecological stability* briefly presented in the next paragraph.

4.1 Indicators of ecological stability

The indicators of ecological stability are the sets of well defined and quantified variables, evaluating the quality of the environment on the regular basis. The basic set is defined by European Environmental Agency (EEA) Core Set of Indicators ([7], see also [4]) and includes such themes as air quality (for example: emissions of acidifying substances, emissions of ozone precursors, etc.), biodiversity (number of bird species, protected areas, etc.), and many others. Some of the indicators (especially indicator of efficiency and total prosperity) are not yet standardized, but could be easily incorporated into actual set.

Using the EEA indicators our stochastic model significantly simplifies. First, we join together legislative and utility functions – just simply because most of the known legislative limits are defined through the already observed values of the EEA indicators. The second step is to use classical Allen's indifference curves ([1]) to model the levels of equal utility and thus to enable the possibility to compensate a lack in one criteria by an improved value in another one. Let $g(x;\xi)$ now represent the values of the EEA indicators and let w be the vector of prescribed weights assigned to every indicator. Then the model *maximizing the weighted expected value* of the indicators reads:

$$\text{maximize } \mathbb{E}w^T g(x;\xi) \text{ subject to } c^T x \leq B, x \in X_0. \tag{6}$$

This is a standard stochastic programming model with recourse (see e. g. [3]); approximation and/or linearization of the objective function would lead to a large scale but computable linear or non-linear optimization model and so that to the numerically tractable problem. Such approximation is leaved outside the scope of this paper.

A modification to the last model could be imposing the limit $L \geq 0$ to the weighted value of indicators and *maximize the probability* that the limit will be achieved, resulting in the final model of this paper:

$$\text{maximize } \mathbb{P}\{w^T g(x;\xi) \geq L\} \text{ subject to } c^T x \leq B, x \in X_0. \tag{7}$$

Selection of the parameters L and w is still rather subjective actions but much less complicated than determining many parameters of model of type (3).

5 Conclusion

In this paper we presented several approaches to model the environmental aspect of different (especially line) constructions by means of the stochastic programming models. This is a novel direction of stochastic programming area that was not yet explored as far as our knowledge goes on. We designed different versions of stochastic programming models that deals with uncertain nature of the parameters – especially the unknown future values of ecological loads, and the very subjective character of the evaluation of quality of environment itself. The research would to be extended by many directions, starting with explicit listing of the indicators of ecological stability and numerical studies. But this one and other extensions is leaved out of this paper.

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