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ASSESSMENT OF TRANSPORT INFRASTRUCTURE PROJECTS BY THE USE OF MONTE CARLO SIMULATION: THE CBA-DK MODEL

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ABSTRACT

This paper presents the Danish CBA-DK software model for assessment of transport infrastructure projects. The assessment model is based on both a deterministic calculation following the cost-benefit analysis (CBA) methodology in a Danish manual from the Ministry of Transport and on a stochastic calculation, where risk analysis (RA) is carried out using Monte Carlo Simulation (MCS). After a description of the deterministic and stochastic calculations emphasis is paid to the RA part of CBA-DK with considerations about which probability distributions to make use of. Furthermore, a comprehensive assessment of the set of distributions are made. Finally conclusions and a perspective are presented.

1 INTRODUCTION

The idea of supporting decisions regarding new transport infrastructure projects by the use of cost-benefit analysis (CBA) is well established in Europe. In Denmark the foundation of such analyses is made up by the relatively recent manual for socio-economic analysis published by the Danish Ministry of Transport in 2003 (DMT 2003). Based on the principles in this manual an Excel-based software model CBA-DK has been developed in collaboration between the Danish Road Directorate and the Technical University of Denmark (Salling et al. 2005). CBA-DK contains as one of its features a risk analysis (RA) module. Therefore Danish infrastructure projects can be appraised based both on a deterministic calculation which follows the Danish manual's CBA methodology and a more elaborate stochastic calculation where the RA methodology is based on Monte Carlo Simulation (MCS) making use of @RISK software (Palisade 2002). The module structure of CBA-DK is shown in Figure 1. This paper is disposed as follows: After this short introduction the two types of calculations are described respectively by a deterministic (CBA approach) and stochastic calculation (MCS approach). The final section 4 presents some conclusions and gives a perspective on the further work on the development of the model.

2 THE DETERMINISTIC CALCULATION

The basic approach behind a CBA consists of modeling net changes in a number of effects due to the implementation of a new transport infrastructure project. After assessing the value of these changes obtained benefits can be set against the cost of the project resulting in various evaluation criteria.

The CBA module of CBA-DK consists of 4 categories: Passenger Cars, Lorries, Heavy Vehicles and External Effects. The three vehicle categories are modeled in the before – and after project situation with regard to the following impacts: travel time savings, vehicle operating costs, congestion and changing traffic. It can be noted that changing traffic is assessed by making use of the so-called rule-of-a-half principle (Leleur 2000 pp. 89-91). The external effects are of different types such as accidents, air-pollution, barrier and perceived risk, severance and noise. Additional entries in the input sheet are the main data concerning the case project: construction cost (investment cost), operating and maintenance costs, evaluation period and key parameters such as discount rate, growth in the economy, etc. Figure 2 is showing the input data sheet. The Danish methodology is further described in (Leleur 2000 pp. 129-134) and (DTM 2003).

By applying the net changes within the user impacts and the external effects as input to a socio-economic analysis, it is possible to obtain decision criteria such as the Benefit-Cost ratio (B/C-rate), Net Present Value (NPV), Internal Rate of Return (IRR) and First Year Rate of Return (FYRR). A run of CBA-DK ends up with a result sheet shown in Figure 3. The two bars on the right depict the costs and the benefits presented in the same absolute scale.

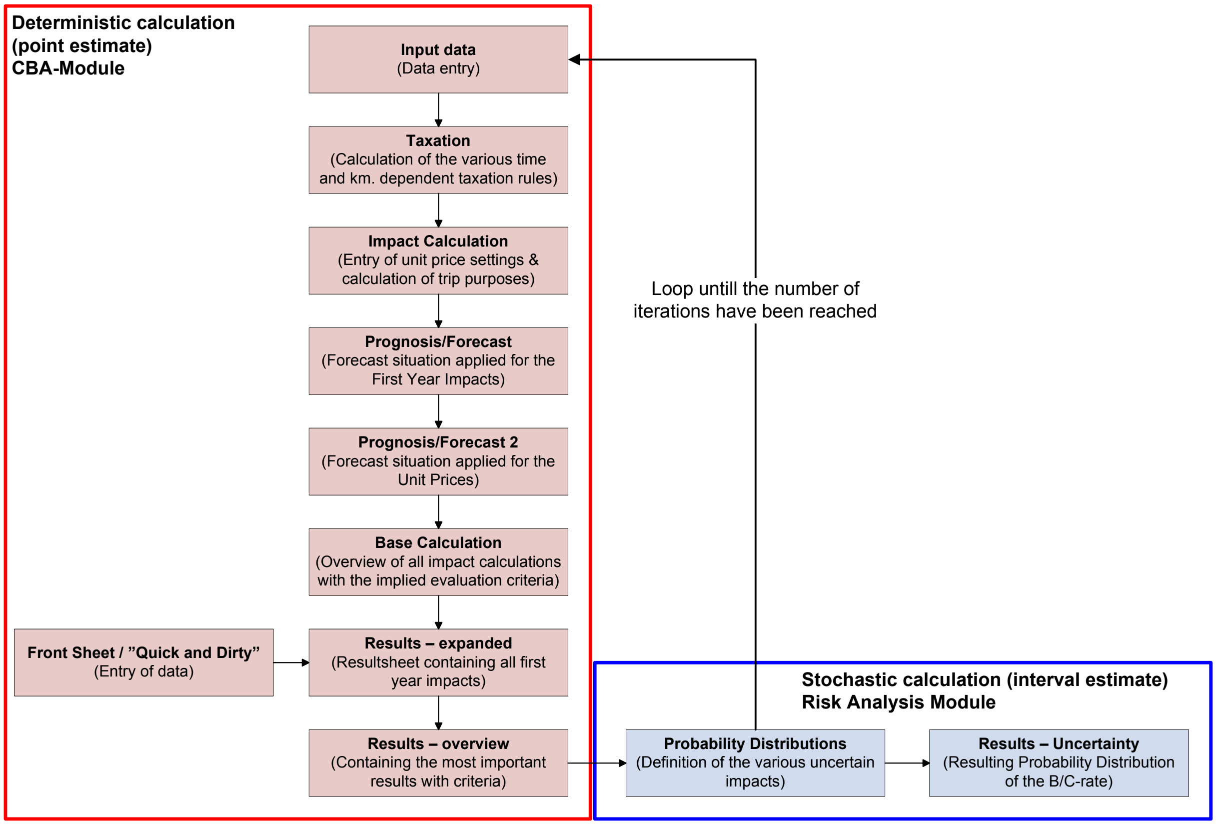

Figure 1: The Module Structure of CBA-DK Illustrated by the Various Worksheets (Salling et al. 2005)

The coloring scheme only serves the purpose of illustration. By comparing the decision criteria from different runs on different projects a prioritization can be made e.g. (Leleur 2000 pp. 99-105).

It is increasingly a requirement within model based decision support to map and communicate the uncertainty underlying any decision support model. The deterministic runs illustrates point estimates, however, by applying risk analyses it is possible to achieve B/C-rate intervals as the output. This provides a broader basis for assessing the individual projects.

3 THE STOCHASTIC CALCULATION

To make a CBA, as performed in the modeling framework, it is necessary to obtain information from various traffic and impact models. The various types of models combined with varying degrees of effort and resource input for impact modeling result in different degrees of uncertainties. In this respect it is necessary to use different probability distributions, in accordance with the variability/uncertainty (Vose 2002) that characterizes the parameters set focus upon in the risk analysis, such as the construction cost, maintenance cost, travel time savings etc., see Figure 1. The Danish manual determines unit prices which in CBA-DK remain fixed (time unit price, vehicle operating costs a.o.). In the view of this work these parameters are assumed as certain (DMT 2006). The modeling system examines selected parameters that are considered the most important for RA such as: construction costs, number of hours saved per year for traveling time, maintenance unit costs and safety unit price (Salling 2006). The first two are matters of variability and the latter two of uncertainty as discussed in Vose 2002 p. 18. Variability and uncertainty reflect ontological and epistemic issues, see Figure 4 from (Walker et al. 2003 p. 13).

The epistemic uncertainty is defined as imperfection of our knowledge, which may be reduced by more research and empirical efforts. The ontological uncertainty is due to inherent variability, which is especially applicable in human and natural systems and concerning social, economic, and technological developments. Assessing the nature of uncertainty may help to understand how specific uncertainties can be addressed. In the case of epistemic uncertainty, additional research may improve the quality of our knowledge and thereby improve the quality of the output. However, in the case of variability uncertainty, additional research may not yield an improvement in the quality of the output (Walker et al. 2003).

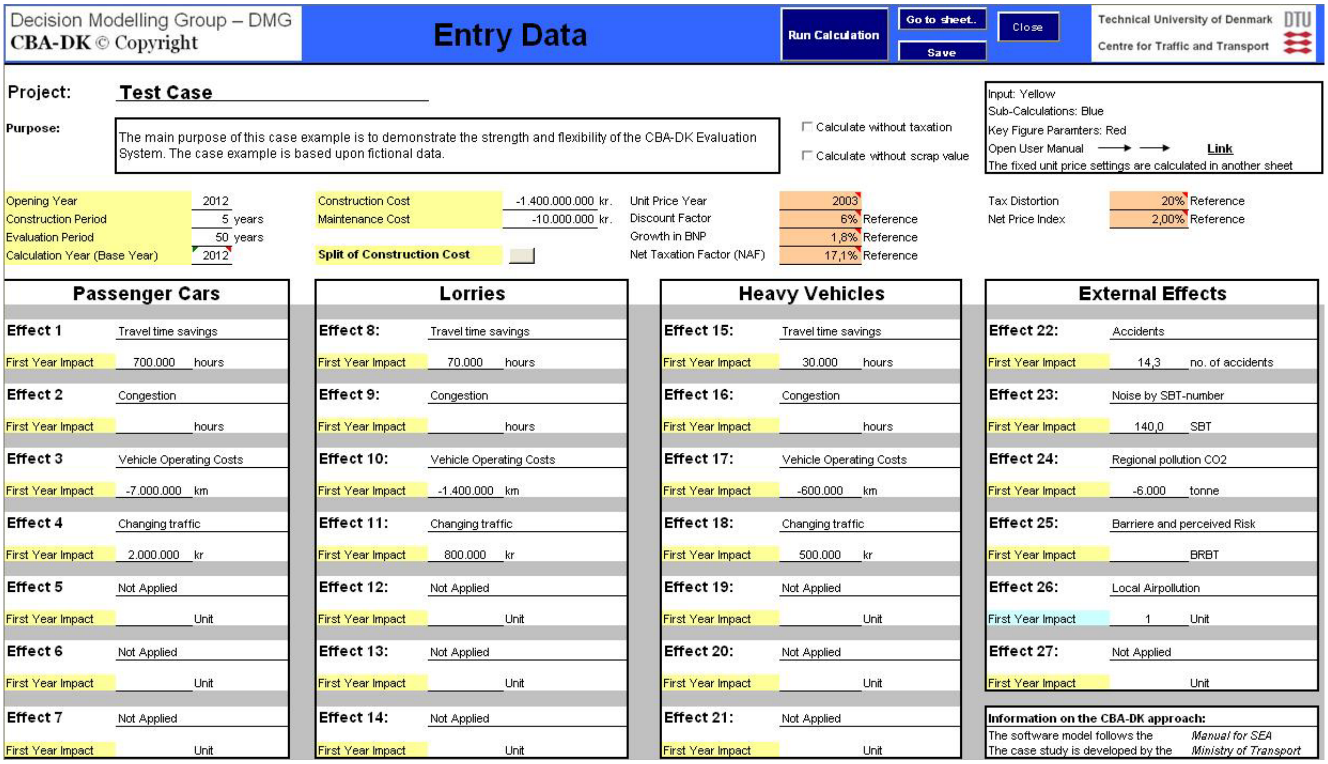

Figure 2: Overview of the Input Data Sheet from CBA-DK

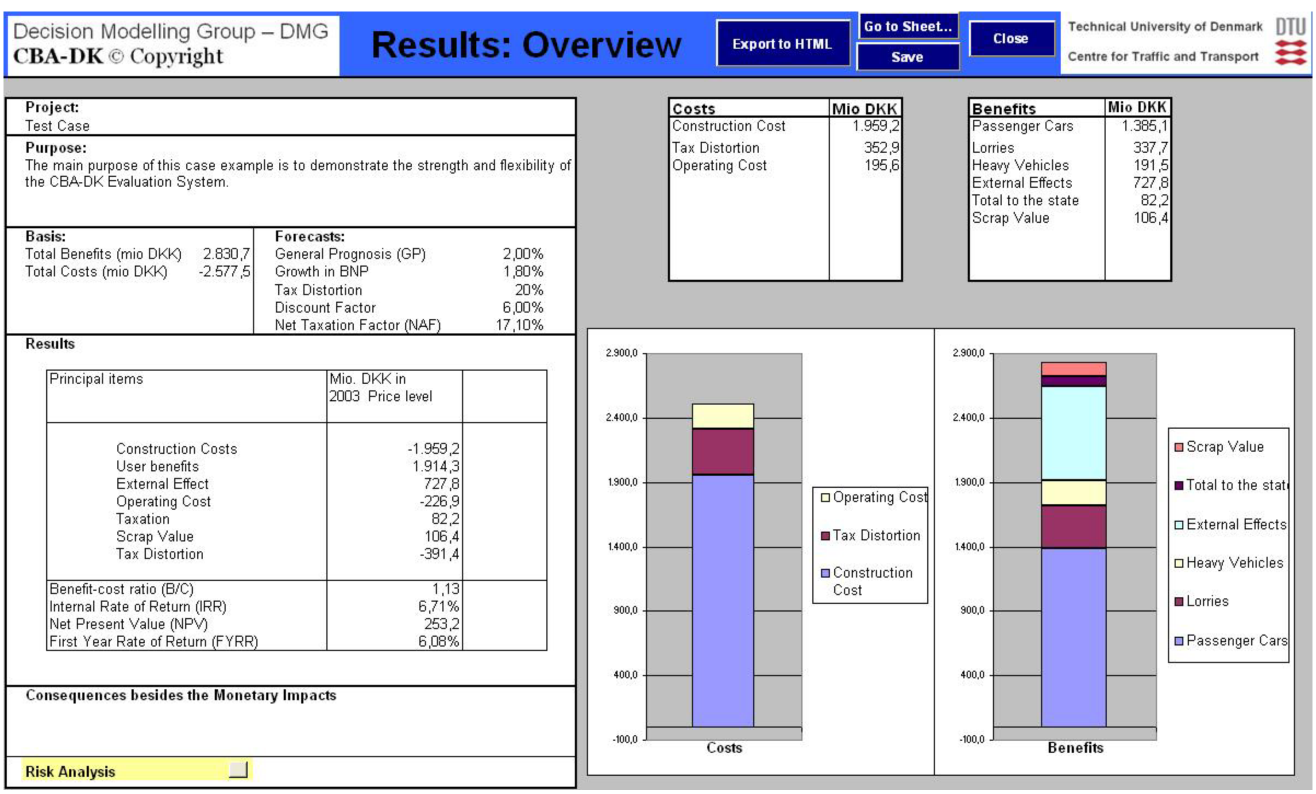

Figure 3: Overview of the Results Overview Sheet Containing the Most Important Results from the Implied Case

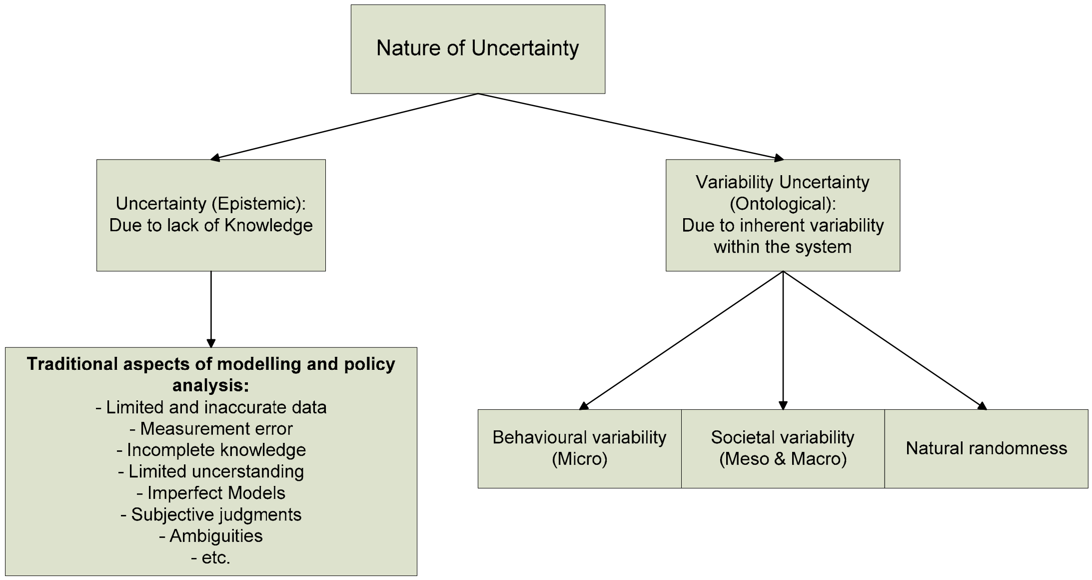

Figure 4: The nature of Uncertainty: Inherent Variability or Lack of Knowledge (Walker et al. 2003)

The essence of the traditional risk analysis approach is to give the decision-maker a mean by which he can look ahead to the totality of any future outcome. The advantage of using any risk analysis approach is the possibility of differentiating the feature of risk information in terms of outcome criteria such as the Benefit/Cost rate (B/C-Rate) by probability distributions (Hertz & Thomas 1984).

An ongoing Ph.D. study (Salling 2006) seeks to define a set of suitable distributions for examination of feasibility risk relating to examination of transport infrastructure projects. Based on data available on a number of studies the following five distributions have been adopted and tested within the CBA-DK framework:

- Uniform distribution
- Normal distribution
- Triangular distribution
- PERT (Program Evaluation and Review Technique) distribution
- Erlang (Gamma) distribution

In the analysis work so far this set has been adequate. In the case of some other distributions will be needed e.g. on the basis of new data analysis etc. this can be added to the set.

3.1 The Construction Cost

The cost of investing in a project ex-ante is often predicted lower than the actual cost e.g. due to technical problems, delays, etc. Four bullet points for estimating construction costs with probability distributions have been proposed in (Back et al. 2000).

- Upper and lower limits which ensures that the analyst is relatively certain values does not exceed. Consequently, a **closed-ended** distribution is desirable.
- The distribution must be **continuous**
- The distribution will be **unimodal**; presenting a most likely value
- The distribution must be able to have a greater freedom to be higher than lower with respect to the estimation – **skewness** must be expected.

Three probability distributions come into mind when looking at the four bullets. The most obvious choice is the triangular distribution or the PERT distribution. However, the authors point out the Gamma distribution as a likely and suitable distribution even though it is not entirely following the first bullet point due to the open ended tail (Back et al. 2000 p. 30 tab. 1).

A Danish statistician has developed a principle based upon successive calculation (Lichtenberg 2000). The strength of applying the so-called Lichtenberg principle is that the decision-maker only has to consider a minimum, most likely (ML) and maximum value. Then by use of a so-called triple estimation approach the mean and standard deviation are calculated by the two following formulas (Lichtenberg 2000 p. 125):

$$\mu = \frac{(\min. + 2.9 \cdot ML + \max.)}{4.9} \tag{1}$$

$$s = \frac{|\max. - \min.|}{4.65} \tag{2}$$

Lichtenberg further documents the use of an Erlang distribution towards estimation of the construction cost which corresponds to the article by (Back et al. 2000) due to the fact that an Erlang distribution is a Gamma distribution.

The properties of the Erlang distribution requires a scale (k) and a shape (θ) parameter. It has been found that a scale parameter of $k = 5$ matches the distribution of the uncertainty involved in determining the construction cost (Salling 2006). From the triple estimation is the mean (μ) calculated by (1). The relationship to the shape parameter is found by the equation: $\theta = \frac{\mu}{k}$. The applicability of the Erlang distribution is related to the variation of the scale parameter. For $k = 1$ the distribution is similar to an Exponential distribution, whereas with increasing k the distribution will begin to resemble a Normal distribution.

3.2 Travel Time Savings

Travel Time Savings in transport infrastructure projects are of great importance when it comes to appraisal studies. Benefits stemming from this category often make up a share in the range from 70-90% of the overall benefits (Leleur 2000 p 108). The travel time savings have been found to follow a Normal distribution where the mean is based upon the net change in hours spent on traveling in the influence area of the road project. Standard deviations relating to traffic models applied in Denmark have been found to be around 10-20% (Knudsen 2006). By testing a traffic model in several scenarios it has been proven that the standard error within this model is around 11% for the transport mode and 16% for the traffic loads. Further investigations show that a standard deviation in the area of 10% for smaller projects and 20% for large projects are not unlikely (Ibid.).

Further studies relating to the latter impact is concerning the Lognormal distribution due to the inherent relationship with the Normal distribution (Vose 2006).

3.3 The Maintenance Cost

The maintenance costs (MC) are developed based on empirical accounting formulas considering different cost factors (Leleur 2000 p. 158). The modeling scheme of determining MC has been found by analyzing previous expenditures together with the road type, average daily traffic and the width of the lanes. Furthermore, it has been found suitable to use a Triangular distribution to illustrate the uncertainty (Salling 2006). Specifically, the uncertainty assigned to this parameter using the Triangular distribution is defined by 10% possibility of achieving a lower MC (min.), the most likely value is the previously calculated MC and 50% possibility of achieving a higher value at the tales (max.). It should be noted that this effect is a disbenefit towards society.

An alternative distribution to the Triangular distribution is known as the PERT distribution. These types of distribution, requires the same three parameters, but interprets them with a smooth curve that places less emphasis on the furthest extreme, see Figure 5.

The advantage of using a PERT distribution is to be seen from the differences in their mean values i.e.

$$Mean_{Triang} = \frac{Min + Mode + Max}{3}$$ vs.

$$Mean_{PERT} = \frac{Min + 4 \cdot Mode + Max}{6}$$. The average of all three parameters in the PERT distribution has got four time the weighting on the Mode. In real-life problems we are usually capable of giving a more confident guess at the mode than the extreme values hence the PERT distribution brings a much smoother description of the tales of the impacts to be considered.

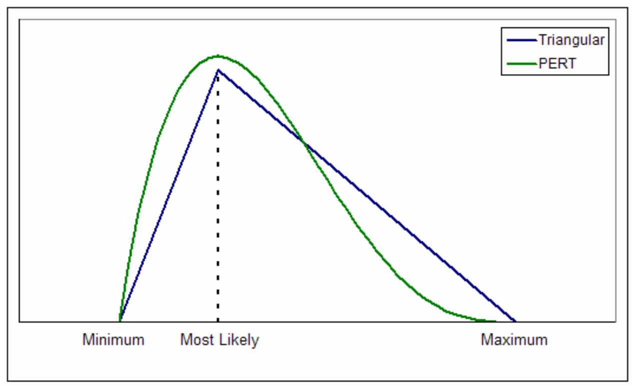

Figure 5. Illustration of the Triangular Distribution vs. a PERT Distribution (Vose 2006)

3.4 Accident Unit Price

The accident benefits are determined by their value towards the society stemming from multiplying the expected number of accidents saved with a societal unit price. Then dependent on the road type a total amount of personal injuries can be determined calibrated on a 1 km section of the given road. The unit price settings for accidents is constructed through several different aspects which further contributes to the uncertainty involved. The Uniform distribution shows the assumed uncertainty included in the price-setting where information on a high and low range is estimated. In the actual case run an estimate with ± 10% to the standard unit price has been applied.

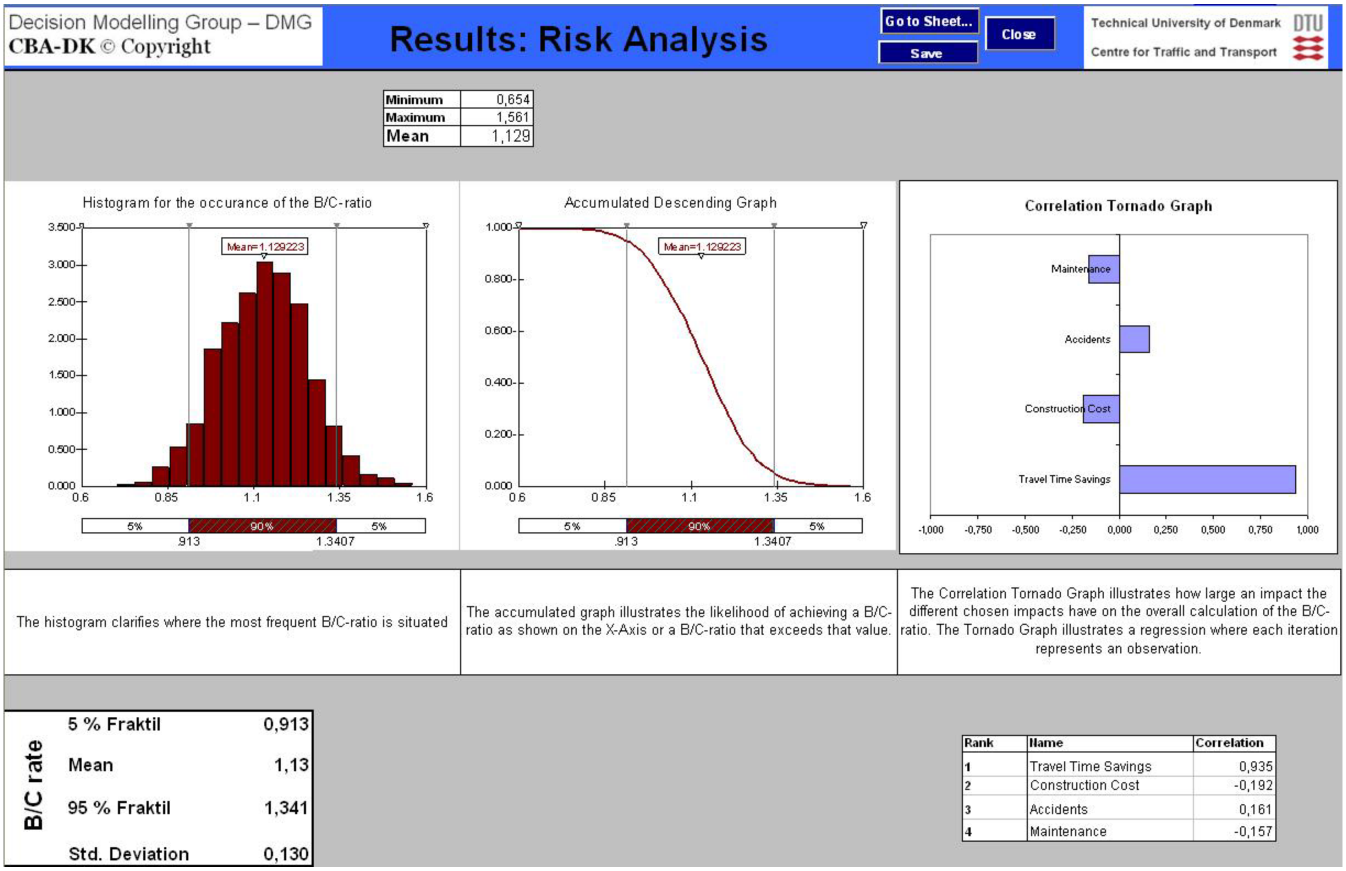

Figure 6: Screen-Dump of the Resulting Sheet from a Monte Carlo Simulation in CBA-DK.

3.5 The Risk Analysis and its Results

The actual Monte Carlo Simulation shown in Figure 6 is based upon the two sets of previous mentioned parameters and distributions. The purpose of the CBA-DK RA result sheet is to give the decision-makers a mean to widen their assessment of the possible B/C-rate (Hertz & Thomas 1984). Specifically, Figure 6 shows three reports based on @RISK: Histogram showing the most frequent B/C-rate, a descending accumulated graph that shows the "certainty" of achieving a certain B/C-ratio or better and finally a correlation tornado graph that illustrates the impact (correlation) of each variable or parameter to the overall B/C-ratio (Salling 2006). Obtaining a probabilistic view of the B/C-ratio is especially beneficial when several projects are to be evaluated. The possibility of applying e.g. different scenarios, evidently by various input parameters creates varying degrees of uncertainty expressed by the steepness of the descending accumulated graph (Leleur et al. 2004).

The feasibility risk to be adopted in the actual case is of course up to the decision-makers to debate but the features to deal with uncertainty in the CBA-DK model may help support their considerations. Some of these will be to get acquainted with the various assumptions behind the scenarios, probability distributions, and the way the latter have been assessed/estimated and related to the different scenarios. The resulting graph illustrated in Figure 7 shows the variation of the B/C-ratio with interval results spanning from 0.65 to 1.56. Note that for the descending cumulative curves with the probability on the y-axis and the rate of return on the x-axis more reliable data will lead to steeper curves.

The cross section shown on Figure 7 indicates a B/C-ratio of 1.00 with an 80% feasibility or less of achieving a societal reasonable project. A higher degree of certainty corresponds to a lower B/C-ratio and visa versa.

4 CONCLUSION AND PERSPECTIVE

The CBA-DK model software makes it possible to conduct a comprehensive assessment of transport infrastructure projects. By use so far in practical studies it has been seen as an advantage that conventional CBA can be supplemented with a RA examination. However, even though MCS is an established technique in the field of risk analysis, it still lacks a generally approved way of implementation in the transport infrastructure area. A particular interest is the variety of various probability distributions and

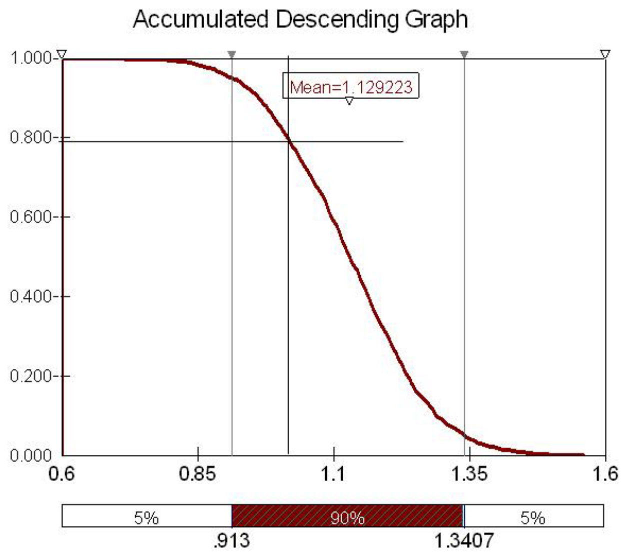

Figure 7: Resulting Accumulated Graph Illustrating the Variation of the B/C-ratio

their strengths and weaknesses. Five types of probability distributions has been set out as a suitable set for RA consisting of Uniform, Normal, Triangular, PERT and Erlang distributions. The Lognormal distribution is currently considered as a candidate for inclusion in the set.

The decision support model will be further developed in future studies. Thus it can be mentioned that a new modelling scheme is applied in a large transport study on Greenland with focus upon appraisal of airfields. In this study the CBA-DK and its RA module will be tested further.

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