Quantitative Risk Analysis – Fallacy of the Single Number

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1. Summary

Risk analysis is a proven method to identify, characterize, and address potential risks and to allow development of risk management plans to reduce impacts to projects. In this way, limited resources can be best used and value added. In this paper we will illustrate the application of risk analysis with respect to one key element – the cost of these projects. Cost is critical to owners in terms of meeting budget and to contractors in terms of realizing a profit.

2. Introduction

Every forecast of a future event comes with uncertainties. This means that any cost estimate must include this uncertainty and that uncertainty has to be quantified, characterized, and well understood.

This is especially true for cost estimates where owners require a reliable budget, and uncertainties complicate the challenge for these owners, legislatures, and stakeholders. The uncertainty about any single-point (i.e., deterministic) value means that there is a good probability that the "real" answer may be significantly different than that single-point value. The uncertainty does not mean that we do not know the answer – the uncertainty is an essential part of the answer and therefore it must be sufficiently addressed and quantified.

Probabilistic methods have been used in many industries for years now to increase the reliability and applicability of cost estimates. In the construction industry, the probabilistic approach may be considered "state of the art," but it is not used frequently. Especially for the production of prototypes – typical for construction projects – where costs and risks can have significant variation, it is necessary to use a probabilistic approach in order to sufficiently include and characterize these uncertainties.

Cost is key. It is clear that the public is very skeptical that the final costs of large, complex public projects can be managed within their authorized budgets. In spite of the fact that many projects are completed within or close to budget and schedule (Reilly 2013), several high-visibility projects that have substantially exceeded their budget nourish this reasonable doubt. The following questions are relevant:

1. Why do we fail to complete some key projects at or below their budgets?
2. Why does it seem to the public that costs have a tendency to always increase?

Reasons why these questions might not have been answered clearly to date include a large variety of impacting factors including large size, complexity, advanced technology, long implementation timeframes, and political circumstances. Furthermore, inadequate cost estimating and risk management methods have frequently been used (Reilly 2005).

3. Methods for Quantitative Risk Analysis

Deterministic and probabilistic methods are used but differ significantly in their approach. Quantitative methods use a defined amount (e.g., a percentage) for the probability of occurrence of risk as well as for the financial impact (in EUR, USD($), or any other currency). They consider risk by multiplying probability of occurrence [p] and impact [I]. The result is the expected value of the risk impact. If multiple risks are to be addressed, the total risk is often expressed as the mathematical sum of all single, individual risks, in accordance with the following equation:

$$R_{total} = \sum p_i * I_i$$

However, such a simple summation of risks delivers no information about probability and best and worst case scenarios. It is also necessary to add an overall contingency to account for other unknowns, but such an overall contingency is subject to bias since there may be no rational basis for how unknowns are aggregated or estimated.

By using probabilistic methods to include risk (which is the product of probability and impact), the individual risks can be aggregated to produce a "probability distribution" (a probability density function). The aggregation of those risks cannot be done with a simple mathematical addition. Aggregating individual risks requires mathematical simulations (Monte Carlo Simulation, Latin Hypercube Sampling) to characterize the total risk set in terms of a probability distribution, which shows the potential impact of that risk set.

Value at Risk (VaR) defines a value (e.g., in USD) which will not be exceeded at the corresponding probability.

Table 1 *Deterministic versus probabilistic method for risks (Sander 2012)*

	Deterministic Method	**Probabilistic Method**
Input	Definition of a single number for consequence which is the probability of occurrence multiplied by the impact of each risk.	The probabilistic assessment of risks requires one number for the probability of occurrence and several values for the impact (e.g., minimum, most likely, and maximum), therefore including uncertainty.
Result	A simple mathematical addition to give the aggregated consequence for all risks. This results in an expected consequence for the aggregated risks but does not adequately represent the bandwidth (range) of the aggregated consequences.	Simulation methods produce a bandwidth (range) of aggregated project risks as a probability distribution based on thousands of coincidental but realistic scenarios (depiction of realistic risk combinations).
Qualification	Results are displayed as a single, sharp number, which, in itself, does not have an associated probability.	Results are displayed using probability distributions, which allow Value at Risk (VaR) interpretation for each value within the bandwidth (range).

Probabilistic methods are more sophisticated than deterministic methods, which are often based on a normal spreadsheet approach. The main reasons why a risk-based, probabilistic approach is recommended can be summarized as follows (Tecklenburg 2003):

- A deterministic method can give equal weight to those risks that have a low probability of occurrence and high impact and to those risks that have a high probability of occurrence and low impact if using a simple multiplication of probability and impact. This approach is incorrect.

- By multiplying the two elements of probability and impact, these values are no longer independent. Therefore, this method is not adequate for aggregation of risks where both probability and impact information need to remain available. Due to multiplication, the only information that remains is the mean value.
- The actual impact will definitely deviate from the deterministic value (i.e., the mean).
- Without the Value at Risk information, there is no way to determine how reliable the mean value is and how likely it might be exceeded.

Through the application of probabilistic methods, the impact of a risk, for example potential financial consequences, can be modelled and represented more accurately by a probability distribution.

4. Probabilistic Method - Inclusion of Uncertainties

Since empirical/historical data as input for risk analysis is often not available, risk probabilities and consequences can be difficult and complex to estimate. Normally, experts are involved in a workshop using, for example, Delphi technique. The risk-based method characterizes each risk with individual and specific distributions such as a large range for large uncertainties or a narrower range for smaller uncertainties. Using this approach, the uncertainty contributing to a particular cost estimate can be modelled more specifically and in greater detail than by use of a single-point deterministic estimate (Sander et al. 2009).

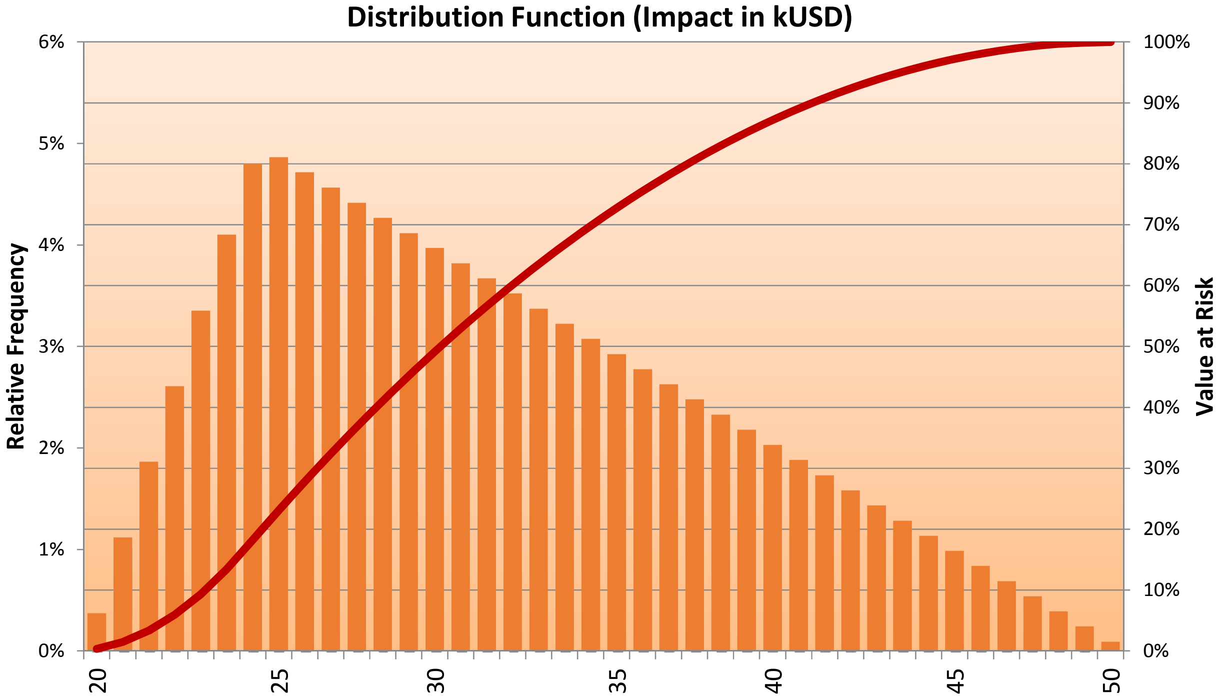


Fig. 1 *Probability Distribution for an individual risk with weighted values using triangle function*

The above figure shows an example of a probability distribution. Costs are estimated to range between 20k (Thousand USD) and 50k and are additionally weighted. The most likely forecasted value is 25k (bandwidth 20–25–50).

Cost estimates, especially if only deterministic approaches are considered, can come with a high degree of uncertainty. This is especially true for early phases of projects when neither the exact quantities nor the exact costs or prices are yet known. Quantities will be determined for known project elements, but allowances must be made for unknown elements. Often a more detailed analysis is not yet available at this stage of the project due to a lack of precise information. With a deterministic approach, information about potential deviations (variability due to potential higher or lower values) for quantities and prices is not usually taken into consideration although this information is available or could easily be estimated.

However, if the information about potential cost bandwidth is accounted for by including uncertainties (probability distributions), the owner will have better information about how likely it will be that costs (and budgets) will or will not be exceeded. Therefore, the owner can better define a budget that allows for variability in base costs (quantities and prices) and for the probable cost of risk events related to his risk tolerance.

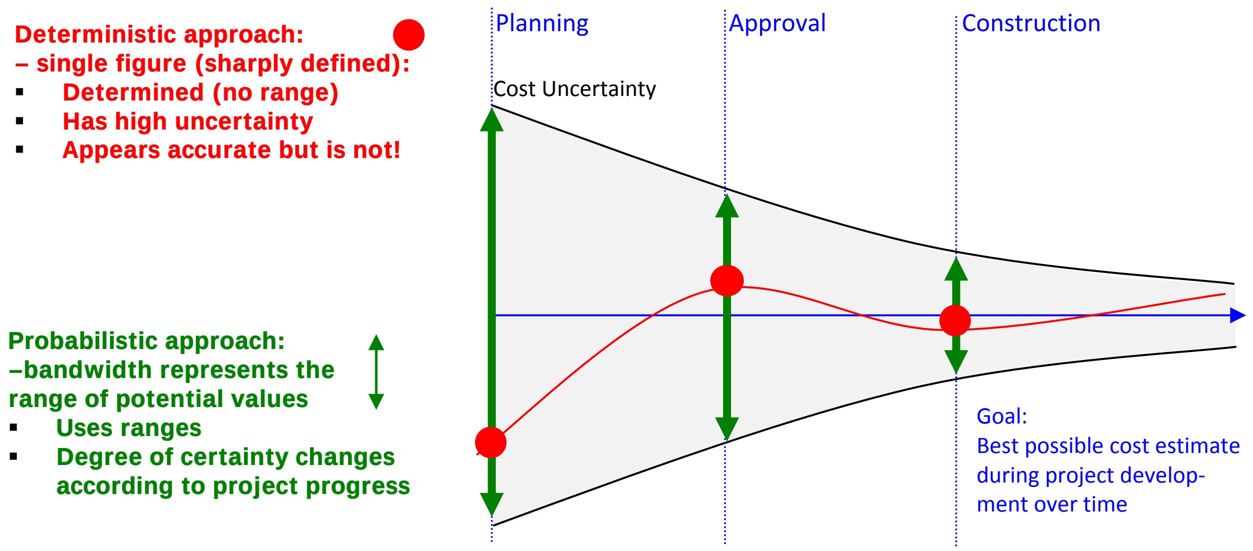


Fig. 2 *Information re deterministic versus probabilistic method in project development*

At first sight, probability functions might seem more uncertain compared with what might seem to be a "totally defined deterministic value" – however, exactly the opposite is true (Rohr 2003) because the accuracy of a forecast is greater when the uncertainty component is included. The uncertainty is part of the answer and so not including it means that part of the answer is missing, therefore that answer is less accurate.

Consideration of the probability and impact of future events, as explicitly required by the probabilistic method, is required because (Reilly 2004):

- Any value in the future includes significant uncertainty and variability.
- The future value will depend on the influence of, and relationship between, many factors.
- Many of these factors are, in the beginning, unknown or known only approximately.
- We cannot predict outcomes exactly but we can estimate probability and impact.
- Aggregated probability and impact can produce a reasonable estimate of potential outcomes.

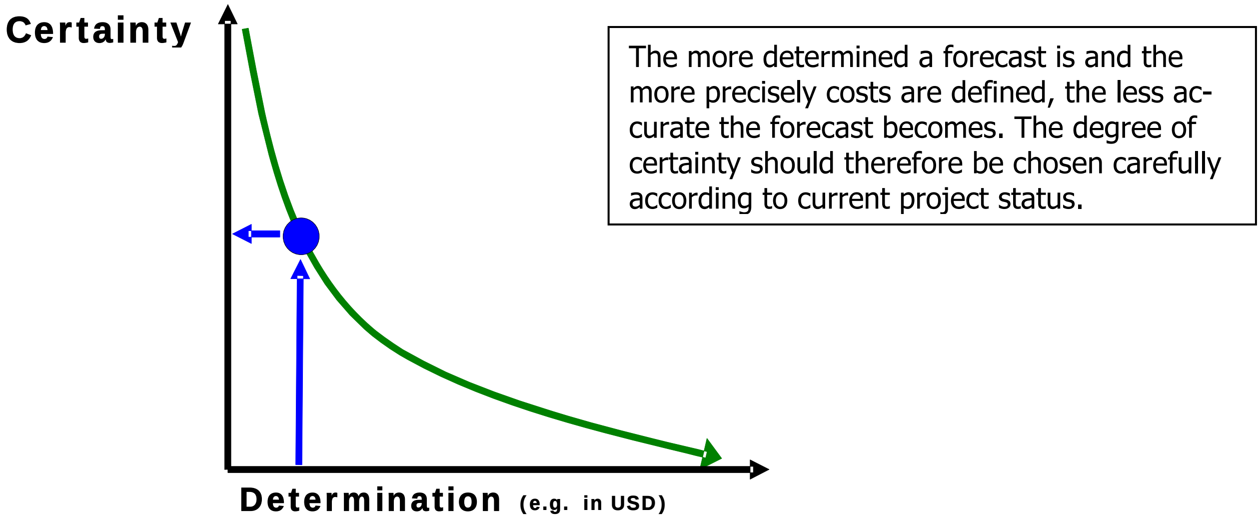


Fig. 3 *Certainty versus Determination (Sander 2012)*

Professional risk assessment requires the inclusion of uncertain information because most project risks can have various impacts. Additionally, experience shows that for most professionals the estimation of a probable range (bandwidth) is more reliable than trying to define a single sharp number.

Bier summarizes the opportunities for probabilistic risk assessment as follows (Bier 1997):

- Probabilistic risk analysis allows reasonable modeling of deviations from normal (expected) values for complex projects and systems.
- Probabilistic risk analysis can characterize any element of system performance, including the performance of subsystems and their interactions.
- As a consequence, specific impacts from different interacting systems can be identified and differentiated.
- Probabilistic risk analysis delivers a quantitative risk characterization, which can lead to better decision-making and risk response/mitigation.
- Probabilistic risk analysis takes uncertainties into consideration. This is especially valuable if statistical data about potential impacts are sparsely available and large uncertainties dominate.

5. Fallacy of the Deterministic Approach

The following example is from a construction project depicted as an event tree scenario. In a first step, the probability of occurrence will be assessed (Sander 2011).

The scenario is as follows:

With the upgrade of a reservoir for a hydropower plant, a new access road to the reservoir is planned and costs are estimated. Construction costs for the new access road are estimated at 1,000,000 USD. Due to the expected approval process, a risk of 40% has been identified that the new access road might not be permitted.

In this case (materialization of the risk) there are two alternatives:

1. Upgrade the existing partly public road to the reservoir. The probability for this case is estimated as low as **20%**.

2. If use of the public road is not permitted, a cableway for material transport for the duration of the project must be erected, commissioned, and operated. This is certainly the most costly alternative (with an estimated probability of **80**%).

This scenario may be developed graphically as an event tree as follows.

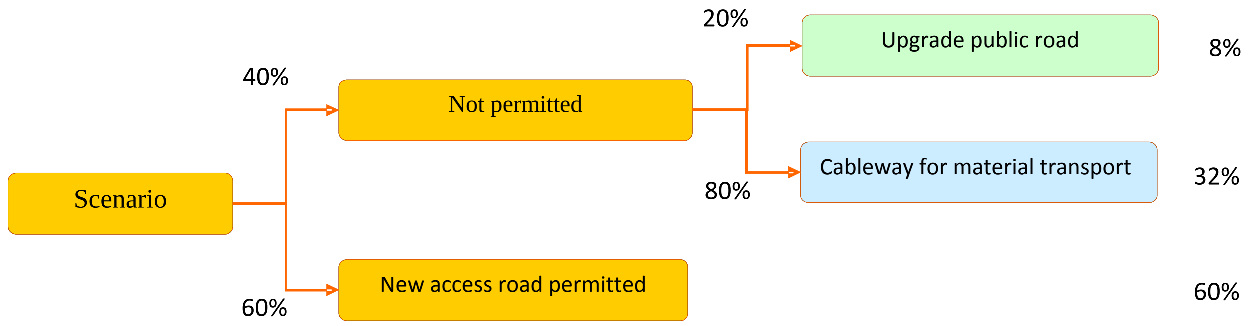


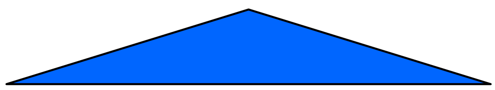
Fig. 4 *Event Tree*

In 60% of all cases, the risk will not occur, and there will be no deviations from the original cost estimation (1,000,000 USD). In this case, the cost item "New Access Road" will have to be taken into consideration.

Through multiplication of the specific probabilities of the branches of the event tree, a resulting probability of occurrence can be calculated for any of the three scenarios, which will then be used for the probabilistic estimation of the risk costs of each scenario.

In a second step, the costs for the new scenarios ("Upgrade Public Road" or "Cableway") are assessed. If the new access road is not approved, one of these scenarios will occur (40%) and there will be no costs for the new access road. Therefore, there will be negative costs of 1,000,000 USD for both scenarios (without Life Cycle Cost evaluations).

Bandwidths (Minimum – Most likely – Maximum) can normally be modelled with a triangle function with sufficient accuracy.



Minimum (Min.) Most likely (Ml.) Maximum (Max.)

Fig. 5 *Conceptual Triangle Function*

Therefore, all risk scenarios are assessed as follows:

1) Public Road scenario, probability of occurrence = 8%:

Table 2 *Values for Public Road scenario*

Cost Item	**Unit**	**Function**	**Min. [USD]**	**Ml. [USD]**	**Max. [USD]**
Omitted access road	LS	Deterministic	-1,000,000	-1,000,000	-1,000,000
Upgraded existing road	LS	Triangle	467,500	550,000	880,000

2) Cableway scenario, probability of occurrence = 32%:

Table 3 *Values for Cableway scenario*

Cost Item	**Unit**	**Function**	**Min. [USD]**	**Ml. [USD]**	**Max. [USD]**
No new access road	LS	Deterministic	-1,000,000	-1,000,000	-1,000,000
Erection, commissioning, & operation of cableway	LS	Triangle	1,912,500	2,250,000	2,925,000

For these exemplary scenarios, all inputs have been heavily simplified. In reality, of course, a more detailed analysis is required.

The simulation shows the following result as a probability distribution:

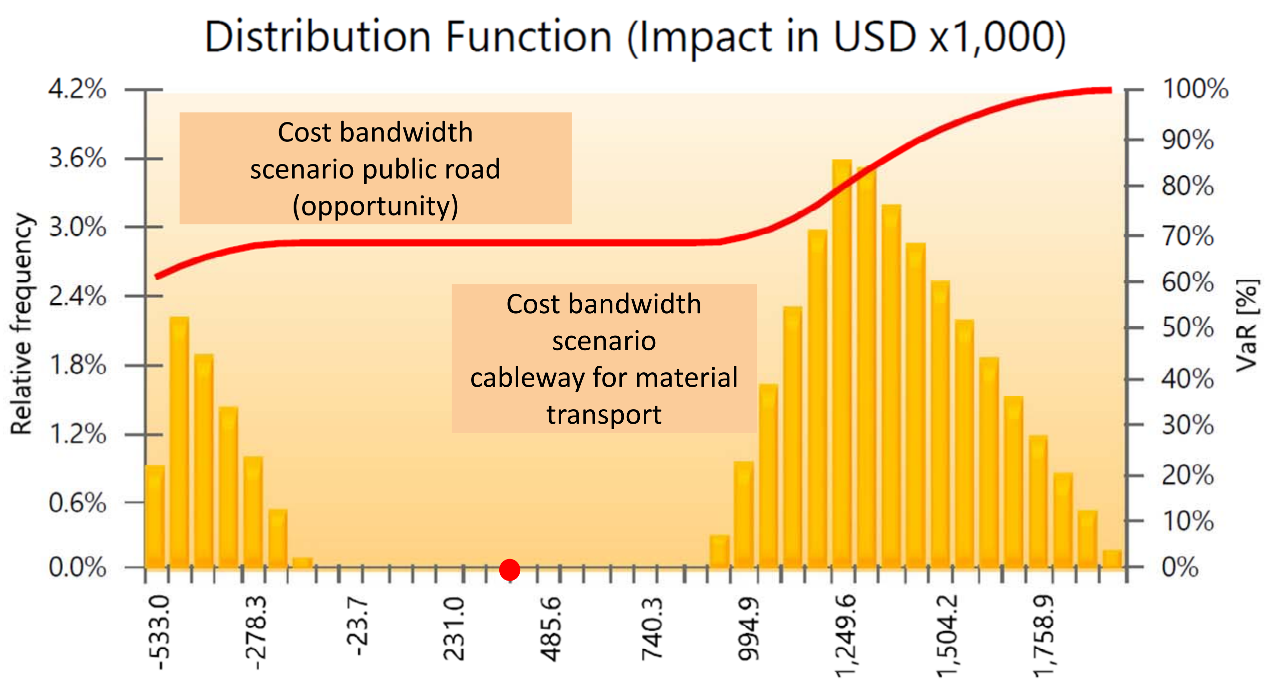


Fig. 6 *Probability distribution resulting from simulation*

The integral of the probability distribution (Value at Risk, VaR, red line) starts at a probability of 60%. Below 60% probability, the risk will not materialize, and therefore, the base cost estimation was correct.

The complete probability distribution features two distributions: the "Upgrade Public Road" scenario on the left hand side and the "Cableway" scenario on the right hand side. The ratio of the depicted areas indicates the probability of occurrence of both scenarios, about 8% versus 32% or a factor of 1 to 4.

The horizontal axis depicts the potential bandwidth (range) for both scenarios. The bandwidth of the "Use Public Road" scenario shows only negative costs because the 1,000,000 USD that will be saved by not constructing a new access road will not be fully compensated by the costs for the upgrade of the existing road.

The bandwidth "Use Public Road" stretches between negative costs of about −100,000 USD to about −530,000 USD. The most likely figure is represented by the value with the biggest frequency within the bandwidth, about −400,000 USD.

The bandwidth for the "Cableway" scenario covers a range from about 900,000 USD to about 2,000,000 USD. However, there are additional costs compared with the basic cost estimation. The erection, commissioning, and operation of the cableway will cost substantially more than can be economized by not constructing the access road. The most likely value for this scenario is about 1,300,000 USD of additional costs.

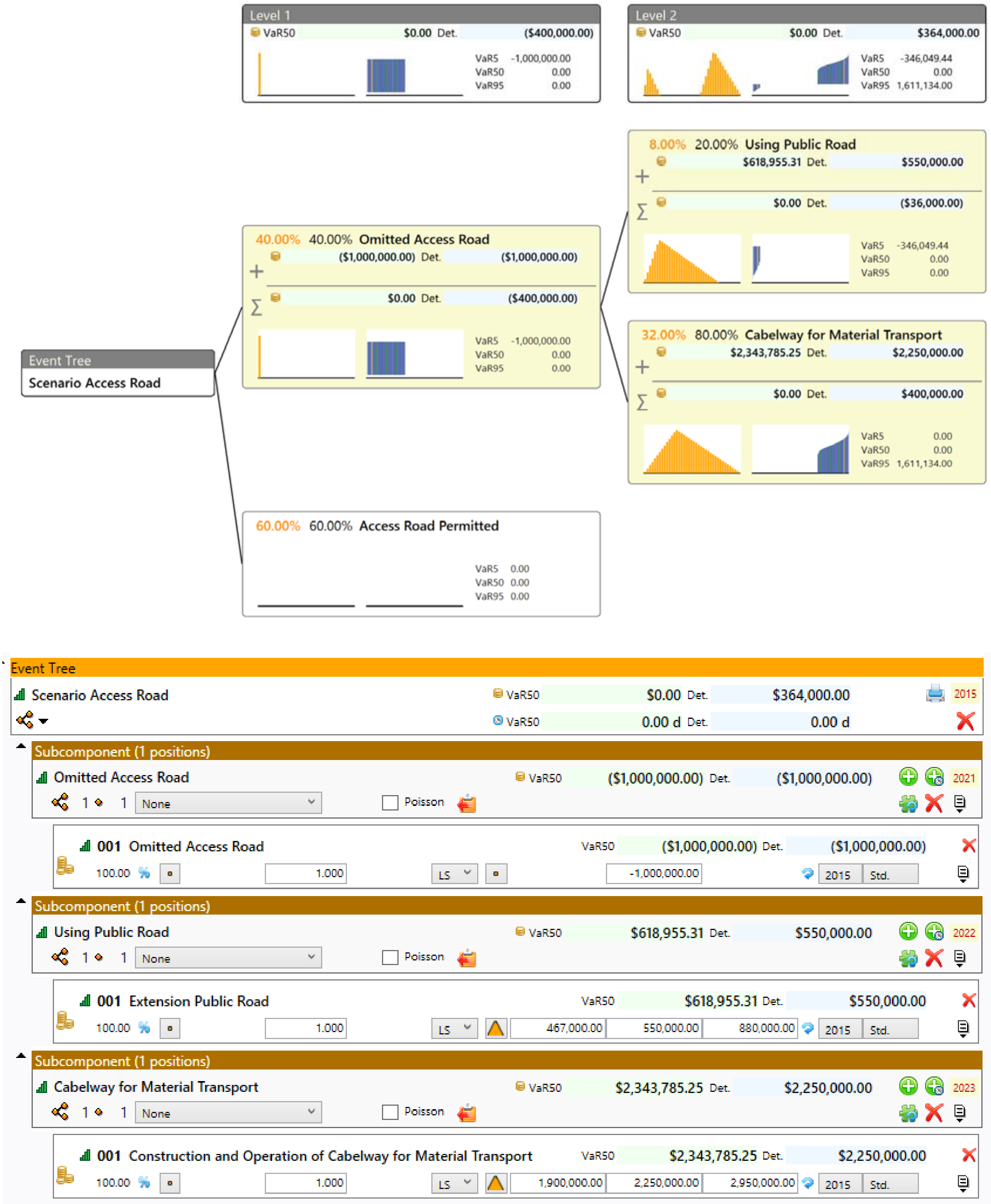


***Fig. 7** Scenarios from the discussed example, as visualized in RIAAT software (RIAAT 2014)*

This example emphasizes how even complex scenarios can easily be solved and visualized by using a probabilistic approach, while a deterministic method in this case completely fails.

For the above example, a deterministic estimation would provide the following result:

  8% x (−1,000,000 USD + 550,000 USD)
\+ 32% x (−1,000,000 USD + 2,250,000 USD)
\+ 60% x 0 USD
= −36,000 USD + 400,000 USD + 0 USD
= 364,000 USD

This deterministic result falls into a range of values that is impossible based on a factual analysis. The potential real costs are either well below or above, as the result of the probabilistic analysis demonstrates (Fig. 6). The low degree of information provided by the "limited" deterministic estimation leads to a completely false result although the mathematical process itself is correct. This might entail wrong decision-making as a consequence.

6. Example of a Probability Distribution

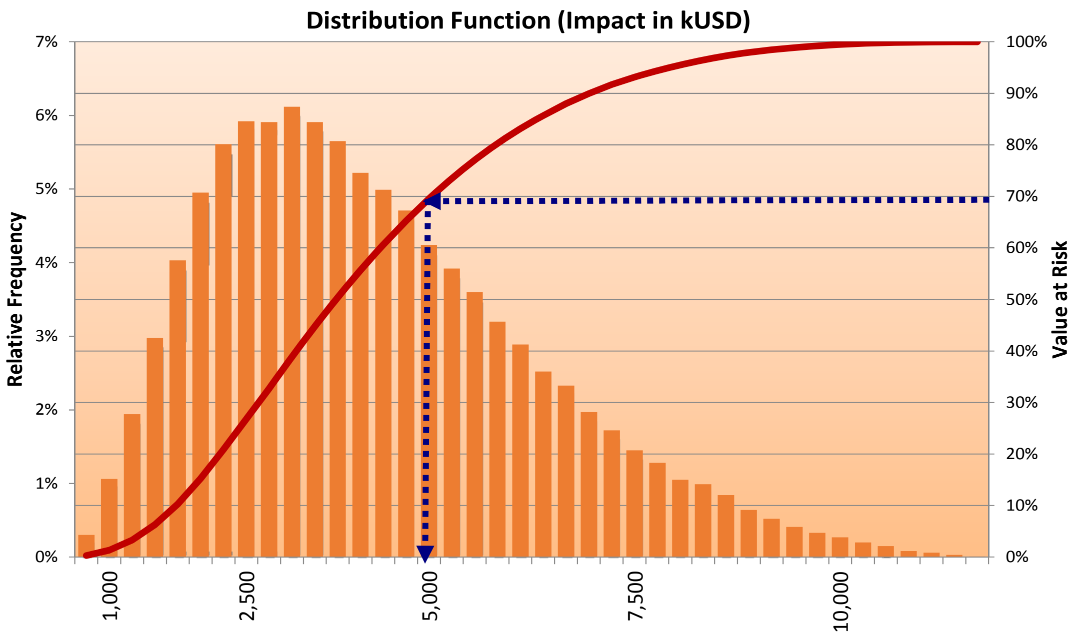


Fig. 8 *Probability distribution showing probable project risk cost with Value at Risk (VaR) information*

In the example above, VaR 70 (Value at Risk 70%) means that a 5M USD cost would not be exceeded in 70% of all simulated scenarios. However, even with such coverage, there remains a 30% probability that the 5M USD cost will be exceeded (Sander 2012).

7. Conclusions

Every cost estimate for future events comes with significant uncertainties. The deterministic method focuses on a limited range of scenarios and considers uncertainty only in gross terms (contingency, allowances). The probabilistic method can deliver much more comprehensive information (e.g., a range of probable cost, Value at Risk information, specifics of potential risk events) to allow establishment of an appropriate budget, considering the owner's and contractor's tolerance for risk and uncertainty. In particular, probabilistic methods help owners and contractors by defining and characterizing key risks earlier in the project development and thus allowing for early risk management and response actions.

The earlier consideration of risk additionally allows for a better bidding environment, allowing contractors to price their work knowing those risks and to budget accordingly as well as evaluating their competitive position relative to potential outcomes and their specific construction management strategies.

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