Bei diesem Beitrag handelt es sich um einen wissenschaftlich begutachteten und freigegebenen Fachaufsatz („reviewed paper“).

Modelling of input data uncertainty for the financial evaluation of complex infrastructure projects

M. Beisler, H. Klapperich, D. Jacob, H. Schweiger

Abstract The planning of complex infrastructure projects represents an interdisciplinary process, which is characterised and heavily influenced by uncertain information and imprecise input parameters. During early planning stages the majority of technical as well as economic parameters, which are of crucial importance for the detailed design and project implementation, cannot be determined with precision. It is therefore common practice that these figures are selected as deterministic values, which require extensive optimisation throughout subsequent planning stages. A major disadvantage inherent to commonly used deterministic analysis is the lack of objectivity for the selection of input parameters. Moreover, it cannot be ensured that the entire existing parameter range and all possible parameter combinations are covered.
Probabilistic methods utilise discrete probability distributions or parameter input ranges to cover the entire range of uncertainties resulting from an information deficit during the planning phase and integrate them into the optimisation process by means of alternative calculation methods.
In the field of geotechnical engineering this approach has been employed successfully to objectively account for uncertainties related to geological conditions and material properties in the context of design analysis.
The article examines to what extent the random set theory (RST) is suitable as a reliable, scientific methodology that can be utilised for handling of vague information and imprecise input parameters in the context of economic project appraisal. The primary applications of RST in this context are the identification, analysis and management of project risks. The method can also be utilised to stipulate and evaluate the decision criteria, which are used to support the process of investment decision making. Furthermore the RST can represent a suitable instrument for the re- evaluation of a project's feasibility under changed technical and economic boundary conditions. This is of particular interest for energy projects such as hydropower generation, under consideration of the steadily increasing energy prices and a significantly growing demand for renewable energy (compare Pöttler [13]).

Dr.-Ing. Matthias Beisler
ILF Consulting Engineers
ILF Beratende Ingenieure ZT Gesellschaft mbH
Feldkreuzstraße 3, A-6063 Rum / Innsbruck
+43 / 512 / 24 12–5562
matthias.beisler@ilf.com

Prof. Dr.-Ing. Herbert Klapperich
TU Bergakademie Freiberg
Institut für Geotechnik
Lehrstuhl Bodenmechanik,
bergbauliche Geotechnik und Grundbau
Gustav-Zeuner-Straße 1, 09596 Freiberg
Phone: +49 3731 39–3614
herbert.klapperich@ifgt.tu-freiberg.de

Univ.-Prof. Dr.-Ing. Dipl.-Kfm. Dieter Jacob
TU Bergakademie Freiberg
Lehrstuhl für ABWL, insb. Baubetriebslehre
Fakultät für Wirtschaftswissenschaften
Lessingstraße 45, 09596 Freiberg
Tel.: +49 (0) 37 31/39–4081
jacob@bwl.tu-freiberg.de

Prof. Dipl.-Ing. Dr.techn. Helmut Schweiger
Technische Universität Graz
Institut für Bodenmechanik und Grundbau
Rechbauerstrasse 12, A-8010 Graz
Tel.: +43 (316) 873 – 6234
helmut.schweiger@tugraz.at

1

Modellierung unscharfer Eingangsgrößen zur Wirtschaftlichkeitsuntersuchung komplexer Infrastrukturprojekte

Zusammenfassung Der Planungsablauf komplexer Infrastrukturprojekte stellt einen interdisziplinären Prozess dar, welcher durch unsichere Information sowie unscharfe Eingangsgrößen geprägt und von diesen wesentlich beeinflusst wird. In frühen Planungsstadien kann ein Großteil der für die Detailplanung und Projektimplementierung entscheidenden, technischen und wirtschaftlichen Parameter meist nicht exakt bestimmt werden. Es ist daher üblich, dass maßgebende technische sowie ökonomische Entwurfsparameter des Vorhabens deterministisch bestimmt werden und im Zuge der fortschreitenden Planungsstadien einen umfangreichen Optimierungsprozess durchlaufen. Ein Nachteil gebräuchlicher, deterministischer Berechnungsansätze besteht in der zumeist unzureichenden Objektivität bei der Bestimmung der Eingangsparameter, sowie der Tatsache, dass die Erfassung der Parameter in ihrer gesamten Streubreite und sämtlichen, maßgeblichen Parameterkombinationen nicht sichergestellt werden kann.
Probabilistische Verfahren verwenden Eingangsparameter in ihrer statistischen Verteilung bzw. in Form von Bandbreiten, mit dem Ziel, Unsicherheiten, die sich aus dem in der Planungsphase unausweichlichen Informationsdefizit ergeben, durch Anwendung einer alternativen Berechnungsmethode mathematisch zu erfassen und in die Berechnung einzubeziehen.
Im Fachgebiet der Geotechnik wird diese Vorgehensweise bereits erfolgreich eingesetzt, um Baugrundverhältnisse und Materialeigenschaften objektiv in ihrer gesamten Streubreite zu erfassen und somit Systemversagenswahrscheinlichkeiten zu definieren.
Der Beitrag untersucht, in wie fern die Random Set Theorie eine zuverlässige, wissenschaftliche Methode darstellt, um ungenaue Information und unscharfe Eingangsgrößen bei der ökonomischen Beurteilung von Infrastrukturprojekten zu berücksichtigen. Die Hauptanwendungsgebiete der Random Set Theorie stellen in diesem Zusammenhang die Risikoanalyse und das Risikomanagement dar. Weiterhin findet die RST ein geeignetes Einsatzgebiet bei der Festlegung und Bewertung von Entscheidungskriterien zur Rechtfertigung der Investitionsentscheidung und ist gleichfalls bei der Neubewertung von Projekten unter geänderten technischen und

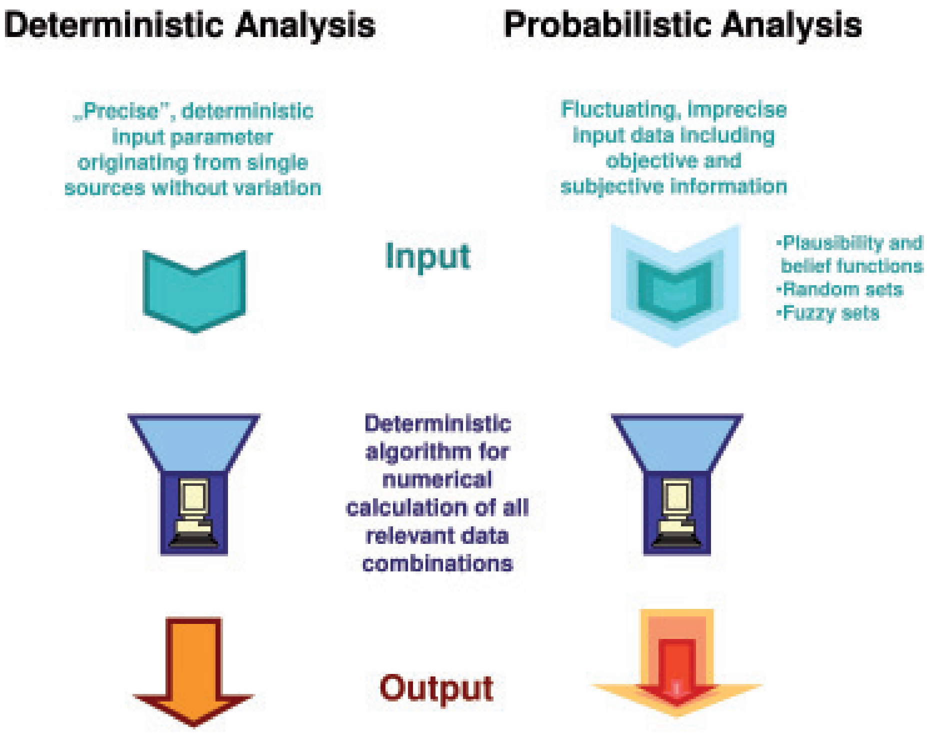

Fig. 1. **Deterministic versus probabilistic approach for analysis**
Bild 1. Gegenüberstellung deterministischer und probabilistischer Berechnungsansätze

ökonomischen Rahmenbedingungen einsetzbar. In Anbetracht stetig steigender Strompreise und einer stark zunehmenden Nachfrage nach erneuerbaren Energien gilt dies insbesondere für Energieerzeugungsprojekte wie Wasserkraftanlagen (vergleiche Pöttler [13]).

1 Uncertainty modelling in civil engineering

Most traditional engineering models are deterministic and can be described as input-output systems. If the input data consist of a single, deterministic data set, the model produces a uniquely determined output. Irrespective of the vagueness of the input data and the uncertainties related to such a model, the analysis will yield a crisp and seemingly exact result. Probabilistic methods have been introduced to account for fluctuations in a rational manner and open new opportunities by reflecting the lack of information and uncertainties related to the input parameters, which should in response impact the results of engineering computations. If the input data fluctuate, the output varies accordingly and may be described by valued intervals. This opens room for further assessment and responsible interpretation of results.
In view of the apparent deficiencies inherent to a deterministic approach Fetz et al. suggest "...the engineer should face the limitations of the modelling process, put the range of imprecision into the open and make it accessible to responsible assessment by all participants in the construction process. This will involve processing not only data but also the available objective and subjective information on their uncertainty" [5].
The general principles characterising a probabilistic approach in the context of engineering calculations are schematically illustrated in **Fig. 1** comparing deterministic and probabilistic concepts of analysis.

2 Random Set Theory

RST is closely related to the Dempster-Shafer Theory (DST), which represents a mathematical theory of evidence and can be interpreted as a generalisation of probability theory where probabilities are assigned to sets as opposed to singletons [2, 16]. In traditional probability theory, evidence is associated with only one possible event whereas in DST, evidence can be associated with multiple possible events, e.g. sets of events.
Dempster-Shafer structures are similar to discrete probability distributions except for the difference that probability masses are assigned to sets instead of discrete values. Consequently their probability mass function is not a mapping $R \rightarrow [0,1]$, but $2^R \rightarrow [0,1]$ [8].
Within the framework of classical discrete probability theories, a mass $m(a)$ is defined for each possible value of X and $p(X=a)=m(a)$. A random set consists of a finite number of subsets A_i, $i=1,\dots,n$ of a given set X, which are called focal sets. Each focal set possesses a probability weight $m_i = m(A_i)$, $\Sigma m(A_i)=1$ [3, 4]. The correspondence of probability masses associated with the focal elements is called a basic probability assignment.
In contrast to a discrete probability distribution, where the mass is concentrated at distinct points, the focal elements of a random set may overlap each other.
Founded on the basic probability assignment it is possible to define the upper and lower bounds of an interval that contains the precise probability of a set of interest, which is enclosed by two non-additive continuous measures called Belief and Plausibility (compare **Fig. 2**). The imprecise nature of the formulation prevents the calculation of the 'precise' probability Pro of a generic $x \in X$ or of a generic subset $E \subset X$. Consequently it is only possible to determine lower and upper bounds of this probability in the following format (Tonon et al. [19, 20]):

$$Bel(E) \leq Pro\ (E) \leq Pl\ (E) \qquad (1)$$

If the support of the random set $\Im$ is composed of single values only (singletons), then Bel (E) = Pro (E) = Pl (E) and m is a probability distribution function.

3 Geotechnical applications

Random Set Theory has been used successfully by Tonon et al. [18, 19 and 20] to account for uncertainties in rock engineering and tunnel lining design where statistics of imprecise data arise in rock mass characterisation. The uncertainties related to the imprecise parameters are used in a RST based calculation to determine upper and lower bounds of the stability of a tunnel lining. Within this field the RST can provide an appropriate mathematical model of uncertainty when the information about mechanical properties of a rock mass is not complete or when the result of each observation is not point valued but set valued, which makes it impossible to assume the existence of a unique probability measure. Based on the investigations by Tonon et al. studies within the field of geotechnical engineering by Pöttler, Schweiger and Peschl [10, 11, 15] have extended RST to be combined with the finite element method, called Random-Set-Finite-Element-Method (RS-FEM). The investigations conclude that the RS-FEM provides a convenient tool to account for the scatter in material and model parameters and has the potential to increase the value of numerical analysis significantly. The typical sequence of calculations involving the RSM consists of the following steps and is depicted in **Fig. 3.**

- Determination of parameters that are considered as basic variables
- Construction of random sets
- Sensitivity analysis to reduce computational effort (if necessary)
- Generation of calculation matrix (random set model)
- Execution of all calculations
- Result as interval bounds of cumulative distributions

For cost estimation and cost management purposes the RST has already been used in the context of brownfield development, land recycling and cleanup of contaminated sites [7]. A similar approach may be employed to assess the financial feasibility of a complex infrastructure project.

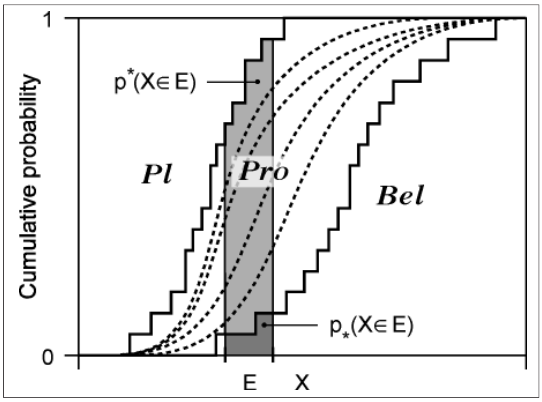

Fig. 2. Upper bound (Pl) and lower bound (Bel) on 'precise' probability (Pro)
Bild 2. Obere (Plausibilitätsfunktion Pl) und untere (Belieffunktion Bel) Einhüllende der ‚exakten' Wahrscheinlichkeit (Pro)

4 Economic project appraisal

4.1 Benefit and cost streams – Financial Analysis

A financial project analysis is carried out to assess whether future benefits of the intended project are worth the investment required. Furthermore, if a certain choice of investment or financing decision is more beneficial than other existing alternatives, the advantages must be quantified by a certain standard. All capital investments possess a time value and attract interest. When money is used for a capital investment it is diverted from other productive uses. The cost of capital is consequently an opportunity cost and a capital investment can only be justified if its return on money is at least as high as the return generated through alternative opportunities of comparable risk. In order to ensure that adequate recognition is given to the time value of money, economic and financial evaluations are usually based on the discounted cash flow technique.

4.2 Discounted cash flow method

In order to compare different projects or project options the return to investors from cash flows occurring at different times is evaluated by reducing them to a common basis through discounted cash flow calculations. The merit of a potential project in financial terms is con-

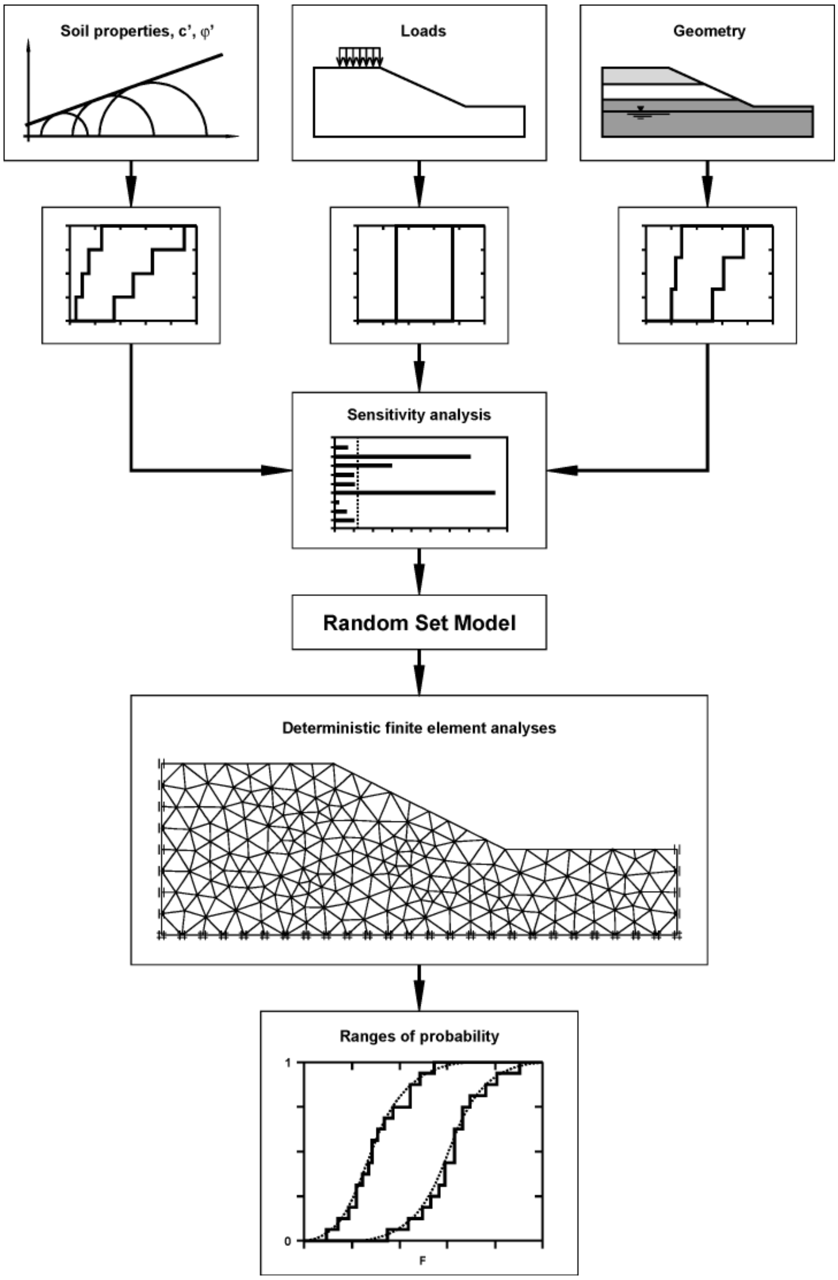

Fig. 3. Concept of RS-FEM calculation in geotechnical engineering [10]
Bild 3. Konzept des RS-FEM (Random-Set-Finite-Elemente-Methode) Berechnungsverfahrens im Fachgebiet Geotechnik [10]

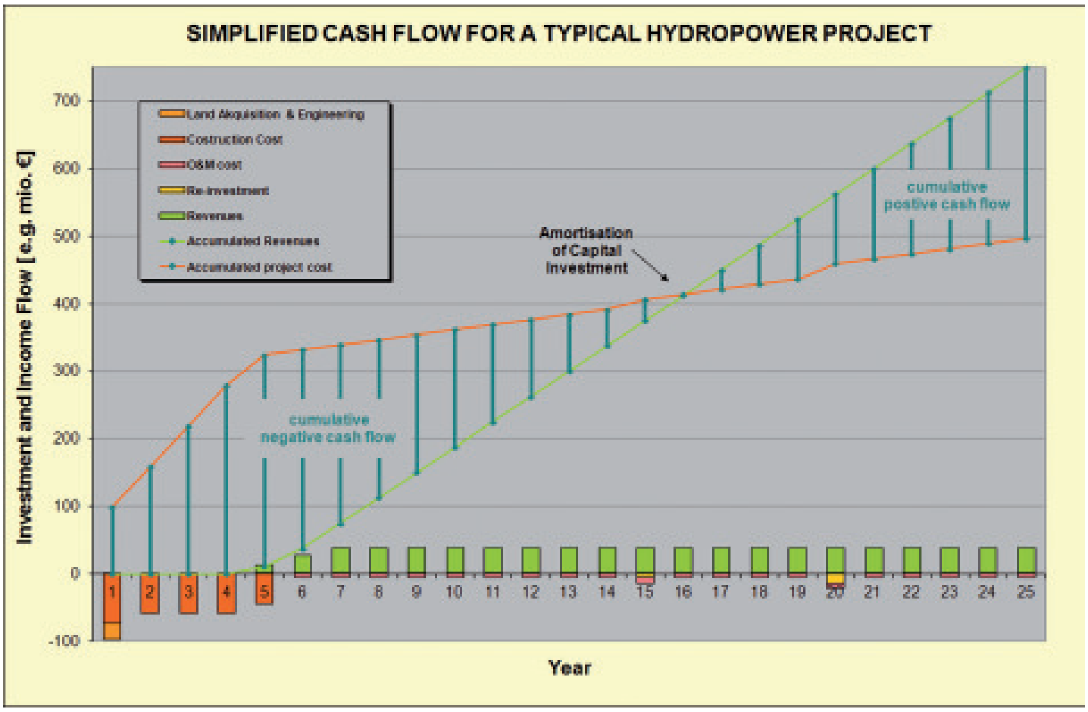

Fig. 4. **Typical cash flow distribution for a hydro electric power project**
Bild 4. Typische Cash Flow Verteilung eines Wasserkraftprojektes

firmed by identifying the revenue requirements necessary to cope with the additional outlay for the project. The cash flow presents the incidence of costs and benefits over the period of analysis of a given project. Inputs to the cash flow are positive for benefits (or revenues) or negative for costs. The discounted cash flow (DCF) model converts the cash flow for a project to a single present value by discounting it from year to year. Discounted cash flow methods are widely used for economic project appraisal due to their simplicity as well as easy computerisation by means of financial calculators and spread-sheet software.
The advantages presented by the RST in the context of financial analysis are illustrated using the example of a planned hydropower project. The typical cash flow related to a hydropower development showing corresponding costs and benefits is depicted in **Fig. 4.** In comparison to other forms of energy generation, the cash flow of a typical hydropower development can be differentiated through the following characteristics:

- Hydropower schemes are capital intensive and require a high initial investment but usually possess a longer economic life compared to thermal power plants.
- Planning activities for a hydropower development require an extensive pre-investment phase to study the feasibility of the project through basic investigations.
- Long construction periods without revenues are leading to negative cash flows.
- Operation, maintenance and management costs are negligible compared to the overall capital investment.
- In contrast to thermal power generation, the hydropower development is characterised by the absence of fuel costs.

5 Indices of merit for a selected scheme

5.1 Primary investment criteria

Methodologies that employ financial feasibility indicators such as net present value (NPV) and internal rate of return (IRR) calculations for project analysis reflect the return on a cash investment by measuring the value of a future cash flow adjusted for the time value of money. The NPV methodology has developed into a widely established tool for supporting investment decisions, which is considered theoretically reliable and suggested by many corporate finance textbooks (compare [6, 14, 17, 21]).
Recognised as a robust measure of investment desirability and thus regarded as a key guideline for capital investment decisions the NPV can be expressed by means of the following formula:

$$NPV = \sum_{t=1}^{n} \frac{CF_t}{(1+k)^t} - I_0 \qquad (1)$$

n:	project life
t:	period (year)
k:	rate of return that can be earned from alternative investments
I_0:	initial outlay
CF_t:	cash flow at the end of period n
$CF_n/(1+k)^n$:	present value of amount CF_n

The following investment decision criteria are applicable with regard to the NPV:

- A positive NPV (NPV>0) indicates a desirable capital investment. Since the total of discounted benefits exceeds the sum of the discounted costs the project is profitable and adds monetary value to the firm, thus increasing the wealth of the owners.
- A NPV of zero (NPV=0) denotes that the project repays the original investment plus the required rate of return (reflecting opportunity cost). The investor should be indifferent in the decision whether to accept or reject the project since this investment neither gains nor loses monetary value.

– If the NPV is below zero (NPV<0) the investment should be rejected since it does not yield any benefits.
– If several acceptable investment alternatives of similar risk are to be compared, the option yielding the highest NPV should be selected.

Another commonly used feasibility indicator is the IRR, which measures the return on the investment over its life. It is the discount rate at which the NPV of the cash flow is zero and therefore may not be suitable for projects where the cash flow varies between negative and positive values. The IRR is calculated by means of an iterative process and can be used to determine the attractiveness, in particular the profitability, of an investment opportunity.
NPV and IRR will generally yield the same accept/reject investment decision as long as the project shows conventional cash flows (cash flow signs do not change more than once) and the indices are not employed to compare mutually exclusive projects where the scale of initial investments or the timing of cash flows are substantially different. The two parameters can provide conflicting signals if they are calculated for the assessment of mutually exclusive investments. Net present value and internal rate of return may also indicate different rankings of projects due to differences in magnitude and timing of cash flow.
While the NPV calculation is based on the assumption that project cash flows are reinvested at the cost of capital, the standard IRR calculation assumes that cash taken out of the project is reinvested at the internal rate of return until the end of the calculation period.

5.2 Secondary investment criteria

Since NPV and IRR may not suffice for attaining a fully conclusive investment decision the use of secondary investment criteria is recommended in order to provide supplementary information to complement the primary decision criteria. Such additional indicators can be benefit cost ratio (BCR), payback period, return on investment, profitability index etc.

6 Input parameter sets for random set based financial project analysis

The size and complexity of large hydropower projects make it inevitable, that numerous different sources of information have to be used for obtaining the input parameters that are required for the technical and financial project analysis. Especially during early planning stages the available input data does not always represent accurate information that can be acquired from confirmed and reliable sources. This may lead to input data that can be described as incomplete, imprecise, inappropriate and sometimes even contradicting. Conflicting interests between the parties involved in the planning of the project and different interpretation of the same observations may further increase the difficulties inherent to the planning process. If reliable first hand information from in-situ field investigations cannot be made available, design parameters are usually acquired using technical literature or textbooks. It may also be necessary to incorporate expert opinions and information based on experience that has been gained from previously completed comparable projects. With regard to possible future project revenues the data entering into the financial model usually has to be obtained from market studies. However, the prediction of energy demand growth and the projection of tariff scenarios in competitive electricity markets are extremely difficult tasks, since these parameters are characterised by a high volatility. The utilisation of deterministic input parameters considers neither the possible parameter variations nor does it capture all decisive parameter combinations. Therefore it seems to be more appropriate to capture the imprecision and possible fluctuation inherent to these parameters by means of imprecise probabilities rather than using deterministic values.

6.1 Construction Costs – Capital Expenses

The purpose of the cost estimation is the comprehensive, realistic and transparent identification of all project costs after project completion. It is therefore evident that the estimation of project costs at planning stage must be based on certain assumptions with regard to construction methods and price development during project implementation.
During initial planning stages construction costs can only be roughly estimated, since exact quantities and factual unit prices are not available. At this stage the cost estimate is usually based on cost curves or specific costs (e.g., € per m^3 of reinforced concrete, € per m^3 of excavated material or for power generation plants € per KW installed capacity), which does not provide a high level of precision. The accuracy level for the cost estimation is considerably improved at prefeasibility and feasibility level, after possible construction methods have been assessed in further detail and cost estimates are based on calculated quantities and unit prices. Realistic prices may be obtained from comparable projects that have been completed under similar conditions in the same or, as far as cost levels are concerned, in a comparable region.
To account for the inevitable imprecision that characterises the cost estimating process, the estimated total project costs must be composed of the two components basic costs and risk costs [9, 12]. Basic costs are defined as costs than can be calculated based on the current planning status by means of the above mentioned deterministic methods. Risk costs reflect an appropriate financial allowance for covering project related risks, constraints and framework conditions, which are not known and considered by the time of elaborating the cost estimate. Under normal conditions, each step of the planning process is characterised by an additional gain of information resulting in a higher level of accuracy for the corresponding calculations. The amount of uncertainty and risk caused by uncertain or imprecise input parameters is consequently gradually reduced during each consecutive step of the planning process resulting in increased basic costs and reduced risk costs while the overall costs should remain constant as depicted in **Fig. 5.**
A high level of accuracy for cost estimates can usually be achieved after completion of the final design phase, once exact quantities and construction methods have been finalised. However, project costs may still not be determined with absolute precision before the implementation of the project has been completed. Uncertainties such as the occurrence of delays and cost overruns leading to claims as well as other unforeseen incidents must still be anticipated during the implementation of a complex infrastructure project. If the project developer or project owner seeks protection against such project risks, this intention can be supported by establishing appropriate legal measures (EPC contract, insurance etc.) to guarantee effective risk mitigation and risk management.

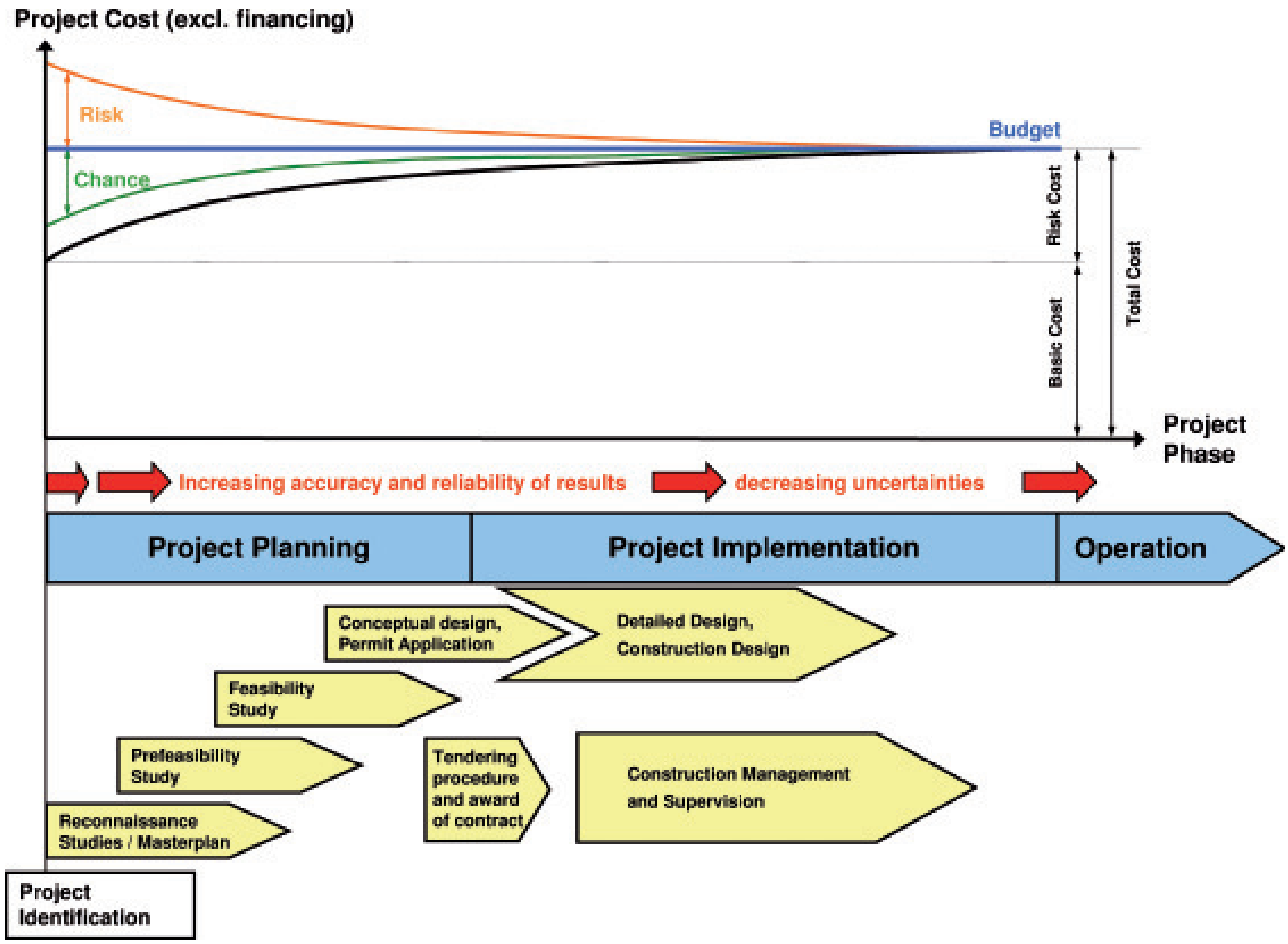

Fig. 5. Increasing accuracy of cost estimation during the project development cycle
Bild 5. Zunehmende Genauigkeit der Kostenschätzung im Zuge des Projektentwicklungszyklus

6.2 Construction of random sets

Random sets can be utilised to formalise the state of knowledge about parameter uncertainty and allow the incorporation of independent sources of information into the financial model. These different information sources may be required to represent different designs and construction methods, alternative concepts for the project developed by different planners involved or disparate standards, which are used for cost calculation (e.g. local cost estimates versus internationally recognised cost estimating methods and selection criteria). The example depicted in **Fig. 6** shows two independent information sources for the estimated capital expenses (amounts are given in Russian roubles RUR since the hydropowerprject is located in Siberia/Russia). Parameters are defined as ranges as estimated by appraisers, experts etc. The probability mass assignments of the focal sets may be identical if both sources are rated with the same credibility. Alternatively a higher probability weight $m(A_i)$ may be assigned to one of the focal sets to reflect a higher level of confidence regarding the information source. The selected interval ranges objectively reflect the amount of uncertainty and imprecision inherent to the respective information source.

One main advantage of the RST is the possibility to further refine the simulation model in order to reflect the progress achieved at different planning stages when more detailed information has been elaborated or can be made available. The increased level of precision achieved at each consecutive planning stage is modelled by reducing the interval range of the input parameters accordingly. With respect to the parameter capital expenditures (CAPEX) this procedure reflects the additional gain of precision

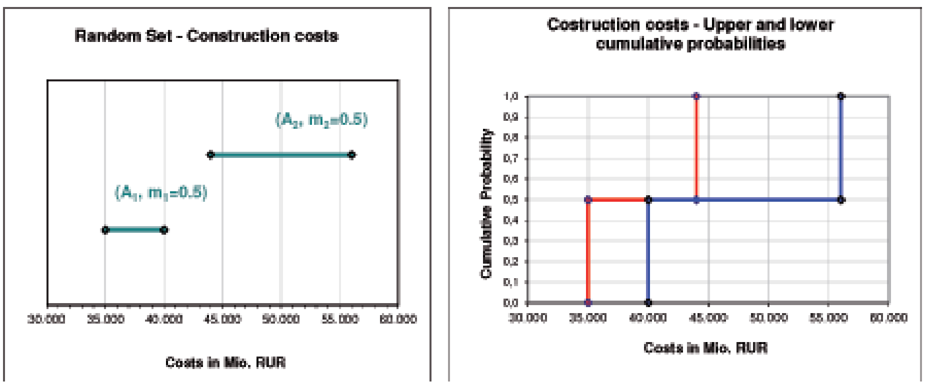

Fig. 6. Random set representing estimated construction cost (in million Russian rubles)
Bild 6. Random Set zur Erfassung der geschätzten Baukosten (in Mio. Russischen Rubel)

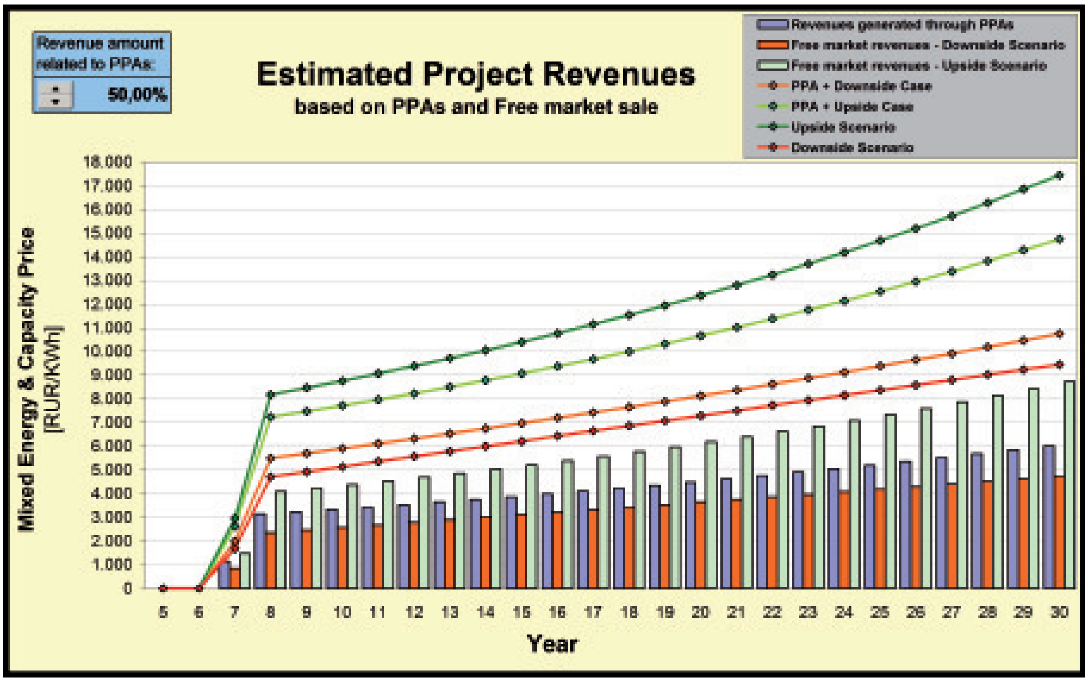

Fig. 7. **Possible range of project revenues**
Bild 7. Mögliche Bandbreite der Projekterträge

for the cost estimation or the decreasing amount of uncertainty inherent to the calculations respectively. The same principle can also be applied for other input parameters of the financial model.

Fig. 8 describes the sequence of calculating the project's financial feasibility indicators NPV, IRR and BCR through utilisation of the RST. The input parameters, which are defined as random sets comprise capital expenditures, discount rate, construction time and project revenues.

Expected project revenues are defined as parameter ranges representing the expected earnings of the power plant over the project life (in this case a period of 25 years). The model also allows the consideration of power purchase agreements (PPAs). A PPA defines that a contractually agreed amount of the generated power output produced by the plant is sold to specified parties at a predetermined rate, which obviously eliminates the risk of price fluctuations for the power producer. The scenario illustrated in **Fig. 7** shows the range of possible project revenues based on the assumption that 50% of the power generated annually will be sold at a predetermined rate through PPAs.

To account for uncertainties and risks related to the selected construction methods and the possible effects on the construction schedule two alternative scenarios are incorporated into the financial model describing the length of the construction period. As illustrated in Fig. 4 the construction time also has a direct impact on the commencement of revenue generation.

The selected discount rate represents a crucial key parameter for the financial model and is subject to the definite future financing conditions of the project. The three different sources of information as well as the wide parameter ranges for this figure as shown in Fig 8. reflect the early planning stage (prefeasibility level) of the study. Once the planning works are more advanced (e.g., at feasibility level or final design stage) it can be expected that the number of information sources that need to be considered can be reduced and that the interval ranges decrease.

7 Financial project analysis

The calculation matrix (Random Set Model) is generated based on the above parameter sets and consists of all possible parameter ranges and combinations representing the defined project. Since uncertain input parameters and boundary conditions are rationally described in form of random sets and propagated through the calculation model, the result of the analysis cannot consist of sharp values.

Consequently the financial indicators NPV, IRR and BCR are calculated as envelopes of all possible cumulative distribution functions. The result is determined as a range between upper and lower probability bounds since the exact probability (Pro) cannot be established.

The results of the analysis indicate that the criteria leading to a positive investment decision can only be met if the calculation is based on the most favourable parameter combinations. Unfavourable parameter combinations lead to values for the NPV < 0 indicating an unprofitable project as shown in **Fig. 9**. The same calculations are performed for IRR and BCR. In view of the project's obvious potential for being profitable, which is indicated by the numerous parameter combinations delivering a NPV > 0, the initial assessment should not necessarily lead to a categorical rejection of the project. The only conclusion that can be drawn from the analysis so far is the awareness, that the profitability of the project cannot be demonstrated based on the currently existing input parameter ranges. Therefore the financial viability of the investigated project must be further assessed by means of a refined analysis based on more precise information, which can justify the reduction of interval ranges for selected parameter sets.

CAPEX:

Adjusted parameter ranges for the input parameter sets representing project costs are reduced and indicate a less pronounced disparity between individual information sources. The focal elements A1 and A2 are now in partial agreement since their parameter ranges partially overlap. The adjust-

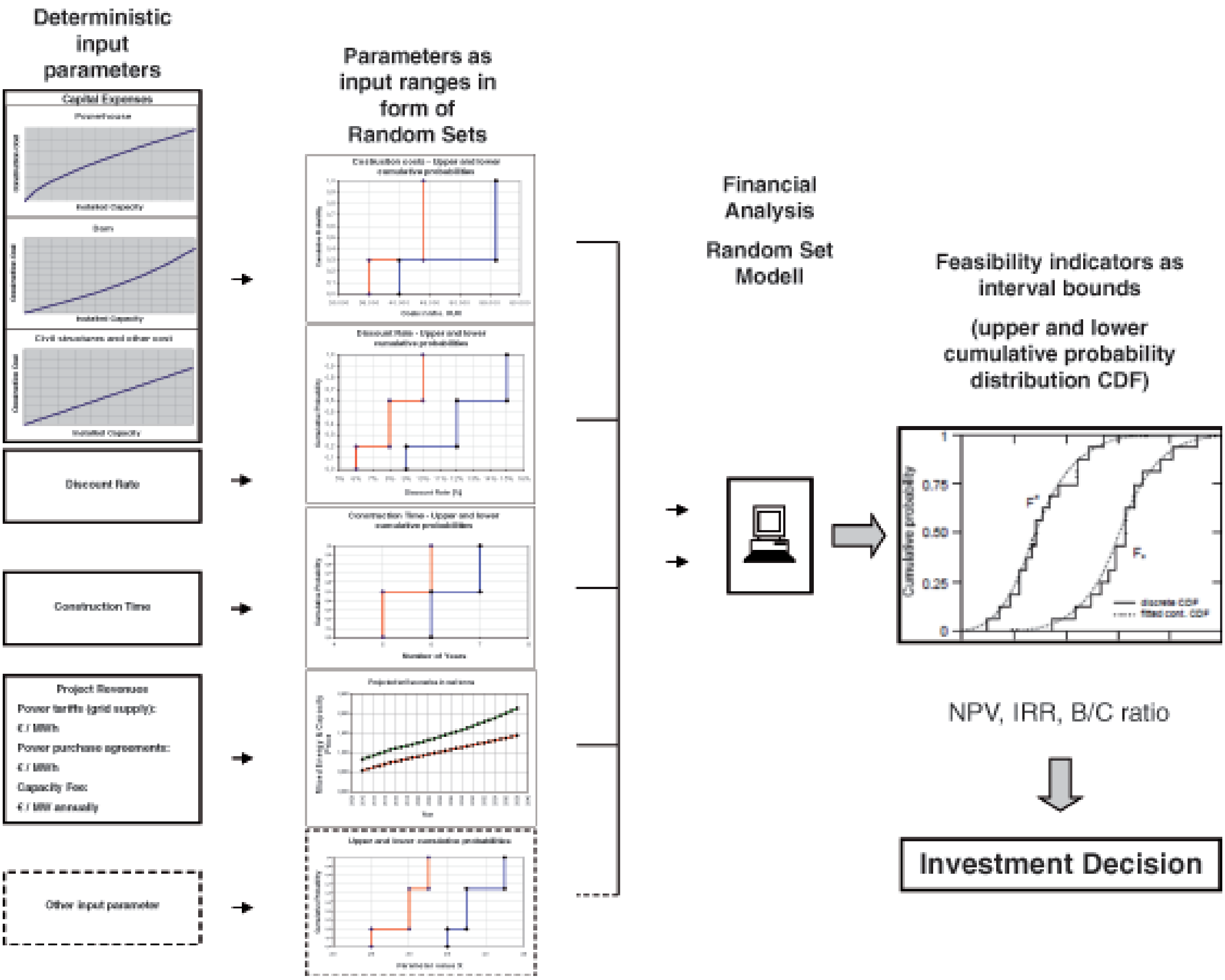

Fig. 8. **Schematic illustration of a random set based approach for the financial analysis of a hydropower project**
Bild 8. Schematische Darstellung eines auf der Random Set Theorie basierenden Ansatzes zur Wirtschaftlichkeitsuntersuchung eines Wasserkraftprojektes

ment of input parameter ranges reflecting the uncertainty reduction is illustrated in **Fig. 10**.

Discount rate:

A progressed level of planning activities also impacts the input parameters for the discount rate. The further analysis is therefore based on two confirmed and independent sources

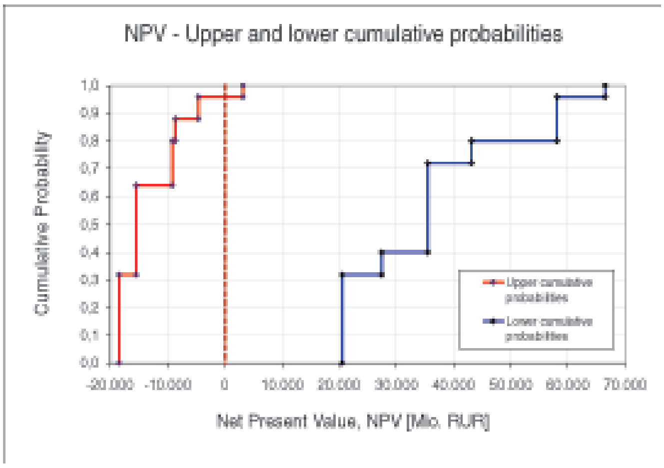

Fig. 9. **Cumulative distribution function (CDF) for NPV**
Bild 9. Kumulative Verteilungsfunktion (CDF) für den Kapitalwert

of information, characterised by different interval ranges as shown in **Fig. 11**.

Project revenues:

As long as the financial model is based on the HPP operation as a merchant power plant the annual project revenues are generated from the sale of power into a competitive market and future income cannot be predicted with a high level of accuracy. The remuneration risk for the producer can be drastically reduced if a certain amount of the plant's output can be sold on the basis of signed power purchase agreements as illustrated in **Fig. 7**. The refined financial project analysis reflects the stipulation that 90% of the power must be sold at a fixed rate, which is confirmed through contractual agreements.

The results of the analysis, displayed as upper and lower bounds of the cumulative probabilities is characterised by a decreasing variability as illustrated in the following **Fig. 12**. The range of results calculated for the NPV (and equally IRR and BCR) is considerably reduced and the bounds of the cumulative probabilities are shifted in a positive direction (characterised by higher values).

In the context of the actual planning process the above alterations of input parameters usually require a gradual progression of adjustments and the financial model is subject to constant optimisation as established by Beisler [1]. In certain cases a detailed assessment of critical parameter combinations may be advisable in order to provide adequate documentation underlining that the profitability of the project can be indisputably demonstrated. The definition of project specific accept and reject criteria stipulates the level of accuracy, which is compulsory for decision makers to reach a conclusive investment decision.

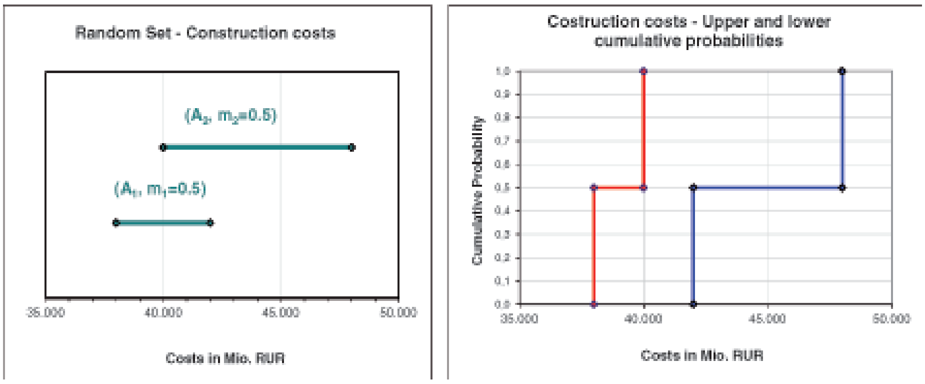

Fig. 10. Adjusted interval ranges for CAPEX reflecting a progressed project phase
Bild 10. Der fortgeschrittenen Projektphase entsprechend angepasste Intervallgrenzen für CAPEX

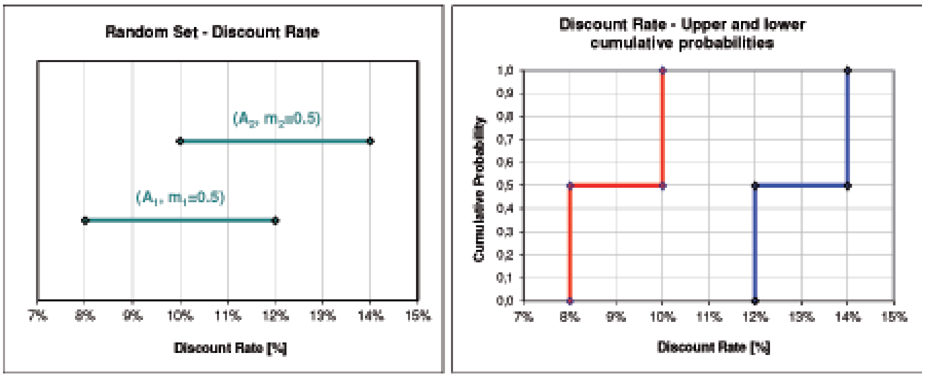

Fig. 11. Input parameter sets defining the discount rate at a progressed planning phase
Bild 11. Eingabeparameter Sets, welche den Kalkulationszinssatz in einer fortgeschrittenen Projektphase definieren

8 Summary of conclusions and outlook

The ignorance of existing input parameter uncertainties at planning stage is likely to produce serious misapprehensions for the financial project appraisal. A methodology based on random set theory was introduced and tested for its suitability to provide a mathematical formalisation, describing the effects, which inherent parameter uncertainties may have on the financial feasibility of a project under investigation.
The financial project assessment supported by the utilisation of imprecise probabilities allows and also forces the engineer to address existing uncertainties and enables planers to recognise and judge the possible range of outputs predicted by the probabilistic model. Further to an objective formalisation of vague data, the methodology facilitates the utilisation of additional sources of information by formalising expert knowledge, information provided by technical literature or experience gained from comparable previous projects.
Based on the findings provided by the RST based analysis it is possible to clearly stipulate the level of accuracy required for specific input parameters, which allows for a responsible and well supported investment decision.
The acceptable uncertainty level for selected input parameters can be defined by decision makers depending on their specific project requirements and risk tolerance.
The project assessment executed under assistance of RST facilitates the determination of additional planning activities and their related expenditures, which are required to reduce the input parameter range to a level, which is regarded as acceptable for decision makers.
The uncertainty exposure of the project can be visualised in matrix format (**Fig. 13**). In order to support risk-informed decision making, the uncertainty matrix identifies project relevant areas of uncertainty within the assessed project and illustrates the magnitude of potential consequences if parameter uncertainties are not reduced to an acceptable level. Through the provision of this instrument the successful mitigation of uncertainties and their related project risks can be supported and initiated.

①Risk No. 1	Exchange rate, inflation and interest risk
②Risk No. 2	Construction cost overrun and delay of completion
③Risk No. 3	O&M cost overrun, interruption of operation
④Risk No. 4	Hydrology
⑤Risk No. 5	Site conditions
⑥Risk No. 6	Future energy demand and energy pricing
⑦Risk No. 7	Force majeure

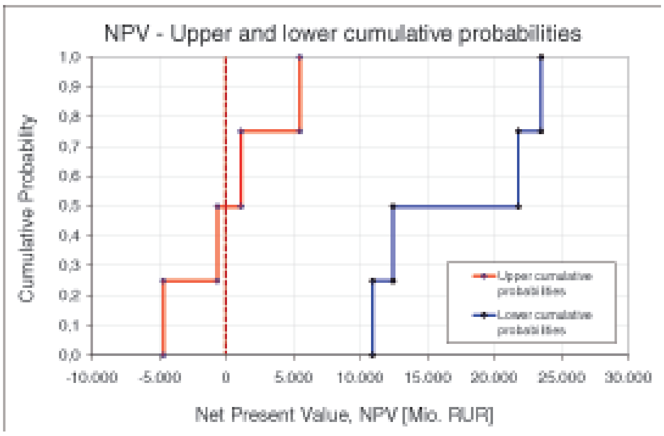

Fig. 12. CDF for NPV based on adjusted parameter sets
Bild 12. Kumulative Verteilungsfunktion für den Kapitalwert basierend auf angepassten Eingabeparameter Sets

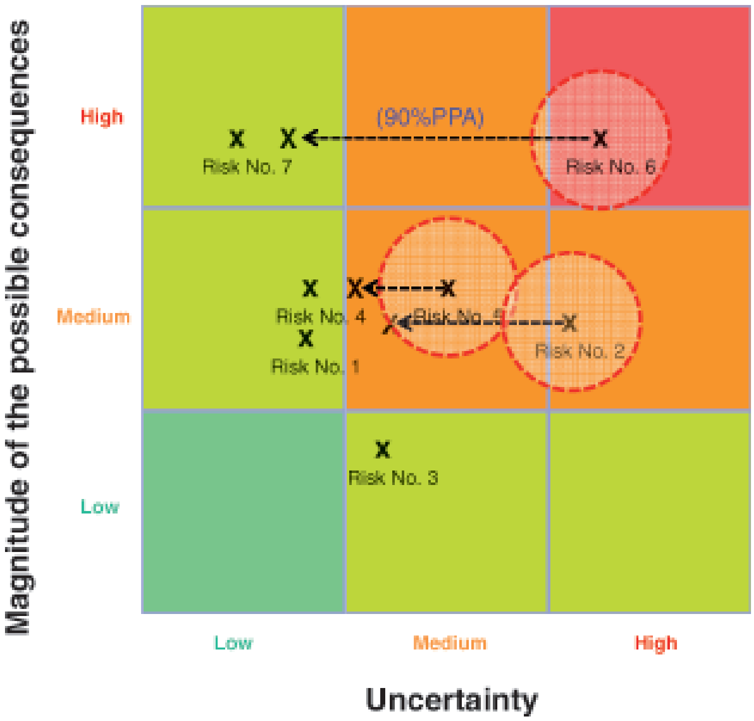

Fig. 13. Uncertainty matrix for risk informed decision making
Bild 13. Unsicherheitsmatrix zur Unterstützung risikobewusster Projektentscheidungen

The study confirms that – similarly to already existing geotechnical applications- the random set method provides a consistent framework for dealing with uncertainties in the context of financial project appraisal throughout the design and construction of a project. The model can be refined by adding more information when available, depending on the project status (feasibility stage, conceptual design, construction etc.) without changing the underlying concept of analysis.

Although it can be demonstrated that the described methodology can efficiently assist the financial project analysis, it must be highlighted that RST does not replace engineering judgement. The presented model is able to provide a framework which enables the engineer to describe and study input data uncertainties and vague boundary conditions as well as their effects on the financial project feasibility in a qualitative manner. In this context the random set theory represents a valuable instrument for the project owner, developer or investor to support the investment decision and can provide clear indications to determine whether a project is worth pursuing or not.

The decision to enter into the next planning stage or to commence with the implementation of the project has to remain with the project owner based on his individual decision criteria.

The main advantages, which RST offers in the context of financial project analysis can be briefly summarised as follows:

- RST provides a consistent framework for dealing with uncertainties throughout the design and construction of a project.
- Computations can be performed directly with focal sets using interval analysis, which limits computational efforts.
- Probability distribution functions are not required since the RST uses intervals (bounds of probability).
- Different sources of information as well as expert opinions can be considered for the financial model since the RST based simulation model can be used for bracketing probability estimates originating from different sources.
- If required, the different information sources can be weighted by assigning different probability weights to individual information sources.
- The entire range of results (NPV, IRR, BCR etc.) is objectively calculated and the discounted cash flow analysis automatically generates best-case and worst-case scenarios.
- The model can be refined by adding more information, reflecting the current project status (feasibility stage, detailed design and construction) without changing the underlying concept of analysis.
- RST represents a robust method for modelling uncertainty and can provide crucial information with regard to the sensitivity of the output related to the input.
- The RST can be used by decision makers for defining the level of accuracy required for selected model parameters based on their specific project requirements and risk tolerance.

References

[1] *Beisler M. (2011):* Modelling of input data uncertainty based on random set theory for evaluation of the financial feasibility for hydropower projects, Veröffentlichungen des Instituts für Geotechnik der TU Bergakademie Freiberg, Heft 2011–3.

[2] *Dempster, A. P. (1967):* Upper and lower probabilities induced by a multivalued mapping. In: Annals of Mathematical Statistics, Jg. 38, S. 325–339.

[3] *Dubois, D., Prade, H. (1990):* Consonant approximation of belief functions. In: International Journal of Approximate Reasoning, Jg. 4, S. 419–449.

[4] *Dubois, D., Prade, H. (1991):* Random sets and fuzzy interval analysis. In: Fuzzy Sets and Systems, Jg. 42, S. 87–101.

[5] *Fetz, T., Jäger, J., Köll, D., Krenn, G., Lessmann, H., Oberguggenberger, M., Stark, R. F. (2005):* Fuzzy models in geotechnical engineering and construction management. In: Fellin, Wolfgang; Lessmann, Heimo; Oberguggenberger, Michael; Vieider, Robert (Hg.): Analyzing Uncertainty in Civil Engineering. Berlin, Heidelberg: Springer-Verlag Berlin Heidelberg (Springer-11647 /Dig. Serial]), S. 211–239.

[6] *Goldsmith, K. (1993):* Economic and financial analysis of hydropower projects. Trondheim: Norwegian Institute of Technology Division of Hydraulic Engineering (Hydropower Development, 6).

[7] *Klapperich H., Pöttler R. (2006):* Flächenrecycling und Flächenmanagement – Altlastensanierung / interdisziplinär, Gruppe Geotechnik Graz, Heft 28, S.245–260.

[8] *Oberguggenberger, M. (2005):* The mathematics of uncertainty: models, methods and interpretations. In: Fellin, Wolfgang; Lessmann, Heimo; Oberguggenberger, Michael; Vieider, Robert (Hg.): Analyzing Uncertainty in Civil Engineering. Berlin, Heidelberg: Springer-Verlag Berlin Heidelberg (Springer-11647 /Dig. Serial]), S. 51–72.

[9] ÖGG (2005), Österreichische Gesellschaft für Geomechanik. ÖGG Richtlinie: Kostenermittlung für Projekte der Verkehrsinfrastruktur unter Berücksichtigung relevanter Projektrisiken.

[10] *Peschl, G. M. (2004):* Reliability Analysis in Geotechnics with the Random Set Finite Element Method. Institut für Bodenmechanik und Grundbau, Technische Universität Graz.

[11] *Pöttler, R., Schweiger, H. F., Peschl, G. M. (2005):* Standsicherheitsnachweise im Tunnelbau – Ein Beitrag zur Weiterentwicklung des Standes der Technik. In: Bauingenieur, H. 9, S. 422–429.

[12] *Pöttler R., Schweiger H. F. (2006):* Cost evaluation for traffic and transport infrastructure taking account of project risks. "Geohazards", Farrokh N., Pöttler R., Einstein H., Klapperich H., St. Kramer Eds, ECI Symposium Series, Volume P7 (2006).

[13] *Pöttler R. (2008):* Energy from hydropower: innovative and regenerative. Institut für Geotechnik der TU bergakademie Freiberg, Heft 2009–1 Statusbericht 2008, Forschungsbeiträge.

[14] *Rolfes, B. (2003):* Moderne Investitionsrechnung. Einführung in die klassische Investitionstheorie und Grundlagen marktorientierter Investitionsentscheidungen. 3. Unwesentl. Veränd. Aufl. München: Oldenbourg (Schierenbeck-Management-Edition).

[15] *Schweiger, H. F., Peschl, G. M. (2005):* Reliability Analysis in Geotechnics with the Random Set finite Element Method. In: Computers and Geotechnics, Jg. 32, S. 422–435.

[16] *Shafer, G. (1976):* A Mathematical Theorie of Evidence: Princton University Press.

[17] *Seitz, N., Ellison, M. (2004):* Capital budgeting and long-term financing decisions. 4. ed. Mason, Ohio: Thomson/South-Western.

[18] *Tonon, F., Mammino, A. (1996):* A random set approach to the uncertainties in rock engineering and tunnel lining design. ISRM International Symposium on Prediction and Performance in Rock Mechanics and Rock Engineering (EUROCK 96), Vol. 2, Barla (ed.) Torino, Italy. Rotterdam: A.A. Balkema, 861–868.

[19] *Tonon, F., Bernardini, A., Mammino, A. (2000a):* Determination of parameters range in rock engineering by means of Random Set Theory. Reliability Engineering & System Safety, Vol. 70, No. 3, 241–261.

[20] *Tonon, F., Bernardini, A., Mammino, A. (2000b):* Determination of parameters range in rock engineering by means of Random Set Theory. Reliability Engineering & System Safety, Vol. 70, No. 3, 263–282.

[21] *Yescombe, E. R. (2006):* Principles of project finance. [Nachdr.]. Amsterdam: Acad. Press.