Comparison of methods to achieve robust design decisions for hydropower projects: A case study

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Robustness in hydropower design is getting a key concept to manage uncertainties of long-term forecasts. In recent years different methods have been developed to follow up this design objective.

Robust Decision Making (RDM) is one of the available methods to support decision –making under deep or severe uncertainty. The method describes uncertainty by considering the performance over a wider range of futures. On the other hand Info-Gap Decision Theory (IGDT) can be applied as a design method to achieve a robust design. Besides these two methods, the classical approach of optimizing the hydropower plant so that it will meet the forecasted scenario and by neglecting uncertainties is still widely applied.

In this case study these three different methods are formulated and applied to a real hydropower project. In order to promote the different new design methods for the application in engineering practice, a simple case has been selected, which represents a typical design issue.

1. Robust decision making

Robust Decision Making (RDM) is a set of methods and tools designed to support decision-making under deep or severe uncertainty. The method describes uncertainty by considering the performance over a wider range of futures. For the selection of a design alternative, preference is given to robustness over optimality. The decision framework combines features of both classic decision analysis and scenario planning.
An RDM analysis for hydropower design basically follows the following working steps (see also Cervigni et al., 2015):

1. List of possible future states
2. Selection of design alternatives
3. Simulation of performance for different future states: During this working step the performance for many different future states are simulated.
4. Sensitivity and vulnerability: The trade-offs among the design alternatives and the performance across the different futures are analyzed in order to identify the sensitivity and to characterize the vulnerabilities. A differentiation between sensitivity and vulnerability is useful, as some projects may be sensitive to harsh futures but will not be very vulnerable as the overall performance is very high.
5. Ranking of design alternatives: Design alternatives are ranked based on a selected robust decision rule or a combination of them.

These working steps can lead to a final design decision or to a preliminary robust design, which can be used as a new starting point for additional iterations through the process.

The selection of a design alternative is based on a robust decision rule. All rules are based on a measure of regret, which is defined as the difference between the performance of a design alternative in some future and the performance of the best design alternative for that future (Cervigni et al., 2015).

Recent application to hydropower design
Nassopoulos et al. (2012) apply RDM to dam dimensioning in the water management sector. Cervigni et al. (2015) applied the RDM method to five hydropower projects in Sub-Saharan Africa. The test projects cover different types of schemes (run-of-river and storage schemes) and different project purposes (hydropower, irrigation and water supply).

2. Info-Gap decision theory

The IGDT is a methodology developed by Ben-Haim for supporting model-based decisions under severe uncertainty. According to Ben-Haim (2010), an info-gap is defined as follows: *An info-gap is a disparity between what is known and what needs to be known in order to make a comprehensive and reliable decision.*

In general, the info-gap analysis is based on the following three elements:

- **Info-gap model of uncertainty**: This is a non-probability quantification of uncertainty, such as the mean annual energy price over the economic lifetime or the mean inflow volume.
- **System model**: The system model in the context of hydropower design is typically structured in several sub-models (energy price forecast model, hydrological model, energy production model, construction cost estimation and economic model), which leads finally to the performance parameter.
- **Performance requirements**: This can be a set of values that define the outcomes to be achieved, which can be a certain NPV or annual energy production, the reliability of the energy production, or the definition of various types of energy (peak, base or reserve energy), or a combination of these requirements.

Two decision functions are formulated based on the analysis of the info-gap including the components uncertainty model, system model and performance requirements. The following decision functions support the selection of a reliable design concept:

- **Robustness function:** The robustness function assesses the greatest tolerable horizon of uncertainty by satisfying the performance requirements. In other words, how wrong can our assumptions or forecasts be while still providing an acceptable performance of the hydropower plant.
- **Opportuneness function:** The opportuneness function assesses the lowest horizon of uncertainty possible for an outcome better than anticipated. However, this is about potential, not guarantee. Some design parameters may bring great "windfalls", such as additional installed capacity allowing additional energy to be generated in case of unexpected flow from climate change-induced glacier melt.

The robustness and opportuneness functions do not necessarily lead to the same preferred design parameters. The *robust-satisficing* decision strategy selects the more robust option, whereas the *opportune-windfalling* decision strategy chooses the concept that can lead to a better performance than expected.

According to our best knowledge, the IGDT approach was the first time applied on hydropower projects by Oberrauch (2017 or 2018).

3. Case study – Description of analyzed hydropower project

A hydropower project in the Swiss Alps was selected for a case study in order to test and illustrate the application of the new design methods. In order to promote the new design methods, a simple case has been selected, which represents a typical design problem. An adequate plant size needs to be selected based on the design discharge. But the energy price forecasts are highly uncertain and there also is some uncertainty about anticipated inflows. Inflow is expected to increase in the future as the catchment area is partly covered by glacier. Therefore, the classical approach, which would be to select the design discharge on the basis of the highest NPV without taking uncertainties into account, may not lead to an optimum result in terms of design discharge selection.

The project is a high-head run-of hydropower scheme. The headworks consists of a weir equipped with a main gate and a flushing gate, and a two-chamber sand trap. The waterway is designed as an underground structure with a 1.8 km long low pressure reservoir tunnel and a 1.2 km long inclined tunnel which will be equipped with a penstock. Two Pelton units with equal installed capacity are foreseen. The plant size is determined by the installed capacity, which depends on the design discharge. Five different design discharge rates within a range between 2.0 m^3/s and 6.0 m^3/s are considered (see Table 1).

Table 1: Salient features of design alternatives

Parameter	Unit	Alternatives				
		Qd2	Qd3	Qd4	Qd5	Qd6
Design discharge (Q_d)	[m^3/s]	2.0	3.0	4.0	5.0	6.0
Max. generation discharge (Q_{max})	[m^3/s]	2.7	4.0	5.4	6.7	8.0
Gross head(H_g)	[m]	522.0	522.0	522.0	522.0	522.0
Net head (H_n) at Q_d	[m]	507.3	510.2	511.3	511.7	511.4
Specific hydraulic loss coefficient	[-]	3.678	1.316	0.667	0.414	0.295
Efficiency of E&M equipment (η)	[-]	0.88	0.88	0.88	0.88	0.88
Installed capacity (IC)	[MW]	9	13	18	22	26
CAPEX	[CHF million]	40.2	43.7	47.1	50.1	52.7

3.1 Hydrology

The purpose of the hydrological study was to analyze the climate impact on the design choice for various installed capacities of a hydropower project. Therefore, a hydrological model was applied to simulate various climate change scenarios. The discharge series of the different climate change scenarios were simulated at daily time steps and then used for energy production simulations.

The catchment of the hydropower project covers an area of 25 km^2. The catchment is partly glacierized (22%) and its steep alpine topography covers elevations between the altitude of the intake of 999 m asl and 3119 m asl. A gauging station with long-term records is located in the catchment and covers about 82% of the catchment area of the planned hydropower plant. The records from this reference station were used for the calibration and validation of the rainfall-runoff model. In addition, records from the period 1961 to 2013 were selected as reference inflow.
The hydrological model “Routing System” developed at the Laboratory of Hydraulic Constructions (LCH) of Ecole Polytechnique Fédérale de Lausanne (EPFL) was selected for the simulation of the mountainous catchment of the case study. For details on the hydrological study and the set-up of the hydrological model as well as on the calibration and validation procedure reference is made to Oberrauch (2017).

Inflow - Climate change scenarios

The climate change scenarios are based on the data elaborated for the extensive research project “Swiss Climate Change Scenarios CH2011” (CH2011, 2011; Bosshard et al. 2011). This report and the corresponding data provide a detailed basis for climate impact studies. The data is based on 30-year mean temperature and precipitation changes and is generally suitable for analyses of mean annual cycles. The precipitation and temperature datasets were derived from regional climate model data provided by the ENSEMBLES project (Linden and Mitchell, 2009). In total 10 model chains, each consisting of one general circulation model (GCM) driving one regional model (RCM), were studied. The dataset provides changes relative to the reference period from 1980 until 2009 for the scenario periods 2021-2050 (referenced as 2035), 2045-2074 (referenced as 2060), 2070-2099 (referenced as 2085). The changes of temperature and precipitation for the 10 models chains are available for various meteorological stations in Switzerland.

In the near future (2035) all 10 model chains indicate a relatively low increase of the annual runoff (<10%). In the long future (2085) 5 out of 10 model chains lead to a moderate increase of the annual runoff in the range from 15% to 20%.

3.2 Energy model and economic evaluation

An energy production model applicable for a high-head run-of river power plant was elaborated. The spreadsheet model simulates daily energy production of a stand-alone hydropower plant for periods up to 50 years. The model needs long-term daily inflow and the required environmental flow, on the one hand, and the technical parameters of the analyzed design alternative on the other (see Table 1).

A discounted cash flow (DCF) model is used for the calculation of economic performance parameters. Table 2 gives the NPVs for the analyzed design alternatives based on the assumption of a long-term energy price of 65 CHF/MW. The classical approach of selecting the design alternative with the highest NPV while neglecting the uncertainties of climate change and energy price fluctuation leads to a plant size in the middle range (Qd4).

Table 2: NPV of alternatives

		Alternatives				
	Unit	Qd2	Qd3	Qd4	Qd5	Qd6
NPV	[CHF million]	1.32	10.36	13.66	13.30	11.37

4. Application of robust decision making

The objective of the case study is to select a robust design discharge by considering a wide range of possible future states of inflow and energy prices.

The selected design alternatives cover a range of design discharges between 2 m^3/s and 6 m^3/s. The hydrological study considering various climate projections suggests a range of plausible changes of the inflow to the planned hydropower intake. As well as the inflow, the energy price is a highly uncertain parameter. Three scenarios were assumed for future states of the energy price. The “High” energy price scenario corresponds to 120 CHF/MWh, the “Central” energy price scenario assumes 65 CHF/MWh, and the “Low” energy price scenario is based on a mean energy price of 30 CHF/MWh.

Sensitivity to climate change and energy price

The climate change analyses conducted for different projection periods show that the energy production is sensitive to future climate (see Figure 1). All climate change projections for the near up to far future predict an increase of the annual energy production compared with the long-term reference period 1961-2013. In the near future, the climate change may result in an increase up to about 10%. Additional increase can be expected for the periods referenced as 2060 (up to plus 19%) or 2085 (up to plus 28%).

The alternative with the smallest design discharge has the highest sensitivity of the annual energy production to climate change, whereas design alternatives in the middle range (Qd4 and Qd5) show less sensitivity.

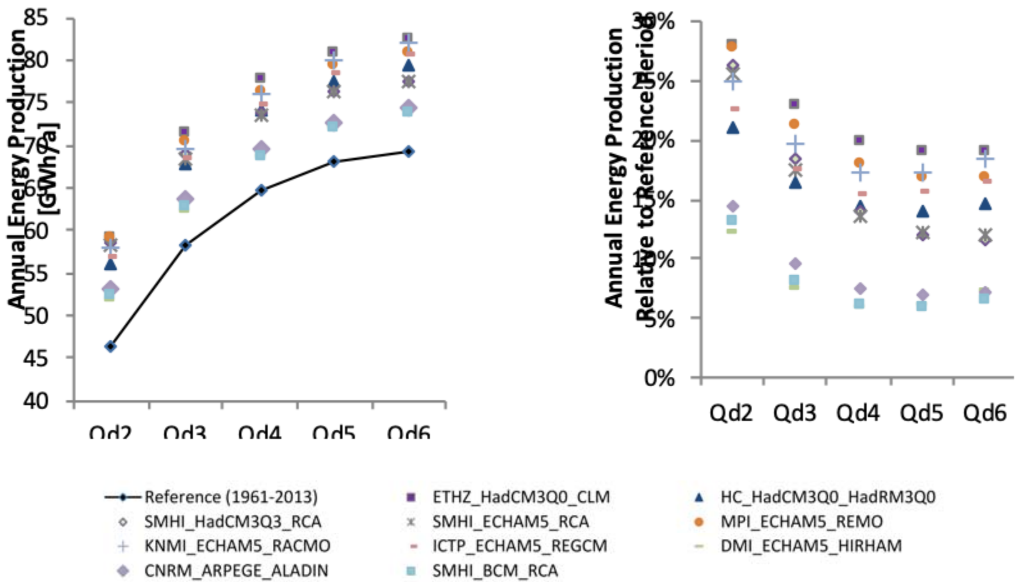

Figure 1: Sensitivity of energy production based on 10 climate change projections for the far future (2085). Left plots: Annual energy production for different climate change projections. Right plots: Relative variation of energy production compared with the reference period.

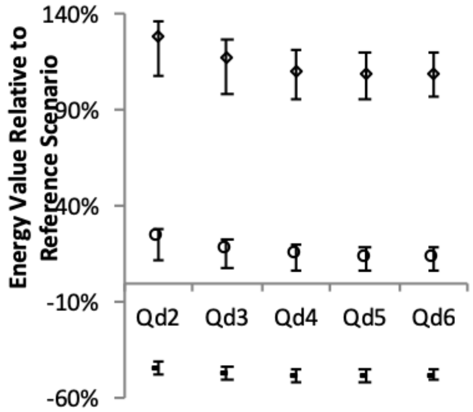

Figure 2: Variation of energy value as compared with the reference scenario as a function of climate change projections and energy price scenarios for the different design alternatives (Qd2 to Qd6). The plot shows the results of the three energy price scenarios: high (diamond), central (circle) and low (horizontal line). Range of results depending on climate change projections are shown as whiskers. Central mark indicates median, whisker extends to the most extreme data points of climate change projections for each energy price scenario.

Figure 2 presents the value of the produced energy for each design alternative relative to the reference scenario. For the reference scenario, the central energy price scenario and the long-term recorded discharge were assumed. The range of the climate change projections is shown by a range plot. The analyses show a very large sensitivity of the energy value to the energy price scenarios. Compared with the energy price scenario, the climate change projections have a very small influence on the energy value. In relation to the reference scenario, the highest increase of the energy value can be expected for the smallest design alternative (Qd2), with an increasing effect over time from the near future to the far future.

Vulnerability to energy price scenarios and climate change projections

In general, some projects can lead to benefits and revenues so high that the chance for negative performances is low, even under harsh futures. Means et al. (2010) defines vulnerability in the context of water planning and dealing with climate change as the degree to which a system is susceptible to an adverse effect.

In the discussed case study, all climate change projections lead to an increase in energy production. Consequently, the only adverse effect stems from an energy price below the reference estimate. The analyses of the vulnerability as defined in terms of NPV show a significant impact on the economic performance of all of the design alternatives. Table 3 summarizes the vulnerabilities of the design alternatives. Compared with the reference scenario, a decrease of the NPV between 2749% and 379% can be expected. Qd2 has the highest relative vulnerability because of the lowest NPV in the reference scenario.

Relative vulnerability, which is defined as the difference between the most adverse performance and the estimates of the reference periods, seems to be less important for decision-making than absolute vulnerability.
For a low energy price, all design alternatives lead to a negative NPV and very high relative and absolute vulnerabilities. The absolute vulnerability increases with increasing project costs (higher design discharge).

Table 3: Absolute vulnerability and relative vulnerability of design alternatives

		Qd2	Qd3	Qd4	Qd5	Qd6
NPV	[CHF million]	1.32	10.36	13.66	13.30	11.37
Lowest NPV	[CHF million]	-34.90	-35.83	-38.09	-40.93	-43.77
Absolute vulnerability	[CHF million]	-36.22	-46.19	-51.74	-54.23	-55.13
Relative vulnerability	[%]	-2749%	-446%	-379%	-408%	-485%

Figure 3 shows the NPVs, taking into account the energy projection as well as the climate change projections. The range of the climate change projections are shown as a range plot. Similar to the observed influence of climate change on the energy value, the climate projections give a very small effect on the NPV compared with the energy price scenarios. For all future climate projections and in case of the High energy price scenario, the largest design alternative Qd6 would be the preferred option. For the Central energy price scenario, a shift from Qd5 in the near future to Qd4 in the far future can be observed. Assuming the Low energy price scenario, Qd2 would minimize the economic loss, independently of the climate change projections.

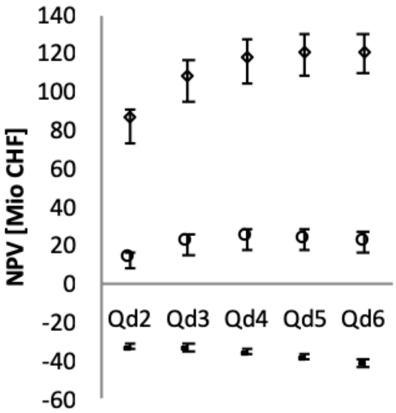

Figure 3: NPV of different design alternatives (Qd2 to Qd6) for high (diamond), central (circle) and low (horizontal line) energy price scenarios. Range of NPVs depending on climate change projections are shown as whiskers. Central mark indicates median, whisker extends to the most extreme data points of climate change projections for each energy price scenario.

4.1 Ranking of design alternatives

As shown by the sensitivity and vulnerability analyses, the various design alternatives have different vulnerabilities and lead to different NPVs depending on the future states. However, the analyses do not provide the information necessary to frame and make a decision. In the following section, the "minimize maximum regret" decision criterion and the domain criterion are discussed.

Minimize maximum regret

The minimize maximum regret criterion leads to the choice of the design alternative Qd5 when all energy price scenarios are considered (see Figure 4). If high energy prices occur, Qd5 leads to better performance than Qd4, and for low energy prices, Qd5 will reduce losses in comparison with Qd6. Climate projections in the near future and in the far future do not influence this design choice, which is determined by the energy price scenarios.

The results show also that in case of high energy prices the "cost" of selecting the small design alternative (Qd2) will be 6-7 times higher than the regret in a case where the largest design alternative (Qd6) was selected and low energy prices will occur.

From a project developer's perspective, the project will most probably be stopped if the low energy price scenario is considered to be a likely scenario. Also when neglecting the low energy price scenario, Qd5 is the most robust concept for the near future. However, if the project is postponed and the central and high energy price scenarios are considered, the "minimize maximum regret" criterion will lead to Qd4.

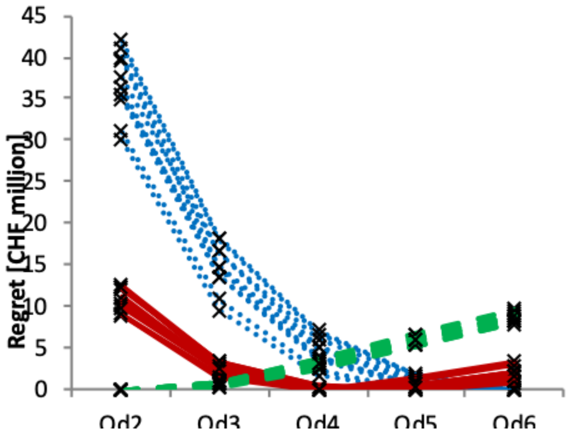

Figure 4: Regret of climate change projections and energy price scenarios for the design alternatives (Qd2 to Qd6) in the climate change projections for the far futures (2085). Regrets based on the high energy price scenarios are shown as blue dotted lines. Red continuous lines refer to the central energy price scenario and green dashed lines represent the results of the low energy price scenarios. Each line stands for a climate change projection.

Satisfice over a wide range of future conditions

The domain criterion defines a robust design as one that performs reasonably compared to the alternatives across a wide range of plausible futures. The aim is to reduce the interval of plausible futures over which a strategy performs poorly (Lempert and Collins, 2007).

A possible approach is to map the regrets over the future states. Figure 5 shows the regrets against the inflow volume and the energy price. The inflow volumes represent the climate change projections. In this case, the mapping shows almost vertical isolines of regret, indicating that the regret is mainly sensitive to the energy price scenarios.
Qd4 has low regrets in the area of the central price estimations. Larger design alternatives have low regrets for higher energy prices, whereas small design alternatives perform better for low energy prices.

In general, the regret criterion does not differentiate between more harsh or more opportune futures. In Figure 5, “A” indicates the area with higher inflow and higher energy prices compared to the reference scenario. All climate projections result in higher inflow volumes than those in the reference period thereby leading to a vertical split of the plots. A comparison between the areas A in each of the various plots shows that a selection of Qd5 is mainly driven by more opportune futures. A robust design choice with focus on more harsh future states would be Qd4.

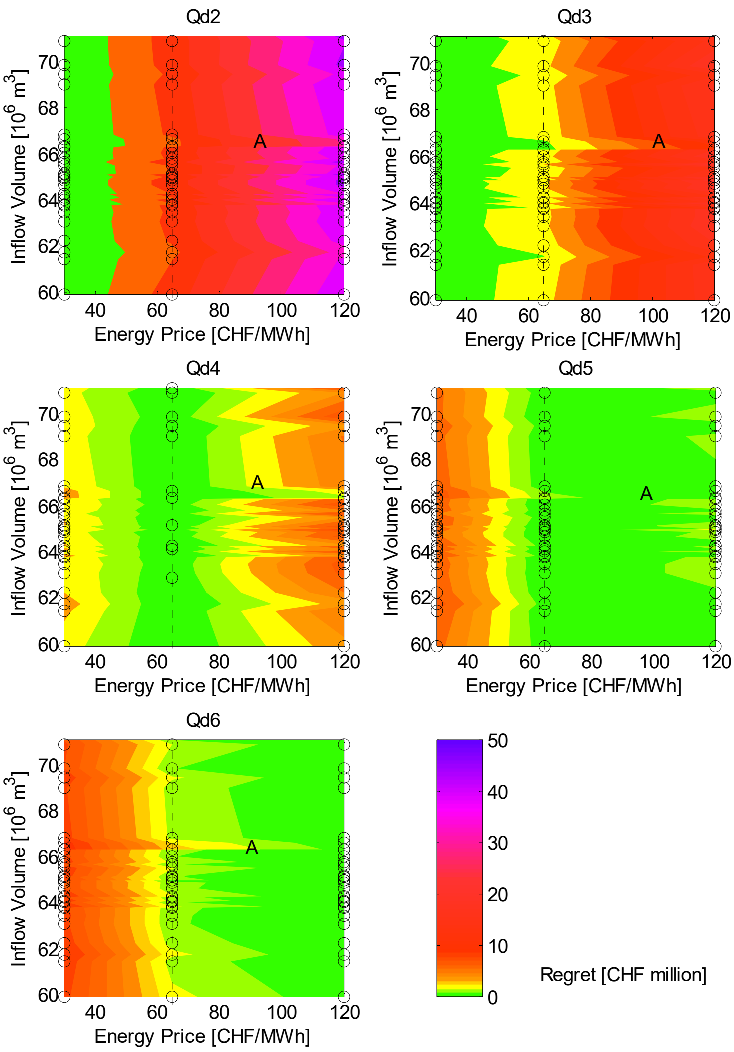

Figure 5: Regrets over the simulation range for the analyzed design alternatives (Qd2 to Qd6), "A" indicates the area with higher inflow and higher energy prices compared to the reference scenario

5. Application of Info-Gap Decision Theory

Uncertainty model

The energy price (u_1) and the inflow volume (u_2) are both highly uncertain and influence the NPV. No probability on the energy price and inflow forecasts can be given, or is agreed on, by the project team. It was assumed that the long-term annual energy price ($\tilde{u}_1$) would be 65 CHF/MWh. The hydrological studies estimated an average inflow volume of 64.51 million m^3/a based on records of the period 1961-2013 ($\tilde{u}_2$).

The energy price might decrease to about 30 CHF/MWh or increase to about 120 CHF/MWh. The hydrological study estimates a range between 59.91 million m^3 (historical long-term average, 1961-2013) and 71.12 million m^3 of annual inflow (highest simulated annual inflow). All inflow series that take climate change into account lead to an increase of the inflow volume.

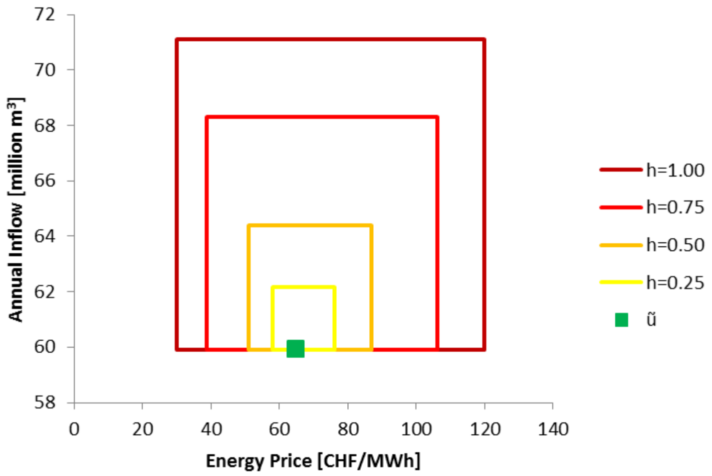

Figure 6: Info-Gap uncertainty model showing the uncertainties from a best estimate (ũ) of the energy price and the annual inflow of each horizon (h).

These ranges of estimates are integrated in an uncertainty model to form upper and lower boundaries, i.e. σ_l (lower boundaries) and σ_r (upper boundaries). The scaling factors are ω_l for the left-hand side and ω_r for the right-hand side. The uncertain parameters (energy price and inflow volume) are scaled by h for each "horizon" or increment of uncertainty (see Figure 6). The info-gap model becomes:

$$U(h,\tilde{u}) = \{u : max[\sigma_l, (1-\omega_l h)\tilde{u}_i] \leq u_i \leq min[\sigma_r, (1+\omega_r h)\tilde{u}_i]\},$$
$$h \geq 0, i = 1,2 \quad (1)$$

The available information and assumptions are summarized in the following table.

Table 4: Input to the IGDT model

	Convention	Value
Estimated energy price	$\tilde{u}_1$	65
Estimated inflow volume	$\tilde{u}_2$	59.91
Lower boundaries	σ_l	σ_l = [30, 59.91]
Upper boundaries	σ_r	σ_r = [120, 71.12]
Scaling factor, left-hand side	ω_l	ω_l = [0.538, 0.000]
Scaling factor, right-hand side	ω_r	ω_r = [0.846, 0.187]

System model

The system model is composed of an energy production model and an economic model. For the simulation of energy production, a model with daily simulation time steps was selected. For details, reference is made Oberrauch (2017).

Performance requirement

A $NPVc = 0$ was selected. That means that the NPV will be always positive under the consideration of the estimated uncertainties.

Robustness and opportuneness functions

The actual net present value of each design alternative (NPV_d) is unknown, as the actual energy price and actual inflow volume are unknown. The robustness to uncertainty of the design alternative is the greatest horizon of uncertainty up to which the NPV_d of that design is not worse than a critical NPV_c. The robustness function for each design alternative (d) is defined as follow:

$$\hat{h}\,(d) = max\left\{h\colon \min_{u_i \in U(h)} NPV_d\,(u_i, d)\; \geq NPV_c\right\} \tag{2}$$

The opportuneness from uncertainty of the various design alternatives is the lowest horizon of uncertainty at which the NPV can be as high as the NPV_w:

$$\hat{\beta}\,(d) = min\left\{h\colon \min_{u_i \in U(h)} NPV_d\,(u_i, d) \geq NPV_w\right\} \tag{3}$$

5.1 Results

The design alternative Qd4 is the most robust solution, tolerating a 14% decrease of the energy price and using the historical inflow, which corresponds to the lowest estimate (level of robustness is 0.26). An annual inflow of about 59.91 million m^3/year and a mean energy price of about 56 CHF/MWh will lead to an NPV equal or higher than zero. For NPVs larger than the critical NPV, the design alternative Qd4 is always the preferred design alternative (see Figure 7). Qd5 is the next most robust design alternative, able to maintain an acceptable level of performance with an energy price 13% lower than the best estimate (level of robustness of 0.24).

The opportuneness curves show the performances of each of the design alternatives that can be achieved in more benign futures (see Figure 8). The focus is on the lowest opportuneness curves with a shallow gradient, which indicate a high increase in performance for small increments of uncertainty. The higher the design discharge is, the smaller the slopes of the opportuneness curves are. Should the inflow and the energy price turn out to be higher than expected, a larger plant size can provide for a higher increase of the NPV.

The opportuneness curves show a crossing of Qd5 and Qd4 at an increment level of about 0.10. In other words, if the inflow volume increases to more than about 61.03 million m^3 and if the energy price exceeds 69 CHF/MWh, Qd5 will result in a higher NPV. Qd6 crosses Qd4 at a horizon of 0.15 (inflow volume of 61.59 million m^3, energy price of 70 CHF/MWh).

In a more benign future, Qd5 and Qd6 will lead to similar results, if the uncertain parameters (inflow volume and energy price) are both scaled together.

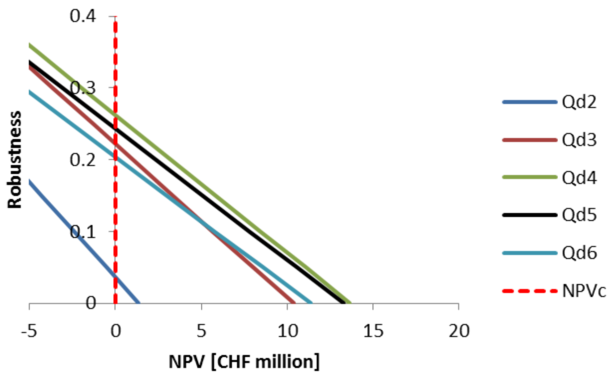

Figure 7: Robustness curves for different design alternatives (Qd2 to Qd6). Qd2 is the design alternative with a design discharge of 2 m^3/s, Qd3 has a design discharge of 3 m^3/s…Qd6 has a design discharge of 6 m^3/s. NPVc is the performance requirement (NPVc = 0). Qd4 is the most robust design alternative.

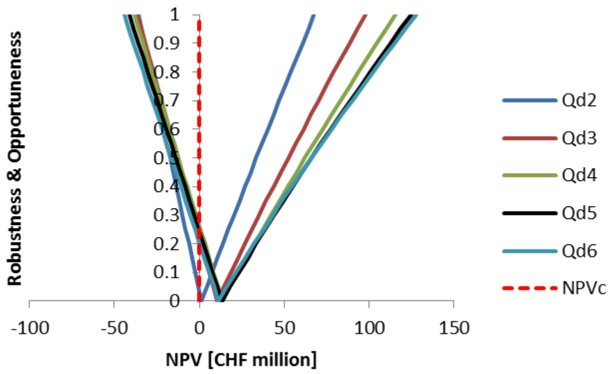

Figure 8: Robustness and opportuneness curves for different design alternatives (Qd2 to Qd6). NPVc is the performance requirement (NPVc = 0).

To summarize, should the project team be risk-averse, Qd4 would be the preferred solution. This design alternative leads to a positive NPV also under harsher futures. If more attention is given to opportuneness, either Qd5 or Qd6 could be selected; Qd6, however, is found to be attractive only if there is an increase in energy price and inflow.

6. Conclusions

The classical approach of selecting the design alternative with the highest NPV while neglecting the uncertainties of climate change and energy price fluctuation leads to a plant size in the middle range (Qd4).

This design choice is confirmed by the Info-Gap Decision Theory for a risk-averse project team. Qd4 leads to a positive NPV also under harsher futures. If more attention is given to opportuneness, larger design alternatives could be preferred.

Robust Decision Making tends to favor a larger design discharge. The minimize maximum regret and domain criteria lead to the choice of the design alternative Qd5. However, as shown by the mapping of the regret, this design selection is mainly driven by the regrets of more opportune futures.

In such case, the classical approach, Info-Gap Decision Theory and Robust Decision Making reached similar although not entirely matching results. The classical approach as well as the robustness curves of Info-Gap Decision Theory support Qd4. Robust Decision Making suggests the larger design alternative Qd5, but only if the decision gives the same weight to both more harsh futures and more opportune futures.

Application of the methods leads to the following main findings: Firstly, the classical approach can lead to a robust design choice although uncertainties are not incorporated into the decision-finding process. Secondly, Info-Gap Decision Theory and Robust Decision Making help assess the robustness of the different design alternatives of a hydropower project and lead to similar but not entirely matching results. The final selection depends primarily on risk attitudes of the decision makers rather than on the method applied.

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Felix Oberrauch studied Land and Water Engineering and Management at University of Natural Resources and Applied Life Science (Austria) from where he graduated in 2004. After his studies, he joined the Hydropower Department of Pöyry Switzerland in 2004 where he has been working on numerous hydropower projects mainly in Asia and Europe. Between 2012 and 2017 he was also working part time as research engineer at Swiss Federal Institute of Technology Lausanne (EPFL), obtaining a Doctorate in 2017. His research work focused on uncertainties affecting hydropower projects and promising new design methods. In 2014 he became Head of the Hydro-Consulting Section at Pöyry Switzerland.

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