Hydropower plants: price and prejudice

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The development of alternative energy solutions to meet the increasing energy demand requires the expansion of the production network. In this context hydropower plants (HPPs) represent a reliable renewable energy source [3] and the possibility of integrating a pumping storage system makes HPPs an excellent way to stock energy. Besides energy generation, hydropower plants present numerous benefits, including flood control and water supply, leisure and storage of electricity [7]. Nevertheless in the recent years some criticism was raised against megaprojects and few studies pointed out that budgets are constantly exceeded and schedules overrun. The methodology proposed by Gomez and Probst [4] is hereafter used allowing to study the hydropower cost evaluation as a complex problem and to reveal the key factors that have a strong influence. The purpose is to identify the processes which leads to an increase of the final cost of large dam project. Results clearly showed the involvement of uncontrollable factors in the process. The reasoning leads to a final statement: the human impossibility to foresee the unpredictable does not justify the criticism and the prejudice that was risen against hydropower plants, whose benefits remain undeniable.

1. Context

This complex issue was addressed and analysed during a course held at *Ecole Polytechnique Fédérale de Lausanne* (EPFL), Switzerland, for the Doctoral program of Civil and Environmental Engineering, under the supervision of Prof. Anton Schleiss. The purpose of this study was to raise awareness among young Ph.D. students in the domain of hydropower and to analyse in details the main factors influencing the budget variability and schedule duration of these large hydropower projects. The project mainly focused on the reasons why budgets and time are overrun, approaching the subject in an objective and rational way.

2. Introduction

The realization of large hydropower schemes is a complex and long-lasting process, carried out in three main phases: a preliminary study regarding important features of the projects such as hydrology, geology and compliance with environmental and social requirements, a detailed design followed by construction and exploitation. During the design engineers have to make assumptions and the price of the project resulting from the preliminary design reflects these uncertainties. Important decisions are made based on this first cost evaluation and a too conservative or unrealistic estimation might result into serious consequences for the project itself. For civil engineers and for designers in general, it is clear that all parameters cannot be taken into account at early design stage. Power plants construction involves multiple interactions at different levels within the parameters and structural, technical, social, environmental and economic aspects have to be considered [9]. The complexity of such projects, the interaction between the different phases and the high level of uncertainties often result into an extended development time. In common practice, uncertainties and risks are accepted because the cost of investigations to reduce them would be too high at an early stage of the projects. All project deviations during construction and the consequent modification of the original design contribute to the increase of the investment and prolongation of construction time. As pointed out by Ansar et al. 2014, the frequency with which the projects are overrun has an influence on their profitability and on its reputation; the same paper offers a statistical analysis to predict the over-cost based on some typical case-studies.

Nevertheless the occurrence of project overrun is a fact, and the following analysis tries to analyse the causes using a well-structured scientific method developed for complex problems. Meanwhile the main question to answer is if hydropower, thinking mainly at the largest power stations, is an investment that still makes sense from an economic and social point of view. As a result, an accurate design project taking into account technical, environmental, social and economic aspects was identified to be the most critical factor.

3. Methodology

Solving complex problems addresses complex multi actor systems that are characterized by a set of many highly interrelated factors whose influences on others are not easily identifiable. Moreover retroactive and coupled effects of the parameters increase the difficulty in the detection of cross-linking. The network thinking approach allows to deal with these types of problems, helping the development of strategies to support decision making. A comprehensive qualitative system assessment method was developed by Gomez and Probst [4] for business planning and was applied to the judgment of multipurpose hydraulic schemes by Heller, Bollaert and Schleiss in 2010 [6]. This problem solving methodology has to extend the knowledge on the complex problem: the current situation has to be entirely represented. All the factors that play a role in the subject have to be listed, considering different points of view. Starting from a central motor (based on the main construction steps), a conceptual method is used to analyse the influence within the factors and to build a network describing the whole system. A holistic approach is therefore necessary to understand the complexity of the system. Finally, active, passive, critical and reactive parameters are identified using an influence matrix.

As suggested by Gomez and Probst, five consecutive steps are defined:

1. **Detection and identification of the problem**: the starting point is the formulation of a concrete goal in agreement with the expectations of the stakeholders involved. In that way the boundary conditions can be fixed and the macro areas of influences (e.g. technical, environmental, social and economic) can be defined. The list of all the key factors involved in the last part of this step allows a comprehensive representation of the complex problem.
2. **Definition of the network**:
   a) **List of influences**: the relationships between the key factors are mapped. The perspective has to focus on a central point that represents the central cycle, a feedback loop, and the network is constructed around it. Arrows are used to illustrate the direction and the effect of the relationships; plus and minus signs provides information about positive or negative effect to the final goal. At this stage only direct relations are considered. In addition, to incorporate time dependencies or period effects, other representations may consist in the use of dashed, thin or thick arrows.

   b) **Influence Matrix**: in order to account not only for the connections between the variables, but also for a more qualitative information, the elements are considered two by two. The crossimpact-matrix is constructed assigning a score between zero and two (according to the intensity of the relation) to each element of the couple that "*is influenced by*" or "*has an influence on*" the other.

   c) **Influence diagram**: from the Influence Matrix the sum of the coefficients of the out-coming relations is calculated. These values are used to build a diagram representing the role of each parameter in function of its activity and reactivity. The variables are classified into four categories: active, critical, reactive or inertial zones, with respect to their position in the diagram.
      - **Active variables**: they influence the other variables intensely whereas they are barely affected. They are the parameters that have the biggest effect on the system.
      - **Critical variables**: these variables have a great influence on the system but they are also affected severely. These are the most delicate parameters since an intervention on them could cause a chain reaction.
      - **Reactive variables**: they weakly affect the other variables but are strongly affected by the others. They do not allow to control the situation but they can be used as indicators since they usually are the purpose of the project.
      - **Inertial variables**: they are the elements with low activity and low reactivity; they have no or little influence on the problem.
3. **Identification of potential solutions**: the result of this procedure is not univocal but it offers possible pictures or visions of the future prediction.
4. **Valuation of problem solving alternatives**: various scenarios should be evaluated to find which one matches the control interventions to the complex problem.
5. **Implementation and stabilization of problem solving**: it is essential to monitor the development of the solution. In fact the problem solutions must be continually reassessed and adapted to the new situation.

Concerning the present work, it will focus on the first three steps that are the most meaningful from a scientific point of view. Furthermore steps 3 to 5 are deeply linked to the uniqueness of the project and a generalisation would imply a simplification of the problem.

3.1 Identification of parameters

The purpose of the present study was to identify the parameters that have potential impact on the studied case, in the most objective manner. In order to reach the final goal the perception of all the parties involved in the planned project was taken into consideration, including the project owner, contractor, employees, governmental institutions, private and public sector. Particular attention was given to the parameters that have direct or indirect effect on the system motors: i.e.: Design, Investment costs, Construction and Project deviation. All the parameters that have a high probability to impact significantly the final cost of the planed hydro-construction were included in the analysis.

The main parameters that were identified are presented in Table 1.

E1	Investment	E2	Design	E3	Construction and equipment supply
E4	Project Deviation	E5	Project reputation	E6	Benefits of the project
E7	Contractor	E8	Suppliers	E9	Adaptability of the project
E10	Geological survey	E11	Environmental survey	E12	Claims
E13	Detail of the contract	E14	Legal costs	E15	Human labour
E16	Schedule quality	E17	Construction time	E18	Quality of the materials
E19	Quantities of the materials	E20	Market Price	E21	Environmental Impact
E22	Project Owner	E23	Resettlement	E24	Cultural and Religious value
E25	Health Accidents	E26	Compensation measures	E27	Opposition
E28	Corruption	E29	Law constraints	E30	Political instabilities
E31	Inflation cost	E32	Currency Exchange Rate	E33	Credit interests
E34	Extraordinary natural event				

Table 1. Parameters considered

3.2 System motor and network

The system motor (Fig. 1) represents the core of the network. The design of the project is the basis to establish the investment cost. Based on the design and the investment cost, a contractor is in charge of the construction during the construction time. Because of the unknowns that engineers faced during the design phase, along with unpredictable events, the construction phase is uncertain and the project may deviate from its original design. In that case the design has to be modified to overpass the construction difficulties and to meet the new requirements. This modification implies a variation of the investment cost. The cycle continues to run until the end of the construction phase. Project deviation may be negative as well as positive for the design and the investment cost.

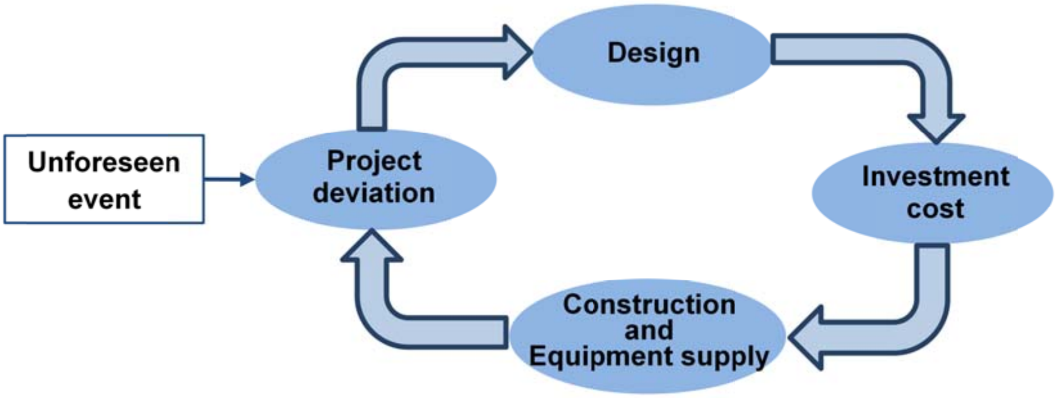

Fig. 1. System motor.

Starting from the parameters listed above, a network was developed around the central motor in order to clarify the main first order interactions between the chosen parameters. The network is presented in Fig.2.

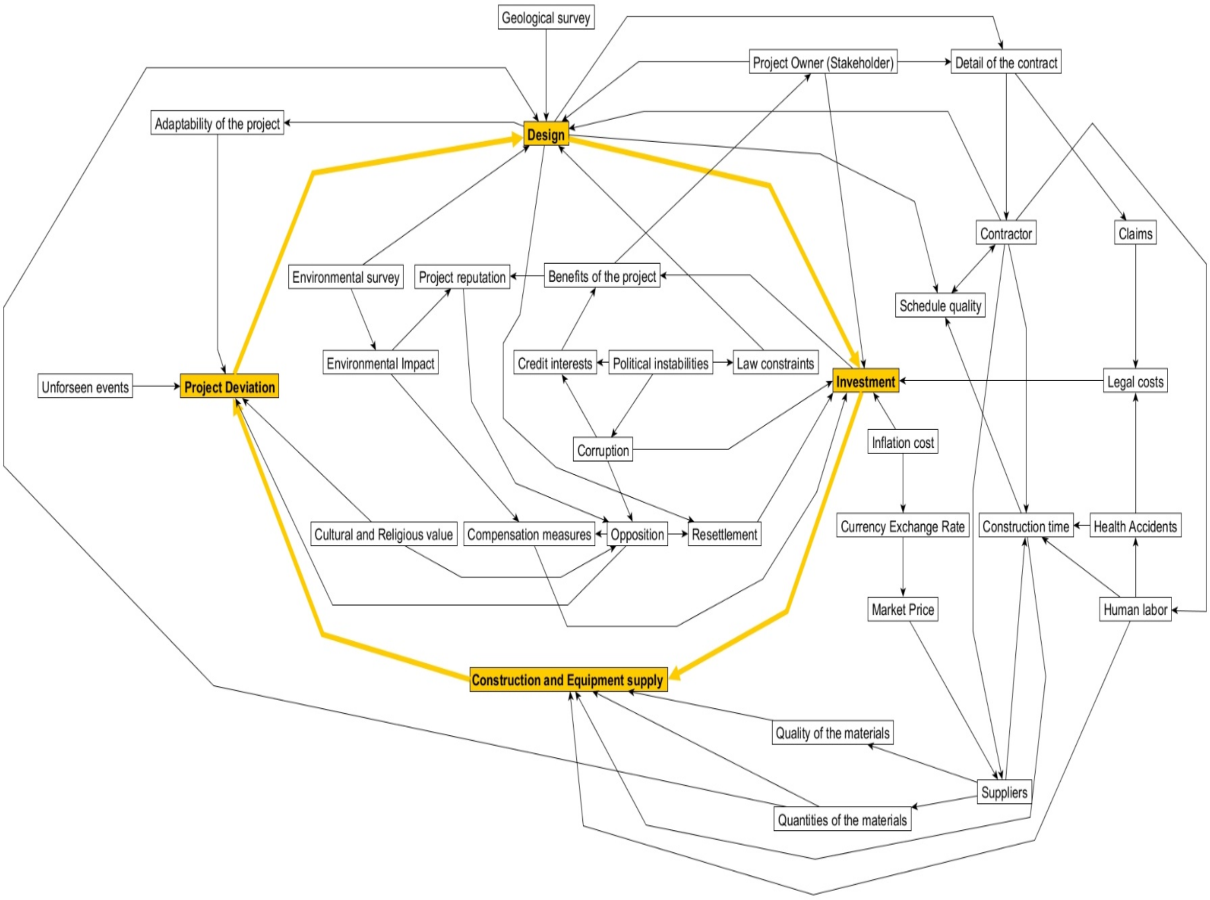

Fig 2. System network with the main first order interactions between the parameters.

3.2 Influence Matrix

Applying the method described in Section 3, the Influence Matrix was obtained (Fig. 3). Based on the results of the Influence Matrix, the following classification was identified:

- **Active elements –** The most active elements are the contractor (E7), project owner competence (E22), corruption (E28), political instabilities (E30), geological survey (E10) and the environmental survey (E11). They are the most active elements and at the same time, they are some of the least reactive elements.
- **Critical elements** – There is only a single critical element: the quality of the design (E2). Elements such as investment costs (E1), project deviation (E4), Benefits of the project (E6) and detail of the contract (E13) could also be considered as critical as they are located in the proximity of the boundaries of the critical zone. The quality of the design has a strong influence on the other elements and is also strongly influenced by the others. As for all critical elements, special care is required when treating these items.
- **Reactive elements** – The most reactive element is the investment cost (E1) with a 100% of reactivity. This result is meaningful since the global approach is applied in order to identify the elements influencing the investment cost. Other elements that have a strong reactivity are the project deviation (E4) and the construction (E3).
- **Inertial elements** – Inertial elements are currency exchange rate (E32), extraordinary event (34), claims (E12), quality of materials (E18) and credit interests (E33).

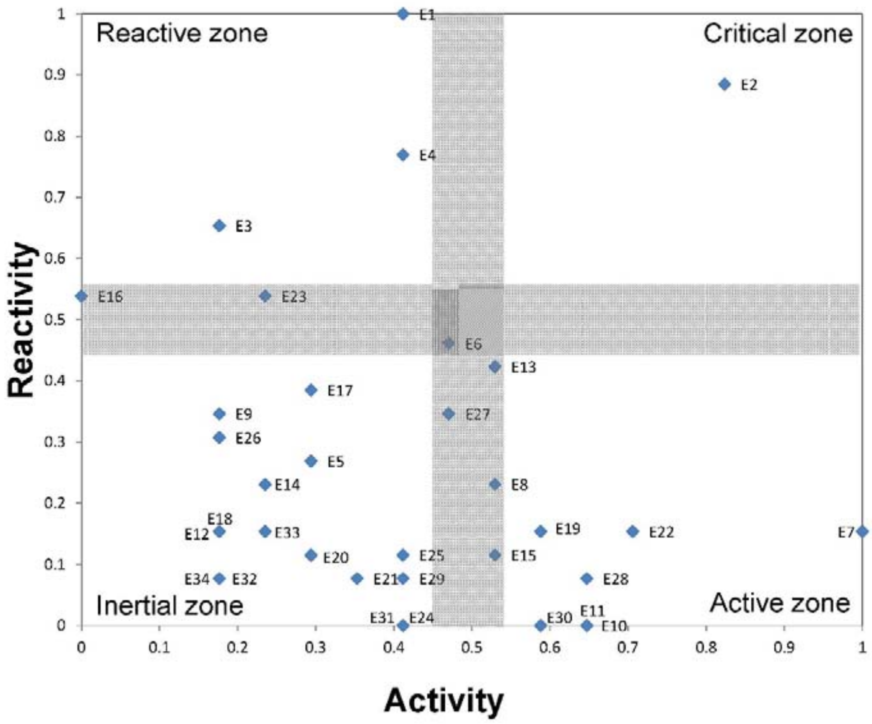

Fig. 3. Influence matrix

Levers: Some of the active elements that are identified are uncontrollable elements since they are linked to the political and economic situation of the region/country (corruption, political instabilities). Nevertheless, there are elements that are not the most active elements that can be controlled:

- Contractor competence (E7): since the contractor is in charge of the construction, he represents a sensitive factor to the design, to the project and to construction time. All these are direct and influential factors for the variation of the investment costs.
- Project stakeholder owner (E22): if the project owner is not competent, there exist a high risk of an increase of the investment costs.
- Geological (E10) and environmental survey (E11): the higher quality of the survey, the better the design and the lesser the costs induced by the project deviation and the opposition.

4. Results

The first estimation of the investment cost is defined at an early stage of the project, once the preliminary design of the project is completed. The first estimation of the investment cost is defined as the combination of the cost estimation given by the first design and the offers of each potential contracting company for the construction. The cost overrun is then defined by the difference between the effective cost at the end of the construction and the investment cost estimated at the end of the early stage of the project.

In our analysis, following the preliminary study and during the whole construction phase, many elements influence the progress of the project and have a direct or indirect influence on its final cost. All these processes generally induce a modification of the design, which induces subsequently an overrun of the cost. The circular mechanism of the modification of the design was illustrated by the system motor. As one could imagine, the design (E2) turned out to be the most critical element, meaning that it is severely affected by the other elements and it has a strong influence on the final cost. This element can cause a chain reaction as shown by the system motor. It is nevertheless important to consider the design as not only the structural part of the project conceived by the engineers, but as a whole, including every single component of the project. The centre point of this motor is the project deviation that could happen after unforeseen events, which have not been included in the first design of the project.

As a result of the present study, some of the main influential factors are non-controllable elements which are especially linked to the actual and near-future situation of the region where the project is built; an example would be the political situation and the existence of corruption in the region. These elements are obviously uncontrollable and unpredictable, which means that the first estimation of the investment cost cannot take them into account. Controllable elements which influence the cost overrun of the project, are more or less defined at an early stage of the project, including the competences of the project stakeholder and the contracting company, the quality of the environmental and geological surveys. These elements can only be controlled to a certain extent. For instance, the competence of the owner representatives can be rarely influenced as it depends on the government or the private company which owns the project. Nevertheless, and this is generally the case in developing countries, financial and technical supports can be provided by international organizations to insure the good progress of the project. Concerning the competences of the contracting company, and particularly in the countries which signed the GATT agreement, the choice of the contracting company is generally based on the price they offer and, to a lesser extent, on the real performance of the company. Competences are therefore hardly controllable in this specific case.

The preservation of the environment is a central point in the success of large hydropower project and the environmental impacts [2] are so important that they can definitely stop the construction. The quality of the environmental survey has a direct influence on elements such as the oppositions against the project (E27) that could easily cause a chain reaction. Nowadays, in some countries, legislation encourage project actors to lead in-depth environmental impact assessments (art. 10a "Water Protection Act, WPA" for Switzerland), in order to reduce the possibility of oppositions. Similarly the geological survey has a big influence on the progress of the project and an effective geological survey can prevent further difficulties and the project can be re-adapted before the construction phase begins.

5. Discussion

The previous study showed that the cost over-run is mainly due to a non-exhaustive design project and to the occurrence of unforeseen events. More precise estimations can be obtained through improved design and investigations; however the latter implies higher costs at an early stage of the project, often seen as premature regarding the non-licensing of the project.

Ansar et al. [1] presented a study identifying the reason why the cost of hydropower megaprojects often overruns. In their point of view, the final cost of hydropower dams is too high to be a good investment unless the risk is enough managed. They claimed that the actors in a large dam project are too optimistic on the cost of such projects. According to their point of view, energy alternatives are clearly preferable because of their flexibility and the fact that they are less time consuming. These assumptions threat the future of large hydropower projects as they, by nature, require more time to be developed and higher investments upfront compared with other attractions such as Hard Plants (gas-fuel, coal and fuel and nuclear).

The problem is nevertheless far more complex than it was approached in the above mentioned project. Cost estimation is facing two different problems: first of all projects can be influenced by unforeseen elements and non-controllable elements as it was explained in the present study. The only way to estimate accurately the final cost is to take these elements into account in a tangible way, but this leads to the second problem which is the acceptance of the project. A too conservative estimation of the budged would decrease the chances of the project being financed or would otherwise require back-up guarantees from public authorities. It is interesting to point out that not only hydropower megaprojects are subjects to cost overrun, but also all other big infrastructure projects. As an example, a study on the actual and estimated costs in transportation infrastructure projects is given in Flyvbjerg et al. [5] and showed that, in 9 out of 10 projects built from 1910 to 1998, costs were underestimated.

Results clearly showed the involvement of uncontrollable factors in the process. It is our opinion that the cost overrun should not be a parameter used to denigrate hydropower plans, but a consequence that should be accepted to benefits its various advantages. The human impossibility to foresee the unpredictable does not justify the criticism and the prejudice that was risen against hydropower plants, whose benefits remain undeniable. Cost is probably not the best way to evaluate such big projects and other criteria must be taken into account because hydropower dams are one of the more effective and renewable way to face current and future energy shortage, aiming in parallel at providing the most essential resource on Earth: water [8].

References

1. **Ansar A., Flyvbjerg B., Budzier A. and Lunn D.**, "Should we build more large dams? The actual costs of hydropower magaprojects development", *Energy Policy*, 2014.
2. **European Environment Agency,** "Annual report 2011 and Environmental Statement 2012", 2011.
3. **European Environment Agency,** "Renewable energy in Europe - approximated recent growth and knock-on effects, 2015.
4. **Gomez P. and Probst G.**, "Die Praxis des ganzheitlichen Problemlösens", *Bern/Stuttgart/Wien: Haupt*, 1999.
5. **Flyvbjerg B., Holm M. S., Buhl S.**, "Underestimating Costs in Public Works Projects. Errors or Lie?", *APA Journal*, Vol. 68, No. 3, pp. 279-295, 2002.
6. **Heller P., Bollaert E.F.R. and Schleiss A.J.**, "Comprehensive System Analysis of a multipurpose run-of-river power plant with holistic qualitative assessment", *International Journal of River Basin Management*, Vol. 8, No. 3-4, pp. 295-304, 2010.
7. **International Commission On Large Dams (ICOLD)**, "Risk Assessment in Dam Safety Management: A Reconnaissance of Benefits, Methods and Current Application", *ICOLD Bulletin 130*, 2005.
8. **Schleiss A.J.**, "The importance of hydraulic schemes for sustainable development in the 21st century", *The International Journal of Hydropower and Dam*, Vol. 7, No.1, pp. 19-24, 2000.
9. **World Water Council,** "Water and Green Growth: Beyond the Theory for Sustainable Future", 2015.

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