

Methodology for the Development of Hydroelectric Power Plants

by

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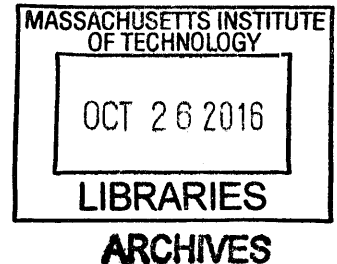
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ABSTRACT

Hydropower has sufficient resources available and is actively promoted by Governments as part of their energy matrix, but its development is constrained by the difficulty of addressing location particularities, including technical features such as geology or hydrology, and institutional features such as social acceptance, environmental constraints and the regulatory framework.

Project results emerge from the interactions of these Inherent Features and the Project Architecture and do not always meet stakeholders' expectations, leading to deficient project results and lost value.

This thesis proposes a methodology for prototyping projects to reflect these particularities and inform project shaping and decision-making early in the process. The proposed methodology was built on three systems engineering and project complexity frameworks, and lessons learned from four case studies. Its contribution to hydropower development is related to (i) the incorporation of systems evolution over time on the development process, (ii) the identification and management of relationships among the various decomposed elements of the development, (iii) the identification of emergent properties from the interactions among all features, (iv) a prototype for developers to optimize or search for project architectures that meet stakeholders objectives while complying with restrictions, (v) the delivery of unbiased information for decision-makers, (vi) the opportunity of stakeholders to participate in the project shaping in a continuous fashion, and (vii) the delivery of a tool for the implementation team to evaluate and challenge changes to the project during construction.

The usage of this methodology does not guarantee the avoidance of errors or unforeseen project outcomes, but it does reduce the chance for unknown risks emerging from the interactions of the evaluated features.

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I. INTRODUCTION

Hydropower is recognized to have many advantages relative to other power sources: (i) it is a renewable source, not dependent on fossil fuels or its price variations, (ii) creates infrastructure for neighbor communities, (iii) provides secure energy supply, (iv) complements other renewable energy sources (such as seasonal complementary or storage when considered on its design) (v) has secondary benefits as water regulation for other uses (drinking, navigation, recreation, aquaculture or irrigation), (vi) provides protection such as flood control, and (vii) long term life cycle (50 years extended up to 100 years). However, hydropower is also known for different problems related to its implementation, such as (a) relocation of people/communities, (b) long payback periods, (c) long construction schedules, (d) high cost overruns, and (e) serious impact to the surrounding area in case of failures.

Nowadays climate change is imposing more uncertainty to hydropower plants' operation as hydrological cycles are changing in different patterns depending on their location (for example, more rain in wet season is followed by higher droughts on dry season). This reduces the ability of hydropower plants to produce or control the river flow, increasing the production risk when a project is evaluated.

Up to 2013 worldwide there is 1,034 GW of hydropower installed capacity (International Energy Agency - IEA, 2015) and it is expected to grow up to 1,947 GW in 2050 (International Energy Agency - IEA, 2012), mainly in developing countries where potential is not completely employed. Even though there is a higher potential in terms of water resource, not all is feasible (they may be too expensive, or there may be environmental or social restrictions that prevents its development).

The thesis proposes a Methodology for the Development of Hydroelectric Power Plants that allows developers to clearly define the objectives of a particular project and, evaluate or optimize the development results, by early prototyping of the interaction between architectural choices and the existing inherent features of the system.

A case studies will show how well the reviewed projects fits into this proposal, and how the application of the proposed methodology during the development phase would reduce the uncertainties that lead to negative outcomes during implementation.

1.1. Problem definition

Hydropower plants are Large Engineering Projects, and their development, implementation and operation are unique (Lessard & Miller, The shaping of large engineering projects, 2013) compared to the other conventional energy sources, as they are “always custom-designed site-specific projects” (International Finance Corporation - IFC, 2015)

Based on their nature, hydropower projects are challenging enterprises that depend on site conditions (such as geology, hydrology, environmental aspects), but also on several stakeholders (from local communities to lenders) that imply uncertainty regarding the project final cost and schedule, on top of the market risk during the operational period (not limited to demand and supply evolution, but also to changes on market rules or regulation imposed by Governments) which extend for long periods of time, perhaps even centuries. Further, hydro projects are not always the most environmental friendly solutions because they may impose higher environmental and social impacts, mainly related to the reservoir.

As shown in “Should we build more large dams? the actual cost of hydropower megaproject development” (Ansar, Flyvbjerg, Budzier, & Lunn, 2014), hydropower projects were on average 96% higher than estimated costs (the median overrun was 27%); these statistics are irrespective of the year or decade of the project construction, therefore there appears to be little learning from past mistakes. Regarding on schedule performance, large dams took 8.6 years in average, 44% in average higher than the estimated time to completion (median schedule overrun of 27%). According to this study, decision-makers are often biased towards optimistic benefits of a decision and optimistic judgements.

Because major architectural definitions are defined and fixed during the development phase (from concept definition to implementation planning) a holistic approach must be taken in order to define project architecture(s) that provide the best results within the project restrictions, while

identifying and mitigating (or promoting) emergence properties. The evaluation of the final development results will lead to decisions related to the start of the construction phase (project implementation) or the project cancellation.

1.2. Hypothesis and Proposed solution

Each hydroelectric project is a unique infrastructure development that, due to its uniqueness and complexity, must follow a systematic approach during its development.

Unforeseen events during construction or operation appear because current development practices (i) are not fully coordinated among stakeholders and not always involve joint decisions on major aspects of the project (such as site selection, social and environmental impacts, actual and future potential use), and (ii) don't include flexibility for changes due to the dynamic nature, emergence and long timeframes of this type of projects.

The proposed solution is a methodology that allows developers to (i) define and challenge its objectives and restrictions, (ii) prototypes the interaction between architectural definitions and the existing inherent features of the system early in the development process, (iii) optimize the expected results in compliance with the project restrictions, and (iv) provide the implementation team with a model to evaluate potential changes or findings during the project construction.

The methodology consists of three components: concept definition, development prototype and results evaluation and shaping.

II. SCOPE OF WORK

2.1. Life-cycle

The lifecycle of a hydropower project can be divided into the following phases:

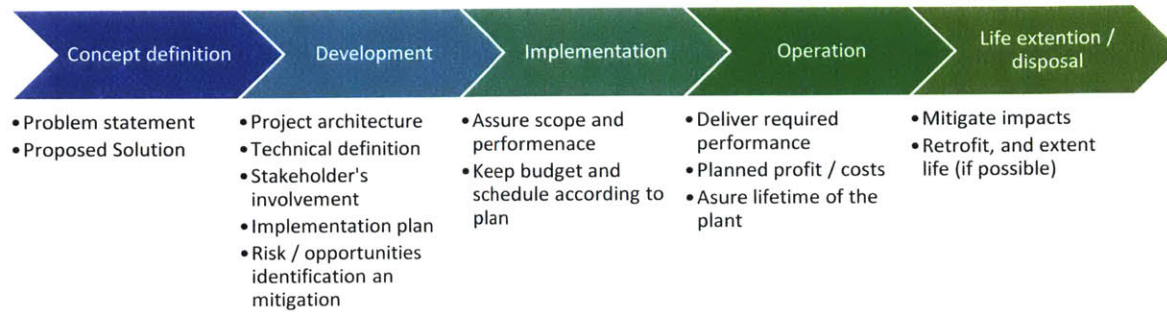


Figure 1. Project lifecycle

These phases typically proceed in a linear or “waterfall” fashion. Even though there is a dynamic behavior within each phase, there are clear deliverables at the end of each one (some of them may be completed in the next phase). Due to the level of commitment at the beginning of each phase (especially at the beginning of the implementation), there is normally no return to an earlier phase, unless major changes are required. Iterations involves repetition or rework, and when unplanned, they lead an increase in project cost, schedule and/or risks (Eppinger & Browning, 2012).

Within the **concept definition** phase, the system problem statement must be defined, which may content the following structure "to by using". The analysis must include the context definition and stakeholder needs (including their required value creation). The required form and function of the system must be identified in a solution neutral environment. The intention of this phase is to validate the real need of a hydropower plant within the context, and must deliver the following items:

- A set of objectives and restrictions
- A concept of the system, and its operations (including contingency and emergency operations)
- A functional description of the system with at least two layers of decomposition (form and function)

- Required external interfaces

The **development** phase is the most critical in terms of risks identification and mitigation; within this stage the inherent features are broadly identified, the project architecture is defined and the emergence functionalities and risks are forecasted; leading to the preparation of an implementation plan (budget, schedule, performance). The initial plan is defined and the stakeholder's major commitments are required in order to start the next phase.

As defined in “System Architecture, Strategy and Product Development for Complex Systems” (Crawley, Cameron, & Selva, 2015), the role of the developer includes “reducing ambiguity (fuzzy information, uncertainty, missing information, conflicting information, and incorrect information), employing creativity, and managing complexity”

The **implementation** is related to the project construction where detailed design is produced and construction entities are deployed with the objective to have the project in budget on schedule. Deficits from the previous phases are materialized and project management skills are required to mitigate any emergent, not foreseen, risk. “The long duration of large projects means there are many changes in personnel, organization, management and market conditions between the handshake between client and contractor and the handoff of a finished facility, so it is difficult to attribute outcomes to decisions made months or years before – John Sterman” (Cooper & Lee, 2009)

The **operational** phase provides the value required, and the project performance to deliver the required energy is materialized, this phase is the longest and requires some additional investment from time to time to extend the project lifetime.

The **life extension or disposal** phase must be planned and designed as a new hydropower project, and has to go through a development phase, to allow stakeholders to participate and define/mitigate the impacts within surrounding areas. A clear scope of works and authorities permitting is required, but also contractors and a project management organization to execute the works. It is not always evident during the development phase how the project will be “closed out”,

abandoned, or remediated at the end of its technical/economic life, as we expect very long lifetimes for most hydropower plants (Zheng & Hobbs, 2013).

2.2. Scope of work and employed frameworks

The result of the Concept Definition and the Development phases provides

- information and expected results and emergence for decision makers to decide the future of the project, either to invest or to cancel the project. This decision implies the major commitment of the sponsors, by signing construction contracts, long term power purchase agreements, construction commitments with authorities, among others,
- project architecture and a risk assessment for implementation teams to follow and start the project construction,
- production forecast and market commitments for operators to deliver the expected value, and
- design elements for the decision of life extension or disposal of the project.

Because of the importance of this two phases on the final project results, this thesis will be limited to the Concept definition and the Development phases, as shown in Figure 1.

Our framework draws directly on three models/frameworks: the systems engineering VEE, the House of Project Complexity (HOPC), and the Multidisciplinary System Design Optimization (MSDO).

The Vee model is a representation of the project lifecycle, formulated as a V, where time and system maturity proceed from left to right; the left downward stroke of the “V” has the early systems engineering activities that move from requirements to design specifications, and the upward stroke completes design engineering and moves through the construction and integration of system (Eisner, 2011).

The Vee shown on Figure 2 highlights the need to (i) define verification plans during all lifecycle of the project, (ii) continuous validate with stakeholders, (iii) early prototype the project architecture, and (iv) perform continuous risk and opportunity assessment. Time and system maturity proceeds

from left to the right, and “Since one can never go backward in time, all iterations in the Vee are performed on the vertical “time now” line. Upward iterations involve the stakeholders and are the in-process validation activities that ensure that the proposed baselines are acceptable” (International Council on Systems Engineering - INCOSE, 2011)

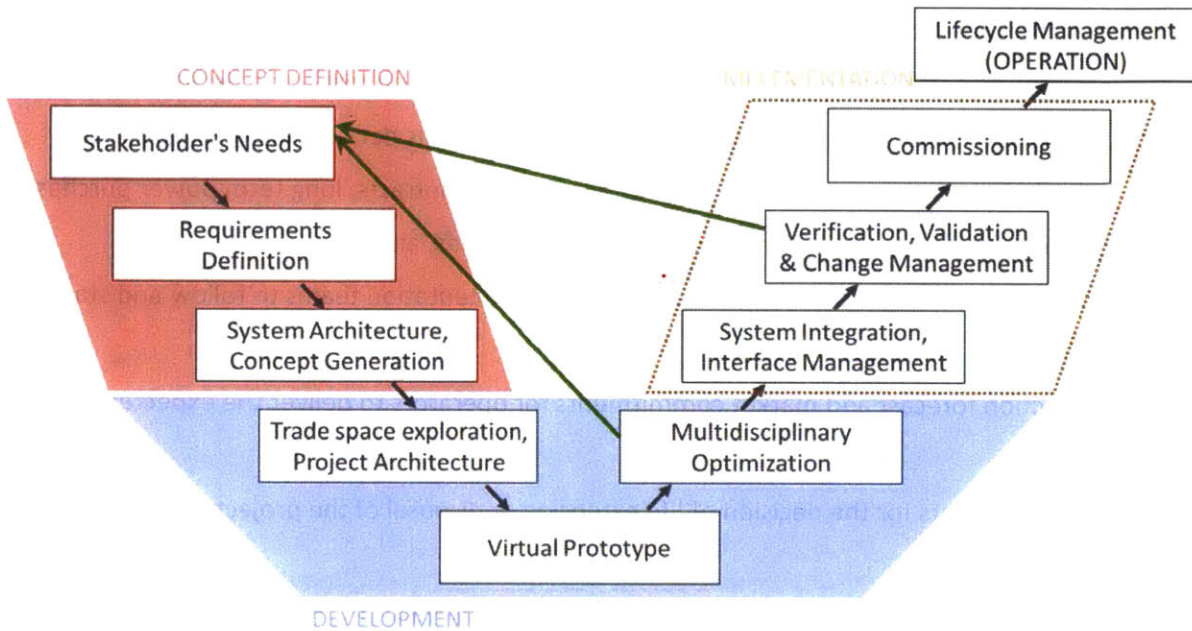


Figure 2. The Vee model for hydropower project

The House of Project Complexity (HoPC) is a “combined structural and process-based theoretical framework for understanding contributors to complexity”. Its contribution to the understanding of complexity in large infrastructure projects is based on the relationship between “architectural features” and “inherent project features” (which can be separated into technical and institutional domains), and their relationship with the project outcomes or results (Lessard, Sakhrani, & Miller, House of Project Complexity—understanding complexity in large infrastructure projects, 2014)

Hydropower projects are complex and multidisciplinary with several inherent features and architectural choices (as described in section 3 and figure 6). Therefore, the HoPC will define the first level of decomposition and the interaction between architectural choices, inherent features and its results.

Multidisciplinary system design optimization (MSDO) is an engineering field which objective is to find a system design that will minimize some objective functions. As complex systems require more than one traditional disciplinary area, MSDO avoids the tendency to have individual discipline optimization and individual constraint satisfaction. MSDO takes advantage of numerical and computational techniques to search for optimal designs, but also when non-numerical or qualitative models are used, tradespace exploration allows the adjustments of the design to comply with this non-numerical models. The challenge of MSDO is "how to decide what to change, and to what extent to change it, when everything influences everything else" (American Institute of Aeronautics and Astronautics - AIAA, 1991).

The complexity of hydropower projects requires the expertise of several disciplines to deploy one or several project architectures that optimizes the results while complying with restrictions (either technical or institutional), therefore, an MSDO approach must be taken to propose different project architectures in a tradespace where technical and institutional restrictions are complied.

Some other used frameworks or tools to improve the analysis process or the modeling are (i) System decomposition, a tool to decompose any system into sub system or entities, while maintaining the couplings among them, to better forecast the relationship among them and preserve the advantages of individual analysis, (ii) design structured matrix (DSM), a tool to analyze the relationship between several components of a system which shows potential commonality among these components to bundle or unbundle them, (iii) the House of Quality (HQ), a framework to better integrate stakeholder's need into project objectives, and (iv) system dynamics (SD), a method to enhance the understanding of complex systems and its dynamic behavior.

2.3. Development framework

The interaction between the HoPC, the Vee model and MSDO provides an analysis of every hydropower project beyond the House of Project Complexity, allowing early prototyping and optimization or tradespace search before the implementation commitment.

Including a virtual prototype and optimization or tradespace search loops based on this prototype before committing the project implementation increases our chances to discover and understand unexpected emergence (positive or negative) and mitigate or potentiate them.

The development phase is a process of understanding the nature of the project, and its fundamental requirements, but also the relationship between the different choices towards a feasible project that complies with all requirements from stakeholders. Therefore, I propose that hydropower projects should be analyzed within the proposed development framework as described herein (see Fig. 3)

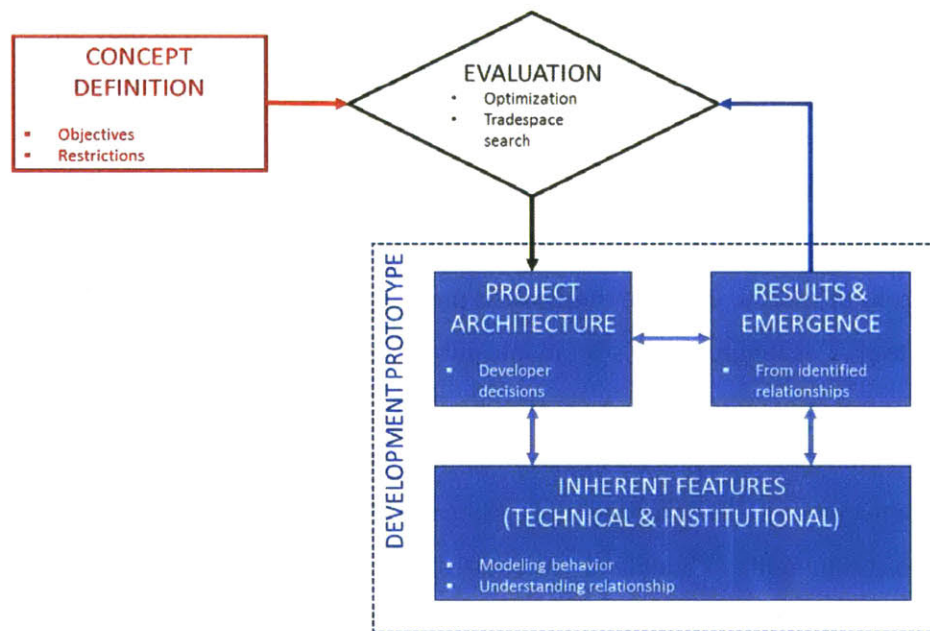


Figure 3. Hydropower development framework

The Concept Definition intends to demonstrate the need of the project for given stakeholders or society, and outlines the project objectives (ex. maximize the rate of return on investment or maximize the yearly electricity production) and its restrictions (ex. minimum reservoir storage and social acceptance).

Then Project Architecture is defined on the nature of the project (such as design or construction methodology) and the way we will execute the project (such as permits strategy, or how we organize the project team).

Understanding the Inherent Features of the existing system and its behavior is the most demanding activity within the development process, but is the key element to allow design an early prototype of the project.

The Results or Emergence from the interaction between architectural choices and inherent features are the output of the development prototype. As hydropower projects are complex, there are interactions between Results, Project Architecture and Inherent Features therefore all these entities are coupled and several internal loops must be performed.

Finally, we Evaluate the results and analyze possibilities of optimization or tradespace search. Based on the degree of compliance with objectives and restrictions or acceptance criteria, we may start further studies to optimize the project or minimize uncertainties.

There are time constraints when applying the framework and its methodology, for example in terms of due dates for the delivery of final project results, impacting, among others, (i) the degree of understanding the inherent features, (ii) the detail on the project architecture and its architectural choices, and (iii) the number of evaluation and optimization/tradespace loops.

III. DEVELOPMENT METHODOLOGY

The purpose of the concept definition and development phases is to mature the project up to a level of implementation commitment, where the project origination must be continuously challenged in view of the inherent features and emergence properties discovered during this phases. This process may take several years; therefore, the project origination criteria and its promoters may change, impacting its attractiveness.

The main idea is to develop the project through an evolving prototype, where all assumptions are updated and challenged, mainly the foundational ones. The conclusion of each analysis may lead to the conclusion/suspension/continue/acceleration of the development. The nature of the project, linked to its long development timeframe, requires this type of development.

3.1. Concept definition

This phase of the project outlines the rationale behind the need of hydropower, why and how is it proposed to meet this need. Is important the outline the factors that leads to hydropower and continuous challenge this factors during the development phase.

We should start the Concept definition by analyzing the Need of hydropower and the Context on which this need emerges. Understanding need and context allows the definition of the Problem statement and a proposed Solution neutral to end with the Concept of the project.

The interaction between the Concept of the project and the stakeholder's need are translated into project requirements in terms of objectives and restrictions that must be complied during the development phase.

3.1.1. The need of hydropower

The problem normally comes from the need for electricity in the country, region or major industries. Needs from hydropower are normally:

- Guaranteed capacity and energy; has to do with an amount of energy to be supplied as base load, or during peak hours, or during some months of the year.
- Auxiliary services to the grid, has to do with frequency control, voltage control, and energy storage.
- Water management for flood control, and avoid damage to human activities during extreme weather conditions
- Water storage for irrigation or human consumptions, saving water from rainy seasons to be used during dry seasons.

Electricity requirements may be triggered due to (i) demand growth, (ii) high electricity costs (if mainly sourced from fossil fuels), (iii) political decision for a balanced energy portfolio, (iv) grid transport restrictions, (v) energy storage, (vi) non-connected industries, such as mining companies, among others.

As the problem may be solved by the installation of a hydropower plant, it is relevant to define the sources or income that provide for its financial feasibility:

- Energy and capacity income. Normally energy is valued at a tariff which may have one or all of the following characteristics: fixed/indexed price, take-or-pay volumes, Spot market or private power purchase agreements (PPA), country's regulation may impose limits or restrictions to the tariff as energy is a public service.
- Auxiliary services income, such as differential price between peak hour and low demand hours for pump-storage facilities.
- Water use income, in case water is also used for other services such as farming or human consumption. This income may be in conflict with energy income, because the timing and required volume may differ from electricity needs

Normally a quick forecast of project viability is made with referential designs and ratios from similar projects, that help the decision maker to evaluate the timing to initiate the development phase and try to identify the major risks (mainly from the expected income, such as plant availability, volatility of the spot market, long term forecast of energy prices, and availability of the resource). This approach assumes that institutional features in place (such as market regulation,

applicable law, or authorities' behavior) will remain constant; these assumptions will be challenged and further studied during the development phase.

Because the development phase will take some years to be completed, market forecasts (such as demand and prices) will have to be updated on every iteration during the development phase. Other major risks should be identified, mainly related to the viability of the project such as Environmental constraints (i.e. location within national parks or reserved areas, local geology, hydrological resource not enough or with high variability within the year, flooded area with people relocation, among others).

3.1.2. Context analysis

The origin of any hydropower project is linked to the society's need for electricity; therefore, the society's context (past, present and future) is relevant to measure its need and its evolution overtime, for example a continuous growth of a country, which creates an increase of the electricity demand, will open the following development opportunities for hydropower:

- The Government may anticipate the required supply and propose incentives for the development of new power plants, and can even set a target for hydropower
- Industrial clients or distribution companies may want to secure their supply, but also the long term price, via long term PPAs

For example, in Peru hydroelectricity was promoted by the Government in order to balance its energy matrix (currently ~40% of the electricity supply comes from hydro) via (i) long term PPAs with distribution companies applying a differentiation factor of 0.85 for comparison with other technologies, or (ii) guaranteed income for a guaranteed energy production, and (iii) incentives such as accelerated depreciation (up to 20% per year).

The electricity market is a relevant institutional feature to understand at this phase, as this market will define the operation rules of the hydropower project (which includes economical dispatch criterion, peak demand participation, water storage, transmission restrictions, grid access, and grid stability) and its remuneration scheme (marginal costs or prices for energy, capacity remuneration, reliability options, ancillary services, among others).

Applicable law may promote the development of hydropower by several incentives, such as feed-in-tariffs, long term energy contracts, carbon reduction mechanisms, and tax incentives; but it will impose some requirements related to environment protection, human rights, community consultation, participation in public services, among others. It is relevant to assess the existence of a water resource plan for the river the project will impact, its validity and the level of participation of stakeholders in the preparation of such plan.

Due to the long time required to mature any hydro project, its development can start early by independent private or public initiative, starting from resource analysis and portfolio identification, up to the development phase, in order to be ready to take any commercial opportunity in the future

Also water supply projects may lead to hydro projects, as an improvement of the projected infrastructure; dams developed for water storage, human consumption, irrigation, transportation and/or flood mitigation may easily be used for electricity generation with a lower incremental cost.

3.1.3. Problem statement

The context described before, identifies and understand the need(s) of the beneficiaries. Needs are fuzzy, ambiguous and ill stated, they exist on the beneficiary, outside the company or project team (Crawley, Cameron, & Selva, 2015). The beneficiaries may require more alternatives to cover their needs, but also they may have additional non identified needs.

It is important to set the main attributes of the proposed solution, as the attribute of the delivered product by defining what is planned to be accomplished and what we achieve to obtain.

The Principle of the System Problem Statement says: “the statement of the problem defines the high level goal and establishes the boundaries of the system” (Crawley, Cameron, & Selva, 2015). Due to its impact on the project architecture and design it has to be continuously challenged and refined.

The easiest way of defining it is by using the “To-by-using” framework, for example:

- To (solution-neutral transformation) → “To supply electricity”
- By (solution specific operating process) → “... by storing and transforming water flow energy”
- Using (specific system form object) → “... using a hydroelectric power plant”

The basic drivers for the project implementation must be outlined in relation to the need or the problem to be solved; this statement must provide answers to the following challenging questions (International Finance Corporation - IFC, 2015):

- What role would the proposed HPP project play in the power market?
- Does the power market require additional capacity or energy and when?
- Are current or future electricity prices sufficient to cover hydro investments?
- Are there other substitutes to hydroelectricity? but also other competitors?
- Are key stakeholders informed of the advantages or disadvantages of this type of technology?
- Have major environmental or social findings been identified?

3.1.4. Form and function, solution neutral

The “neutral” concept is founded on a solution to the problem statement, which in this case is related to hydropower as the main alternative, it shall include form (i.e. hydroelectric power plant and its dam), function (i.e. transform natural water flow into electricity and/or regulated water flow), operand (i.e. energy, water flow), and processes (i.e. conversion of mechanical energy into electricity).

The Principle of Solution-Neutral Function says that “poor system specifications frequently contain clues about an intended solution, function, or form, and these clues may lead the architect to a narrower set of potential options. Use solution-neutral functions where possible, and use the hierarchy of solution-neutral statements to scope how broad an exploration of the problem is to be undertaken” (Crawley, Cameron, & Selva, 2015).

The intent, expressed as a solution neutral-function, designate the goals for a system. The procedure to define the intent is:

- Consider the beneficiary and its need. Identify the need we are trying to fill.
- Identify the solution neutral operand that, if acted upon, will yield the desired benefit.
- Identify the attribute of the solution-neutral operand that, if changed, will yield the desired benefit. Also identify other relevant attributes, if any, important to the statement and fulfillment of the goal.
- Define the solution-neutral process that changes de benefit-related attribute

This solution neutral statement, and its assumptions must be continuously challenged during the process to anticipate potential changes that may lead into changes in the project architecture before major commitments are made.

3.1.5. Concept

The concept embodies both the function (how it will work) and an abstraction of the form, allowing a high level reasoning and initial prototyping. It should be developed from a set of possible options.

Concept is based in a hierarchy of functions, where one level becomes the solution-neutral function at the next level down the hierarchy. Project architecture is about the understanding of all levels of this hierarchy. In the example below, the value delivery goes from the operand to the beneficiary.

In the example (see Fig.4), the concept is electricity as a conversion “of energy” from river water flow using a hydroelectric power plant, but it is also shown other potential alternatives to fill the need; the feasibility of these alternatives must evaluated in the statement analysis, and results continuously challenged. NCRE (non-conventional renewable energy) can evolve during the project development timeframe to became the best alternative, cancelling our project.

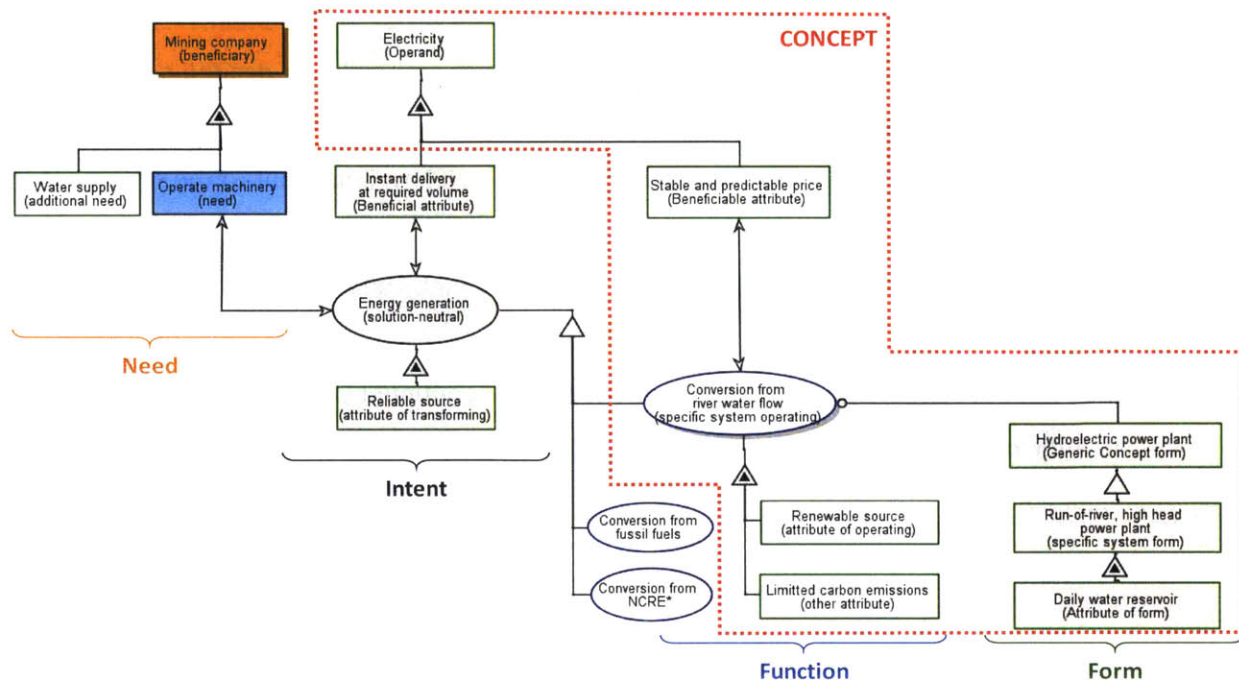


Figure 4. Example of a Concept and System Problem Statement

By decomposing the form showed in the example, we start analyzing inherent features, such as the hydraulic energy resource, which is related to:

- Water flow, continuously varying due to seasonality, climate change, other uses upstream, floods; its expected forecast is based on the past elements (two or more years of site measurements). Flow measurements are essential for the dimensioning of the power plant and its safety. This inherent feature is normally the more uncertain at the beginning of the project and the most important element to study, as other users or stakeholders may hold interests on water availability
- Head (difference between intake and discharge levels) is defined by the topography of the site and the design of the project; therefore, changes along the development process are minimum and its controllable by the design which adjusts the final value. It may be constraint by local communities (flood restrictions) or mitigation of environmental impacts.

3.1.6. Objectives and Restrictions

The result of the Concept Definition is to translate the needs from customers to a set objectives and restrictions, which will be used by the development team to evaluate the project results during the development phase.

A useful tool to execute this task is called the House of Quality (Hauser & Clausing, 1988) which helps the developer to define (1) the relationship between the customer's needs (WHATs) and the project requirements or features (HOWs), (2) define the correlation between project requirements or features (HOWs vs HOWs), (3) define the project goals or objectives (HOW MUCH), and (4) define the importance of the WHATs and the goals. This analysis can be expanded and cascaded to a lower level, where the HOWs became the WHATs, increasing the details of objectives for the project.

Using the example above (see Fig.4), we may infer that the need of the beneficiary (the Mining company) can be met by producing electricity with instant delivery at required volume, but also at a stable and predictable price. By using the House of Quality (see Fig.5), we can define the following Objectives, to be used during the development phase:

- maximization of the water reservoir,
- maximization of the plant capacity,
- maximization of the grid connection to allow the export/import of electricity, and
- minimize the required fixed PPA price

We can define the project development of hydropower plants as multi objective projects, and some objectives may be contradictory, such as water storage vs generation capacity, therefore the trade-off between conflicting objectives must be set at the beginning or during the evaluation phase, to allow for an adequate optimization/tradespace options of the project

Customer's requirements (WHAT)	Functional requirements (HOW)			
		▼	▼	▼▼
	maximize	maximize	maximize	minimize
	Water reservoir	Plant capacity	grid connection	Fixed priced PPA
<input checked="" type="checkbox"/> Energy volume to meet load diagram	+	++	+	
<input checked="" type="checkbox"/> Instant delivery at maximum demand	++	+	++	
Stable price	++		-	++
Predictable price	+			++
	7h peak hour storage <input checked="" type="checkbox"/>	Peak demand (150MW)	Plant capacity (150MW)	Market price (50 USD/MWh)
	Objectives (Target or limit value)			

Relationship between customer and project requirements

- ++ Strong
- + Moderate
- Weak

Importance

- High

Correlation between project requirement

- ▼▼ Strong Positive
- ▼ Positive
- ▽ Negative
- ▽▽ Strong Negative

Figure 5. Example of a Quality Function Deployment (House of Quality)

According to the principle of balance: “many factors influence and act on the conception, design, implementation, and operation of a system. One must find a balance among the factors that satisfies the most important stakeholders” (Crawley, Cameron, & Selva, 2015); these factors leads to constraints that the project must met while trying to achieve its goals.

The house of quality sets restrictions to the goals or objectives. In our example:

- water reservoir with a minimum of 7h peak hour storage,
- plant capacity sufficient to withstand the mining peak demand (i.e. greater than 150MW),
- grid connection capacity to allow the export/import of electricity, sufficient to export the plant capacity (i.e. greater than 150MW), and
- required fixed PPA price at lower values than market prices (i.e. lower than 75 USD/MWh)

But there are other restrictions related to the Inherent Features of the project, for example:

- project rate of return at higher values than shareholders’ requirement
- minimum land obtained/purchased to approve the project for construction
- approval of the environmental impact assessment by authorities
- maximum reservoir water level lower than the community flooding level
- guaranteed flow into the river greater than the ecological flow.

3.2. Development Prototype

Once the concept has been defined, the objectives of the project have been clarified and the needs of key stakeholders has been confirmed, we must explore the project creatively, completely and rationally.

Complexity is inherent to any hydropower project and emerges when going through the development and more information and concerns appears. The role of the development team is to keep complexity as low as possible, and keep the system from becoming unduly complicated.

Interfaces among elements or modules contribute directly to complexity.

As interfaces are connecting points between interacting elements and defines the boundaries of a system. It has the following characteristics: object and process nature, complexity and stability. At the interface form has some structural relationship (usually compatible), a function is performed (usually the process is the same or the complement) and the operand is the same.

Based on the House of Project Complexity “HoPC” (Lessard, Sakhrani, & Miller, 2014) and the Multidisciplinary System Design Optimization “MSDO” (de Weck, 2016), I propose that the development process must be aligned to the framework presented in section 2.3.

The system is defined by its inherent features, which are interacting among them in a relative stable behavior without the project; by implementing a project within the system boundary, we will impact these inherent features in intended and non-intended ways; therefore, after project definition, an analysis of the inherent features and its behavior must be done, in order to forecast the impact of the different architectural choices, anticipate the emergence and match its compliance with the project objectives. Once project results match the objectives, optimization/tradespace loops must be performed to (i) optimize results, (ii) include new information (from inherent features or architectural choices). After optimization/tradespace iterations, the project must be challenged against its objectives.

The intention of this framework is to build a prototype of the system, where we can test our Project Architecture and evaluate the results without making implementation commitments.

The model will also provide unintended results (emergence) that we must mitigate (or promote) on the development process, either with more studies to understand the inherent features, but also changing the architectural choices or accepting the new results.

Understanding and modeling the inherent features are the most expensive activities within the development process; therefore, it may be realized in an evolving matter. The model must evolve over time, from low fidelity at the Concept Definition phase to a high fidelity model at the end of the Development phase, including better information and model responses from inherent features, which in turn requires more detailed architectural choices to provide more certain results, but also allowing optimization/tradespace loops to improve them.

To build the prototype, we have to define a certain level of decomposition that allows a better understanding of the system, the proposed decomposition integrates the major aspects to be considered when developing a hydroelectric project, but also this list is not exhaustive and must be adapted to each project in particular:

- Project Architecture: Design / technology, Construction, Organizational set-up, Permitting strategy, Financing strategy, Social management plan
- Inherent Features:
 - o Technical: Resource availability, Location features, Environment status, Facilities availability
 - o Institutional: Authorities, Local organizations, Project members, Law and regulation, Market
- Results: models and results from the interaction between architectural choices, inherent features and the model results

Normally, Inherent Technical features are given, driven by nature process; therefore, our goal is to understand the current conditions and initially build the Project Architecture based on them.

Inherent Institutional features are highly coupled with all components of the prototype; as they

tend to react on changes to Inherent Technical features, to the Project Architecture, and even to some Results; this features are evolving over time during the development phase, and developer should guide this evolution. The Project Architecture includes all adjustable decisions and features to adapt them to restrictions imposed by the Inherent Features, while trying to obtain Results that meet project Objectives and Restrictions.

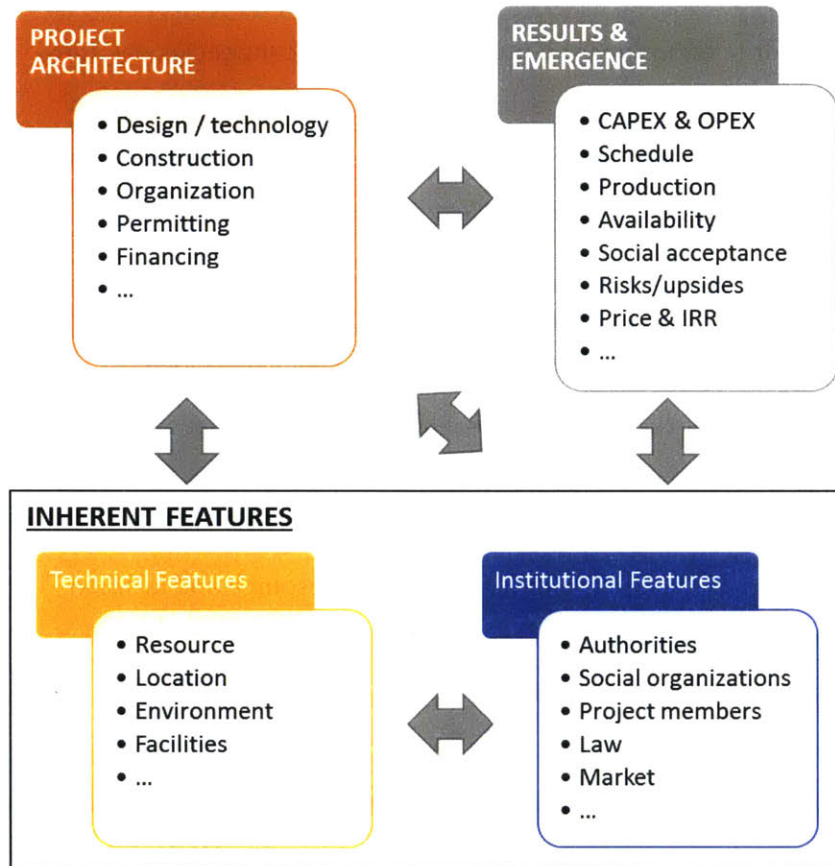


Figure 6. Major components of the Development prototype and its relationship

Each entity must be further decomposed to better understand its impact and/or behavior on the system.

The complexity on this type of projects can be seen in the high level of coupling among the architectural choices and the inherent features. The example below shows a potential sequence of activities for a particular project, but this assessment must be repeated for every particular project

and at a lower level of decomposition to integrate the relationship between other aspects of the project.

Building the prototype requires a clear understanding of the relationship among all elements of the prototype, but also plan the loops between them. In order to map this relationships, I propose to use the Design Structured Matrix (DSM) framework. DSM allows us to understand how the project features work together to deliver results, in it we map the hierarquical decomposition of the project features, input and output relationships and mutual resource dependencies. By using DSM, we can plan our activities identifying which can be done sequentially or in parallel, which features are coupled (each feature needs input from others, so they must iterate), and which are conditional (they have impact on downstream features) (Eppinger & Browning, 2012)

The example shown in figure 7 is an N-1 level DSM, and it shows that:

- almost all elements of the prototype are coupled therefore a change of one of them impacts several other elements (i.e. the design and technology of the project architecture impacts several features such as permitting, but some features of the permitting process impact some features of the design and technology).
- the project analysis might start understanding and modeling the resource and location features as they don't depend on any other feature (they are given)
- is possible to cluster some features to treat them together due to its high interrelationship
- this low fidelity DSM guides an initial prototyping and development from inherent technical features to a clustered project architecture (mainly project design) and inherent institutional features, to end with the project architecture (except project design)
- Inherent Institutional Features are in the middle of the DSM with high interdependency with other features

PARTITIONED DSM	Resource	Location	Environment	Design and technology	Facilities	Organizations	Authorities	Project Members	Law	Construction	Organization	Permitting	Operation	Financing
	1	2	3	9	4	6	5	7	8	10	12	13	11	14
Resource	1	1												
Location		2												
Environment			3	1						1				
Design and technology	9	1	1	9	1	1		1	1		1	1		
Facilities				1	4									
Organizations	6			1	1	6	1	1	1	1			1	
Authorities				1			5		1					
Project Members								7	1	1	1	1		
Law								1	8					
Construction				1						10	1	1		
Organization		1						1		1	12	1	1	1
Permitting				1					1	1		13	1	
Operation								1					11	
Financing								1	1		1			14

Figure 7. DSM of the relationship between architectural choices and inherent features

3.2.1. Inherent Technical Features

Resource

- Water availability: based on hydrological measurements (either flow stations or pluviometry stations), is the most important feature. Specific hydrological studies must be performed and its validation should be done by more than one independent engineer. Early studies will prevent the stakeholders from expending money in non-feasible projects. It impacts several inherent features (technical such as water usage, existent fauna and flora, and architectural choices, but also institutional such as the behavior of regulatory bodies, system operators) and architectural choices (such as several aspects of the design, construction and permitting). Its direct impact on the results (production or usage) drives the feasibility of the project to meet the project needs and objectives.
- Water usage: based on current and known future use that may reduce its availability for the project and/or the behavior of the resource (such as farming, cattle, human consumption). Its impact on society is the driver of authorities' interest, but also drives changes in law and regulation. The project must respect current usage and include these

restrictions within its design. If water usage is located upstream the project, then its behavior will also impact the project production.

- Flow variance: based mainly on exceptional events that may lead to damage on the works or the property, and must be addressed during the design and construction of the Plant. It may drive another project objective of flood control where high river floods are expected. Its exceptional occurrence bring emergence to the project such as risks to construction or operation, floods to communities and farming areas, but also changes to the site topography, destruction of flora and fauna habitat); therefore, its analysis must be included within the design and construction methodology with mitigations driven by the probability of occurrence

Location

- Sediments: based on the river basin, river may from time to time carry sediments in different nature which may (i) reduce the useful volume of the reservoir, or (ii) erosion the mechanical parts in contact with the water (gates, valves, distributors or turbines); but also the impact of sediment retention in downstream ecosystem (Morris, 2015)
- Geology and seismicity: based on site tests, inspected by experts or based on empirical or historical data. It will define the technical solution to be implemented, which must reduce construction and operation risks. As its impact is normally huge in terms of project CAPEX and schedule, it is heavily studied by other institutional features such as lenders, insurance companies, constructors; impacting the design of the project.
“The basic problem faced by a designer in attempting to predict the geological and geotechnical risks in the construction of a highway, a long tunnel, an underground power house or a dam foundation is the adequacy of the information obtained from the site investigation program” (Hoek & Palmeiri, 1998)
- Topography: defines the basis for the design in terms of head, quantities. Shows the physical reality of the site impacting the construction. It also defines the actual usage of the land from local communities.
- Morphology: superficial stability of the project site and surrounding areas, which may be instable causing at some point in time damages to the project, but also change of a river basin, based on the effects of natural water flow during time.

Environmental

- **Climate:** sets the historical variations of the weather (ambient temperature, humidity, wind velocity and direction, irradiation, among others) and its frequency, it allows the design of equipment exposed to some of this climatic conditions or climate change. Climate change is currently a major concern for hydropower projects due to its impact to water availability and flow variance in the long run (Rikard, 2015).
- **Fauna and flora:** defines the species using the area as its habitat, therefore its study will show us the impact of the project implementation and operation to this species which may be or not acceptable; special attention to aquatic fauna must be considered. Mitigation of these impacts will adjust the project design by imposing one or several restrictions.
- **Soil and air:** may be impacted, especially during construction due to emissions or effluents from machinery, but also during operation (such as methane from big reservoirs or increase in water draft level)
- **Archeology:** remains of any time may turn non useful the site where are located, some may be rescued and removed, but others must stay, impacting the feasibility of the project if the project cannot be re-located.

Existing Infrastructure or Facilities

- **Access and roads:** its existence will define the transport requirements and the scope for changes on existing roads or the construction of new ones. It is normally required that a project must have access in good conditions to its components and the extra cost will impact heavily the project. Also they serve local communities and are operated by local or private companies.
- **Electrical grid connection:** same as above but related to transmission grid; the distance to any connection point will impact the cost and risk of the project. Its operation is made by the system/grid operator and access to the service may need a direct negotiation with owner, if not regulated. Transmission restrictions may limit the production of the project.
- **Construction materials:** availability of construction materials will define the conceptual design of some components, but also the planning and budget. Some activities must be performed prior the exploitation of these materials.

3.2.2. Inherent Institutional Features

Authorities

- Governmental authorities: sets policies and grants permits to activities based on its authority level, for example (i) National/Regional Government sets national policies related the Country's objectives, such as growth objectives, social inclusion, industrialization, etc., (ii) Sectorial authorities set energy, water usage, environmental or transportation policies that allows support to specific technologies (these specific policies may promote the development of hydropower through direct investment, income guarantee, long term contracting, tax advantage among others, but also cancellation of hydropower to favor other natural sources, (iii) Local/municipal authorities which grant permits to some activities such as environmental permitting, archeological release, operation permits (some of them may be granted at the National/Regional level), and (iv) Other related authorities involved in the project due to its national impact or requirements, such as customs for importation of machinery, transport authority due to inland transportation of machinery/material, but also the construction of bridges and new roads, environmental authorities due to the supervision of the implementation impacts, among others
- Regulatory bodies: which role is the control of the project activities and its compliance with laws, permits, contracts and industry practices. They may set rules for the project, inspect its activities and require changes. They also regulate the market in which the project will operate and also the tariffs and commercial conditions that remunerates the project during its operation
- Utility system operators (water and electricity) which defines the operating procedures and technical requirements for new projects to integrate the system without impacting its current operation and reliability

Social Organizations

- Local communities and associations: may use the site or the resources within the area therefore the construction and operation of the project may limit their current activities; they may also take advantage of employment during construction and potential new activities during the operation. Their sustainable support to the project is within the most

important tasks of the project developers, which must seek for cooperation with them. Their impact is not only related to changes in the design or additional scope to compensate impacts, but also to project feasibility

- Impacted persons: direct impacted people or families due to relocation, flooding, cease of their activities, or any other way of changing their day to day way of living. Their presence may lead to major changes in the project design.
- NGOs: organizations with freedom on their activities which normally seeks for some environmental or social objectives, normally they are well founded. These organizations may jeopardize the image of the project due to its presence in media, but also abroad communication.
- Public services: that grants the project with immediate attention to its needs, such as fire department, schools, medical centers, restaurants, laundry, among others. If not available, the project may include the supply of this services within its scope on any phase of the project.

Project members

- Development or Operational Company: internal organization (local/international) related to the project and corporate teams, and their motivation, goals and experience. Their focus should be aligned to the sponsors' interest and the final client solution, but their motivation or bonus may be driven by cost and schedule commitments. DevCo or OpCos relies on Consultants to acquire expert support in specific areas of knowledge (technical, financial, commercial) in order to allow the project team to take decisions based on their recommendations. Their impact is mainly within Authorities or Market features, but also it may shape the results.
- Suppliers / Contractors: provides machinery or services that will allow the implementation or operation of the project, taking their value through pre/agreed prices or contracting schemes (such as EPC, EPC-M, unit price, cost plus, cooperation agreement, among others). Their impact is mainly on the construction methodology, on the design layout (driving constructability criteria), but also to the social acceptance in the way its workers are immersed in the local communities and the Contractor manages its internal strikes and labor disputes.

- Lenders and insurance: lenders provide with resources to implement the project; depending on their nature and the proposed project schedule, they may impose restrictions to the project during its construction and / or implementation that secures the payback of the loan. Insurance covers mainly financial losses due to unforeseen risks such as machinery breakdown, loss during transportation, and business impact for specific causes. Their risks assessment is crucial for the project implementation and their recommendations during implementation or operation may be mandatory or may imply an increase on the paid premium.

Law

- National law: provides the foundations of the relationships among the parties and the environment (including the use of natural resources), it includes supra national agreements or requirements for certain activities such as financing, carbon pricing, international grid operation and energy exchanges.
- Sectorial regulation and laws: laws specific to the energy sector, or water usage. For electricity market, there are rules related to the operation of the market in the long, medium and short term; they also grant different authority levels to Government entities to rule not defined aspects of the Law. It includes subsidies or governmental support: granting specific rights to the project to facilitate implementation; but also sets some requirements that must be complied to benefit from this advantages.
- Municipal regulation and Native communities' rules and customs: set the rules and permitting for activities at site, and in order to obtain social approval, the project must respect and comply with this rules (if not contradictory to higher level norms)
- Technical standards and Grid code: Technical standards and practices are published by known organizations such as ICOLD, SHA, IEEE, ISO, ASTM, NFPA, among others. Grid code allows the correct operation of the grid without decreasing its availability or reliability, and may change based on the characteristics of each project.

Market

- Competitors: other companies willing to take over the project (if the bid is to acquire the project) or provide services with their own projects with the same or different technologies.

- Market agents: acting in the market to support its operation with other services, such as energy transmission, retail and distribution for electric markets, brokers for transportation, or tourist agents.
- Off takers and clients: direct beneficiaries of the services provided which pays in return the price or tariffs

3.2.3. Project architecture

Project architecture is seen as the cause of cost overruns and delays during the implementation phase, where the implementation of the Project Architecture leads to unforeseen emergence properties that has to be managed by the implementation team. Causes for cost overrun or delays can include one or more of the following project architecture features: “poor site management and supervision, poor project management assistance, financial difficulties of owners, financial difficulties of contractor and design changes” (Le-Hoai, Lee, & Lee, 2008)

Design / Technology selection

- Layout: is the result of the design which includes the physical location of the components, and the type of components considered for the plant, therefore its definition impacts the technical features. It is also important as a communication and planning tool impacting other architectural decisions such organizational or permitting
- Criteria/safety limits: is a summary of main assumptions taken for the design, and comes from regulation, industry practices or consultant experience, taking into account all findings from studies on inherent features.
- Components: required for the project, such as dams, tunnels, channels flood control, power house, penstock, turbines, generators, gates, locks, discharge, access roads, grid connection, camps, quarries, dump areas, among others. Its impact is mainly on the CAPEX and schedule of the project, but also on other architectural features of the design and some inherent technical features (for example turbine impact on migrating fishes, or discharge gate control on sediments) or inherent institutional features (for example, the system operator will be impacted by the volume of water stored in the reservoir)
- Access: in order to get to every major component of the project, and its connection to the national roadmap, but also improvement on the national roadmap to allow equipment of

the project get to site. Based on the topography, this definition may imply a huge challenge and its construction may start prior the construction of anything of the project.

- grid connection: are transmission line(s) and required sub stations that allows the project to deliver energy into the national grid. Based on its distance, it may have big impacts to the environment, but also to local communities, therefore it may require a similar analysis or framework as the one proposed on this thesis for hydropower.

Construction

- Methodology: defined by the design, constructor procedures, availability of construction materials on site and site coordination; it sets the activities and their execution sequence. Once defined, the quality assurance and quality control are important to guarantee the lifetime of the construction or erection of the plant. Its definition has impacts on inherent technical features such as the topography of the site, the use of existing materials; but also inherent institutional features such as work for local communities and NGOs claims.
- Required facilities, camps, laydown, deposits: its construction is relevant to assure that the defined methodology can be executed and people can live and arrive to site and any other part of the project on time.
- Transportation: it defines the alternatives to allow the supply of materials to the project site (either locally, from other areas of the country or from abroad)

Organization

- Project organization: outlines the required people and its competences (either internal or external) to be part of the Project management team (which includes among others the following teams: owner's engineer, permitting and social, health and safety, environmental, contract management, finance, claim management and operations). This team has to manage the division of responsibilities among all project participants, from purely construction activities to representation against authorities; but also assure a smooth transition to the operational phase providing training, manuals, spare parts and tools. The O&M team's main objective is to keep the Plant available and reliable.
- Construction contracting scheme: defines the construction organization among contractors and its subcontractors. It is based on skills, market context, and risk

acceptance. Contracting options goes from turn-key EPC with one contractor, to cost plus margin with several contractors.

Permitting

- Environmental assessment: normally required to start any activity within the site, must be preceded from environmental studies (performed by independent consultants) that demonstrate that impacts on environment are mitigable or acceptable. Findings from the environmental assessment may lead to changes in the project design, the construction methodology and its expected production, but also may lead to impacts on other institutional features and also drive social acceptance.
- Social and stakeholders' management plan, based on the identification of its inherent features (such as behavior, cultural heritage, legal framework). Normally its implementation starts within the development phase with the objective of buy in support to the project and address social concern.
- Archeological release: archeological exploration in sensitive areas must be performed and if no finding or remains were found, access to site are allowed by competent authority; nevertheless, continued supervision is required during construction to identify, if any, archeological remain. Its impact is on the design, but also on the construction methodology.
- Construction licenses: also required to start activities within the site and its mainly related to civil works, can include or not materials exploitation permits (granted to allow the project to extract materials from quarries to build the project, such as earth, rocks or sand).
- Operation governmental permits, such as (i) Generation and transmission permit (to produce and transport electricity from natural resources), (ii) Grid connection permit (required from the regulator or grid operator to allow commercial operation of the plant within the national grid), and (iii) Water use right (issued by the water authority, and is related to the final use and applicable tariff. It takes into account the availability of the resource and current usage).
- Land rights / or acquisition: land, if owned by the Government, is granted together with the sectorial permits; but if privately owned, it shall be negotiated among the parties. Law normally has rules for expropriation of private land if the project has national interest

- Transportation permits: granted by sectorial authorities to allow transportation of heavy equipment through national roads, even with stoppage of transit among these roads.

Financing

- Debt Structure: defines the structure of the loan (project finance or corporate loans) and potential sources, such as multilaterals, private banks or government loans; also loan tenors and conditions has to be assessed.
- Equity structure: defines the need of potential investor or investors that can provide equity to the project; including its agreement and interest on the project.
- Currency structure: depending on the Project location and the applicable law, several currencies might be needed and the development team must define the number of currencies, but also the quantity of each one and exchange rate risk mitigation. Its evolution among time, driven by macroeconomic policies, change the project results mainly because of impacts on CAPEX estimation, but also on the revenue forecast.

3.2.4. System boundaries

Hydro project can have boundaries at every subsystem; these boundaries must be defined based on the expected impact of the project architecture in the inherent features (either direct or indirect). Boundaries have to be updated with every optimization/tradespace loop.

Geographical boundaries are normally related to inherent technical features, and can be defined by the construction and operations area, including the reservoir dam, access roads, transmission line, camps for personnel, or the river basin when studying the resource availability.

When describing institutional inherent features, it may vary based on the characteristics of each one; for example, the number and level of authorities involved or interested in the project, or the extend of neighboring communities indirectly impacted.

There may be other type of system boundaries related to the specific nature of its inherent features, such as the electrical grid system in which the project will operate, with direct impact on

The relationship between entities is a continuous interaction between quantitative and qualitative stream towards converging into a result; for example, to gain social acceptance, the design may be adjusted to allow activities that benefits the community.

3.2.6. Development models

Modeling a hydropower project is a Multidisciplinary activity, involving several disciplines to work on both inherent features and architectural choices, but also to understand and evaluate the results.

The model may include several modules as disciplines or components are included in the project, and the relationship among them must be clearly defined by the variable they exchange. Example in figure 9 is a simplified version of the design of a hydropower plant, including the main variables and parameters between each module.

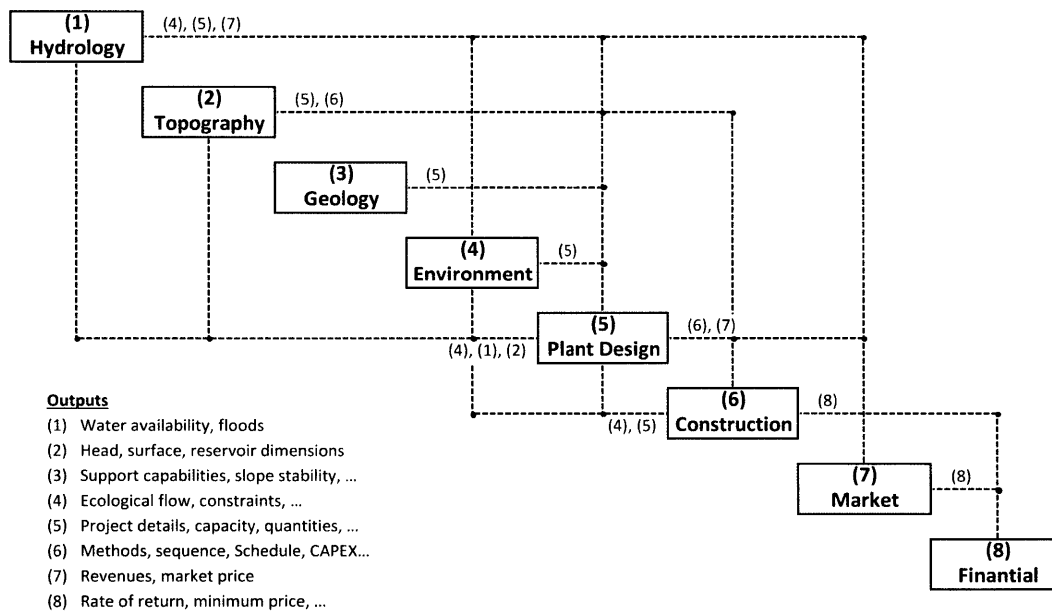


Figure 9. Example of dependences between modeling modules

Models also requires the forecast of exogenous variables such as system's electricity demand or political stability. Forecasts are required to evaluate the project results over its life cycle, and its results depend on external models to the Project

The residual known uncertainty must be identified and modeled as part of the prototype, some studies and projects employ Monte Carlo simulation to forecast the uncertainty distribution of the project Results, given any uncertainty imposed by some feature (i.e. geological conditions for underground works may lead to over break the rock during excavations). In this case we take advantage of subjective judgements of experienced experts, but “determining a value to such judgements without distorting the subjective judgements is very essential” (Panthi, 2007)

Inherent institutional features are normally complex (many links among them), evolving among time (such as social acceptance, project team management, among others), or pass-fail (such as some permits) or qualitative based (such as NGOs’ position), we can take advantage of using System Dynamics methods to model their behavior whenever possible.

System Dynamics (SD) is a method that enables the understanding of the structure and dynamics of complex systems, by building of mental models of the behavior and impact of these systems (Sterman, System Dynamics: systems thinking and modeling for a complex world, 2002).

Social acceptance may be modeled using System Dynamics approach as several factors may create balancing or reinforcing loops towards the behavior of a community when a new project concept is proposed affecting several parameters of their behavior.

Actions to mitigate the downsides of the project on directly impacted people, such as resettlement, is one of the major Project Architecture definitions; therefore the following risks to these people must be deeply analyzed as a cumulative effect: landlessness (expropriating land removes people’s commercial activities and livelihoods), joblessness (loss of wages), homelessness (loss of housing and shelter, that can be expanded to the loss of a group’s cultural space), marginalization (reduction of people’s economic power), increased morbidity and mortality (due to the displacement, but also increase of epidemic disease such as malaria), food insecurity, loss of access to common property, and social disarticulation (fragments the social organization and interpersonal ties) (Cernea, 1997).

A model can be assessed in terms of its quality (fidelity) and its credibility; for this type of projects models must be credible to a point that decision makers and relevant stakeholders believe on its outcome, for example the hydrological model, the financial evaluation or the environmental impact assessment (Flanagan, 2012). Model quality (fidelity) must be accompanied by the certainty of the information feeding the model, therefore it evolves over time, from low fidelity at Concept definition to high fidelity at the end of the development process. The high level of uncertainties at the beginning of the development phase, requires that the low fidelity prototype must allow for high flexibility on its design to allow major changes and exploration of additional options. Design flexibility will be reduced as the fidelity is increased.

We can use of low fidelity models (or surrogate models) to optimize or to perform tradespace search and high fidelity to validate the results at the best selected alternatives.

Even though the complexity of hydro projects shows that internal optimization/tradespace loops have to be addressed, but also feedback loops that updates performed analysis makes optimization a complex task; therefore, we have to work the development in some modular activities that can work sequentially (model decomposition). To accomplish that, MSDO proposes the following approaches:

- Distributed analysis: disciplinary models only provide functional analysis; therefore, we choose the architectural choices, and see the outcome of every disciplinary model as a response (results and constraint compliance). The optimization of the system, based on the response of each disciplinary analysis is done at a higher level. It allows each module to work independently of each other. Optimization is then executed through iteration with changes on the architectural choices. As hydropower includes several required modules to describe its potential behavior, then data handling is a major issue during the development phase. Sequential design may be encouraged by taking into account all feedback loops within the design process increasing the development timeframe.
- Distributed design: optimization occurs both at the project level and at the disciplinary model level. On this approach the project level sets the goals and targets for each sublevel, and each disciplinary module optimizes to meet the targets and reports its results and the feasibility of the targets. The key issue is how to decouple the modules to work in parallel rather than sequentially

3.2.7. Results

Once inherent features are analyzed and the project architecture have been defined, expected results from this stage are:

- Capital Expenditures (CAPEX) and contingencies: is the expected cost of the project implementation, and is a key variable for the project approval; CAPEX must be as much accurate and firm as possible with contracts or agreements with experienced counterparties that secures that the implementation will be executed to comply with the project definition and scope under required guarantees and warranties. Contingencies definition is the base of cost overrun risk and may cover any unknown unknown or unknown known or known unknown that may emerge during project implementation. Quantities for budget are defined by design, sets the volume or amount of work to be done and/or supplies to be acquired during the implementation of the project.
- Schedule and its critical path: defines the activities and its sequence for the project implementation, it also outlines the interface between different scope of works in time and requirements, showing the expected critical path of the project. It is and important communication tool to stakeholders, but also to model the financial consequences of a long construction period and the expected date to start receiving revenues. Project schedule must include analysis of potential rework cycles to avoid reaching schedule trap loops during construction; empirical data shows that project delays during construction contributed to the cost overruns of the project (Sovacool, Gilbert, & Nugent, Risk, innovation, electricity infrastructure and construction cost overruns: Testing six hypotheses, 2014)
- Capacity and production/utilization: is related to the expected performance of the Plant to deliver the production or service which is required to during the Plant lifetime and is key to define the income and revenues. The metric may have one or several values depending on the serving needs, such as Electric capacity and energy (if related to electricity production), guaranteed water discharge (if related to farming, tourism, ecological or human use), ship transit (if related to transportation) or maybe guaranteed flood control (if related to communities' safety). It has to assure some guaranteed level that allows

users or off-takers to commit on long term contracts. It impacts on several entities therefore its selection must be continuously challenged.

Even though bigger project capacity may take advantage of economies of scale, this result should be deeply analyzed on each shaping loop. Empirical evidence shows that bigger projects had the worst cost overrun impacts during implementation phase. (Sovacool, Gilbert, & Nugent, Risk, innovation, electricity infrastructure and construction cost overruns: Testing six hypotheses, 2014)

- Service Price: expected price or tariff required by the project to allow the recovery of its costs and investments, that can be divided by each service that it provides (as shown before).
- Availability and reliability: Design may be executed considering this parameters, such as redundancy, different class on instrumentation, storage, among others; also considering enough reserve capacity for equipment definition
- Operating and maintenance expenditures (OPEX) estimation: based on the final design, it shall include expected costs in order to operate and maintain the asset during its lifetime, such as spare parts, equipment replacement, access roads and other civil works, among others. Maintenance CAPEX related to replacements or refurbishments anticipated during the design face must be identified.
- Risks/upside identification and mitigation: related to emergent features of the project, which may be positive or negative, the result of this phase is to define mitigation or contingent measures in case this risks are materialized; or activities to make the opportunities real. It is clearly a result without impact within the model, but it does meet uncertainty objectives for the project to be approved for construction.

Risks management plans requires risk identification; therefore, a risk management framework must be developed for every hydropower project to be applied on every feature of the development. (Wang, Fadhil, & Aguria, 2004)

- Rate of return of investment: return granted by the project based on its expected revenues, costs, investments, risks and upsides. It may impact the behavior of the equity investors.
- Required permits (obtained or to be obtained) on each stage of the project, based on the construction and O&M activities. Its impact is on the project schedule mainly, but also on the main commitment entities (investors, lenders, DevCo)

- Public opinion and social acceptance: everybody with some degree of interest in the project and its impact on society.

3.3 Evaluation

Development is a dynamic process of project shaping (Lessard & Miller, The shaping of large engineering projects, 2013). Evaluation and optimization or tradespace search allows the project architecture to mature, a better understanding of the inherent features, the comparison between results and objectives or restrictions, and also the prediction of emergence.

Each optimization/tradespace loop requires resources to be committed by developers or the shareholders, therefore the evaluation of the results may lead to project cancelation.

The objective is to evaluate project feasibility, but also push for improvement towards (i) an optimal design or options within the Pareto frontier or (ii) equivalent project architectures complying non-numerical restrictions.

The process goes from early first prototyping, with minimum but relevant information to a continuously evolving model based on a better understanding of the Inherent Features and precise definition of architectural choices. Several documents define the development steps such as: reconnaissance, pre-feasibility, feasibility, definitive plan/engineering and contracting (Ravn, 1992), but this waterfall process may lead to a limited amount of iterations and poor evaluation of the relationship between all entities involved in the project.

3.3.1. Multi-objective optimization and tradespace search

Architectural choices attempt to satisfy several and conflicting objectives at the end of the development process. The solution of multi-objective optimization projects can be based on two possible approaches:

- Scalarization: where the preferences among objectives are defined upfront, for example by defining weights for each objective.

- Pareto: where a set of possible objectives are shown and preferences are set after the first results are available.

Development results are not precise, especially if related to inherent institutional features, therefore its evaluation must involve an acceptable risk of not meeting the objective. The main intent of the optimization and tradespace loops is to improve our understanding of the behavior of the inherent features towards our project architecture, to reduce uncertainty and better predict the project outcome.

Results are evaluated in terms of its uncertainty to meet objectives and constraints; and given the timeframe to develop the project, not all results will have acceptable risks, as shown in Fig.10.

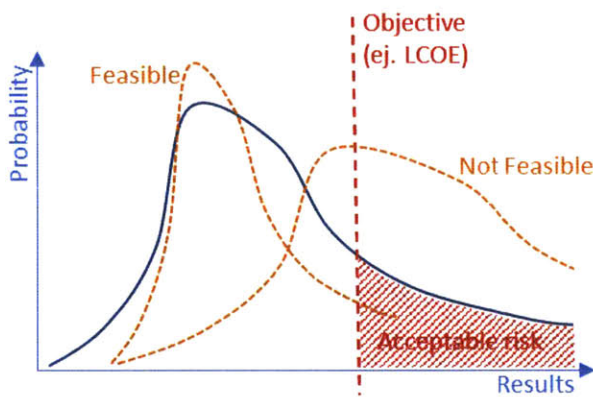


Figure 10. Uncertainty evaluation (for example towards a minimum energy price, LCOE)

Optimization is made for quantitative project architecture, but also once an optimized design is produced; stakeholders may shape it to accommodate their needs or interests. As Inherent Institutional features evolve over time, their requirements and restrictions may evolve over time changing the design from an optimal solution to several equivalent non-optimal choices that will be reviewed in a tradespace of choices.

3.3.2. Project shaping loops

Project shaping requires several loops to optimize the project while meeting the restrictions and improving the results (see Fig.11); for each of the shaping loop, developers and sponsors must evaluate the results and issues to be solved.

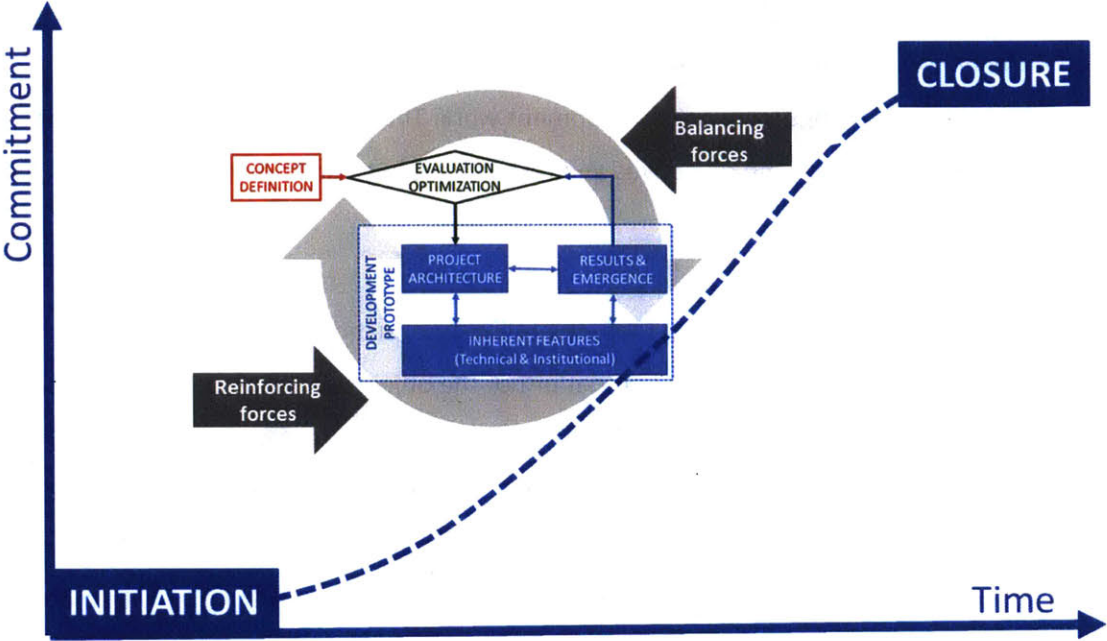


Figure 11. Shaping hydropower projects

During this process there are reinforcing forces pushing for additional shaping loops (reinforcing forces may include uncertainty reduction, innovation, problem solving, buying from sponsors, better results than expected objectives), but also balancing forces that stops the process or even cancel the project (balancing forces may include unresolved risks, noncompliance with objectives or restrictions, excessive realism, professional challenges and differences of opinion).

Each shaping loop requires incremental resources, and developers requires sponsors to commit on providing this resources. During the development phase, the resources invested on all shaping loops are at risk; nevertheless, the results will improve the implementation phase with much higher commitments or even results will lead to project cancelation avoiding an unsuccessful project.

Shaping of hydropower projects may take several years, therefore the Concept Definition and its related objectives must be continuously challenged and its changes incorporated on each shaping loop.

3.3.3. Building the Project architecture

Through the Evaluation part of the framework, stakeholders are informed about the project results, emergences and findings from the development work. Their feedback is important, not only to compare the results with the objectives and restrictions, but also to guide the project shaping in the next loop.

When evaluating results from each shaping loop, the following situations may arise:

- In terms of Objectives, results may (i) meet or not the objectives, (ii) be better or worse than previous shaping loop, and (iii) may be similar with a different project architecture.
- In terms of Restrictions, results may (i) comply or not, (ii) turn a restriction to active or non-active, (iii) may be similar with a different project architecture.
- In terms of Project architecture, results may (i) show that objectives are met with more than one set of architectural choices (isoperformance), while complying with restrictions, or (ii) one objective is not met or improved by the current architectural choices; therefore, we will look for the best alternative that approximates our results to meets the objective (goal seeking).

The next shaping loop must include the following:

- unexpected emergence (new functionalities or risks identified during the results evaluation). The emergent results must be mitigated (if creates additional risks) or promoted (if creates additional value to the project) in the next shaping loops. Emergence properties are results from the interaction of the different entities in the project,
- new information coming from (i) the studies or modeling of inherent features, and (ii) different options or major detail of the project architecture. Which will be integrated into the new shaping loop, and
- Changes in the objectives and restrictions (new requirements, adjusted requirements or removed requirements), based on shaping loop results and concept adjustments.

When defining changes to the Project architecture, we find that they are not continuous variables, or even there may be qualitative variables; therefore, the Design of Experiments “DoE” framework (developed by R. Fisher in 1921) may help to define the required architectural choices to change, providing statistical techniques to sample the design space and evaluate the impact on one or more results.

As our implemented methodology works as a virtual prototype of the project, with a defined set of architectural choices (or factors “n” in DoE), each of them with a certain level “l” of values. Changes on factors and its levels leads to different Results from the development prototype (called Observations in DoE). There are different techniques to define the experiment or change in architectural choices based on number of shaping loops required, such as Full factorial design (where all possible changes are evaluated, and the number of loops will be l^n leading to an expensive development process), Orthogonal arrays, One-at-a-time (which aims to define a baseline and change one factor at a time, the number of loops required are $1+n(l-1)$), Latin hypercube, and Parameter study.

After an optimum solution is achieved, we should look into the robustness of that solution to changes on our assumptions, objectives, constraints or restrictions, architectural choices or inherent features behavior. This process is called sensitivity analysis and helps to understand which elements of the model are important for the optimal solution. By doing this analysis we may want to evaluate the impact of changes in our assumptions or parameters to (i) the optimal architectural choices and (ii) the nature of the restrictions or constraint (active or inactive)

3.3.4. Closure of the development process

Closure or end of the development phase occurs due to one or all of the following situations: (i) demonstrated non-feasibility of the project at any time, (ii) demonstrated feasibility of the project, (iii) bid date for the energy production, (iv) regulatory term for the resource rights, (v) lack of resources from sponsors.

Closure must include deliverables such as:

- Prototype and project architecture, including all documentation required to (i) implement or construct the project, (ii) re-develop the project at a later stage when Objectives or restrictions change, or (iii) document project cancelation.
- Obtained permits, such as environmental impact approval, that will allow project implementation.
- Contracts or agreements related to the project to be executed or terminated.

IV. CASE STUDY ANALYSIS

The objective of this chapter is to show, how in selected cases, the proposed methodology and framework would be applied and the lessons learned from the cases that supports or challenges the methodology and framework. This is not a completely independent “test”, since these cases were the basis for the development of the proposed methodology. However, it does serve to determine the extent to which the abstraction of reality into a methodology maps back onto that reality.

The approach for the following cases is to describe (i) the context and origination of the project, (ii) the main activities, decisions and actions taken within the proposed framework, and (iii) the actual project outcomes. and how the application of the methodology and framework would have improved the project results. The four cases are two run of river hydropower plants (25 and 58 MW of installed capacity) built between 2008 and 2012 in Central America and two developed projects (112 and 220 MW of installed capacity) in South America cancelled between 2013 and 2015 at different stages.

4.1. Case A – 25 MW run of river hydropower project

4.1.1. Energy auctions drives hydropower opportunity

This project was developed in order for the Company to participate in the upcoming energy auctions through which regulated distributions companies must secure their energy needs in the long term. The bid was required to be for a firm capacity and its related energy production.

This energy auction grants the winner a secure price for its production, which minimizes the market risk. Also, the market at that time was mainly supplied by existing hydro but also fuel oil and diesel. The expected high prices with secured revenues for the long term attracted major energy companies to develop projects and participate in these auctions.

However, the bases for the volume award were not completely clear in the auction terms, and were subject to regulatory discretion. Nevertheless, in the previous auctions the regulator had

followed an allocation criteria of awarding partially the offers from many developers to diversify the portfolio of the energy matrix of the country. Based on this, the owner expected that if they won the bid, it would be only a part of the bid capacity.

Concept Definition

The project was designed to participate in the upcoming energy auction, where the main objective was to minimize the levelized cost of electricity (LCOE). In order to achieve this goal, the major driver was the reduction of the capital expenditures (CAPEX), while preparing the bid also required the following key definitions:

- The expected energy production during the project lifetime
- The required return on investment
- The construction schedule

4.1.2. Developing based on pre-existing studies

Due to the good prospects for the auction terms, the Company decided to purchase three yet to be build projects to participate in the bid. This means that other developers had performed the design and studies for each project, and then sold them to the Project Company.

The project documentation was validated during the acquisition due diligence process by an engineering firm, which also performed a new basic design and construction specifications with additional geotechnical studies.

Development Prototype

The design was performed by the original developers, and the Company only validated these studies and the underlying geotechnical studies that seller performed to produce the design and construction specifications. These studies were used to invite construction and supply contractors to bid for the project execution.

Water availability was not considered a risk, as the current river received regulated water coming from two upstream power plants which deviated water to two reservoirs on a seasonal and daily

basis. As a result, this project didn't need a storage reservoir. It also was assumed that project's upside was reliable. However, during the project construction the upstream power plant had technical problems which led it to stop its production for several months, and consequently the lack of water supply for the project.

Early interaction with community helped reach social support and acceptance, the interaction with the community in open forums allowed the presentation of the project design, and potential impacts and proposed mitigation, but also record claims from the population. Before the construction was started, the project team had finished a major project for the community, the improvement of the potable water supply distribution.

Land was not purchased during development; therefore, the construction schedule included a timeframe to release the land, but the construction team failed to release the land according to schedule. As shown in figure 12, the water conduction channel divides almost all properties by passing in the middle of those areas, but also several roads connecting them to populated areas.

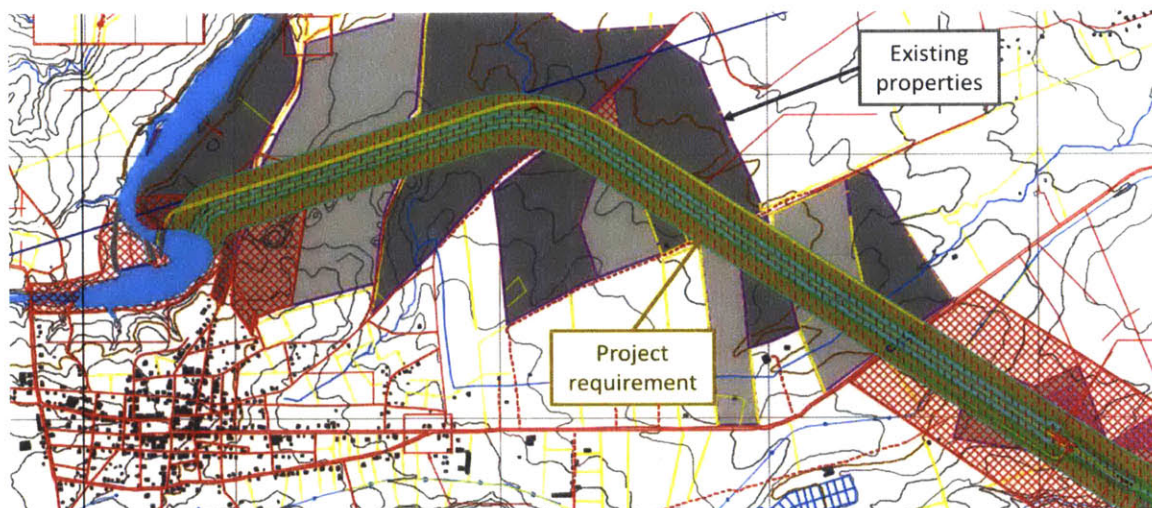


Figure 12. Impact of the project (yellow area) on land owner's (gray areas)

Project Architecture

The basic design didn't include several project details such as the lining specifications or the drainage system. During construction the gaps led to re-work or additional work.

The construction scope was decomposed into four major parts: (i) civil works under a unitary fixed-price contract, (ii) hydro mechanical and electromechanical equipment supply, erection and commissioning under an EPC contract, (iii) the supply and construction of a high voltage transmission line, and (iv) the detailed design and owner's engineering service. The construction market was saturated due to many large infrastructure projects in the country. Therefore, when construction bids were requested, only one company per lot presented their offer; which gave them more bargaining power during contract negotiations.

Only the environmental impact assessment was approved by Authorities during the development, for the construction phase the project team will have to get all other required permits.

A multilateral bank was selected to finance 50% of the project.

Modeling and results

As the project was designed by another developer, the basic design only included construction aspects within its reports, and models were not linked among themselves to analyze transversal changes.

4.1.3. Challenging baseline assumptions

The first developers had conducted feasibility studies that led to the base design, which was then reviewed and validated during the acquisition due diligence process. Following this, further design was performed in the following stages:

- a. Basic design, optimizing the original design
- b. Development design, which included recommendations from contractors to the Basic Design
- c. Detailed design was performed after construction started.

This process was not iterative, and maintained original assumptions, building optimization based on original design. On the other hand, the social approach was effective, and public forums added

value by allowing early actions to mitigate impacts on the community. Social acceptance was maintained during project implementation.

4.1.4. Key take away

Even though it was an acquisition of a developed project, if the methodology were to be applied, we should be able to conduct a review on the assumptions, considering the uncertainty of each inherent feature, and not taken for granted as true information. The following issues, for example, would have been identified and included in the project valuation:

- Availability of the upstream power plants to produce electricity, and its impact in the expected generation.
- The construction market was not approach until bids were requested, leading to high construction costs
- Budget for additional work (such as channels or lining) would be included
- Land purchase strategy may have been tested with owners to define the expected time to release the land.
- The methodology sequence needed to approach key local stakeholders (such as land owners or authorities) was not usually available, due to the lack of information related to land release and permitting; creating a delay reinforcing loop.

The construction took 28 months (6 additional months to the original plan) of delay, but the plant was not able to operate due to lack of water. Land costs doubled its original budget (without including the impact on overall construction from upstream power plant additional costs due to change in the construction sequence).

4.2. Case B – 112 MW daily storage hydropower project

4.2.1. Preparing for the future

In this country, the Government has decided to increase the participation of hydroelectricity in the energy mix, therefore they have been promoting the construction of hydropower projects through different mechanisms:

1. Hydroelectricity energy auctions, promoted by the government where winners (based on lower LCOE price) are granted a long term PPA with the public utility.
2. Energy auctions from Distribution Companies, where hydroelectricity from new projects were granted a 0.85 comparison factor, for them to compete with existing power producers.

Given this, the company's decision was to be prepared for the next auctions and develop a hydro project that could take advantage of the continuity from another hydro project under construction downstream. It would require a fast development process. The main objective was to minimize the LCOE which will be the basis for the potential bid.

Concept Definition

The project was designed to be ready on the next energy auction, where the main objective was to minimize the levelized cost of electricity (LCOE). In order to achieve this goal, the major key objectives were to be met:

- CAPEX reduction
- Increase of expected energy production during the project lifetime
- Allow daily storage to increase capacity payment
- Minimize the construction schedule

Comply with the required return on investment

4.2.2. Fast track development

As previous energy auctions had come c with short notice, the Company wanted to be prepared if a new auction appears. The expectation was that it may happen soon, and also in order to take advantage from synergies of the mobilized contractors due to the downstream project, we should be able to start construction within the upcoming three years.

To perform the development, the following plan was approved with the required budget. As shown it is a straightforward plan without iteration loops, which may lead to wrong conclusions if basic fundamentals are not well defined. Some control loops were defined in order to evaluate the

Contact with Authorities were limited due to its continuous relationship with the downstream project, and there were several cases of social unrest with existent project that both raised the project's profile with the authorities

The neighboring community was in favor of the project at the start, but after suffering impacts from the construction of the downstream project, their behavior changed.

No additional project members were included on this stage, such as potential lenders, contractors or insurance companies.

There was no clear vision on when the energy auction may take place, therefore the project was developed in an expediting fashion, leaving little room for revisiting assumptions.

Also regulation related to the minimum ecological flow in the river was being updated, and there was no clear direction from authorities about the required criteria to calculate its value.

Project Architecture

High level project design was frozen from pre-feasibility design, therefore components' optimization was done during the feasibility stage, but design was available once studies were released and design optimization was done at the component level without an overall integration and optimization

Modeling and results

Due to the reduced water availability (low energy production) and increased design requirements (high investment costs), the resultant LCOE was above market expectations

4.2.3. Stopping at the right time?

Because the initial results showed an LCOE high and above market expectation, the project was cancelled and 78% of the approved development budget was lost at the finalization date. The

main driver was the reduced water available for electricity generation. Had this forecast available ahead of time and built into a development prototype which updates local measurements and changes on the design, the project might be cancelled at the middle of the feasibility stage, avoiding part of the final loss (for example site geotechnical studies may be stopped)

4.2.4. Key take away

Even though the project has a fast track approach, the value of the evaluation process to decide when to stop expending money mitigates the loss, but it may be improved if continuous evaluation is made when a prototype is available to test new information in a dynamic fashion.

The design during the feasibility stage was done by a different engineering company than the one in the pre-feasibility. Even though results were similar, not all the insights were handed over at the beginning of the feasibility (only reports were available); therefore, the best way is to hand over the prototype developed within the pre-feasibility to be shaped and updated during feasibility.

Market forecast may change during the development phase, because of the time required to develop the project; therefore, continuous update on the project Concept Definition (objectives and restrictions) is required to evaluate the project results or shape the project accordingly.

Implementation of peer review mechanism improves the project architecture and the direction on where to look during the studies of the Inherent Features.

4.3. Case C – 58 MW run of river hydropower project

4.3.1. Again energy auctions

This project was part of the portfolio of projects similar to the Case A, developed by a different company to participate in the upcoming energy. The company decided to buy the project company, which secured the environmental permit and finalized the feasibility studies.

Concept Definition

As Case A, the main objective was to minimize the levelized cost of electricity (LCOE), but in this case, as this was the last power plant in the cascade, it was supposed to start later on the projects portfolio delating its commercial operation.

4.3.2. Developing the last project of the portfolio

The development conditions were equal to Case A, but with the difference that this project was the last one to be studied and it was located closed to the main city of the area.

Development Prototype

Even though it was the last project of a cascade portfolio; it also was going to take water from two additional rivers increasing the capacity of the plant by ~25%. But the last part of the feasibility study didn't consider that there was a potential project that might use water from one of the rivers for an upstream the power plant. When the plant was in operation, and the upstream project was materialized, the energy generation was reduced.

Interaction with the community was not performed in advance, but also the proximity of this community to the main city granted special attention (mainly from NGOs established in the area). This behavior was not analyzed prior the construction started.

As land was not purchased prior the construction start, its price went up significantly, leading to a reduction of the required area (reducing contingency zones). Long negotiation time with land owner's lead to increase their price expectations, but also delay some construction activities or change the construction methodology to allow access to released areas.

Project Architecture

The project was treated as a part of a portfolio of project, together with Case A; therefore, its architecture and development process were equal; only with minor adjustments to some specific geotechnical and hydraulically conditions

sequence but roughly at the same time and the last one needed the water from the previous ones; the financial evaluation and the bid price was aggregating all investment costs and energy production. But if there were to be constraints on of water availability in the first project (Case A), then it will impact the three projects in the portfolio.

Even tough from the financial perspective it was modeled as a three power houses single power plant, from the engineering perspective, there were three projects with only one interface (water delivery point).

Not having a whole model or prototype for all three projects reduced the ability of the project team to anticipate transversal risks among this projects.

4.3.4. Key take away

As with case A, the development of a single prototype, even if with low fidelity, will enable a whole picture of the portfolio and may generate warning signals from emerging risks coming from other projects (for example the date where the reservoir of the last power plant has to be filled with water was different with the date were the second power plant needed to discharge its water).

By not delivering a prototype to the implementation/construction team; they couldn't evaluate properly changes to the project (independently of the origin of the change) and its impact on the project final results (investment cost, energy production, ...)

Even though the interface plan will change based on actual project execution, by not having them in the development prototype reduces the ability of the implementation team to evaluate the impact of changes on the interface plan and the contractors' response to this change.

By not assessing the NGOs during development, the project team couldn't anticipate the links between local and international NGO's, but also the links between multilateral banks and international NGOs. When issues occurred in the project and advance notices were issued to lender, local NGOs had the information prior local announcements were made.

4.4. Case D – ~220 MW daily storage hydropower project

The project was originated from the mismatch between the following schedules: energy actions from major clients or regulated utilities (between 6 months to 1 year) and the development time of hydro projects (between 2 to 5 years). Also the long construction time required that long term energy auctions must have delayed contract starting date.

In order to have projects ready to be offered to clients when required, the Company started a program to identify potential projects within the country. This project, among others, is the result of this project identification process based on global measurements with low fidelity models to estimate CAPEX and energy production.



Figure 15. Case D development plan

4.4.1. Conceptualizing from scratch

As there were no clients, there were no requirements, restrictions or objectives but also there was no site definition, only the river where the project might be installed the project has to first select a site within the river.

The first stage was related to identify potential projects within the river and rank them based on an index based on Investment cost and annual energy production, plus some additional criteria such as existing facilities or nearby communities.

Even though a classical approach of pre-feasibility and feasibility stages were defined, the key elements of this plan was the ability to start prototyping the design and including several control milestones to evaluate results.

The first prototypes were built to optimize in a low fidelity model the design and estimate the energy production per potential project site. The first prototypes also served to contact the communities nearby the best two projects and collect their impression and restrictions, which were included as qualitative measurements of social acceptance and value in the site selection.

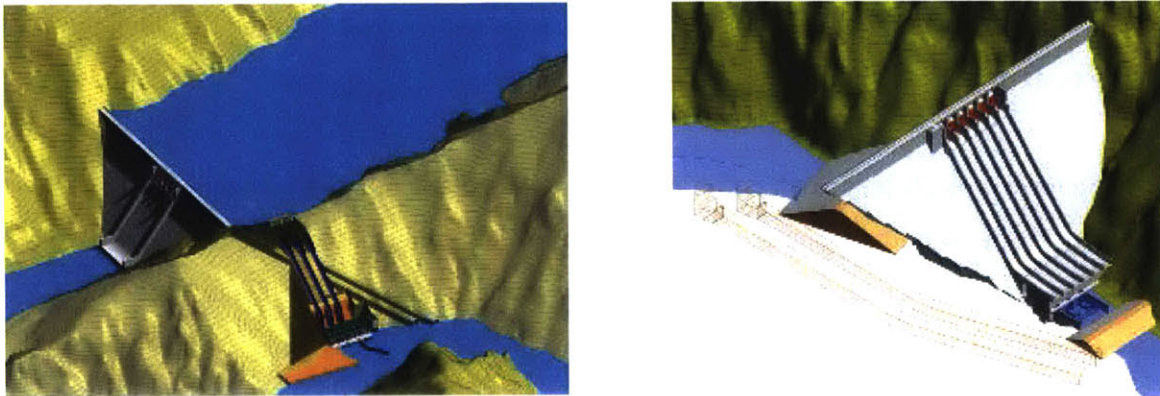


Figure 16. First low fidelity prototypes of the best two project sites.

4.4.2. Increasing the fidelity of the prototype

Once the site was selected, a prototype was built to optimize the conceptual design, some modules were related to:

- Water availability and energy production, based on a given hydrology: the module estimated the energy production for any given dam height (including the reservoir capabilities and plant capacity). Input variables are related to the site topography, potential demand of water users upstream, required storage. It also provides the statistical assurance of the results, such as firm capacity based on a 95% exceeding levels. As hydrology was based on pluviometry records and some flow measurements outside the project area, the module allow for an update once local flow measurement was available from the project site.
- Key quantities calculation, based on dam height and site topography, by using 3D modeling software. It also provides graphic visualization used by the social team to start consultation with neighboring communities and collect their first impression and concerns, or the environmental assessment team to evaluate impacts to the environment;

feedback from these teams was used to redefine some aspects of the project, such as potential impact to native bird species living in the area.



Figure 17. Visualization using ortophotos

- At this stage, geology was not deeply studied and regional information plus site visits were used to include design restrictions to the prototype.
- Also grid connection alternatives were deployed and capacity and costs estimations were made.

Because the development plan considered an increased number of control milestones, an evaluation model was defined to estimate the results of the project, compiled in a singular Expected Bid which is based on some assumptions on the average requirements from clients and required return on investment.

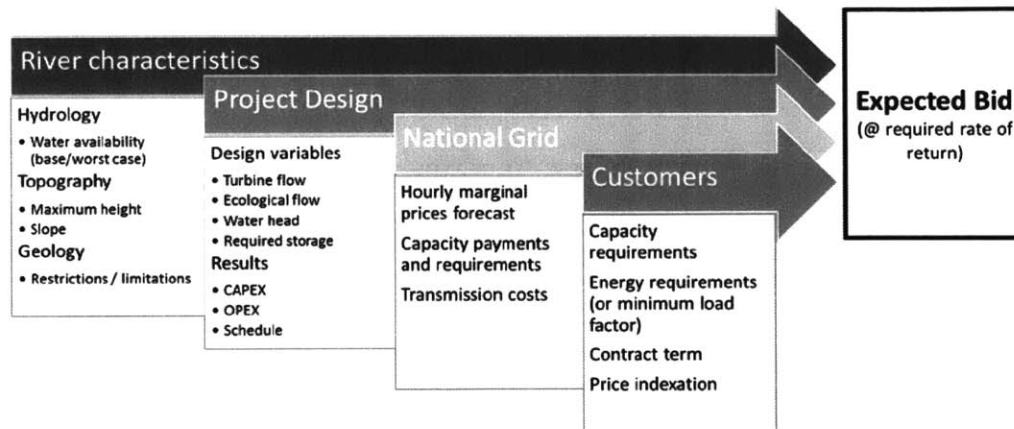


Figure 18. Case D, Evaluation model

The optimization of the design was set to minimize the expected bid, but the result must not be higher than the actual market value of prices defined for similar contracts.

4.4.3. Preparing the evaluation and search space

As this project was part of a greater portfolio of potential projects in other rivers of the country, and (i) the results were slightly higher than market values, (ii) there were potential issues with sensitive species in the site, and (iii) projects in other rivers showed better results at the same stage and uncertainty.

Because the reasons above The project was cancelled at the end of the pre-feasibility stage at a loss of ~18% of approved development budget.

4.4.4. Key take-away

This case shows how the use of a prototype, even not fully integrated can improve a global evaluation and faster updates of the results when new information is available.

Even though the project was canceled, additional expenses were avoided when results didn't meet the Company's expectations; and allow to deviate resources to other projects at the same level of development with better results.

4.5. Case Study Summary

The cases show deficiencies during the development process that might be avoided or reduced by applying the proposed methodology:

- Over commitment of electricity generation might be avoided by completing the Concept definition.
- Changes of stakeholder's expectations can be anticipated by involving them in the shaping process. Continuous reports of results, together with the collection of their feedback, will improve the shaping process or will cancel the project before major commitment.
- Handover problems from different development teams, or between development and implementation teams, might be avoided by delivering the Development Prototype. It is not only a complete summary of all assumptions and knowledge of Inherent Features, but also allows the next team to model and evaluate potential changes to the Project Architecture.
- The Development Prototype will clearly define the boundaries of the project; therefore, external links (or communication flows) among Institutional Features must be monitored; also changes driven by external entities or features might be easily modeled and results will include a holistic view of the project.
- Main deficiencies showed up during construction phase because shaping loops were not part of the development process.

	A - 25MW run-of-river	B - 112MW daily storage	C - 58MW run-of-river	D - 220MW daily storage
Concept Definition	Challenging the assumptions of the Energy Auction rules on every shaping loop would avoid volume over commitment; also the Evaluation would show the sensitivity of the bid to the committed volume.	Continuous challenge/revision of the assumptions made to built the objectives and restrictions (when need and context are not clear), must be continuously challenged, as they may change during the development process (such as electricity market forecast)	Challenging the assumptions of the Energy Auction rules on every shaping loop would avoid volume over commitment; also the Evaluation would show the sensitivity of the bid to the committed volume.	When need and context of the project are not clearly defined, the relationship between the market institutional features and our assumptions made to build objectives and restrictions are relevant when challenging both.
Development Prototype				
Technical Inherent Features	Identifying and analyzing the relationship between resource availability (technical inherent feature) and the operation of our competitors (upstream power plants) would show water supply risks; which mitigation would be included in the project architecture.	Identifying the key inherent technical features and its link (such as glaciers and climate change) may prioritize some studies about its impact on water availability among time.		
Institutional Inherent Features	Contacting the potential contractors early in advance would encourage more participation during the construction auctions. Connecting the land owners demands and requirements to the project design or construction methodology would minimize changes during construction (therefore minimization of costs overruns and delays)		Identifying the relationship between some elements of the institutional features (and the information flow among them) would improve the communication scheme set in the project architecture; for example information leaks from lenders to NGOs would be considered in the details of disclosed information.	Early involvement of the community in the project design allowed the identification of new environmental features (such as protected wildlife)
Project Architecture	Shaping loops would allow the identification of important components such as superficial water drains, membrane installation procedure and impact of a new water draft on the overall project. These components were not included in the Project specifications, therefore they lead to delays and cost overruns during implementations phase.	Identifying the link between archeological remains and project design on an early stage would prevent building unfeasible designs during the shaping process	By identifying and defining all links between the construction methodology and other features (such as land availability, permits, grid access, mitigation measures for impacted people, operation of other plants upstream or downstream this project), the project schedule will be defined and potential shifts on the critical path may be evaluated. It will allow the implementation team to evaluate changes on the project architecture and its impact on the overall results.	By including river users, such as tourism companies, the project design might include features relevant for their activities.
Modeling and Results	Building a prototype and integrating the modules where clear links between them (information flow) are mapped would allow an overall evaluation of changes during the development, such as the impact of not releasing a particular land in the reservoir to the construction methodology, the reservoir water level, the energy yield and the water draft.		A single prototype would enable an schedule analysis of scenarios to fill the dam based on different conditions (permitting, hydrology, water usage from upstream and downstream people, operation of upstream power plants), and design it for flexibility if major changes were required.	In this case a not fully integrated prototype allowed faster evaluation of results to different architectural choices and new information from inherent features, improving the development time
Evaluation	Even tough a deadline was set (approval date to participate in the Energy Auction) , by including one or more shaping loops would improve of our knowledge of the project and its expected outcome showing emergence such as uncertainty on the CAPEX, energy forecasts, Auction rules, among others	By applying continuous shaping loops and comparison of results (even from low fidelity models) with objectives and restrictions, stakeholder's participation or decision would be anticipated; in this case, project cancelation might be performed earlier avoiding some development cost.	Even tough a deadline was set (approval date to participate in the Energy Auction) , by including one or more shaping loops would improve of our knowledge of the project and its expected outcome showing emergence such as uncertainty on the CAPEX, energy forecasts, Auction rules, among others	Even though the project was canceled, additional expenses were avoided when results didn't meet the Company's expectations; and allow to deviate resources to other projects at the same level of development with better results.

Figure 19. Potential improvement to studied cases

V. CONCLUSIONS

Hydropower projects are developed to meet the need for sustainable electricity, but also for flood control and water storage for irrigation or human consumption. A hydropower project involves several risks due to its uniqueness and complexity, and the decision to start the construction of a power plant must be based on a deep evaluation of benefits and costs in a holistic way.

The proposed methodology provides a systems thinking approach (system design principles, models and frameworks) and its contribution is related to (i) the incorporation of systems evolution among time on the development process, (ii) the definition of project objectives and restrictions, (iii) the identification and management of relationships among decomposed elements of the development, (iv) the identification of emergent properties from the interactions among all features, (v) a prototype for developers to optimize or search for project architectures that meet stakeholders objectives while complying with restrictions, (vi) the delivery of unbiased information for decision-makers, (vii) the opportunity of stakeholders to participate in the project shaping in a continuous fashion.

The development phase is a process of (a) understanding the project requirements and its sustainability and rationale (Concept Definition), (b) identification of the relationship between the project architecture and the environment elements or inherent features (Development Prototype), and (c) shaping the project through several optimization or tradespace search loops (Evaluation).

The Concept Definition has to do with (i) the definition of the need (i.e. electricity) and the project context (i.e. auction for long term electricity supply, country's law and regulations, among others), (ii) the clear translation into to a problem statement and solution neutral proposals, and (iii) the concept definition with objectives and restrictions.

The value from building a Development Prototype is related to the ability of (i) decompose and re-integrate all elements of the project architecture and inherent features, while maintaining the relationship among them, (ii) evolve from low fidelity models with a variety of options to high fidelity models, high detail on the architectural choices and better knowledge of the inherent

features, (iii) facilitate the update, optimization, or tradespace search of solutions on each shaping loop, (iv) facilitate internal loops that will improve the certainty of the results.

The Development Prototype is composed of the following elements: Project Architecture, Inherent Technical Features, Inherent Institutional Features, and Results or emergence from the interaction of previous elements. Normally Inherent Technical features are given, driven by nature (i.e. hydrology, geology) or human activities (i.e. roads, transmission lines); therefore, the development goal is to understand the current conditions and initially set Project Architecture choices based on them. Inherent Institutional Features are highly coupled with all components of the prototype; as they tend to react to (i) changes of Inherent Technical features, (ii) proposed Project Architecture, and even (iii) the potential outcome of the Results; the behavior of this institutional features (such as local communities, impacted people) evolves during the development phase, and developer should guide this evolution. The Project Architecture includes all adjustable decisions and features to obtain Results that meet project objectives, and restrictions imposed by the Inherent Features.

Project shaping is an evolving activity, that requires resources for each shaping loop to improve our models, our understanding of the Inherent Features, or the detail of the project architecture. The objective is to optimize the Project Architecture, or propose alternatives in a tradespace among several objectives. This part of the development framework, called Evaluation, informs stakeholders about the project results, emergences and findings; at the same time collects their feedback or guidance for the project shaping in the next loop, or even cancel the project based on the available project results.

Even though the proposed methodology was developed for hydropower projects, its key principles and framework can be applied to other types of infrastructure projects by adjusting the elements of the project features and the relationship among these elements.

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APPENDIXES

A1. 25 MW constructed power plant in Central America

Development methodology evaluation			Critical input	Outcome
Concept Definition				
Objectives		Minimize required bid price		
Restrictions		Comply with Owner's IRR, guaranteed energy production to commit		
Development Prototype		Traditional feasibility studies with sound basic design definition and construction specifications		
Technical Inherent Features				
Resources	water availability, water usage, flow variance	High water availability due to existing power plants upstream with dialy and seasonal reservoirs	Market, to evaluate upstream power plant operation	Upstream power plant suffered severe damage deviating the water to another river, no production was possible during some years, until upstream plant is back to service
Location	sediments, geology, topography, morphology	Flat area with uniform geological conditions, allowing the construction of a small dam and open channels to transport the water		
Environment	climate, fauna&flora, air&soil, archeology	Environmental assessment performed some around 3 years before the implementation, no mayor finding		After dam and channel were flooded, water draft increased, leading to water leakage on current waterways
Infrastructure	access roads, electrical network, materials	good access points for grid connection and land transportation. Materials to be obtained from project excavations		
Institutional Inherent Features				
Authorities	Gov authorities, regulatory bodies, system operators	Supporting behaviour towards the project, local authorities requested support for community projects	Social management plan	Potable water delivery project and continuous communication via public forums assured social acceptance
Social	local communities, impacted persons, NGOs, public services	Support from local community, but negotiations with land owner's took time, even impacting the construction	Social management plan + land rights	Higher land costs and impact on construction schedule
Project members	DevCo/OpCo, contractors, lenders/insurance	DevCo/OpCo belonged to the same mother company. There was a lack of interest from Contractors to participate in the project		higher construction costs, due to lack of contractors to built the project
Law	national law, sectorial regulation, local regulation, standards/grid	Sound regulation was in place		
Market	competitors, market agents, clients	Competitor has a plant upstream and its water flow was used by the project		Difficult discussions to agree on the joint operation of the water basin, but also after their plant were out of service.
Project Architecture				
Design	layout, criteria/safety, components, access, grid connection	Design was performed by a recognized engineering firm, based on their previous projects. No mayor challenge to the basic design was done	Geological consitions and water availability; Environment, the increased draft level lead to damaged lining of the channels	Lack of detail during the bidding process led to important amount of additional work (increasing the project CAPEX)
Construction methodology	methodology, required facilities, transportation	Assumed 100% available land for construction logistics, but also was based on an insufficient design detail	land rights, design	Change in working methods to accomodate additional work, but also changes in the planning due to lack of access to some project areas
Organization set-up	project team, contracting	Project team not allocated 100% to the project, but also relying on the Owner's Engineering contractor to phase an EPCM project were civil works were contracted on a unit price basis	DevCo/OpCo, Contractors, Construction methodology, permitting	Difficult to deal with several development activities while the project was already on construction
Permitting	EIA, social plan, archeological, construction license, operation, land rights	Only EIA for the project was obtained prior project construction; all other permits were to be obtained by the Project team	Design, Methodology	Because methodology was continuously changing, permitting was not obtained, but also because land was not available, design was changed to allow construction requiring other areas to be obtained
Finantial structure	debt, equity	Project was financed by a Multilateral bank		The bank financed NGOs to counter balance and critique their decitions, therefore the project suffered from international NGOs coming to raise social concern
Modeling and Results				
Modeling		Only design specific model were build to solve specific technical problems, there was no relationship even between technical models		Energy yield models were not integrated to the project design, therefore impact of design changes were not fully integrated into the decicion process; also market and pricing models were never integrated.
Results	Capex, Schedule, Production, Service Price, availability, Opex, New Emergence, IRR, Permits list, Social acceptance			high CAPEX, project delayed, no operation when ready due to lack of water. Expected IRR was much lower than expected
Evaluation and Optimization				
Multi-objective		Only CAPEX and schedule were defined as the drivers of electricity price		
Loops		No iteration loops were made, only specific design reports were evaluated to confirm project technical feasibility		NO integral analysis, and impact of changes on architectural choices were made
Closure		Project was bidded and approved for construction		

A2. 112 MW developed power plant in South America

Development methodology evaluation		Critical input	Outcome
Concept Definition			
Objectives		Feasibility and minimum electricity cost	
Restrictions		Social acceptance and required IRR	Project canceled
Development Prototype			
Technical Inherent Features			
Resources	water availability, water usage, flow variance	water coming from glacier melt, per-feasibility data showed sufficient resources	low plant factor due to limited resource
Location	sediments, geology, topography, morphology	Good site conditions, but sediments were a concern	sediments study not concluded due to cancellation
Environment	climate, fauna&flora, air&soil, archeology	a lot of archeological sites within the projected construction acces roads	
Infrastructure	access roads, electrical network, materials	Main access road under construction by a downstream hydroproject, but also grid connection was nearby	
Institutional Inherent Features			
Authorities	Gov authorities, regulatory bodies, system operators	approach to authorities was limited, because of the other construction project ongoing	
Social	local communities, impacted persons, NGOs, public services	good relationship with neighbor community, but conflicting issues with other communities and the project under construction presented a social risk	social plan, but developed by the project under construction
Project members	DevCo/OpCo, contractors, lenders/insurance	DevCo/OpCo was the same building the other project; contractors working on the other project willing to take over this one	Organization set-up of the project under construction
Law	national law, sectorial regulation, local regulation, standards/grid	regulation related to communities land limits was not clear	
Market	competitors, market agents, clients	uncertain auction date	leaded to a fast development to be prepared for the auction (it was never done)
Project Architecture			
Design	layout, criteria/safety, components, access, grid connection	restricted by the minimum siez of the components (ex. The minimum diamater of the tunnel was much higher than the required diameter), and archeological restrictions complicate the design of new access roads.	water availability, archeology and construction methodology
Construction metho	methodology, required facilities, transportation	not evaluated with contractors	no discussions with constructors were made
Organization set-up	project team, contracting	not evaluated	
Permitting	EIA, social plan, archeological, construction license, operation, land rights	EIA started, but difficulties to progress due to changes in design and new regulation related to original communities rights	Regulation, design, methodology
Finantial structure	debt, equity	not evaluated	
Modeling and Results			
Modeling		no models were developed, only some technical and market specific	
Results	Capex, Schedule, Production, Service Price, availability, Opex, New Emergence, IRR, Permits list, Social acceptance		Hydrology, design, construction methodology
Evaluation and Optimization			
Multi-objective		No	
Loops		Just 2 loops (pre-feasibility and fesibility)	No optimization was made with only 2 optimization loops
Development termination		Cancelled by not acheiving market price for electricity	

A3. 58 MW developed power plant in Central America

Development methodology evaluation			Critical input	Outcome
Concept Definition				
Objectives		Minimize required bid price		
Restrictions		Comply with Owner's IRR, guaranteed energy production to commit		
Development Prototype				
		Traditional feasibility studies with sound basic design definition and construction specifications		
Technical Inherent Features				
Resources	water availability, water usage, flow variance	High water availability, but after feasibility, it was found a potential upstream user of the water		Less water for the operational phase, potential user builded its plant (lower energy production)
Location	sediments, geology, topography, morphology	geological conditions were evaluated through boring		During construction excavation instability emerged, leading to re-work (CAPEX and Schedule)
Environment	climate, fauna&flora, air&soil, archeology	A large area of reservoir was required; a channel will partially separate the landscape		Drainage channel had to be built during construction to connect landscape
Infrastructure	access roads, electrical network, materials	Excelent access roads to project sites, an existing transmission line was to be relocated due to the reservoir	Reservoir area	
Institutional Inherent Features				
Authorities	Gov authorities, regulatory bodies, system operators	Support from Authorities was achieved by cooperation agreements with municipality		
Social	local communities, impacted persons, NGOs, public services	NGO, financed by Lender, actively move the population against the project. Land was not released when construction started	Lender's stakeholders	Unrest, and project paralization during 3 days, but also international press published articles about the project. Land was more expensive as construction was progressing
Project members	DevCo/OpCo, contractors, lenders/insurance	DevCo/OpCo belonged to the same mother company. There was a lack of interest from Contractors to participate in the project		higher construction costs, due to lack of contractors to built the project
Law	national law, sectorial regulation, local regulation, standards/grid	Sound regulation was in place		
Market	competitors, market agents, clients			
Project Architecture				
Design	layout, criteria/safety, components, access, grid connection	After project approval, changes were made to optimize the production, but with assumptions from the feasibility study		Changes in the design didn't consider potential reduction of water flow, but also issues related to a larger discharge channel (land purchase, geotechnical studies on new areas). One detail in the design was not well studied leading to an embankment rupture.
Construction methodology	methodology, required facilities, transportation	It assumed a complete land release prior starting construction, but land was not released, but also changes to design were to be negotiated with Contractor after Contract was signed		Re-work costs were high, but also contract prices were adjusted to reflect changes in the design; leading to higher CAPEX and longer schedules
Organization set-up	project team, contracting	Project team not allocated 100% to the project, but also relying on the Owner's Engineering contractor to phase an EPCM project were civil works were contracted on a unit price basis	DevCo/OpCo, Contractors, Construction methodology, permitting	Difficult to deal with several development activities while the project was already on construction
Permitting	EIA, social plan, archeological, construction license, operation, land rights	Only EIA for the project was obtained prior project construction; all other permits were to be obtained by the Project team	Design, Methodology	Because methodology was continuously changing, permitting was not obtained, but also because land was not available, design was changed to allow construction requiring other areas to be obtained. Even Environmental Impact study had to be ammended
Finantial structure	debt, equity	Project was financed by a Multilateral bank		The bank financed NGOs to counter balance and critique their decitions, therefore the project suffered from international NGOs coming to raise social concern
Modeling and Results				
Modeling				
Results	Capex, Schedule, Production, Service Price, availability, Opex, New Emergence, IRR, Permits list, Social acceptance			
Evaluation and Optimization				
Multi-objective				
Loops		No iteration loops were made, only specific design reports were evaluated to confirm project technical feasibility		NO integral analysis, and impact of changes on architectural choices were made
Closure		Project was bidded and approved for construction		

A4. 220 MW developed power plant in South America

Development methodology evaluation		Critical input	Outcome
Concept Definition			
Objectives		Minimize LCOE, but with some options related to the revenues option	
Restrictions		Required IRR, social acceptance, environmental permit approved	
Development Prototype			
Technical Inherent Features			
Resources	water availability, water usage, flow variance	water availability has high variability, and a potential consumer upstream	Stakeholder identification
Location	sediments, geology, topography, morphology	not deeply analyzed	
Environment	climate, fauna&flora, air&soil, archeology	nursing area for "andean condor" was found nearby the dam location	
Infrastructure	access roads, electrical network, materials	good access roads, but no electrical connection point nearby	Market evolution and national grid expansion
Institutional Inherent Features			
Authorities	Gov authorities, regulatory bodies, system operators	contact with local authorities was minimum due to the initial stages of the project.	
Social	local communities, impacted persons, NGOs, public services	local communities were approached and early consultation was made. Continuous follow up was agreed	basic design and required areas
Project members	DevCo/OpCo, contractors, lenders/insurance		
Law	national law, sectorial regulation, local regulation, standards/grid		
Market	competitors, market agents, clients	Uncertainty regarding future market conditions. Other competitors trying to develop projects within the same area	
Project Architecture			
Design	layout, criteria/safety, components, access, grid connection	Basic design was optimized from the technical perspective towards minimum CAPEX	topography and geology
Construction methodology	methodology, required facilities, transportation	Defined by engineering consultant, not reviewed with contractors	
Organization set-up	project team, contracting	not defined	
Permitting	EIA, social plan, archeological, construction license, operation, land rights	not started	
Financial structure	debt, equity	not started	
Modeling and Results			
Modeling			
Results	Capex, Schedule, Production, Service Price, availability, Opex, New Emergence, IRR, Permits list, Social acceptance	Complete integrated model for the design of the components, and other module for the energy yield analysis based on measured hydrology.	Flexibility to search among project alternatives
Evaluation and Optimization			
Multi-objective			
Loops		Several loops based on inherent technical features only	
Development termination		Cancelled, as project was not economically feasible.	

A5. Case D detailed development plan

(Original Spanish version)

	Optimización Sitio	Pre-factibilidad	Factibilidad (1/2)	Factibilidad (2/2)	Desarrollo Final
	Advance Notice	Hito de Control 1 [*]	Hito de Control 2	Hito de Control 3 [*]	Update Note
	3 meses	4 meses	5 meses	12 meses	12 meses
Hidrología					
Estaciones de medición	- Calibración	- Calibración	- Mantenimiento	- Mantenimiento	
Uso de Agua	- Colección de data secundaria	- Hidrometría (+5 meses)	- Hidrometría (+1 año)	- Hidrometría (+2 años)	- Hidrometría (+3 años)
Parámetros de Diseño	- Identificación de trasvases	- Identificación de usuarios/trasvases	- Est. de Aprovechamiento Hidrico	- Series de caudales	- Series de caudales
Sedimentos	- Caudal de diseño	- Caudal de diseño / crecidas	- Caudal de diseño / crecidas		
	- Alternativas de Afianzamiento [*]	- Definición de Afianzamiento [*]			
		- Análisis (+5 meses de data) [*]	- Análisis mensual (+1 año)		
			- Estrategia de Manejo		
Geología & Geotécnia					
Gabinete	- Colección de data secundaria	- TdR de Investigación	- Riesgo sísmico	- Informe de Geología	
Investigaciones	- Visita a Campo	- Mapeo	- Riesgo geológico	- Ejecución de Investigación	
Topografía	- (1:5,000)	- (1:1,000)		- Según componentes	
Diseño					
Arreglo General	- Esquema de Proyectos	- Arreglo general alternativas		- Arreglo general, detalles	
Criterios Diseño/Seguridad		- Definición [*]		- Memorias de cálculo	
Componentes	- Identificación de Alternativas	- Diseño conceptual		- Diseño básico	- Diseño definitivo
Turbinas	- Selección de tipo	- Número de Unidades		- Características Técnicas	
Accesos		- Alternativas de Accesos [*]	- Diseño básico [*]	- Diseño definitivo [*]	
Canteras y botaderos		- Identificación de Alternativas		- Definición de áreas	
Construcción					
Metodología Constructiva		- Identificación de Alternativas/tecnología		- Definición de metodología	- TdR para Licitación
		- Campamentos		- Campamentos	
Cantidades de Obra		- Riesgos constructivos		- Est. Transporte Equipos	- Validación de constructibilidad
Cronograma		- Estimación para alternativas		- Definición de cantidades	
		- Cronogramas para Alternativas		- Cronograma de construcción	
Transmisión Eléctrica					
Punto de conexión	- Opciones de SE de conexión				- Est. de Pre-Operatividad
Línea de Transmisión		- Trazo preliminar de línea		- Diseño definitivo	
Medio Ambiente					
Ambiental		- Evaluación preliminar	- Línea base ambiental	- TdR para EIA	- Est. de Impacto Ambiental
Arqueología		- Riesgos ambientales	- Investigación arqueológica [*]	- Plan de Evaluación Arqueológica	
		- Restos arqueológicos [*]			
Social					
Comunidad	- Estrategia de Ingreso [*]	- Viabilidad Social [*]	- Inversión (Instituciones locales)		- Plan de Relaciones Comunitarias
	- Análisis de Entorno Social [*]	- Análisis de Entorno para LT [*]	- Inversión (Comunidades Camp.)		- Plan de inversión para desarrollo
Interesados	- Identificación de actores y redes [*]	- Municipios distritales [*]	- Municipios distritales [*]	- Contacto para opción de compra [*]	- Plan de Participación Ciudadana
	- Identificación dueños tierras [*]	- Comunidades Campesinas [*]			- Compra (opción de compra) [*]
Financiamiento					
Alternativas	- Identificación de Alternativas	- Requisitos Multilaterales		- Opción de ECAs para Equipos	- Definición de Estrategia
Bonos de Carbono			- Opciones y precios	- Evaluación de Alternativas	- Registro
Evaluación					
CAPEX	- Estimado paramétrico	- De cantidades preliminares		- Cotizaciones Indicativas (EM, OE)	
		- Estimación de precios unitarios		- Estimación de precios unitarios	
Energía	- Potencia Instalada	- Potencia Instalada	- Potencia Instalada	- Identificación otros (social, supervisión, ...)	
	- Energía	- Potencia Firme	- Potencia Firme	- Potencia Instalada	
Comercial	- Identificación de competidores	- Definición de criterios	- Análisis de competidores	- Est. de Mercado Eléctrico	
		- FEM simplificado	- FEM (actualización general)	- Optimización de PPA	- Búsqueda de clientes
				- FEM (sensibilidades)	