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Case Study: Use of the Hybrid Parametric and Expected Value QRA Method on the Keeyask Hydropower Megaproject

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Abstract–Keeyask is a new 695-megawatt hydroelectric generating station on the Nelson River in Canada's Manitoba province developed as a collaborative effort between Manitoba Hydro (MH) and four First Nations – Tataskweyak Cree Nation and War Lake First Nation (operating as the Cree Nation Partners), York Factory First Nation, and Fox Lake Cree Nation – working together as the Keeyask Hydropower Limited Partnership (KHLP). MH managed the construction and operates Keeyask, which has been fully online since 2022. The primary Keeyask project scope included earth-filled dams and earthen dikes, a powerhouse with seven turbine units, and a seven-bay spillway. In the early stages of Keeyask's stage-gate process, quantitative risk analysis (QRA) was performed using range estimation. In 2013, prior to the start of construction, Keeyask switched to using cost and schedule QRA applying the hybrid parametric and expected value (P+EV) method along with analyses of specific management reserves and a tipping point (non-linearity) assessment (AACE Recommended Practice 113R-20 covers the P+EV method). This case study reviews the use of the P+EV method on a megaproject during execution.

P+EV has advantages for early stages; however, Keeyask applied it during construction. Identified, but under-appreciated, systemic fragility challenges led to non-linear behavior; total cost increased from $6.5 to $8.2 billion Canadian dollars and the first unit in-service milestone slipped 15 months from November 2019 to February 2021. This is not a story of flawless prediction, but is a practical lesson learned guide on applying P+EV on a project in which the nature of the risk and analysis teeters on the brink of statistical disorder. Learnings and recommendations are provided.

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1. Introduction

In 2021, the AACE® International (AACE) Technical Board decided to no longer recommend "range estimating" as covered in the original Recommended Practice (RP) 41R-08 "Risk Analysis and Contingency Determination Using Range Estimating" as a specific estimate ranging practice [1]. At the same time, RP 113R-20 was published entitled "Integrated Cost and Schedule Risk Analysis and Contingency Determination using Combined Parametric and Expected Value" (P+EV). [2] This paper presents a case study of using extended P+EV quantitative risk analysis (QRA), which included analyses of specific management reserves and a tipping point (non-linearity) assessment, during the execution of a megaproject as systemic challenges led to non-linear behavior. Learnings and recommendations are provided.

The paper starts with a description of the subject megaproject; the Keeyask Generation Project. It also describes Keeyask's development history leading up to execution. It then summarizes the P+EV method (readers are referred to RP 113R-20 for a full description). This summary is followed by a timeline and discussion of each of the three P+EV QRA analyses performed during project execution as the project tilted towards a potential tipping point into disorder; a threat that was identified, but not fully appreciated at the start. The case study serves as a practical lessons learned guide on using the P+EV method on a complex megaproject during execution, with a focus on the potential for disorder from a risk perspective. Learnings gained during the execution phase will enhance QRA at earlier project stages before execution strategies are committed to.

The study covers three P+EV and related method analyses from 2013, prior to the approval to construct, through the last QRA update in 2017, in mid-construction and achievement of stable construction performance. In 2017, the headline project budget increased from $6.5 billion to $8.7 billion Canadian dollars, with the projected first unit in-service date (ISD) slipping 21 months from November 2019 to August 2021. The risk analysis identified the potential for a tipping point at that time. However, the tipping point was ultimately avoided. The expected project cost was $8.2B, and the delay to the first unit in-service date was reduced from 21 months to 15 months. While more than half of the project-specific risks identified in 2013 occurred (including labor shortage, productivity, weather, camp delays, geotechnical conditions, multiple blockades, fire, high flow, and reservoir filling delay), they were unremarkable from a QRA case study perspective. Keeyask's seven units have been fully online since 2022.

Several ancillary topics are also addressed. First, the project's earlier use of range estimating (RP 41R-08) and the reasons for switching to P+EV (RP 113R-20) are discussed. Also, an empirical 2013 Canadian hydropower industry cost accuracy study used as a benchmark is described [3]. Also, the project's use of a QRA method *toolbox* (as recommended in AACE Professional Guidance Document No. PGD-02 "Guide to Quantitative Risk Analysis" [4]) is discussed. In addition to basic P+EV, the toolbox included quantifying high impact/low probability (HILP) risks and addressing the threat of the project risk behavior crossing a tipping point into disorder [5] [1]. Also, mid-stream studies, including cost and schedule forecasts, prepared by independent consultants on behalf of the regulators are described [6].

P+EV has advantages for QRA during early stages; however, Keeyask applied it during construction. Identified, but under-appreciated systemic challenges led to non-linear behavior. Total cost increased from $6.5 to $8.2 billion Canadian dollars and the first unit in-service milestone slipped 15 months from 2019 to 2021. This story is not about flawless prediction (albeit the final outcome was within the initial p90 confidence level range), but provides a practicum on applying P+EV on a project for which the risk analysis is at the edge of disorder. It is a story of systemic fragility. Decision makers and stakeholders were informed by the QRA; initial systemic and critical project specific risks were noted, and effective risk response actions were taken by Manitoba Hydro (MH) and the contractor. A simplistic explanation of the cause of the overrun would be optimism bias, but the fact is that the QRA method as applied missed a risk factor; the overrun is a QRA shortcoming story (told from the perspective of a risk analyst), not a tale of misrepresentation. The case study provides lessons learned for complex megaprojects at any stage of development.

[1] Per regulator policy, MH chose not to use probabilistic escalation (RP 68R-11 [13]) as called for in the PGD-02 QRA toolbox. That practice is recommended for all long duration megaprojects. However, the project did include a specific risk for escalation resulting from schedule slip.

2. Keeyask Scope

This section describes the project's physical scope and execution strategy; the risks associated with this scope will be discussed later. Keeyask is a greenfield 695-megawatt hydroelectric generating station on the lower Nelson River in Canada's Manitoba province. It was developed by the Keeyask Hydropower Limited Partnership (KHLP), a partnership of Manitoba Hydro and four First Nations (Tataskweyak Cree Nation, War Lake First Nation, York Factory First Nation, and Fox Lake Cree Nation). MH operates Keeyask on behalf of the Partnership.The renewable energy produced is integrated into the MH electric system for use in Manitoba and for export.

The project scope included earth-filled dams and earthen dikes, a powerhouse with seven turbine/generator units, and a seven-bay spillway. The station uses a relatively low 18 meters of head. A 93 square kilometer reservoir was created. Supporting infrastructure included an access road, construction camps, contractor work areas, construction power services, borrow areas, cofferdams, and an ice boom. The main camp facility had about 2,400 private rooms (originally sized for about 1,500). Power transmission scope is not included in this case study. Figure 1 illustrates Keeyask's general arrangement on the Nelson River which is about 2 kilometers wide at the site.

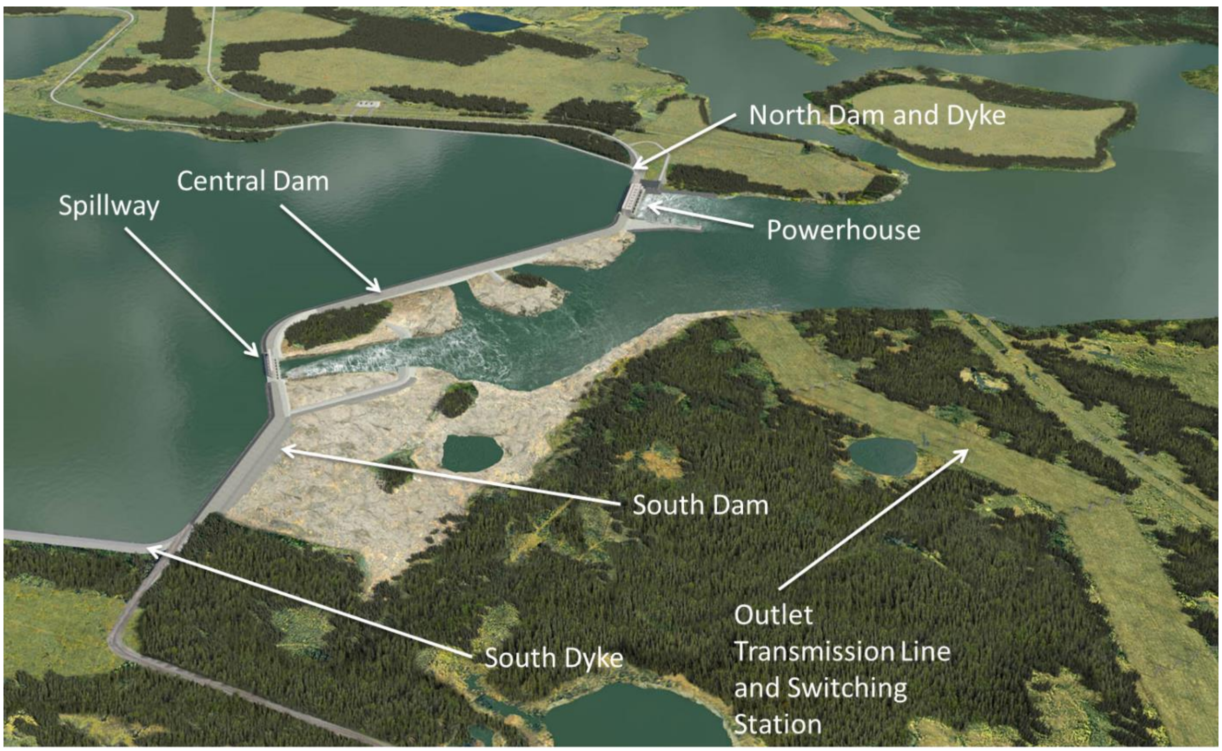

Figure 1–Keeyask General Arrangement on the Nelson River

Keeyask is located in northeastern Manitoba about 725 kilometers north of Winnipeg and 10 degrees south of the Arctic Circle as shown in Figure 2. Major equipment was transported on a 180-kilometer gravel road from the city of Thompson. While Keeyask was a greenfield project, it is operated in conjunction with several other generation stations on the Nelson River as shown in Figure 2.

Most construction workers were flown in from Winnipeg to Thompson, followed by a several hour bus ride to the camp on the gravel road. Most construction personnel worked on a 21-days-on, seven-days-off work schedule. The hiring priority was indigenous workers first, Manitoba workers second and workers from other provinces third; there was significant representation from each group. Figure 2 shows the location of the partner First Nations communities relative to Keeyask. The project is located within their traditional territories.

The site experiences long, severe winters. Temperatures may reach as low as -40 degrees C with wind chill as low as -70 degrees. The river freezes over in winter, and in the spring, ice dams may form with associated flooding (ice booms were used to protect the cofferdams). The typical concrete work season is from June through October; however, while not originally planned, the project worked through several winters. The site is also subject to potential forest fires.

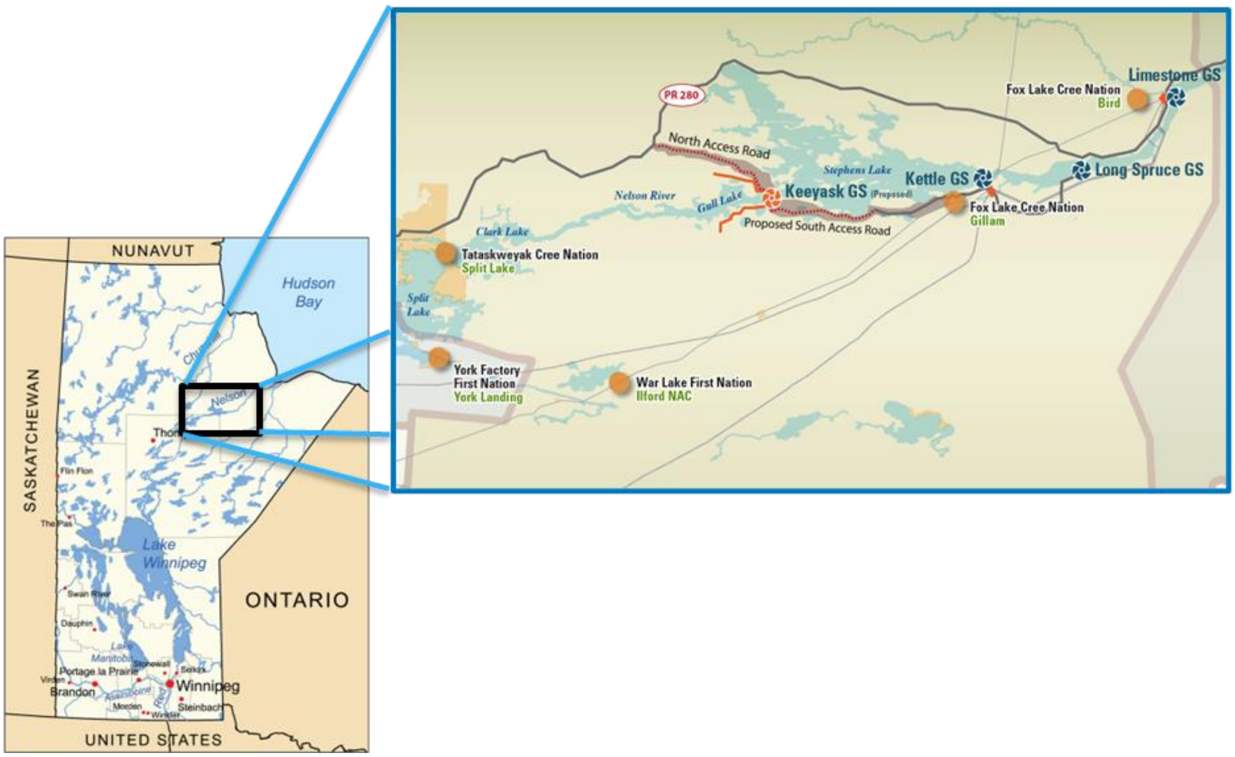

Figure 2–Keeyask Generating Station Location in Manitoba Province, Canada

The civil portion of the project, including the dam, dikes, and spillway, accounted for much of the cost (and most of the cost overrun and delay). A general civil works contract (GCC) was awarded in March 2014 to a joint venture with three partners. The contract type was target-price, cost-reimbursable with incentives. Table 1 summarizes the civil quantities in the GCC scope.

Civil Scope Element	Quantity (million cubic meters)
River Management (cofferdams)	4.1
Excavation	6.5
Dams and Dikes	6.6
Concrete	0.33

Table 1–Keeyask Civil Works Quantities

3. Keeyask Stage-Gate Process and Early QRA Development History

3.1. The Manitoba Hydro Stage Gate Scope Development Process

MH's stage gate process was roughly aligned with the AACE estimate classification framework. While AACE RP 69R-12 "Cost Estimate Classification Systems – as Applied in Engineering, Construction and Procurement for the Hydropower Industry" was drafted in 2013 (including input from MH), the RP was not used directly on the Keeyask project which was well underway by that time [7]. The MH stage-gate process stages relevant to this study included Stages III, IV, and V which are roughly aligned with AACE Class 4, 3, and 2 per RP 69R-12. Reflecting the provincial regulatory approval regime, Stage III was referred to as the concept phase, Stage IV was referred to as the pre-investment or pre-construction license phase and Stage V, based on contract tenders, referred to as the construction phase.

3.2. Keeyask Early Scope Development and Context

During Keeyask's early development, multiple MH hydropower projects were being studied or under construction. Construction of the $1.6 billion (2011 Canadian $) Wuskwatim Generation Station project was underway and was completed in 2012. A proposal for a larger Conawapa Generation Station as an alternative to Keeyask was also under consideration (it was not approved). In addition, MH was developing the BiPole III transmission megaproject and the smaller Manitoba-Minnesota transmission project (P+EV was applied to these projects as well but are not covered by the case study). While generation and transmission were separate MH business units, they drew from some of the same project organization and other resources.

The MH project organization was lean. As with many, if not most owner firms, there was significant dependency on consultants and contractors. However, the MH staff covered the key roles including project managers, estimators, schedulers, project control leads, and so on. Much of the experience gained during construction of the 1992 Limestone generation station project (see Figure 2) had moved on, although the Wuskwatim project completed in 2012 provided useful current experience albeit on a smaller station. The overall level of project system maturity and project control capability might be called fair but not excellent.

During the Keeyask project execution, nearby Alberta province was experiencing a boom in capex spending driven primarily by oil and gas investments related to oil sands development. This resulted in wide spread shortages of skilled engineering and construction labor. Project costs there and in other parts of Canada were increasing rapidly with many projects experiencing major cost overruns and delays.

Hydropower was undergoing its own boom in Canada. Nalcor Energy's similarly sized Muskrat Falls Generating Station project in Newfoundland and Labrador was proceeding about a year ahead of Keeyask's schedule and the larger BC Hydro Site C Generation Station project in British Columbia was trailing about a year behind. Also, Hydro Quebec's sequential series of four generation station projects on the Romaine River in Quebec (the Romaine Hydroelectric Power Complex [HQ Romaine]; each station being somewhat smaller than Keeyask) was also in progress.

3.3. Change in QRA Method During Early Keeyask Stages

For the early Keeyask Stage III and IV estimates, MH applied *range estimating* per the original RP 41R-08 for its cost QRA. MH had growing concerns as to the subjective nature of the method, the consistency of results from analysis to analysis, and reliability in forecasting the cost growth that was occurring. In 2008, AACE RP 42R-08 "Risk Analysis and Contingency Determination Using Parametric Estimating" was published which offered a more objective, consistent, and empirically-grounded method [8]. In 2008, MH decided to have a risk consultant facilitate a pilot test P+EV QRA analysis of a major spillway project. While RP 113R-20 for P+EV was not published at that time, the consultant had reported on the hybrid method in a 2007 AACE paper [9] and its use by Enbridge Pipelines was published in 2009 [10]. MH next applied P+EV on a Conawapa estimate in 2010. Having gained confidence in the method, the team was ready to apply it to Keeyask.

4. The Hybrid, Extended Parametric and Expected Value (P+EV) QRA Methods

This section provides a summary description of the P+EV QRA method. Readers should refer to the AACE RP 113R-20 [2] or the book titled "Project Risk Quantification" [11] for a complete description. P+EV is a hybrid method; it combines the parametric method based on empirical research with the excepted value method using Monte Carlo simulation (MCS) to align uncertainty and risk types with the best method for their quantification.

The parametric method quantifies systemic risks which are uncertainties in cost and schedule resulting from the nature or attributes of the project system; it takes a systems view. Research shows that systemic risks are the dominant driver of uncertainty when there are project system deficiencies. The parametric method used on Keeyask was based on historical industry research using multiple linear regression that correlated systemic rating measurements with project cost growth and execution schedule slip. It is optimally calibrated to a company's experience (not performed for MH given insufficient recent data). The parametric method provides empirical grounding and consistency while focusing management attention on the risks that they own, e.g., the strengths and weaknesses of their stage-gate system, team development, project control capability, and so on. The parametric method also quantifies the impact of the level of project technology and complexity and the bias and quality of the base estimate and schedule. Subjective range estimating tends to fall short in respect to those identified risk drivers.

The expected value (EV) method quantifies residual critical project-specific risks (which may include specific uncertainties) using the time-tested probability multiplied by impact approach. Cost and schedule impacts are entered for each risk as probability distributions based on team input and MCS is then applied to generate overall cost and schedule impact distributions. Critical risks are those which individually may result in a project failing to meet its cost and schedule objectives. They are usually the *red* risks in terms of extreme cost and/or schedule impact in the risk register. The impact of these risks is excluded in parametric model development, so their impact must be addressed with the EV method. A key element of the EV method is to base the impact estimates on assumed risk responses; the response is the action the team will take IF the risk occurs. The EV tool includes the parametric model of systemic risks as the first risk in the EV with a probability of 100 percent (systemic risk being an uncertainty). Hence the EV with MCS tool output includes all the considered risks. Figure 3 illustrates the base P+EV method concept.

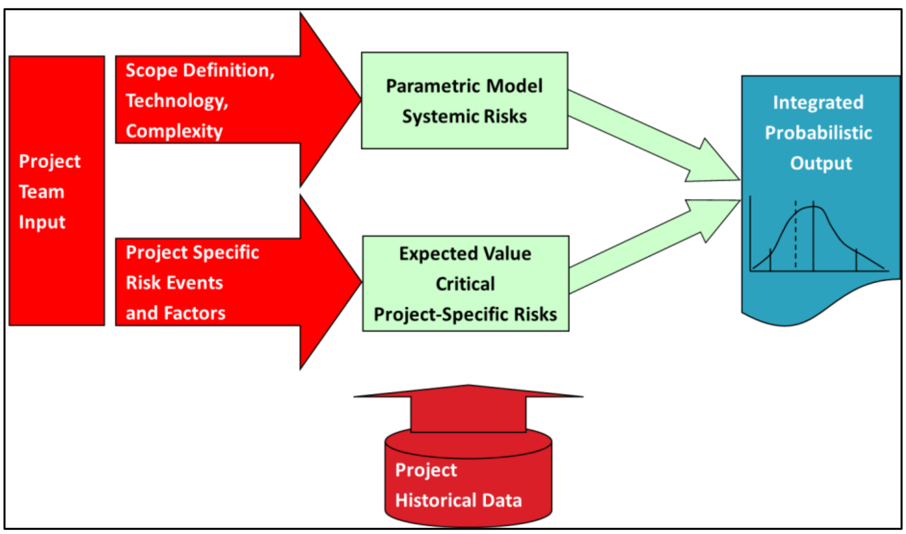

Figure 3–The Hybrid P+EV Method Concept (i.e. RP 113R-20)

The EV tool, used to determine contingency under the project manager's authority, does not appropriately quantify high impact/low probability (HILP) risks. In the P+EV approach, each HILP's cost and schedule impact is quantified individually assuming that it occurs. Management must then decide whether and how to fund the potential impact of one or more of these risks occurring. On long duration megaprojects there is usually a high probability that at least one HILP will occur (i.e. they are not black swans or unknown unknowns). Specific management reserve(s) is recommended for HILP funding. Figure 4 illustrates the *extended* P+EV approach including the HILP analyses.

Having quantified the systemic, project-specific, and HILP risks, the last step is to assess the risk of the project crossing into a non-linear, disorderly behavior mode. The base QRA methods assume orderly behavior. A *tipping point* (TP) method for assessing the potential of this disorderly behavior occurring is addressed in the literature [5] [12]. This method addresses attributes common to disorderly projects including complexity, decision making, aggressiveness and teams, plus stressors (e.g., HILPs) that can push a project over the edge into disorder. It is not generally used as a basis for funding, but instead to warn the project team to place more effort into treating the risk drivers. Figure 4 illustrates the *extended* P+EV approach including the TP assessment.

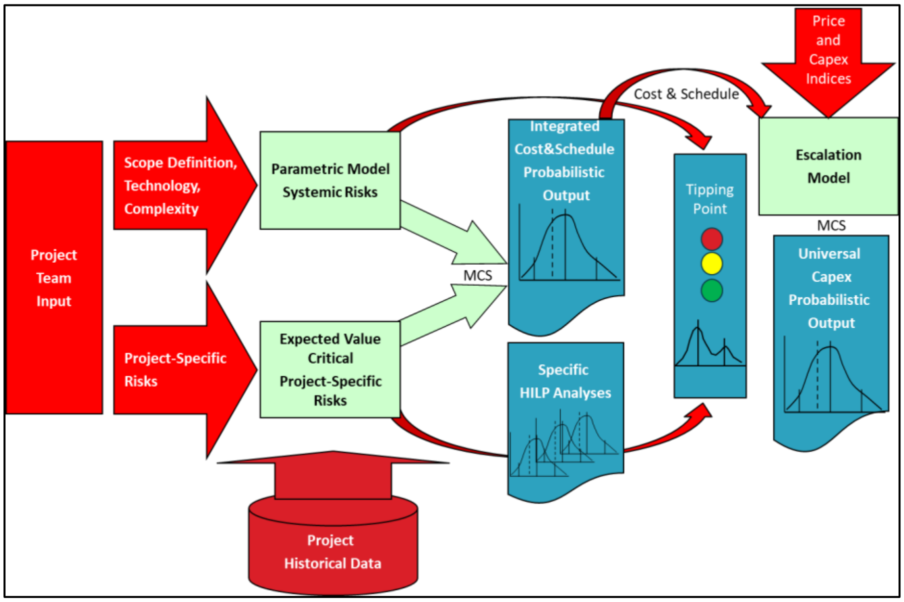

Figure 4–The Hybrid, Extended P+EV Method Concept for Megaprojects

A fully elaborated approach, as shown in Figure 4, also quantifies escalation risk which is driven by the economy and market conditions. Escalation should be quantified probabilistically using specialized methods [13]. Probabilistic escalation includes cost and schedule QRA outputs as inputs to escalation which can generate a *universal* capex distribution for use in business cases. This last step was not done on Keeyask. Instead, an escalation model was developed to account for construction escalation, which was independent from the risk analysis. However, price volatility and inflation were not major risk drivers for Keeyask execution (although it was during earlier project phases during the regional capex boom). The 2014 to 2021 Keeyask construction duration fortuitously fell between the end of the boom and start of the COVID inflation. It should be noted that the Keeyask QRA did include escalation caused by schedule slip as a specific risk in the EV method.

5. QRA, Risks and Responses: as Analyzed and Budgeted For, and as Occurred

This section shares the execution phase QRA experiences from the point of view of the risk analysts as uncertainties and risks evolved, occurred and risk responses were planned, and actions taken. Lessons learned are provided in respect to each analysis (but particularly the third QRA). Figure 5 summarizes the timeline of the QRA analyses from before the start of construction in 2013 through the first turbine unit in-service date in 2021. Figure 6 illustrates where the QRA fit into the overall MH Keeyask budgeting scheme that includes contingency and specific management reserves but excludes general management reserves, interest, and escalation as part of QRA.

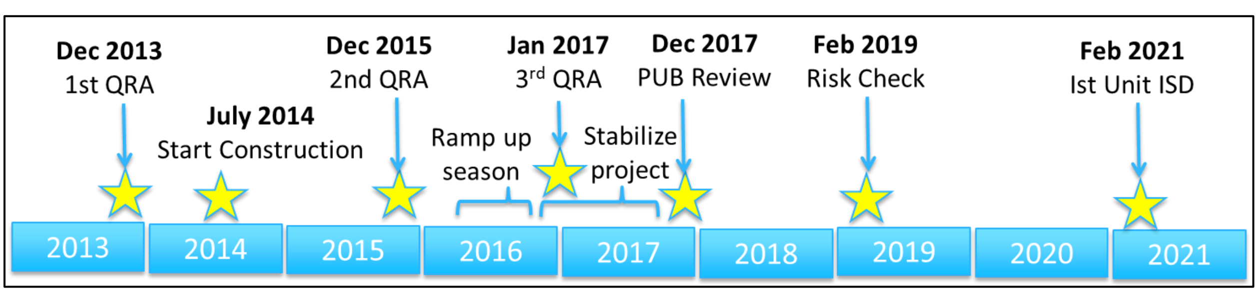

Figure 5–Keeyask QRA Timeline

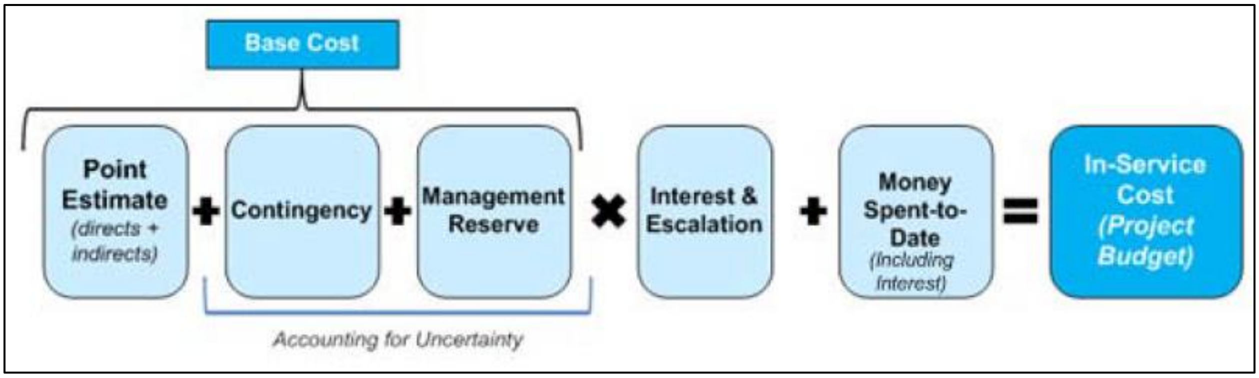

Figure 6–Keeyask Budgeting Scheme

5.1. Pre-2013

In 2009, Keeyask submitted an environmental impact statement for the Keeyask Infrastructure Project (KIP) which included road and initial camp work. KIP construction started in 2012. In 2012, Keeyask investigated the market for the main GCC contract and issued a request for proposals. Also in 2012, the 2009 Stage IV (nominal Class 3) estimate, using range estimating for QRA for the last time, and using Wuskwatim learnings, was updated to a cost estimate of $6.2 billion (2012 Canadian $).

5.2. 2013 Uncertainty Context

Some of the Keeyask project physical and environmental attributes were described earlier. The following list summarizes the attributes that relate to Keeyask's project uncertainty and risks. These were knowns in 2013 prior to the QRA.

- Capex Market: Tail end of the super-cycle, but megaprojects still wrapping up in Alberta.
- Hydro Market: Other hydropower projects/programs in parallel: Muskrat Falls, Romaine, Site C.
- Transmission Market: MH BiPole III and Manitoba-Minnesota transmission projects.
- Power Market: Commercial agreement to supply export power by 2022.
- Social License: Development agreement with the First Nations communities whose traditional territories would be impacted by the development.
- Government: Regulated Utility; Manitoba Public Utility Board and Ministerial oversight.
- Remoteness: Workers flown in; 21-days-on, seven-days-off.
- Weather: Severe winters; concrete work normally limited to June to October.
- Complexity: Complicated megaproject, but only moderately complex with GCC; no new technology.
- Contract Strategy: Target-price, cost-reimbursable (shifts most risk to the owner)
- MH Project System: Average owner capabilities with resource challenges

As will be discussed later, all of these attributes and stressors played into Keeyask's systemic fragility. The cause of Keeyask's eventual cost overrun and schedule slip was not project-specific risk events (such as are found in traditional risk registers or that can be found and quantified by digging deep into project details) but was instead due to tipping point behavior.

5.3. 2013 Benchmarking

Another known in 2013 was learnings from comparable projects. The parametric method explicitly rates the estimate and schedule bias. Optimally, this is based on validation of the base plans against historical data and metrics, i.e., benchmarking. Two key benchmarking inputs to the QRA were recent data from MH's Wuskwatim Generation Station project completed in 2012 and a Canadian hydropower industry cost growth study conducted in 2013 [3]. The Wuskwatim learnings were directly factored into the 2013 Keeyask Stage IV base estimate and schedule update.

Also of note, the MH Limestone Generating Station downstream of Keeyask completed construction in 1992. While being over a decade prior to Keeyask, the Limestone experience provided some points of reference.

The Canadian cost growth study included data from four provincial power authorities. The study's results for cost growth for nominal Class 3 estimates are shown in Table 2. The data was normalized to remove escalation. The p50 cost growth (i.e., required contingency and reserves) was 24 percent with a p90/p10 confidence interval around a nominal Class 3 base estimate of +63/-1 percent. Industry schedule slip (not included in the reference paper) was 9 percent at p50 with a p90/p10 confidence interval of +54/-23 percent for a project of Keeyask's size at Class 3. The range is of particular note; it is much wider than most team member and management expectations for Class 3.

Actual/Base Estimate	Class 3
number of observations	*21*
Mean	1.24
p90	1.63
p50	1.24
p10	0.99

Table 2–Canadian Hydropower Cost Growth Study (2014) [3]

5.4. First QRA: Pre-Construction; December 2013

MH management was committed to the QRA method and process, and they let the team know. They would later prove receptive to and would generally incorporate the recommendations of the risk consultant. Of note, the project basis and analyses were subject to hearings and independent reviews, thereby encouraging best practice.

In preparation for regulatory approval and the start of construction in 2014, MH updated the 2009 Stage IV (nominal Class 3) project estimate and schedule in August 2013. GCC input was not yet available. The risk register was also updated. The consultant and MH risk staff (with several P+EV analyses under their belt) led two QRA workshops at the end of November 2013. The first workshop interviewed key project team leaders to rate the level of scope development and other systemic risks for input to the parametric tool. The next workshop was with key members of the project team to identify critical project-specific risks, quantify their probability of occurrence, and estimate their cost and schedule impacts in consideration of likely risk responses for input to the EV tool. The consultant issued a draft QRA report two weeks after the workshops (an advantage of the P+EV method is its speed). GCC bids were received in December 2013 and the final QRA report was issued in March 2014 at about the same time that the GCC contract was awarded. The following summarizes the risk profile at that time.

5.4.1. Systemic Risk

Systemic risks were rated as moderate in general. Ratings below Class 3 expectations were geotechnical definition (no borings of the Nelson River bottom), team development, implementation planning and execution strategy, and MH's project management and systems were still maturing and experiencing resource challenges. Physical complexity was relatively low for a megaproject, but execution complexity was moderate given the seasonality and remote site challenges.

5.4.2. Critical Project-Specific Risks

Excluding reserve risks, specific risks were moderate. However, ten critical risks were quantified and the major finding was that, cumulatively, the risks threatened to drive the project into an additional year's construction considering seasonality and the labor force size being constrained by camp capacity.

5.4.3. High Impact/Low Probability (Reserve) Risks

Five HILP risks were identified with high probability that one or more of them would occur, resulting in a potential second added year of construction beyond the contingency risks. With a peak planned construction workforce exceeding 1,000 plus seasonal volatility, and somewhat aggressive GCC bid cost (bids were known by the time of final QRA report issuance), the project was particularly susceptible to severe adverse labor productivity impacts from skilled labor shortages, particularly for supervision. An additional labor cost reserve was recommended to cover this risk.

5.4.4. Tipping Point

The potential for disorderly behavior was addressed as a labor reserve analysis. Of the factors considered in the tipping point approach, the project size, perceived aggressiveness of the GCC bid, and the team development/resources being challenged were moderately concerning factors. The probability of experiencing disorderly behavior was considered low; however, there was enough concern to include a labor reserve.

5.4.5. Recommended Risk Funding

In total, contingency at p50 and reserve allowances of approximately 28 percent on the remaining (to be spent) base cost and 13 percent on remaining base schedule were recommended. Note that these outcomes were comparable to the Canadian hydropower benchmarks in Table 2. At the p95 (i.e., nominal worst case) confidence level of the contingency portion, holding the other elements constant, the overall risk allowance, though not recommended, would have been 52 percent of the remaining base cost.

The contingency and reserves on the cost remaining were made up of the following elements:

- Contingency (p50): 10 percent on cost and 13 percent (10 months) on schedule; worst case of p95 adds an additional 24 percent on cost remaining;
- Escalation on schedule delay (but no other escalation risk): 2 percent on cost;
- HILP reserve: 6 percent on cost (for potential one year delay);
- Specific labor reserve: 10 percent on cost;
- Interest: excluded from risk analysis at that time.

The project control budget was established at $6.5 billion (2013 Canadian $) including contingency, escalation and interest. The planned in-service date (ISD) for the first turbine unit was November 2019 with first power export in 2020. The project did not apply a schedule contingency per se but considered potential slip in making supply commitments to customers. The GCC was awarded in March 2014 and the approval for construction, after “Needs For and Alternatives To” (NFAT) hearings by the Manitoba Public Utilities Board (PUB), was received in July 2014.

5.5. Second QRA: Mid Construction, Pre-Ramp Up; December 2015

After the first full season of construction in 2015, a mid-stream, QRA was performed including holding both systemic and project-specific risk workshops. The QRA was based on the remaining cost and schedule of the original control budget; no major re-forecast was prepared. At that point, all the major procurements had been bid and the engineering models were near completion. The temporary river management structures (cofferdams) which allowed for dewatering work areas and excavation to occur for the powerhouse and spillway were complete. Spillway excavation was in progress and some minor concrete work was done. Work was generally on track and the general perception was that the risk profile had not changed significantly since the first QRA. The team felt they would be ready for the 2016 GCC labor force ramp-up season ahead. The following paragraphs summarize the updated risk profile as recorded at that time.

5.5.1. Systemic Risk

Systemic risks continued to be rated as moderate. Team development and staffing concerns remained. Given a reimbursable contract where the owner assumes productivity risks, the effectiveness of the MH project system in handling project control and change management, both during and after the ramp-up phase in the crucial year ahead, remained an unresolved question.

5.5.2. Critical Project-Specific Risks

The specific risks were moderate and similar to the first QRA. Two risks were closed (e.g., cofferdam over-topping), but four new near-critical specific risks had emerged. The major critical risk of labor productivity remained. As in the first QRA, the specific schedule risks cumulatively threatened to drive the project into an additional year's construction.

5.5.3. High Impact/Low Probability (Reserve) Risks

As in the first QRA, there are multiple HILP reserve risk events. One more was added leaving a high probability that one or more of them would occur, resulting in an added year of construction in addition to the contingency risks.

5.5.4. Tipping Point

There was no change from the first QRA assessment. Concern remained for labor productivity in 2016. In perhaps a sobering forewarning, the QRA report noted that Nalcor Energy's Muskrat Falls in Newfoundland, started about a year ahead of Keeyask, was reporting difficulties [14]. BC Hydro's Site C project in British Columbia had just awarded its major civil contract.

5.5.5. Recommended Risk Funds

A specific reserve risk was added for interest cost due to schedule slip (this had not been included in the first QRA). Although there were modest changes to the various contingency and reserve allowances, the control budget was left unchanged at $6.5 billion (2015 Canadian $) and the planned ISD for the first unit was still November 2019 (but with recognition of the schedule risks in respect to commercial service).

5.6. Third QRA: Mid Construction, Post Ramp Up; January 2017

5.6.1. Tipping Point Threat Realized; Recovery/Stabilization Plan Initiated

During the 2016 construction season, GCC labor productivity did not meet expectations. While procurement was well advanced and engineering complete, the GCC only achieved 41% of the concrete plan and 65% of the earthworks plan. The challenging situation was quickly evident that summer; a potential *tipping point* situation was faced. Driven by a call to action - including the project team and MH and GCC Executive Sponsors and CEOs - a recovery plan was put in place in September 2016 that included:

- The development of a plan for the continuation of concrete through the severe winter months.
- Identifying root causes of performance issues
- Initiating activities to reforecast the cost and schedule for the project.
- Undertaking analysis around Contractor's claims.
- Supplementing the commercial expertise of the Manitoba Hydro team.

Also, the Manitoba Hydro-Electric Board (MHEB) initiated a review; its report was released in September 2016. The review concluded that continuing with Keeyask remained the most cost-effective option to meet future load requirements. The report also included an independent consulting study that projected (based on mid-season 2016 construction experience) a 21 to 31-month delay to first unit ISD and a cost increase from $6.5 billion to between $7.2 and $7.8 billion.

As construction work proceeded into the winter of 2016/2017, the recovery plan activity continued with improved construction management. In particular, MH did an in-depth evaluation of alternatives for and impacts to the GCC. The evaluation determined that the best course of action was to amend the existing GCC contract. All other alternatives introduced significant additional risks as well as guaranteed impacts to cost and schedule that were greater than the option of amending the contract. The QRA, including tipping point consideration, contributed to this evaluation. The contract decision was made in February 2017 and by March the project had been re-baselined with approval of the Keeyask partnership.

In February 2017, the MHEB approved a new control budget of $8.7 billion and revised first unit ISD of August 2021; an increase from the previous control budget of $6.5 billion and a delay of 21 months from the previous first unit ISD of November 2019.

In respect to the QRA itself, a project re-forecast was prepared in December 2016 to serve as the base of the QRA. Once again, the QRA involved conducting full systemic and project-specific risk workshops. The following discussion presents the findings in the third QRA.

5.6.2. Systemic Risks

Other than having advanced design deliverables and procurements, systemic risks were still moderate with a step downwards from the 2016 QRA. The level of definition of planning was considered to be lower (e.g,. equivalent to Class 4) due to the contract, cost, and schedule planning baselines now being in flux. Also, the execution complexity rating increased based on the recovery plan elements and actions. The rating of MH's project system capability was also lowered based on its 2016 performance. It is often whether performing a parametric analysis in mid-construction is worthwhile. This situation provides an example of how a project system can adapt during the course of a project and emphasizes why full P+EV should be applied not only prior to execution, but during execution to improve project outcomes.

5.6.3. Critical Project-Specific Risks

Critical project-specific risks were still moderate. However, due to the low productivity assumed in the revised baseline for the GCC concrete and increased workforce density, delays from specific risks became more costly.

5.6.4. High Impact/Low Probability (Reserve) Risks

As in prior QRAs, there are still multiple reserve risk events with a high probability that at least one of them will occur, resulting in an added year of construction (this would be additive to the "contingency" risk impacts).

5.6.5. Tipping Point

With a larger workforce and now working in winter, the project continued to be exposed to adverse labor productivity impacts. However, no labor reserve was recommended going forward given the recovery plans and the revised base estimate's conservative assumption of continuation of the 2016 concrete productivity.

In respect to tipping point logic, the QRA report stated, "Once in this distressed mode, control strategies can focus on either 'containment' or 'recovery'. Containment largely accepts the labor and supervision situation and works to ensure predictability with what is at hand. Recovery attempts to restore productivity to something closer to the original plan which adds stress to the project." In other words, aggressiveness and massive disruption (e.g. changing contractors) threaten to push a project over the tipping point into disorder that no typical control strategy can save. Teams need the motivation of potential success (as opposed to a belief that the project is destined for failure). The situation of ever-increasing budgets and duration results in a breakdown of motivation and confidence of all parties, potentially inducing a worse spiral. Keeyask proposed a stabilization/containment strategy that was accepted.

The experience on Keeyask is not isolated to Manitoba. In comparison, Nalcor Energy's Muskrat Falls project in Newfoundland was experiencing increasing budgets [15]. BC Hydro's Site C project in British Columbia faced increased costs as well (in part caused by COVID pandemic impacts) [16].

5.6.6. Recommended Risk Funds

Most of the overall 2017 Keeyask project cost increase was from the occurred labor productivity risk reflected in the revised base estimate, not added contingency and reserves. In total, contingency and reserve allowances of approximately 40 percent on the remaining base cost and 25 percent on the remaining base schedule were recommended (compared to 28 and 13 percent, respectively, for the first QRA).

The contingency and reserves on remaining cost and schedule were made up of the following elements:

- Contingency (p50): 17 percent on cost and 25 percent (11 months) on schedule
- Escalation on schedule delay: 2 percent on cost
- Interest on schedule delay: 5 percent on cost
- HILP reserve: 10 percent on cost (for potential added year delay)
- Interest on HILP added schedule: 6 percent on cost.

The control budget was increased from $6.5 billion to $8.7 billion ($2016 Canadian $). After improvements were made to the project schedule in recovery planning, including working in the winter, the overall delay was kept to 11 months with the planned first unit ISD being revised from November 2019 to October 2020.

5.7. Manitoba Public Utilities Board (PUB) Review: December 2017

The Manitoba PUB had an independent consulting firm review the MH Capital Expenditure Program, including Keeyask. The report included many useful observations and recommendations. In respect to risk, in the consultant's opinion, the total project cost would be $9.5 to $10.5 billion ($2017 Canadian $) with the low value representing the best case if MH addressed the issues in the review. An order-of-magnitude schedule delay of 410 days (about 13 months) beyond the 2017 control base was forecast if MH did not address the issues in the review. MH rebutted the findings and did not change its budget or schedule.

5.8. Risk Check-Up; Work Transition; February 2019

The recovery actions taken in 2016 were successful. Performance was stabilized and the second peak season of 2017 went well and continued on through 2018. However, it was not easy. The project owner and GCC continued to pursue opportunities, make adjustments, and work hard to meet commitments while responding to risks that occurred (e.g., a blockade over First Nation concerns regarding the COVID pandemic in 2020). For example, after 2017, a "Road to 500 (RT500)" initiative was taken that included cost savings, cost avoidance, execution efficiencies and schedule improvement initiatives to carve out $500 million dollars from project costs.

However, in 2019 construction was shifting from civil and concrete to balance-of-plant mechanical and electrical work and there was concern as to whether the risk profile might change. Therefore, this qualitative check assessment was performed in January 2019; the energized, enhanced, focused team concluded that another QRA update was not necessary.

5.9. Final Result: 2021

The balance-of-plant work went well despite the COVID pandemic occurring towards the end of the project duration. The first turbine unit was brought online February 2021, 6 months ahead of the August 2021 date forecasted in

2017. Overall, the construction schedule duration slipped 15 months or 25% from 2014 (from 59 to 74 months). The cost forecast was on track with the 2017 revised budget of $8.7 billion. However, the later final cost after all turbine units were in service in 2022 was $8.2 billion, a 26% increase from 2014. Referring back to the first QA risk allowance values (52% of the base remaining cost in 2013), and allowing for interest not included in the QRA, $8.2 billion was approximately at the very high end of the 2013 extended P+EV. While of little comfort to anyone but a risk analyst, it was within the range.

5.10. Project-Specific Risk Experience

Looking back on the critical project-specific risks that were quantified using EV, more than half of the risks identified in 2013 occurred including: skilled labor shortage, productivity, weather, camp delays, geotechnical conditions, multiple blockades, fire, high flow, and reservoir filling delay. The team effectively identified these risks, and the P+EV method effectively quantified them. From a QRA case study perspective (not disrespecting all the hard construction work), they were unremarkable for a major hydropower project.

6. QRA Lessons Learned and Recommendations

The first learning is one of success. For the most part, the P+EV with specific reserve analysis worked well for all of the project uncertainties and risks except for the tipping point/labor productivity risk. The other project-specific risks were identified, quantified, and unremarkable for a hydropower project. The Keeyask risk story is about systemic fragility, not risk events or background uncertainty. It is about not fully appreciating the nature of the tipping point threat in 2013 (i.e. the fragility of labor productivity was the risk that mattered).

Another success is that under strong, prudent leadership Keeyask faced reality head-on in the 2016 QRA and implemented a robust risk response. It recognized the tipping point threat, and potential for pushing the project over the edge if the recovery plan was made too aggressive (i.e., forecasting restoration of productivity closer to original estimates and/or off ramping the contractor). The budget was increased once and done. In contrast, other projects in Canada reported successive increases over the years resulting in the approximate doubling of their costs. A case study of the HQ Romaine program coming out nearly on budget and schedule overall would have been a valuable reference here; the author's hypothesis is that its experience confirms the learnings of this study, i.e., by constructing a sequential series of smaller units, leveraging experience and the learning curve, the tipping point was avoided.

Other QRA learnings and potential improvements are discussed below in two parts: tipping point learnings, and then secondary QRA learnings.

6.1. Tipping Point Learnings

A successful tipping point (TP) assessment, which produces a qualitative warning of potential disorder or deficient productivity, would be one where the owner decided to revise the project scope and/or system attributes so as to mitigate the TP drivers (e.g. manage complexity, reduce aggressiveness, strengthen team, improve capabilities, treat HILP risks, etc.).

Only the *extended P+EV* method (Figure 4) explicitly addresses TP risk. No subjective range estimating or detail focused QRA method (e.g., critical-path method with MCS) would recognize, let alone quantify and address what occurred on Keeyask. Also, because the TP threat may emerge in mid-execution, applying the extended P+EV method with TP throughout a megaproject project life cycle is critical.

However, on Keeyask, the TP assessment fell short of expectations. There are three main learnings in respect to improving upon the TP shortcomings. These include:

1. Rating Aggressiveness
2. Rating Team Development/Project System Capability

3. Starting Early with P+EV and Tipping Point

6.1.1. Rating Aggressiveness

The aggressive bias of the base cost and schedule were rated too broadly. An *average point-of-view* was applied across the entire scope and duration as if the manpower loading was steady if not a constant. This is not an uncommon shortcoming when looking only at high level metrics and benchmarks that give no information about the ebb and flow of a project. The expectation that any construction contractor could hit the ground running at peak productivity while ramping up to over 1,000 workers in a 6-month season was, in hindsight, a mistaken assumption. The QRA rated the *general* bias as somewhat aggressive based on a low GCC bid, but in relation to the 2016 ramp-up season (and into 2017), the plan and schedule should have been seen as being very aggressive; a red-flag in a tipping point assessment. In summary, it would be better to assess aggressiveness relative to what may be expected at the peak.

6.1.2. Rating Team Development/Project System Capability

When it came to rating the team development and owner/contractor project management and supervision capability, the QRA once again applied an *average point of view*. A lesson learned is to question whether there might be a project system breaking point considering the situation of extreme peaks of work and the attributes and stressors listed earlier that contribute to systemic fragility. MH and the GCC's project systems were, in fact, able to handle the less demanding workload of 2014/2015 without incident. However, the MH and GCC management and the site and craft supervision, and their project control systems, were not equipped to handle the peak workload of 2016. The significance of this issue should have been escalated in the tipping point assessment. The recovery plan of 2017 enhanced the system and stabilized performance. That sort of planning and enhancement of capabilities should have been identified and executed before construction began, ideally during the prior Stage. In summary, assess team and system capability to handle the peak.

Reflecting on past experiences, it became evident that the assumption of a major contractor's robust project management and oversight capabilities might be misplaced unless both the owner and contractor teams have recently worked on a similar project, such as HQ Romaine. Ideally, this experience would come from a sequence of related projects. Relying on a major contractor, especially within a venture partnership, to swiftly and efficiently mobilize their best resources and operational systems is a risky assumption. This understanding is more apparent in retrospect, highlighting the importance of relevant, recent experience in ensuring project success.

Contractors on megaprojects often take 6 to 9 months at best to get up to speed (and certainly not within a 6-month season), assuming they have the skilled personnel on board. In regard to personnel, another learning is that staffing of field construction management and supervision, particularly at a remote/inclement site, generally lags the plan. Some will counter (as expressed in the third-party reviews of the Keeyask project) that using fixed price, or at least unit rate, contracts will protect the owner from contractors falling short. However, when a contractor performance on a megaproject crosses the tipping point, such contracts offer little protection to the owner. Most contractors cannot absorb such losses, so it is not uncommon to find megaproject contracts renegotiated to keep the work going [17].

Short of benefitting from the learning curve of a series of successive, recent projects, a possible risk mitigation would be to get a head start using early contractor involvement (ECI) or similar contract strategies, but also closely monitoring early construction and supervision performance and resolving problems before ramping up aggressively (even at the price of longer planned duration). Getting off on the right foot is critical. In summary, assess the capability of a contractor's team (including as a partnership) based on its experience from immediately prior job(s). If no such immediate, cogent experience is evident, constructively discount their capability.

6.1.3. Starting Early with P+EV and Tipping Point

As mentioned, mitigating TP drivers (i.e., reducing system fragility) requires challenging and time-consuming efforts such as managing complexity, reducing aggressiveness, strengthening teams, improving capabilities and so on. Extended P+EV was first applied on Keeyask at the same time as the GCC contract was being awarded and application for construction approval was being made. To be effective, extended P+EV should be applied at the Class 4 decision gate (Stage III at MH) when a single scope option and a general execution strategy are approved. Potential TP drivers can then be managed prior to reaching the Class 3 decision gate (Stage IV at MH) and certainly before engaging the major contractor(s) who are optimally brought in early.

6.2. Other QRA Lessons Learned

As mentioned, the P+EV with specific reserves method worked well on Keeyask. While some new risks emerged during the course of construction, by and large the initial QRA identified the risks that mattered and quantified them reasonably well. However, there are several QRA practices that could have been improved upon (and now used as standard practice) and would have allowed for additional appropriate risk funds at the first Keeyask QRA. These practices include the following as will be described:

1. Allow for General Reserves
2. Probabilistic Escalation
3. Avoid Eventification

6.2.1. Allow for General Management Reserves

At the time of Keeyask, the authors' opinion that it was appropriate to fund management reserves in either a general way (e.g., fund at p70 with the difference from the p50 being a reserve for risk tolerance) or based on specific HILP risks which have been identified. However, the consultant author has come to view this approach as being unrealistic; the p70 is about making prudent investment decisions, i.e., not funding a strategic project with major economic import to the owner on a coin toss (i.e. p50) concerning day-to-day uncertainty and risks. The HILP risks are by definition exceptional, and on a megaproject, the likelihood of one or more occurring is high. Both types of management reserve should be funded.

6.2.2. Probabilistic Escalation

As noted, MH did not apply probabilistic escalation (it did allow for escalation resulting from schedule slip as a specific risk.) The Keeyask project was constructed during a fairly stable, non-inflationary economy over the course of six years; it got lucky in that regard. No megaproject should be funded without analyzing escalation as a major risk. Based on the probabilistic distribution (beyond deterministic budgeting), escalation should be funded at the same confidence level as the general management reserve.

6.2.3. Avoid Eventification

In the EV method, project-specific critical risks and uncertainties are quantified. In practice, many risk analysts habitually quantify all project-specific risks as event risks, i.e. risks with less than 100 percent probability of occurring. However, many risks are actually uncertainties; i.e., 100 percent probability of occurring. Many are just attributes of the project resulting in uncertain outcomes (i.e., systemic risks are uncertainties). The author calls this practice *eventification*.

An example specific risk often found in risk registers is *poor productivity* not resulting from a specific event. That is an uncertainty, and in Keeyask's case, a critical one. This is not a binary case of productivity having 50% chance of being poor or otherwise excellent (which results in a bimodal outcome in MCS). There is, in fact, a 100 percent chance that labor productivity will not be exactly as planned. All the uncertainty is in how different the actual productivity will be from the estimate basis, i.e., the impact. For example, the impact might be quantified in a 3-

point distribution as having a low of perhaps some negative labor cost (opportunity for better productivity), a most likely of no impact (as planned), and a high, presumably critical, labor cost (worst case). Using this in a Monte Carlo simulation will typically result in a greater impact than a risk reduced by some percentage probability and it is more realistic (does not produce bimodality). Similar uncertainties are highly variable weather conditions (but not from extreme events), extreme variations in soil conditions, and so on.

7. Conclusions

The use on Keeyask of the extended P+EV method, including specific reserve quantification of HILP risks and applying a tipping point (TP) assessment, was a success with one notable exception; in 2013 the TP assessment did not sufficiently warn of the later failure to achieve anywhere near planned productivity on the concrete and other civil work. However, it is likely that any TP warning made at the same time that the GCC contract was being awarded was too late to perform risk treatment, i.e., scope, strategy, or project system changes. However, Keeyask did not cross into statistical chaos; it stabilized performance, albeit at a costly level. In that respect, the tipping point assessment in 2016 was a success of sorts. The tipping point threat was realistically faced head-on, in full, and only one budget increase had to be made. The cost growth and schedule slip were thereafter contained by a robust, effective recovery plan. This is in contrast to similar megaprojects in the same timeframe that reported successive, cumulative increases in budget and of greater cumulative magnitude.

Lessons learned and recommendations start with the observation that the project risk story was one of systemic fragility, not risk events per se. Traditional QRA methods do not explicitly address fragility; a tipping point or similar non-linearity assessment is crucial. Lessons and recommendations on applying TP more effectively, considering systemic fragility, included rating aggressiveness and team development/project system capability in reference to the peak of construction, not as a general *average* point of view across an entire project. Also, the extended P+EV method should be applied at an earlier pre-sanction phase when there is still time to make scope, strategy, and/or project system changes.

Other lessons learned emphasize the importance of always allowing for both a general risk tolerance management reserve (e.g., set the budget at the p70 or p80 confidence level), along with specific management reserve(s) for HILP risks on strategic megaprojects. Also, apply probabilistic escalation analysis, and fund escalation risk at the same confidence level as used for general reserves. Finally, within the EV method, avoid *eventification*; many critical risks are not events but uncertainties, often with more significant impact than usually modeled.

No QRA method will assure a project will come in on budget and on schedule. However, using a toolbox of methods, addressing each type of risk, applied throughout the project life cycle, QRA should and can realistically capture, quantify, and communicate the risk profile so that executive management can make informed decisions. As a final note, while of little comfort to anyone but the risk analysts, it can be said the final Keeyask cost came within the QRA range.

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