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Using uncertainty analysis to unravel cost risks for nuclear and mine site closure

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Abstract

Closure programs in both the mining and nuclear sectors can run into the hundreds of millions to billions of dollars and are prone to large increases as planning develops, which give rise to budgetary and governance concerns. These increases in cost are often the result of not sufficiently understanding the uncertainty surrounding different activities. The uncertainty is often hidden and derives from a lack of knowledge, assumptions based on a weak knowledge base, an optimism bias (particularly relating to long tail items) and/or the enhanced scope of closure. Cost risk analysis can be used to unravel where uncertainty lies, with the majority of the cost range often being concentrated within a disproportionately small number of items. In understanding which activities provide the greatest levels of uncertainty subsequent studies can be focused to narrow the uncertainty (and cost range) providing better outcomes.

Keywords: *cost, risk, waste management, planning, studies programmes, knowledge base*

1 Introduction

The estimated cost of decommissioning the UK's seven Advanced Gas-cooled Reactor stations, plus the Pressurised Water Reactor at Sizewell B is estimated to be £23.5 billion (House of Commons, 2022), this having doubled from earlier estimates reported in March 2004. Mining too sees its fair share of cost projection increases both in the planning and execution stages, with Giant Mine in Yellowknife having a revised cost estimate of CDN$4.38bn, a program which had earlier been estimated to cost just under CDN$1 billion in 2013 (CTVNews, 2022). Other examples such as the Ranger uranium mine in Australia (ERA, 2022) can be found.

Decommissioning and closure activities present a wide variety of challenges with sometimes multiple solutions. These solutions need to be delivered to align with regulatory and stakeholder expectations. The challenges of closure are not as straight-forward as a construction project, where a logical sequence of construction steps can be anticipated containing a defined approach and a quantifiable set of items. In closure some items can be defined / quantified readily while others require multiple sets of studies to define the extent of a problem and refine a solution. Although widely used within both sectors, a traditional cost estimating approach is confronted with a problem in that many closure activities have a number of unknowns and uncertainties around them and do not sit within the confines of an expected accuracy range for a Class 4 or 5 cost estimate (AACE 2005).

Compounding this is the long-time frame over which closure cost estimates are developed, with initial estimates perhaps being completed decades out from closure and often having a light touch periodic update, and only when closure becomes a near term issue are costs reassessed appropriately, and this can provide an order of magnitude cost increase.

Herein is described how an approach assessing uncertainty can be used to determine a more accurate picture of the cost risk associated with a closure / decommissioning project, this is an approach that can be utilised throughout the life of mine and support in identifying the underlying uncertainties and drive studies programmes that can incrementally address risks.

2 Uncertainty & reliability in the base costs

It is clear that the activities within a closure programme do not have a blanket level of accuracy (+50% / -30% for instance), but that individual items will show a diverse range of accuracies due to different uncertainties. For example the extent of contamination might not be readily understood because it needs to be investigated and assessed, while the extent of works related to demolition of a building can possibly be more readily understood. Even within individual activities certain elements are better understood (or can be more readily estimated) than others.

Compounding the accuracy issue are poor decisions based on the estimation of unknown quantities. Figure 1 demonstrates the uncertainty around the estimation of soil volumes for excavation and remediation by way of selection choices that have been made around four criteria. None of these choices are likely to be correct and a much wider accuracy estimate should be placed around this aspect.

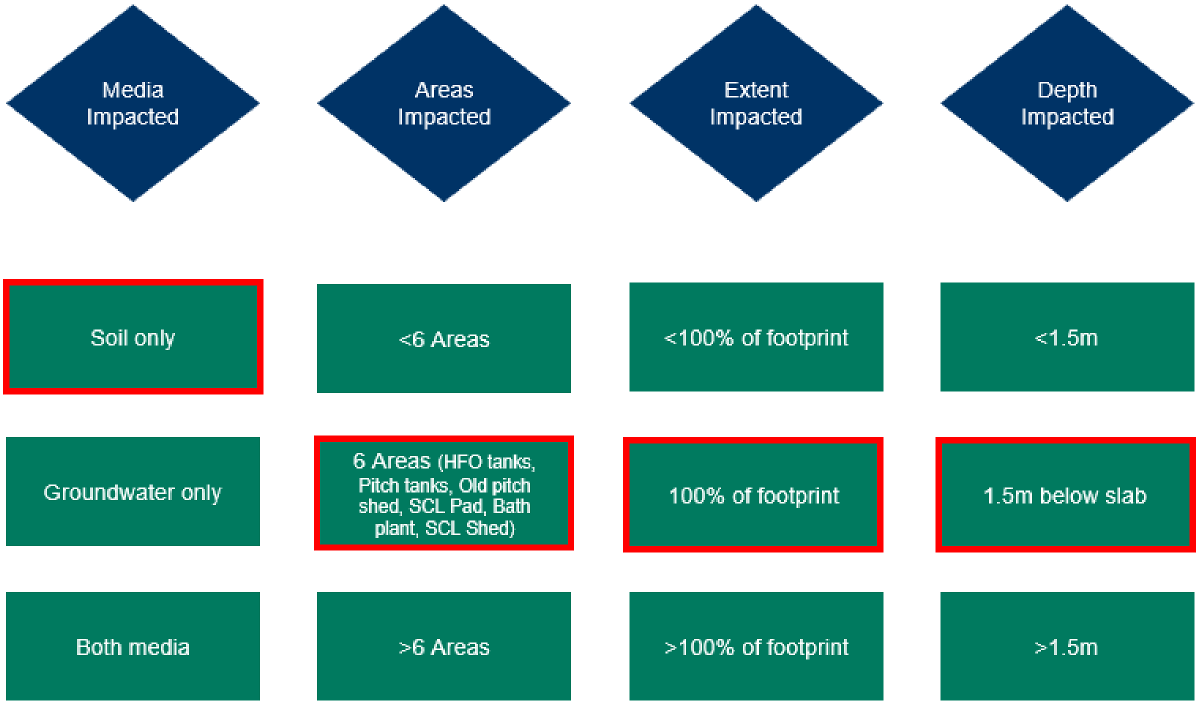

Figure 1 Illustration of options relating to soil & groundwater contamination

The red highlighted boxes represent choices in the base cost model.

These choices simply relate to quantification, a further set of questions need to be asked in relation to optioneering. For instance 'Do the materials need to be treated?', 'Can risk based standards be applied to the remediation criteria?', 'What treatment options are available?', 'Are these treatment options to be applied in-situ, ex-situ or are barrier systems appropriate?', 'What are the practicalities with undertaking the work?', 'Any in-ground obstructions?', 'How does the team intend to deal with water ingress in to any excavations?'. Answers to these questions can fundamentally change the base cost not just by +50/-30% but by orders of magnitude.

In this example it is clear that the cost estimate is unlikely ever to fit the confines of a Class 4 or Class 5 cost estimate unless a set of detailed work has been undertaken, and even then, there is always the uncertainty in relation to the spatial context of any investigation, the sampling density and really what is in the ground. In applying a blanket estimate of accuracy across the cost model a perception of evenness is provided and this ignores the impact of assumptions and exclusions that have been included within the estimation process. It hinders further cost development as all items are perceived as equal and thus equally prone to adjustment.

Assumptions can often be made in areas such as:

- Thickness of materials to be removed e.g. concrete slabs
- Approach to undertaking a specific item of work
- Regulatory position with regard to works undertaken
- Availability of disposal routes
- Material availability
- Labour planning / resources available to do the work
- Specifications meeting external requirements and evolving needs

Additionally cost gaps occur where items are purposefully excluded. This is often done early in cost development because insufficient information is available to understand the broad context of needs within a specific area e.g. resettlement costs.

Within all of this it is clear to see how a base cost estimate can be unreliable and exceed the anticipated realm of accuracy.

3 Overview of the cost risk assessment approach

Cost Risk Analysis (CRA) is a tailored probabilistic model which has been developed specifically for application on large-scale closure projects found in the nuclear and mining sectors. Similar to all models, the quality of the outputs is largely determined by the quality of the inputs. To ensure the modelling has real value, the analysis is combined with an expert review, which allows for the:

- Unbundling of closure activities;
- Identification of material errors/omissions;
- Knowledge ranking;
- Prioritisation of studies to confirm uncertainties; and
- Identification and screening of options, with consideration of costs & risk.

As far back as the 1950s those at the forefront of the fledgling field of computing explained that computers cannot think for themselves, and that "sloppily programmed" inputs inevitably lead to incorrect outputs (Mellin.W,1957). Nothing has changed in the intervening years and consequently, to avoid 'sloppy programming' Cost Risk Analysis needs to focus heavily on engaging site specialist knowledge through workshopping and the subdivision of the model into meaningful subcomponents that match both the reality on the ground (i.e. how would the team actually go about closing this site) and also the available expertise and data.

A key component of mitigating input error is the standardisation of data collection. This is complicated, however, as data availability will in all probability vary from site to site across and between sectors. It is imperative, therefore, to put the emphasis on standardising the input fields in such a way as to avoid the time and cost of bespoke model building whilst remaining flexible enough to accommodate unique data streams as and when they become available. This standardisation of approach through the incorporating, interpreting, and assimilating of existing data formats and spreadsheet layouts adds a level of grounding to the model and builds confidence in results.

At the heart of CRA is Monte Carlo Simulation (MCS). MCS is a tool and, like all tools, can create beauty in the hands of experts but is more often than not dangerous in the hands of the non-expert. The wide availability of spreadsheet add-ins and increases in computational power have made MCS more feasible for everyday use by non-experts. However, like any statistical tool, MCS's have to be built and interpreted correctly. That means, in common with all regression analysis and summary statistics, understanding exactly what went into the model and what is coming out is paramount.

At the heart of this is the underlying fact that with CRA estimating it is dealing with uncertainty, not risk (despite the use of 'Risk' in the title. Risk is the likelihood of an event occurring * the severity of its impact). CRA attempts to model our level of understanding, where our understanding falls short (usually all those things in the assumptions list) and whether that lack of understanding matters, hence increasing certainty, and therefore reducing risk.

However, it is a fundamental principle of mathematics that 'all models are wrong' and the closer you come to reality the less certain you become. It is this contradiction that has driven statistical analysis and led to a perceived need to understand everything in minute detail to build transparent, assured, and defensible estimates from the bottom up.

Commercial MCS software strives to provide a top-level estimate histogram to any number of decimal places without the need to understand (and hence incorporate said understanding of) model granularity, interdependencies, sensitivities, and sources of the underlying data. The upshot of these spreadsheet add-ins is often very precise but inaccurate, a consequence of imperfect data, imperfect understanding, imperfect modelling, or any combination of the three.

In contrast successful CRA is based on the belief that it is better to perform simulations at the lowest possible level, the main reason being that it is easier, and less error-prone, to estimate individual tasks than entire projects. You find that an individual's expertise is inversely related to breadth of knowledge and hence by focusing on smaller areas of interest CRA can appropriately incorporate individual expertise and knowledge with little or no 'third party interpretation'.

By understanding the simulated output probability curves of individual, separate component parts of any complex and chaotic model CRA provides a means to isolate and highlight individual variables of interest and sensitivity that would otherwise be lost in a single level model. Experience tells us that uncertainties are best expressed as shapes rather than numbers and hence it is the mathematical description of the shapes of the output probability curves that provides the means of integrating multiple subcomponents to build ever increasing complexity into CRA models from the ground up.

The CRA approach provides a probabilistic assessment of the likely closure costs, with individual line items having their owns levels of accuracy (depending upon how the item has been quantified). As this is a probabilistic modelling approach, a wide range of potential cost outcomes will be generated. Considering accuracy alone is insufficient for focussed analysis as a small highly inaccurate item could be irrelevant across the grand scheme. The CRA model also outputs a confidence and sensitivity value against each line item. Interrogation of these allows identification of the principal cost driving factors. In the example shown in Figure 2, treatment and disposal of waste is identified as the greatest uncertainty representing almost 40% of the overall cost uncertainty. The CRA approach develops a streamlined set of studies that quickly move the cost model towards a tighter range of probabilities, the tighter the range the more certain the cost outcome. In this case the CRA identifies a need to focus studies on the waste elements.

To develop some conclusions from the data the modelling needs to work along an unhindered review process, this being undertaken in conjunction with studies, engineering, planning and finance teams at the mine site. This allows issues to be explored a view on requirements, approach, alternate considerations, and outputs/consequences undertaken. For example, in development of a closure cost the site was considering the need for capping of waste rocks they owned, and the capping allowing a short wastewater treatment programme. However, the site sat next to older government owned waste dumps, and infiltration from the dumps reported to the wastewater dump. Additional considerations were developed and included within the cost model to provide allowance around the inherent uncertainty in successful completion of works that allowed a short duration wastewater treatment programme post mining. Within the CRA model the wide uncertainty around this aspect / its significance can be ranked and further actions taken to define better the cost. These actions could include studies, additional design work, regulatory negotiation, and potentially cover systems emplaced on the government dumps.

LINE ITEM	MEDIAN	LOWER LIMIT	UPPER LIMIT	FEEDER SHEET	EST. LINE COST 90% Confidence	SENSITIVITY VARIANCE		SENSITIVITY CORRELATION	Dependencies DP1	DP2	DP3	DF
1000 Costs Prior to Closure	$28,491,086	$23,017,677	$34,238,427	1000CoststoClosure	$30,452,731	$11,220,750	18.4%	4.84%				
2000 Demolition and Removal of Permanent Facilities												
0100 Material Handling	$7,252,163	$6,028,879	$8,683,267	100MaterialHandling	$7,594,238	$2,654,388	17.5%	0.06%				
0200 Electrical	$10,769,584	$9,156,464	$12,449,968	200Electrical	$11,369,730	$3,293,504	14.5%	1.26%				
0300 Carbon Bake Area	$20,540,818	$17,504,041	$24,506,671	300Carbon	$21,437,231	$7,002,630	16.3%	2.33%				
0400 Potlines	$60,042,594	$51,436,514	$70,455,124	400Potlines	$62,213,496	$19,018,609	15.3%	6.82%				
0500 Site Improvements - Roadworks & Drainage, Plant	$8,356,663	$6,619,924	$10,134,239	500SiteImp1	$8,855,601	$3,514,315	19.8%	2.54%				
0500 Site Improvements - General Buildings, SCL and	$3,170,144	$2,617,153	$3,907,389	500SiteImp2	$3,314,516	$1,290,236	19.5%	0.32%				
3000 Material Cleaning & Disposal	$12,374,782	$9,795,993	$15,637,695	3000MatClean	$13,215,351	$5,841,702	22.1%	3.60%				
590 Rehabilitation and Revegetation	$12,282,731	$6,062,901	$20,309,789	590RehabReveg	$14,426,941	$14,246,888	49.4%	6.64%				
600 Treatment and Disposal of Wastes	$126,962,410	$88,208,283	$183,784,426	600TreatandDispose	$141,589,563	$95,576,143	33.8%	39.81%				
8100 Human Resources	$37,566,254	$29,532,557	$45,599,952	8100HR	$40,845,566	$16,067,395	19.7%	7.68%				
8200 Community	$1,229,000	$967,284	$1,594,243	8200Community	$35,109,106	$626,959	0.9%					
6000 Post-Closure Monitoring and Other Obligations	$58,116,251	$43,621,085	$74,294,497	6000PostClosureMon	$61,777,078	$30,673,412	24.8%	10.36%				
4000 Closure support Facilities (%)	5	4	6		$6,736,142	2	0.0%	5.38%				
5000 Construction & program Management (%)	5	4	6		$6,716,830	2	0.0%	3.34%				
8000 Owners Costs (%)	10	8	12		$13,418,974	4	0.0%	5.02%				

Figure 2 Typical cost risk assessment output

In some instances, the underlying uncertainties can be compounded by elements that sit within a base cost calculation and these can impact different parts of the model.

4 Information needs

In preparation to develop the Cost Risk Assessment collation of available information (Current Closure Plans, Current Cost Estimate, Current Basis of Estimate, Current Risk Register, and relevant studies) is important, along with Historical Closure Plans, Historical Closure Cost Estimates as these allow an understanding of how plans and costs have developed. These documents allow an understanding of the closure approach, the methodology of work related to each closure activity proposed to be undertaken across the site, and importantly what has been assumed and excluded from the cost base.

Importantly the Cost Risk Assessment approach is tied to expert review, modelling, and workshopping with the individuals responsible for the closure plan / cost estimate.

Experience shows that often base cases for closure are not as well defined as they should be. Having clarity in this regard enables an auditor to understand what was initially proposed, how these proposals have been adapted over time and the relevance of undertaking certain activities.

The importance of maintaining a transparent cost structure cannot be emphasised enough. Periodic reviews of the costs are important, and these should be holistic in nature.

5 Cost risk assessment in practice

The nuclear decommissioning sector is driven by timeframes of hundreds of years and multi-billion dollar budgets (eg UK Parliament £132billion to decommission the UK's civil nuclear sites, with work taking 120 years, House of Commons Public Accounts Committee, 2020) due in part to the underlying uncertainty within a sector where research and innovation are required to develop decommissioning processes. Consequently, with little sector specific decommissioning experience to draw on decommissioning programs are often built around a ‘reverse engineering’ approach with detailed time and motion analysis of taking components apart. To compound this, the lack of sector knowledge relegates many items to the exclusions and assumptions lines below the total, that is if indeed these line items are in fact known at all at these early stages. The result can be a polarised spreadsheet of detailed granularity in some areas that are ‘known’ (or at least familiar) and single line items and unknowns that will in all likelihood come to dominate the overall cost.

World Nuclear Association (2022) detail several options for recycling and reuse and scrap materials derived from the decommissioning of reactor facilities:

- Material which is essentially uncontaminated and unconditionally released.
- Material that can be melted in a regulated environment followed by metal recycle for consumer products (conditional clearance).
- Material with short half-life products that is melted and fabricated in a regulated environment and released for specific industrial applications (e.g. steel bridge).
- Material that cannot be released from regulatory control but which may be recycled in the nuclear industry.

Due to the high hazard nature of the working environment and risk associated with exposure to radiation, labour planning is a critical element within the establishment of processes for decommissioning and removal of equipment. In developing a cost estimate for the decommissioning of one part of the plant many different options had been developed in order to assess the impact of labour requirements and the most appropriate timeline for decommissioning. CRA was employed as an optioneering tool to evaluate these options. The actual outcome that was developed was an understanding that in relation to the overall costs of undertaking the activity, labour staffing costs were negligible against quantifying the mass of metals that were contaminated. As a result of this work the programme was able to pivot and look to undertake a detailed quantification of the amount of material that was contaminated and most suitable disposal routes for the different grades of material i.e. suitable options became focussed in a different direction and a number of activities could be eliminated.

Across a whole closure programme the repeated refinement of CRA allows the identification and elimination of the principal uncertainties / risk drivers on a rolling basis. As there will always be some element of uncertainty driving cost variance this process is akin to highlighting the top three, reducing these elements to acceptable levels, and then another three take their place. Repeat, and in the end the closure programme has a tightly defined cost range. In effect the CRA process promotes optioneering and development of decision-making.

The risk reduction process is the focussed development of the knowledge base by carrying out studies, investigations, looking at alternate options, and having dialogue with external stakeholders including regulators to confirm their expectations.

During another CRA exercise, closure costs at a mine smelter were found to be dominated by the removal of waste materials. Key questions could include:

- Can you optimise disposal?
- What limits their take-off rate?
- Is the bottleneck on site or off-site?
- Is this a technical or regulatory issue?

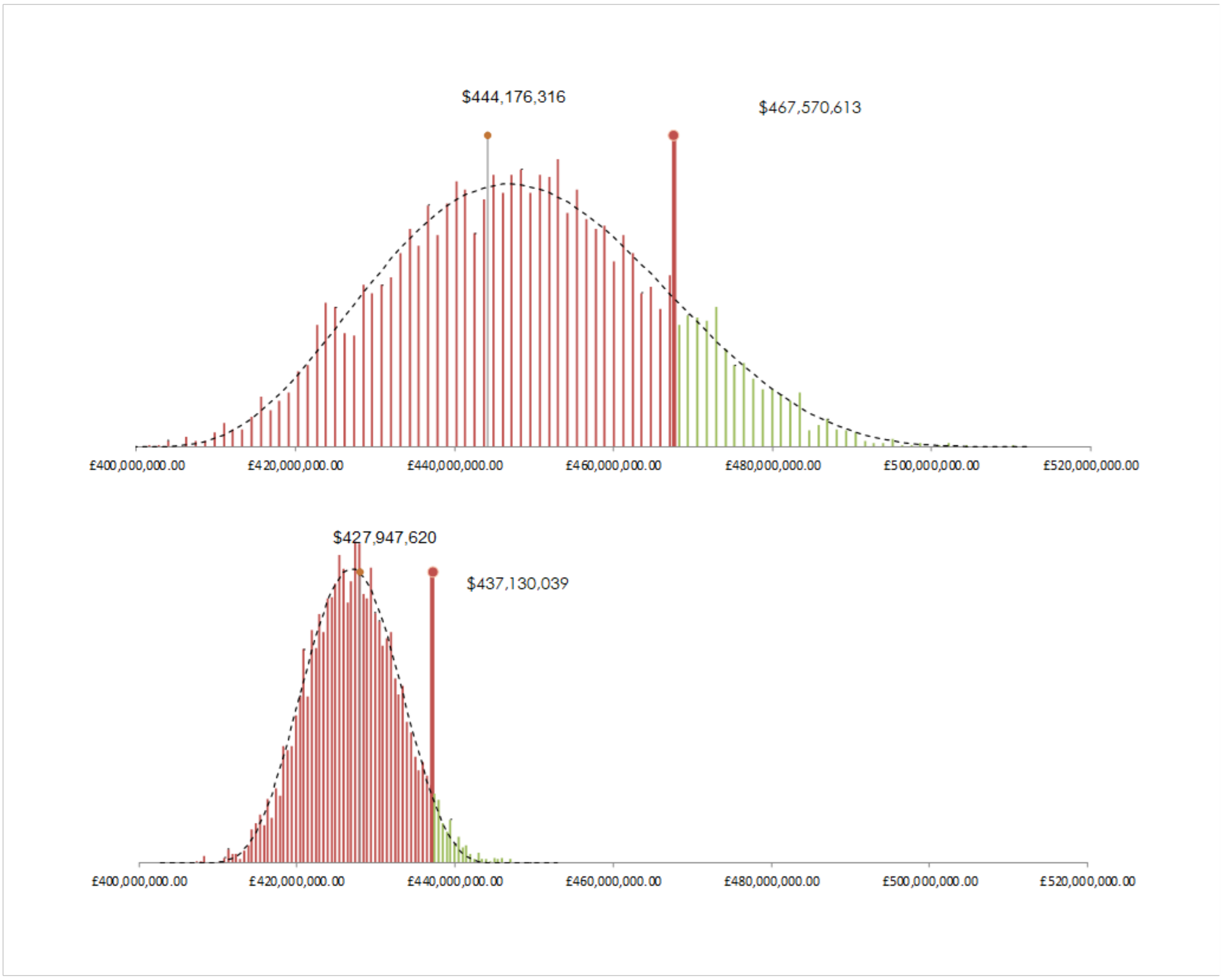

Figure 3 Impact of increased knowledge through studies

The illustration above shows a possible outcome following the results of focussed studies relating to an understanding of smelter waste materials. The top cost curve is based on the initial cost estimate and its stated accuracy, showing a large level of uncertainty. The bottom cost curve shows studies having confirmed an appropriate disposal route / unblocked disposal rates and the generation of a revised model with treatment and disposal of wastes uncertainty narrowed.

With confidence levels increased the Total Project Cost range falls and the level of uncertainty across the project has been narrowed (a tighter overall cost curve), meaning a more reliable cost estimate and less risk in execution.

6 Embedding cost risk analysis

Closure cost uncertainty is a challenge in non-mining industries. Mega-projects and major projects such as infrastructure projects are known globally for significant cost exceedances. The UK Government Infrastructure and Projects Authority have released a Cost Estimating Guidance document (Infrastructure and Projects Authority, 2021) which seeks to bring about best practice in cost estimating, likewise OECD (2017) which advocates for an inclusive approach to cost estimating and the need to address both in-scope and out-of-scope uncertainties comprehensively in order to get a full picture of the potential costs. Key elements in these documents are:

- Choice of method to develop estimate;
- Ability to risk adjust estimates;
- Endeavouring to achieve transparent, robust and evidence based estimates;
- Review and assurance to improve estimates;
- Methodologies that allow for continuous improvement are central to quality of cost estimates.

Mine closure is an inherently complex activity and best practice in developing closure cost estimates needs to be emphasised to increase quality and develop consistency across the sector. The residual uncertainty within a cost estimate needs to be clear to enable a focus to resolve uncertainty and tighten the cost boundaries, in order to ultimately provide confidence to management and other stakeholders.

Common themes relating to risk, uncertainty and cost on large projects include:

- The importance of managing risk and uncertainty in best practice cost estimation;
- The role of bias and how this can impact risk and uncertainty;
- Presenting risk exposure as a range to promote more informed decisions and communications;
- Considering cost estimates and risk assessments in parallel, not separately; and
- Incentivising risk identification, communication and mitigation.

The Cost Risk Analysis (CRA) approach allows better informed decision-making, spending focused on understanding uncertainty not just on what appears to be the lowest costs. This avoids over commitment or under commitment, allows efforts to be concentrated on “best wins”, and provides visuals for rapid decision making at the corporate level. CRA can aid the closure planning process and this can be achieved through a number of different areas:

- Identifying principal cost drivers;
- Assessing the methodology proposed to undertake the work;
- Developing an understanding of activity gaps;
- Providing clarity and reduced uncertainty associated with assumptions and quantification;
- Providing key lines of enquiry / questions to feed into routine programme reviews;
- Providing focus for further studies how these could resolve uncertainty; and
- Identifying potential options which may provide improved cost outcomes.

7 Concluding remarks

Base case closure cost estimates assume nominal accuracy ranges, additionally, they are subject to a range of exclusions and assumptions which are not costed. These exclusions and assumptions represent a hidden and unknown cost and an uncertainty. By considering tailored uncertainty ranges which have been developed for individual line items an assessment can be undertaken to provide an illustration of how differing levels of accuracy could affect Total Project Cost estimates.

As assumptions and exclusions can be forgotten or ignored as base cost estimated are developed over time an initial acknowledgement of these should be included beyond the nominal +50%/-30% ranges that are included in many cost estimates. Within the probabilistic modelling approach integral to Cost Risk Assessment these would show as a long tail and a broad range of costs. Cost Risk Assessment provides a powerful probabilistic tool that enables the identification and unravelling of cost uncertainty. This in turn allows the development of focussed studies programmes, which are designed specifically to ask questions that refine knowledge and allow a tighter cost range to be developed as a result.

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