



Managing Construction Noise and Vibration Impacts by Risk Optimisation

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Environmental noise and vibration from construction sites represents a considerable environmental risk to large engineering projects. Mitigating and managing the environmental impact and loss of amenity for nearby communities can result in significant project costs and delays, both of which the Principal Contractor would typically desire to be minimised or avoided if possible. When viewed from a financial perspective, the requirement to manage environmental noise and vibration impacts is a type of risk exposure for the project since the environmental management obligations consist of a number of committed and potential costs, each with a degree of uncertainty. This paper discusses an approach that a contractor may use to estimate the project's budget to manage noise and vibration from construction works by considering the likelihood and consequence of incurring direct and indirect costs associated with noise and vibration impacts. Any of these items in the project's construction budget that are quantified in terms of costs weighted by probability and/or uncertainty can then be included in the risk optimisation part of the tender pricing calculations. In terms of a project's overall environmental management obligations, the method described herein would be complementary to existing processes such as the standard practice of preparing and implementing construction noise and vibration management plans.

1 INTRODUCTION

Management of environmental noise and vibration from construction works is a complex task, and it can be difficult to identify what mitigation and management measures are available, to evaluate the efficacy of the various options, and to decide which single or combination(s) of actions should be taken.

In practice, most decision-making can be simplified if all relevant factors can be normalised to a common comparative metric. For construction projects this is realised by the tendering process, whereby all prospective construction contractors are often required to submit a business proposal to deliver a fully complete, constructed Project for a fixed lump-sum price (with clearly stated terms, conditions and exclusions).

For most large construction projects, the tenderer typically takes full responsibility that the tender price will be adequate to sufficiently account for any unknowns or unforeseen expenses that are not specifically and particularly excluded from the construction contract. Accordingly, it is standard practice for construction contractors to develop a risk register, comprising an inventory of items with estimates of their individual potential to result in variability of the total project construction costs. The combination of these potential cost items is then included in the overall construction project's tender price as a line item representing a contingency fund, comprising the sum of all risks, in which each is weighted according to its probability (ie. likelihood) and consequence (ie. cost).

For a large construction project, the total overall costs of mitigation and/or management of construction noise and vibration impacts may be difficult to estimate accurately for inclusion in the construction contractor's total tender price. However, for most competitive tenders it will typically not be permitted for any uncertainty associated with this issue to be excluded from the tender contract, as the customer/asset owner will normally insist that the contractor's price must incorporate all costs associated with complying with all applicable laws and regulatory authority's guidelines, including environmental protection requirements.

Construction contractors prefer to account for all potential project costs with as much certainty as possible, to minimise the magnitude of their risk contingency fund, and thereby to reduce their overall tender price, which will in turn maximise their possibility of winning the tender, and subsequently to complete the construction and deliver the project under budget, with the intention of thus maximising their final profit. Furthermore, in developing the project's contingency budget, contractors generally prefer for the range of the uncertainty of every line item to be known with as much certainty as possible. For instance, if a line item in the risk register is $\$(X \pm x\%)$, then it is strongly preferred for the value of the uncertainty $x\%$ of the line item to be known as confidently as possible.

In the case of noise and vibration management, there are many ways in which the cost of mitigating noise and vibration impacts can have flow-on impacts to the total project's overall cost. For instance, if a construction site is required to stop work and rectify excessive noise emissions from on-site activities, the resulting costs can be significant. In such a case it is possible for the combined direct and indirect costs of the site's down-time to be disproportionately large compared to the capital cost of physical noise mitigation measures. For instance, payment of most wages and equipment hire costs will need to continue while site works are stalled until the noise mitigation is in place. Furthermore, if the delay(s) result in late project completion, the contractor may be liable for financial penalties under their contract, the costs of which may far exceed the original estimate of the cost allocated in the tender's risk register to maintain compliance with environmental noise requirements.

A portion of the financial risks associated with large construction projects will typically be managed by purchasing an appropriate insurance package, although the cost of the insurance will not be zero and the insurance policy will have limitations and conditions, so most construction contractors will usually try to self-insure to the extent possible.

2 ENVIRONMENTAL RISK

Environmental risks are defined and discussed differently, in different fields and in different contexts. For example, in the field of disaster and catastrophe management, environmental hazards are defined as natural, human-induced and human-made hazards causing "loss of life or injury, property damage, social and economic disruption or environmental degradation" (Dalezios, 2017). In contrast, from an environmental protection perspective, environmental risks are discussed in terms of hazards with potential to cause damage or harm to the environment (Frantzen, 2001).

In the construction industry, environmental risk is considered as either:

1. A category of risks potentially caused to the project by "the environment" such as poor weather or natural disasters (Ian Hewitt & Associates, 2023) (Indeed Editorial Team, 2024), or
2. A category of compliance business risks, needing to be managed similar to other ordinary project delivery risks.

2.1 Environmental Risk Management

In the construction industry, the types of environmental risks under the first category are typically dealt with by obtaining appropriate insurance policies (Environmental Risk Professionals LLC, 2020).

For the second category, usually the construction contractor will either choose or will be required to take responsibility for managing these types of risks as a project delivery contract condition. In some jurisdictions the environmental regulatory authority will require the construction contractor to produce an environmental management plan for the regulator's approval prior to construction commencing.

A construction environmental management plan (CEMP) will describe the specific environmental management procedures and controls that the contractor must commit to implementing throughout the construction project. Based on these commitments, construction contractors can estimate most of the costs that will likely be incurred to implement the mitigation and management measures stipulated in the CEMP, thereby enabling some degree of certainty in the project budget that would need to be allocated for environmental compliance. However, the existence of an approved CEMP does not guarantee to a construction contractor that all potentially required

environmental management costs have been accounted for in the project budget, as the contractor may still be required to take further action to protect the environment under certain circumstances.

As stated previously it is usually not an option to exclude such additional costs from the delivery contract; the contractor will still be obligated to implement further mitigation measures beyond the CEMP if required to comply with regulations and/or as directed by the regulatory authority. From the point of view of the construction project's financial controls, these unbudgeted costs constitute a financial risk, which can be partly or wholly mitigated if they were anticipated during tender preparation and captured in the tender's risk register and contingency budget.

From the construction contractor's project controls point of view, the fraction of the project's budget allocated for management of environmental noise and vibration is regarded as a "quasi-hard limit": it is a cost breakdown line item that should remain unspent if possible, and should not be exceeded unless unavoidable and necessary.

3 CONTROL OF RISK

Risk-based approaches to management of many types of business functions are well established in many industries, including environmental management (Pritchard, 2000).

3.1 Risk Management

"Risk management" is often described and often assumed to refer to reducing or eliminating risk. However, in the context of a construction contractor preparing a tender price including contingencies, "risk management" is not synonymous with "risk reduction". Rather, risk management refers to controlling risk within acceptable parameters. It means adopting a particular profile of risk exposure and accepting the consequences of that risk profile. Risk assessment and management can be implemented via qualitative and/or quantitative methods (Pritchard, 2000). Qualitative risk management is heavily reliant upon the advice and judgement of experienced experts. With qualitative risk management, the probability and consequences of particular identified hazards occurring in any given scenario are subjectively evaluated by the experts and ranked on an ordinal scale, such as shown in Table 1.

Table 1 – Example Qualitative Risk Assessment Matrix

Consequence	Likelihood					
	Almost Never	Very Unlikely	Unlikely	Likely	Very Likely	Almost Certain
Negligible	Very Low	Very Low	Low	Low	Medium	Medium
Minor	Very Low	Low	Low	Medium	Medium	High
Moderate	Low	Low	Medium	Medium	High	High
Major	Low	Medium	Medium	High	High	Very High
Severe	Medium	Medium	High	High	Very High	Very High
Catastrophic	Medium	High	High	Very High	Very High	Very High

In contrast, Quantitative risk management assigns numerical values to the probabilities and to the consequences of the identified hazards. The probabilities are usually ranked on a Ratio scale (eg. 0% to 100%) and the consequences could be ranked either on an Interval scale or a Ratio scale, as shown in Table 2.

Table 2 – Example Quantitative Risk Assessment Matrix

Probability (%)	Consequence				
	Negligible	Minor	Moderate	Major	Severe
0-10%	Very Low	Very Low	Low	Low	Medium
10-25%	Very Low	Low	Low	Medium	Medium
25-50%	Low	Low	Medium	Medium	High
50-75%	Low	Medium	Medium	High	High
75-90%	Medium	Medium	High	High	Very High
90-100%	Medium	High	High	Very High	Very High

Probability (%)	Consequence				
	Negligible	Minor	Moderate	Major	Severe
Examples:					
Personnel:	Little or no impact on personnel in any area	1 day lost productivity from 10% of the affected personnel	1 day lost productivity from half of the affected personnel	1 day lost productivity from all affected personnel	5 days lost productivity from all affected personnel
Financial:	Impact will cost approx. the same amount to remediate as it would cost to prevent. OR Nil or minimal flow-on costs.	Impact will cost 1.2 to 1.5 times as much to remediate as it would cost to prevent. OR Flow-on costs that are less than 60% of the cost of the project.	Impact will cost one and a half (1.5) to two (2) times as much to remediate as it would cost to prevent. OR Flow-on costs that are 60-100% of the cost of the project.	Impact will cost two (2) to three (3) times as much to remediate as it would cost to prevent. OR Flow-on costs that are >100% of the project cost.	Flow on costs that are greater than 200% of the cost of the project. OR Flow-on costs that are greater than 200% of the cost of the project.

Quantitative risk management has been used extensively in many industries for many years, for instance in the fields of finance and investment, business management, insurance, Defence, epidemiology, and reliability engineering. In particular, the construction industry has long been using well-established quantitative risk management methods for several purposes including project planning, cost estimation and project controls.

Quantitative methods of assessing risk allows numerical modelling using computer algorithms such as Monte Carlo simulation and Fuzzy Logic, both of which are suitable for modelling of environmental risk (Beer & Ziolkowski, 1995) (Pritchard, 2000).

Quantitative methods of risk assessment also allow robust decision-making using computerised calculation methods such as Cost-Benefit Analysis (Ricci, 2006).

3.2 Risk optimisation

“Risk optimisation” is not synonymous with “risk minimisation”. Rather, risk optimisation refers to carefully assessing and selecting the most acceptable risk parameters, aiming to achieve preferred outcome(s). It means mathematically determining a strongly preferred profile of risk exposure, based on a pre-agreed balance of probability and consequences. In a business context, risk optimisation refers to aiming for a desired risk/return profile within the range of available options.

Risk optimisation has been widely used for several decades in several industries including finance (Markowitz, 1952), insurance (Pfaff, 2016) and the construction industry (Golpîra, 2021), and has recently gained popularity in other fields such as business management (Faster Capital, 2024), environmental management (Baklanov, 2010) and cybersecurity (Quinn, Ivy, Barrett, Witte, & Gardner, 2022). Within the field of environmental management, risk optimisation is sometimes used for the management of air quality impacts (Ricci, 2006).

3.3 Environmental risk optimisation in the construction industry

From the perspective of the construction project’s overall financial performance, management of environmental impacts is an unavoidable cost to be minimised. Some of those impacts are inherently difficult to anticipate and the effort potentially involved in managing them can be difficult to predict, consequently the costs to mitigate and control the impacts will have intrinsic uncertainty. The construction firm would prefer not to spend the contingency budget if doing so could be avoided.

In the construction industry, risk optimisation is used to minimise the total costs and maximise the overall project profit. From the perspective of a construction project, environmental risks are not fundamentally different from any other project delivery business risks, and the potential costs associated with environmental risks can be incorporated into the project risk register and allocated a contingency fund alongside all the other project risks.

Optimisation is a process of selectively allocating resources to achieve the best (or near-best) version of a desired outcome. When a construction contractor is preparing a tender, developing a budget for the known costs and a contingency budget for the uncertain costs, the costs to mitigate and manage environmental risks is simply another type of limited resource to be selectively allocated along with all other project expenses.

4 RISK OPTIMISATION OF ENVIRONMENTAL NOISE AND VIBRATION

The noise and vibration mitigation and management measures committed to in the CEMP are ostensibly fixed, and their costs are not typically considered to be optionally available for revision during the construction program. Thus, these funds are effectively unavailable for repurposing without compelling justification.

The need for, relative importance and measures of success for management of noise and vibration are typically discussed in terms of physical metrics including decibels, displacement, velocity, and acceleration. It is a straightforward (though laborious) process to optimise a project's environmental noise and vibration impacts to achieve desired outcomes in those terms.

However, from a construction contractor's perspective, the primary consideration is the overall financial performance at the end of the project relative to the project's starting budget. The physical descriptors of noise and vibration are relatively unimportant; instead the cost implications of the various impact management issues are heavily prioritised when making project decisions regarding mitigation and management of impacts. The costs of some variables are readily apparent and easily quantified as direct expenses (eg. purchase or hire of noise control devices) while others are less obvious and are more difficult to reduce to only a financial dimension (eg. community attitude, or customer dissatisfaction).

In order to optimise the management of environmental risks due to noise and vibration in the construction industry, it is necessary to convert the measurements and rankings of all relevant factors, opportunities and constraints into a common metric. Although the conversion may not be easy or obvious for some of the hazards and variables, nevertheless it is necessary to convert the environmental impacts, mitigation and management measures, penalties, direct and indirect costs into the same metric used to measure the project's overall performance: the local monetary currency.

This necessary condition raises some questions and introduces some challenges. For example:

- What is the overall resultant cost to the project of receiving and eventually resolving complaint(s) about noise from one or more receiver(s)?
 - What is the anticipated cost per complaint, per decibel of exceedance above the noise target?
 - Alternatively, what is the cost of noise mitigation, in terms of cost per decibel of noise reduction?
 - What trade-off between cost of mitigation vs. number of complaints achieves the best outcome for the minimum cost?
- Delays on site associated with regulator enforcement such as orders to stop work and implement noise reduction measures can result in direct costs (eg. noise control treatments) and indirect costs (eg. extra wages and ongoing hire of idle plant & equipment). The indirect costs need to be included in the risk optimisation calculations.
- Unexpected noise impacts may be caused as a flow-on effect from unforeseen issues with other project elements, which could not have been included in the CNVMP or in the construction budget's contingency fund. For example, if an area of hard rock is discovered during earthworks and it must be immediately

removed by noisy works such as rockbreaking, the resulting direct costs (eg. noise control treatments) and indirect costs (eg. extra wages and hire of idle plant & equipment while noise mitigation is installed) associated with the new noise impacts should be regarded as noise management costs. The project's noise and vibration management contingency budget should include a nominal allowance for such potential unforeseen (and unforeseeable) events. Long-established contractors may be able to build up an inventory of such events based on previous experience. By deliberately including these possible costs in the risk optimisation calculations, the contractor may create an opportunity to pre-emptively manage them (eg. mitigating the risk of the specific example of a hard rock surprise by investing in additional Geotechnical surveys).

- Repeated community noise complaints can attract increased attention and involvement from the environmental protection regulator, which might increase the wider project's total number of environmental issues under the regulator's ongoing scrutiny, potentially requiring expensive management of multiple issues that may not otherwise have been identified by the regulator. How could such potential indirect costs be accounted for, in the cost optimisation calculations?
- Poor environmental noise management on a project can affect the contractor's relationship with the customer and/or their reputation in the wider construction industry. How could such indirect financial losses be considered in the cost optimisation calculations?
- There may be some situations in which the ratio of financial penalties and/or rewards may be overwhelming. [Hypothetical scenario]: Late project completion costs the contractor \$2M in contract penalties per day, whereas fines imposed by the environmental protection regulatory authority for breaching conditions and causing construction noise impacts during the night might perhaps cost the contractor much less, for example: between \$25,000 and \$500,000 per event.
- [Hypothetical scenario:] On a certain particular project, it costs approximately \$10k to investigate each complaint from the community, whereas compensation for an affected noise receiver in the form of architectural acoustic treatments is estimated to cost approximately \$25k per receiver.
- [Hypothetical scenario:] On a certain particular project, in the tender contingency budget based on the risk register, there is a line item for noise mitigation with two options for noise mitigation. Either of the two options would satisfy the CNVMP obligations, although neither would guarantee zero community impact. If a sufficient number of valid complaints are received, the regulatory authority may require further noise mitigation actions. The contractor considers noise mitigation options vs. probability of complaints:
 - Noise Mitigation Option A = \$3M; probability of complaints \approx 10%
 - Noise Mitigation Option B = \$1M, probability of complaints \approx 20%.

5 FURTHER DEVELOPMENT

It is beyond the scope of this paper to suggest potential methods of converting all of the relevant factors involved in the assessment, mitigation and management of noise and vibration impacts from construction sites, normalised into purely financial measures.

However, the author would enjoy collaborating with other parties to develop such a system.

Once a conversion system or tableau has been formulated, there are many different types of optimisation algorithms that can be used for risk optimisation (Krokhmal, Zabaranin, & Uryasev, 2011). Many of the available algorithms will be ideal for optimisation of the mitigation and management of risk due to environmental noise and vibration on construction projects, after conversion into the universal equaliser: monetary currency.

6 CLARIFYING REMARKS

In terms of a project's environmental management obligations, the method discussed in this paper would be complementary to existing processes such as the standard practice of preparing and implementing construction noise and vibration management plans.

The author wishes the reader to note that the proposed approach to developing a project budget for noise and vibration mitigation and management measures using risk optimisation would not necessarily achieve all of the environmental noise and vibration management performance outcomes that a construction contractor must meet in terms of statutory compliance and contractual obligations. In this paper, the author is not suggesting that a project's noise and vibration management strategy derived using risk optimisation would be suitable to replace the mitigation and management measures prescribed in a CNVMP that has been prepared in accordance with local statutory instruments.

Indeed, the author suggests that the details and development of the noise and vibration management strategy devised using risk optimisation should be kept confidential between the acoustics specialist and the contractor, as its primary purpose is to assist in the preparation of budget cost estimates. The author cautions the reader that a noise and vibration management strategy developed using risk optimisation is not suitable to be referenced in an environmental impact assessment (EIA), an environmental management plan, a CNVMP, or in the contractor's tender documentation.

7 CONCLUSION

An acoustic specialist practitioner could provide valuable assistance to construction contractors by helping them to estimate the likely overall costs as well as a confident estimate of the range of potential additional costs that may be incurred in the mitigation and management of noise and vibration impacts during construction projects. The contractor could then optimise their tender price based on minimising the likely total costs of managing noise and vibration impacts, including an appropriate contingency for the known potential but uncertain costs. Furthermore, once informed about the costs and probabilities, the contractor would be free to manually adjust the total budget based on their risk appetite for any single specific project. This approach would provide a potentially powerful means for construction contractors to better estimate their budgets and to devise strategies to control their costs associated with noise and vibration mitigation.

Benefits for the contractor to utilise a risk optimisation method to calculate the construction project's budget for the planned noise and vibration mitigation, as well as the potential noise management costs in the contingency fund may include, for example:

- A potential reduction in the budget for noise and vibration management included in the contingency fund, due to having greater certainty around the probability of extra costs incurred,
- A potential reduction in insurance costs due to being able to demonstrate to insurers that many potential unexpected costs have been carefully accounted for in the contingency budget,
- Opportunity to strategise less expensive means of managing potential noise management obligations,
- Freedom to choose a preferred risk profile, by allowing fine-control adjustment to increase or decrease the contingency budget (and therefore also influence the likelihood of winning the tender) based on the contractor's specific risk appetite for each separate project.
- Reduction in contingency budgets, and associated reduction in overall tender price,
- Increased likelihood of winning construction project tenders due to the lower tender price,
- Increased likelihood of completing projects under budget and therefore maximising profit, due to devising and implementing well-informed noise and vibration management strategies, based on maximising the success of the noise and vibration management outcome for the minimum total cost.

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