Uncertainty Quantification of Construction Activity Sound Power Levels

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ABSTRACT

Noise from a construction site is driven by the active plant and equipment items, and the interaction between those items. Traditional construction noise assessments assume that all plant and equipment may operate concurrently. As a result, overly conservative and non-realistic predictions are often relied upon to inform environmental assessments. In this paper, we introduce a framework for modelling construction activities that considers the interaction between active plant and equipment items. This facilitates a quantification of the probability of each item being active on site. The approach detailed in this paper utilises systems-based modelling to simulate the course of a construction activity and produce a probabilistic characterisation of activity sound power levels, instead of only a worst-case estimate. By providing a distribution of sound power levels for a construction activity, instead of a single non-realistic value, practitioners may optimise mitigation measures for realistic scenarios.

1 INTRODUCTION

Construction noise assessments underpin environmental approvals, design of noise mitigation measures, and community consultation. Industry standard assessment methods tend to assume that all plant and equipment listed for an activity may operate concurrently near their maximum sound power levels (SWLs). Assuming full concurrency reduces activity modelling to a summation exercise providing a single worst-case source term. Whilst both straightforward and conservative, this method often produces unrealistic activity SWLs, which in turn can misdirect stakeholder attention to low-probability scenarios, drive specific mitigation measures beyond what is reasonable and necessary, and inflate project costs.

Realistically, instantaneous noise emissions from a construction activity are governed by what items can be active concurrently due to spatial, resource or safety constraints, the activity logic including precedence relationships and stochastic variability in task durations, individual plant noise, and operator behaviour. When these interactions are considered, implicit concurrency constraints limit the combinations of joint plant states, meaning that concurrency of all plant and equipment may have a low chance of occurring.

There is increasing appreciation for understanding discrepancies between predictions and measurements of construction noise (Association of Noise Consultants 2021, Morris and Tabacchi 2024). However, most noise assessment frameworks present single deterministic SWLs for construction activities, meaning that uncertainties are not well handled. Instead, the distribution of construction activity SWLs should be considered a driving factor of assessment uncertainty. Explicitly modelling the distribution of potential construction activity SWLs may assist in providing a proportionate, informed and risk-based mitigation response.

Typical construction noise assessment methods rely on either a summation of all proposed plant and equipment, an informed opinion of typical cases, or simple utilisation scaling factors. These approaches do not encode structural dependencies between plant and equipment items. Without consideration of structural dependencies, the upper tail of the SWL distribution can be overstated, and likely SWL values may be misrepresented.

This paper introduces a systems-based stochastic framework for uncertainty quantification of construction activity SWLs through utilisation of discrete event simulations (DES). A DES models a system, in this case a construction activity, as a discrete sequence of events (Forcael, et al. 2018). In this framework, a construction site is treated as a set of interacting plant and equipment items with task cycles. Rather than outputting a single or set of discrete levels, this framework outputs a probabilistic characterisation of sound power for a construction activity. No propagation is considered in this paper, all modelling discussed represents source modelling only.

2 METHODOLOGY

This section of the paper outlines how a probabilistic description of a construction activity SWL is derived from plant SWLs and a works programme. A works programme will typically detail plant and equipment alongside site constraints, sequencing, and precedence. When modelling the construction activity as a DES with a constant tick duration, the inputs given in the work programme inform the state space (which items can be active at a tick) and stochastic dynamics (how long items are active or inactive).

The general workflow of the systems-based modelling approach is as follows:

1. Define inputs of the DES including;
   a. plant SWLs as probability distributions, and
   b. activity logic from the works programme.
2. Build a DES informed by the inputs.
3. Run the simulation of the system to generate activation sequences for each plant item.
4. Map the activation sequences to SWLs by sampling input SWL distributions.
5. Aggregate the SWLs to $L_{Aeq,15\,min}$ SWLs.
6. Summarise with probability distributions.

The systems-based modelling approach is demonstrated on a shaft excavation and spoil loadout activity (the Activity) in this paper. The Activity involves excavation of rock in the base of a shaft with a rockhammmer, loading of the excavated material with an excavator into a tip bin lifted from the shaft to a tipping frame. On irregular intervals, waves of several spoil trucks enter the site, have the spoil deposited into the truck beds, then leave the site.

2.1 Defining the DES

2.1.1 Plant and Equipment

Let all plant and equipment involved in the construction activity DES be $I = \{1, \dots, N\}$, where I is the total set of plant and equipment. Each item in the set may have multiple modes M_i. In the case of the Activity, spoil trucks have three distinct modes for each of the following states: entering the site, idle, and leaving the site, whilst other items are treated as having single modes. For each potential mode $m \in M_i$, the A weighted SWL $L_{w,i,m}$ is defined as a random variable

$$L_{w,i,m} \sim G_{i,m}(\theta_{i,m}) \quad (1)$$

with $G_{i,m}$ a probability distribution defined by the parameters $\theta_{i,m}$ informed by SWL measurements, manufacturer data and expert judgement. For modelling of the Activity, mode SWL probability distributions are given by three-point PERT distributions shown in Figure 1. In line with the Interim Construction Noise Guideline (ICNG) (Department of Environment & Climate Change NSW 2009), a $5dB(A)$ penalty has been applied to the rockhammer. When activation is mapped to SWLs, Monte-Carlo sampling of $G_{i,m}$ gives $L_{w,i,m}$ for a plant at a tick (Haron and Yahya 2009, Morris and Tabacchi 2024).

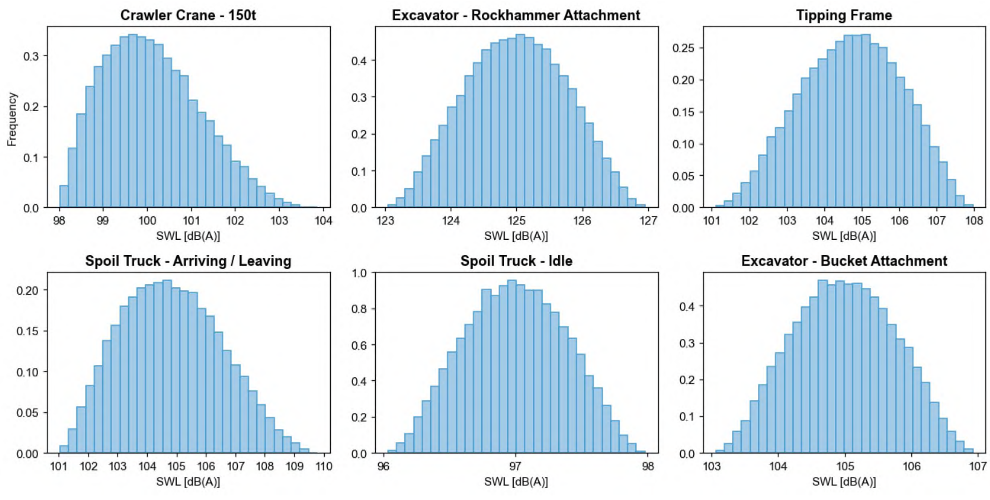

Figure 1: SWL PERT Distributions for modes in the Activity DES

2.1.2 Programme Constraints and Feasible Activations

From the works programme of a construction activity, precedence relationships, resource sharing, staging, and capacity limits can be inferred. In the example of the Activity, the programme constraints include: (i) a truck can only be active in one state at a time; (ii) a truck must enter the site before being loaded; (iii) a truck must be loaded before it can leave the site; (iv) a tipping event can only occur when the truck is on site and idle; and (v) the crane must lift the tip bin onto the platform before the tipping event; (vi) the crane must place the tip bin back in the shaft to be loaded after a tipping event; (vii) the tip bin must have adequate spoil in it before a tipping event; and (viii) rockhammers must have a one hour period of inactivity after three hours of majority activity. With these programme constraints, a feasible activation set as a function of the system's internal state and buffer levels can be defined.

When modelling the Activity as a DES, each item $i \in I$ is given a finite set of mutually exclusive states S_i. At a given tick the collection of individual states can be described as the internal state. To define the internal states, let $I = \{C, E, TF, ST\}$ denoting the crane, excavator, tipping frame and spoil trucks respectively. The following state sets can then be established:

$$S_C = \{off,\ active\} \tag{2}$$

$$S_E = \{off,\ active\} \tag{3}$$

$$S_{TF} = \{off,\ active\} \tag{4}$$

$$S_{ST} = \{not\ present, entering, idle, leaving\ \} \tag{5}$$

In the example of the Activity, the only present buffer level is the fullness of the tip bin. $B_{bin} = \{0, 1, \ldots, K\}$ represents how full the bin is with a maximum capacity of K. Whilst the bin is in the shaft and loaded with spoil, the buffer value is incremented. When the tipping frame empties the tip bin, the buffer value is set back to 0.

The activation of an item i in state $s \in S_i$ at tick t can be represented by the binary $a_{i,s}(t) \in \{0,1\}$ with mutual exclusivity defined by Equation 6.

$$\textstyle\sum_{s \in S_i} a_{i,s}(t) \leq 1 \tag{6}$$

At each tick t, per-item exclusivity and programme guards determine the binary activation vector given in Equation 7.

$$a(t) = \{a_{i,s}(t)\}_{i \in I, s \in S_i} \in \{0,1\}^n \tag{7}$$

The binary activation vector at a given tick comprises ones for states of an item which are active, and zeros for states of an item which are inactive. By implementing programme guards reflective the programme constraints in the DES, the DES can determine the per tick feasible binary activation vector; or what combinations of items in certain states can occur at that tick.

Consideration of feasible activation sets ensures that non-realistic concurrency can be avoided, and activation is reflective of the staging and sequencing dictated by the works programme. To produce a timeline, the evolution of the systems internal state and buffer levels from tick to tick must be modelled.

2.1.3 State Space and Stochastic Variables

Modelling the evolution of a systems internal state is achieved by tracking both where the programme is up to and buffer levels. At any tick in the simulation, we know the current buffer levels and the current internal state. With fixed logic rules and stochastic variables informed by the works programme, the next likely feasible activation set can be calculated.

In the example of the Activity, the fixed logic rules are the programme constraints identified in Section 2.1.2. At each new tick, the activation set must comply with the fixed logic rules. Whilst it is possible to be deterministic about feasible activation sets, there is uncertainty surrounding the duration of phases or sub phases of a construction activity. To account for this in a DES, exogenous randomness is introduced through stochastic variables, for example a random time delay between phases.

Through observation of a construction activity, discussion with site contacts, or observation of similar construction activities to the one being simulated, stochastic variables describing the duration of phases can be estimated. In the example of the Activity, estimations were made around: (i) the time it takes for a truck to enter the site and position itself beneath the tipping frame; (ii) the time a truck will wait beneath the tipping frame before the tipping frame is active; (iii) the time it takes for a truck to leave the site; (iv) the number of trucks turning up to the site in a wave; (vi) the duration of the tipping event; (vii) the time it takes for the crane to lift the tip bin into the tipping frame; (viii) the time it takes for the crane to move the tip bin from the tipping frame to the shaft; and (ix) the portion of the time that the rockhammers are active for.

Defining each stochastic variable as a draw from a reasonably bound distribution informed by best available information allows for the likelihood of the simulation moving from one phase to the next to be determined. When moving from one tick to the next, a change in state will occur with respect to the likelihood provided by the stochastic variables.

The evolution of the Activity over half a daytime period, generated by the DES created with respect to the above-mentioned fixed logic rules and stochastic variables, is shown in Figure 2. For the rockhammer, excavator with bucket, crane and tipping frame, having a value of 1 at tick t represents the item being active, and 0 the item being inactive. Each tick in the simulation is representative of one minute. Individual truck states $s \in S_{ST}$ identify when the truck is off site, entering the site, idle on site and leaving the site by integer values $0, 1, 2,$ and 3 respectively.

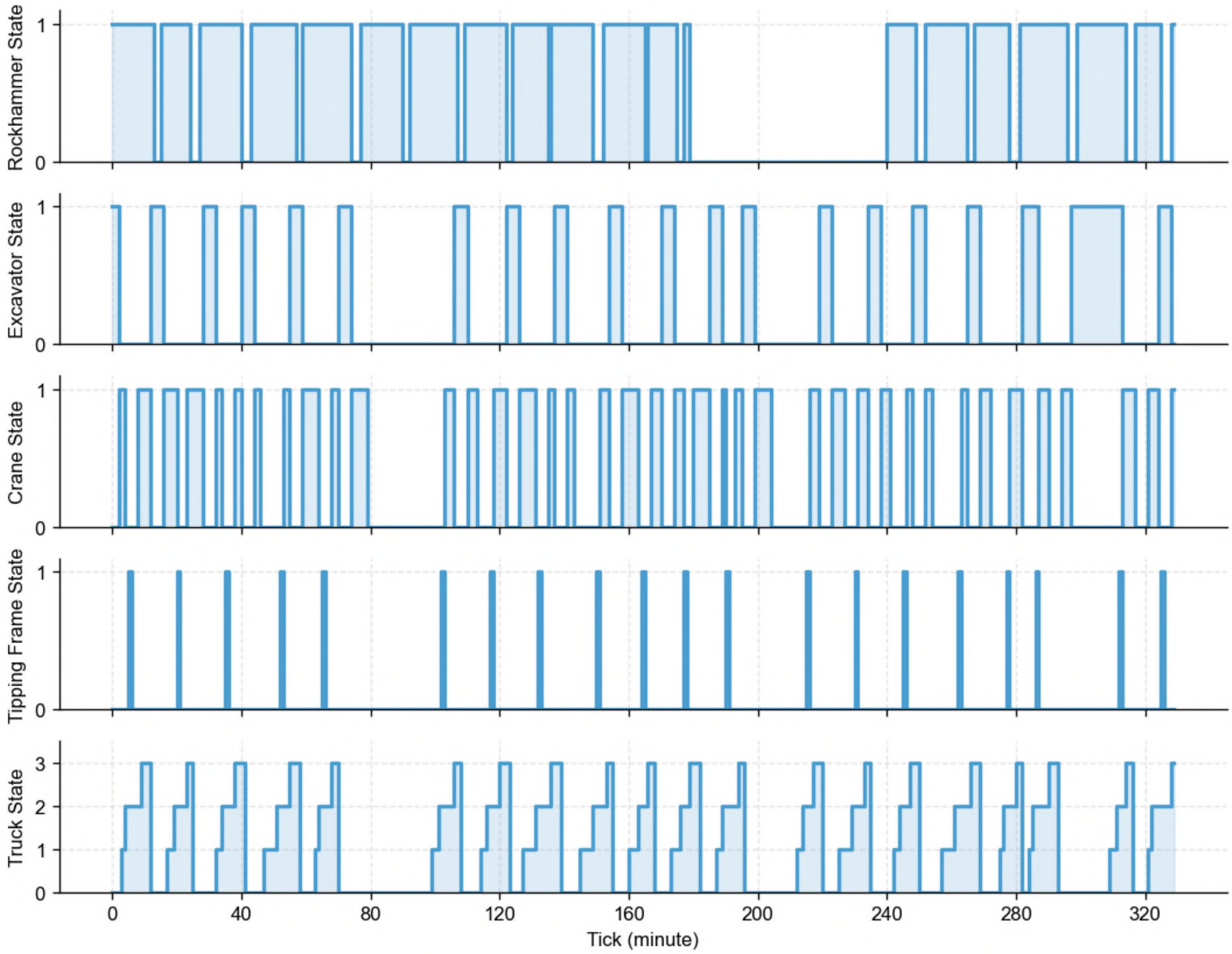

Figure 2: State Time Series Generated by the Activity DES

2.2 Noise Emissions from the Activity

From the output per tick binary activation vectors, noise emission from the site can be predicted. When a plant is active in a certain state, the activation is mapped to a sound power level by Monte-Carlo sampling of the respective mode distributions. At tick t, the Activity SWL can be calculated as the energetic summation across concurrently active items.

As per the Table 2 of the ICNG, construction activities should be assessed based on predicted or measured $L_{Aeq,15\,min}$ (Department of Environment & Climate Change NSW 2009). With the per tick SWLs, $L_{Aeq,15\,min}$ SWLs representative of the simulated activity can be calculated by creating a sliding window of 15 ticks and time averaging the noise levels in tick stepped window through the simulation. The list of aggregated $L_{Aeq,15\,min}$ SWLs enables a probabilistic description of an activity SWL. Notably when represented as a probability distribution, uncertainty around specific construction activity SWLs can be quantified and the likelihood of discrete SWLs can be predicted.

3 RESULTS

Construction activity $L_{Aeq,15\,min}$ SWL distribution predicted with the systems-based stochastic framework outlined in Section 2 for the Activity have been compared to full concurrency $L_{Aeq,15\,min}$ SWLs in Figure 3. Full concurrency $L_{Aeq,15\,min}$ SWLs have been calculated with the assumption that all plant and equipment will be active 100% of the time at their worst case SWLs.

The Activity to which the framework was applied was dominated by the rockhammer, given it was approximately more than $20\ dB(A)$ louder and active more consistently than any other plant item in the simulation. Resultantly, the difference between the major mode in the simulated Activity's SWL bimodal probability distribution, shown in Figure 3, and the rockhammer's SWL probability distribution, shown in Figure 1, is minimal.

When the rockhammer is removed from the simulation, leaving a unimodal distribution reflective of the minor mode of the bimodal distribution, the difference between full concurrency assumption and results generated by the systems-based stochastic framework is foregrounded. Most notably, $95th$ percentile $L_{Aeq,15\,min}$ SWL for the simulation with the rockhammer excluded is $7\ dB(A)$ less than the full concurrency assumption $L_{Aeq,15\,min}$ SWL as shown in Figure 4.

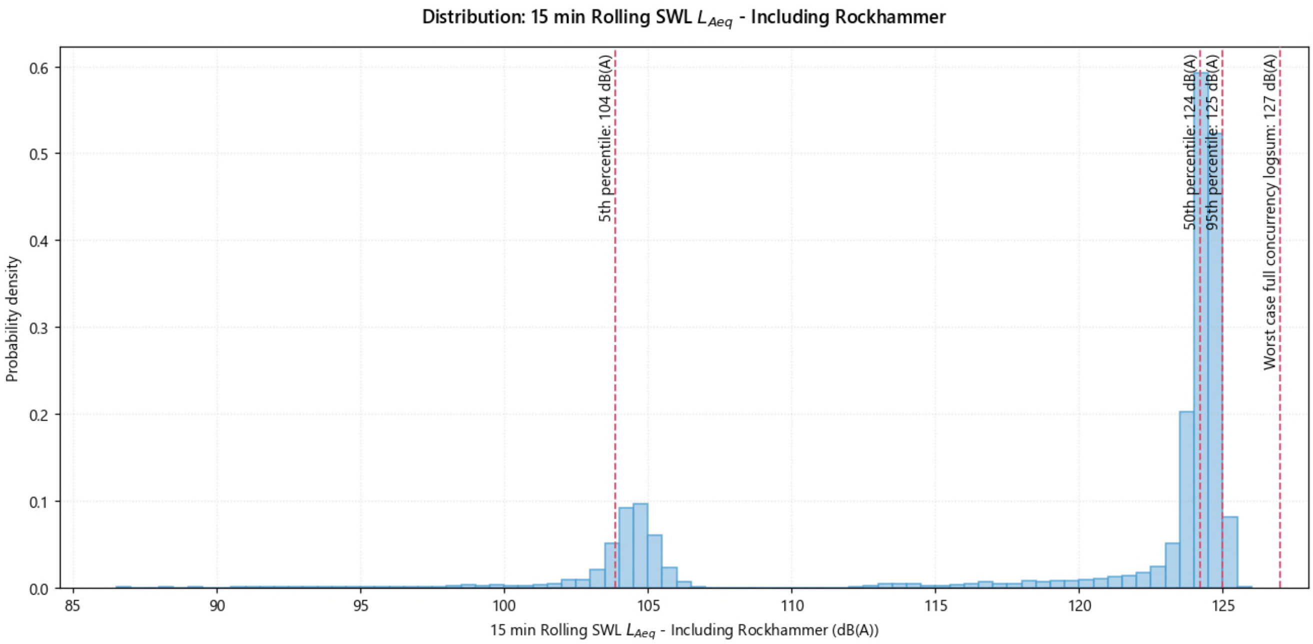

Figure 3: SWL Distribution of the Activity Compared to Full Concurrency Assumption with the Rockhammer Included

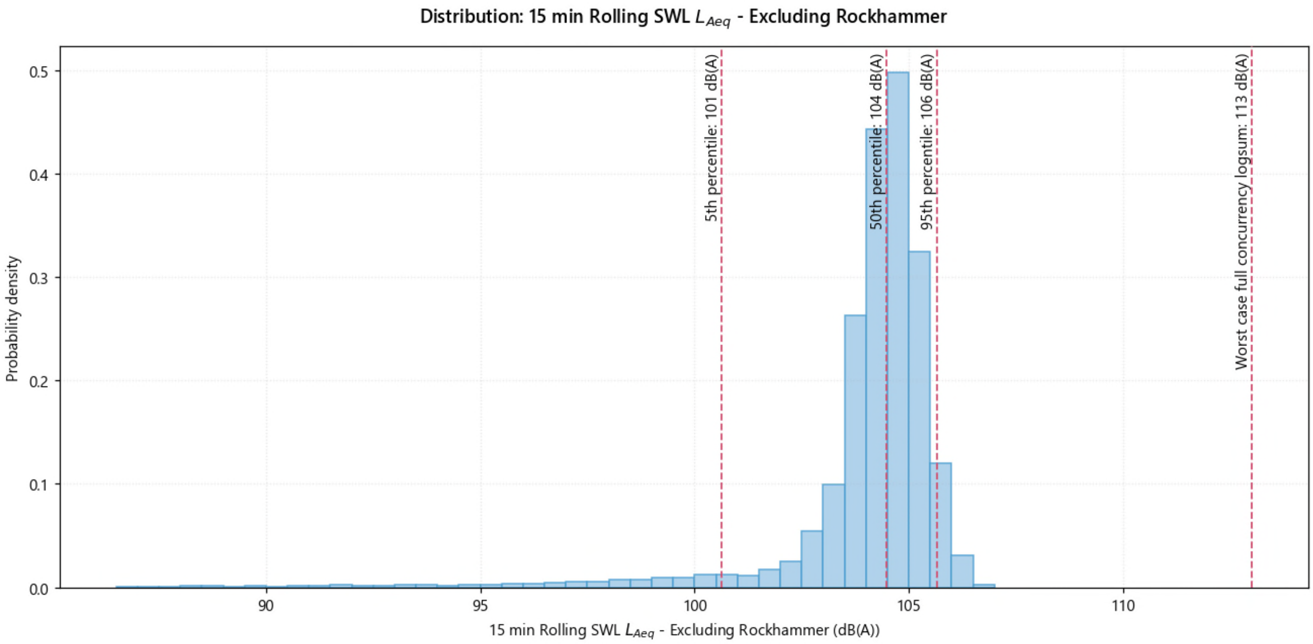

Figure 4: SWL Distribution of the Activity Compared to Full Concurrency Assumption with the Rockhammer Excluded

4 DISCUSSION

4.1 Overview of the Case Study Activity Results

The framework described in Section 2 outputs a distribution of $L_{Aeq,15\,min}$ SWLs that reflects both the programme constraints and stochastic duty cycles. From the SWL results presented in Figure 3, it is apparent that when one plant item dominates an activity in terms of SWL and duration active, the activity SWL is effectively represented by the SWL of that individual plant. In the case of an outlier, there is little difference between the results of the DES and the assumption that all plant items operate concurrently at their catalogue worst-case SWLs, or the full concurrency assumption. In the case of the full concurrency assumption when an outlier is present, the energetic total collapses to the level of the outlier.

Exclusion of the outlier from the Activity demonstrates the utility of the framework. When plant and equipment items involved in a construction activity are similar in terms of SWL and duration active, programme constraints and duty cycles put significant downwards pressure on realistic SWLs. Demonstrated by the significant difference between the upper tail of the distribution in Figure 4 and the full concurrency SWL, the application of DES trims improbable extremes and represents only realistic construction activity SWLs.

4.2 Implications for Implementation of the Framework

With respect to the results of the case study of the Activity, the framework has greatest utility for construction activities where multiple items have comparable SWLs, precedence and queuing impacts activation of plant and equipment, and duty cycles have stochastic variability. In the case of such construction activities, the framework allows for effective quantification of uncertainties surrounding the activity SWL, along with aligning predictions with reality. As opposed to assessing construction activities with a single $L_{Aeq,15\,min}$ SWL value, the framework allows for the presentation of a probabilistic compliance story and quantification of likely activity SWLs.

4.3 Limitations

The framework applied in this paper is limited to source only modelling and neglects spatial considerations beyond implications on programme constraints. To further understand noise impacts from a construction activity, propagation of sources from likely locations on site should be considered. Additional limitations include broadband A-weighted SWLs being sampled independent of co-operating plant items, moving sources being represented as point sources, and computational choices being selected pragmatically to achieve stability of percentile metrics.

5 CONCLUSION

In this paper, a system based stochastic framework for determining uncertainty aware construction activity SWLs was introduced. Modelling of a construction activity as a discrete event system informed by programme constraints, buffer logic and stochastic duty cycles allowed for uncertainty quantification of construction activity SWL through production of a distribution of $L_{Aeq,15\ min}$ SWLs.

The case study Activity demonstrated that construction activities not dominated by an outlier plant item benefit most from application of the framework. Validation of the framework outlined in this paper with attended noise measurements and integration of propagation considerations into the framework will be undertaken. Overarchingly, application of the framework for the determination of construction activity SWLs enables informed decision making by quantifying what levels are likely, how likely they are and why.

6 REFERENCES

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