



Agent-based modelling of construction noise sources for environmental noise predictions

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ABSTRACT

Typical environmental noise assessments in NSW require the assessment of a realistic worst-case scenario. To satisfy this requirement, many quantitative noise assessments adopt worst-case assumptions about noise source location and operation. These multiple worst-case assumptions may lead to an unrealistic result, as some assumptions may not be possible when others are satisfied. However, it may not be immediately obvious which worst-case assumption (or combination thereof) should be held constant while relaxing other conditions.

To determine the potential range of noise predictions from construction sites, a systems-based modelling approach is presented where interconnected agents represent the varying position and operating conditions of noise sources. Consideration is given to how plant and equipment operation may adapt in response to certain events or other work activities. Using this approach, worst-case assumptions can be adopted as simulation rules alongside the dynamics of the site under investigation.

1 INTRODUCTION

In New South Wales (NSW), construction noise is assessed in accordance with the NSW Environment Protection Authority (EPA) Interim Construction Noise Guideline (ICNG 2009). The ICNG outlines the requirements for quantitative assessments of construction noise, including the need to present a 'realistic worst-case or conservative' set of predicted noise levels. To address this requirement, noise assessments present a single predicted noise level for each noise-sensitive receiver. Additional predicted noise levels are given for multiple scenarios as a way of addressing the varying noise emissions of the construction site over the duration of the project.

Noise from construction sites is generally controlled by temporary and variable noise sources, which are not as well understood as transportation noise sources (Parnell 2018). Previous studies (Parnell 2023; Morris et al. 2023; Morris and Tabacchi 2024) have shown that there is a significant degree of variability in the actual noise level from a construction site, compared to the single number prediction that is required in a typical noise assessment. As a result, a single-number noise prediction may not accurately quantify the noise emissions of the site.

Unless there is a high degree of certainty in the site's activities, practitioners must rely on assumptions to guide their setup of a noise model. To remain consistent with EPA's requirements outlined in the ICNG, the noise modelling must represent a realistic worst-case scenario. This requirement tends to be applied to individual noise sources with little consideration for other site aspects, unless strong justification is provided to defend the adopted modelling approach. However, this justification can be difficult to provide when the exact site operations are not yet known, and if the site's exact operations were known, it may not be necessary to make assumptions.

The location of a noise source can significantly affect the noise impacts on a noise-sensitive receiver. However, during the planning stage (and sometimes during project delivery), there may be insufficient information to place a single noise source in a specific location within the site's bounds to then form a realistic worst-case scenario for assessment. To address this uncertainty in an environmental noise assessment, a noise emission area may be defined to represent the potential locations of the noise-generating activity. A realistic worst-case assumption may be to assume the activity is at a position where the attenuation is at its minimum. An alternative assumption, particularly for moving activities, may be to assume noise is emitted from all locations within the area.

By defining and adopting realistic worst-case assumptions per noise source, a cumulative set of realistic worst-case assumptions could be formulated which do not respect the site's limitations. For example, if two excavators with rockbreaker attachments are operating on a construction site, and both are assumed to be operating concurrently at the worst-case location (which on a simple site would be the closest point to a noise-sensitive receiver), it is implied that those two plant items are operating on top of each other. As a result, an environmental noise assessment may present results assuming an inefficient or physically impossible site configuration.

The accumulation of multiple realistic worst-case assumptions tends to result in substantial over-prediction of noise impacts, which could have detrimental effects on the community (Parnell 2023). As described in previous work (Morris et al. 2023), worst-case predictions can be significantly higher than measured noise levels due to compounding worst-case assumptions which are not always realised. Probability distributions for key variables governing site noise emissions can be informed by expert opinion which appear to provide results aligning with empirical evidence (Morris and Tabacchi 2024).

An agent-based modelling approach is proposed which aims to satisfy both the regulatory requirements for realistic worst-case modelling and real-world physical and operational constraints. Realistic worst-case assumptions that would traditionally be cast as macroscale conditions, are instead reformulated as microscale interaction rules and used to guide a simulation of a representative construction site. This work primarily discusses the implications of the agent-based modelling approach on the potential locations of noise sources within a site, but the modelling does display emergent behaviours affecting the noise source usage intensity.

2 NOISE SOURCE LOCATION

When the exact location of a work activity is unknown, there are some common heuristics for deciding where a noise source should be placed to represent that activity. Some source-placement methods are described in Table 1 (names for each heuristic are provided to assist with later reference to each method).

Table 1: Methods for assuming noise source location(s) in speculative assessments

Name	Description	Benefits	Drawbacks
All at Worst Case Location	Some or all noise sources are concentrated at the worst-case location within the defined site boundary.	Viewed as 'conservative' by regulators and some consultants, reducing the potential for under-prediction.	Neglects physical limitations of the site and plant operation as it assumes all plant and equipment occupy the same space simultaneously.
Highest at Worst Case Location	The noise source with the highest sound power level is situated at the worst-case location within the site boundary.	Acknowledges that all plant/equipment cannot occupy the same space concurrently and is generally conservative.	May not describe cumulative impacts for activities with many sources at similar sound power levels.
All at Centroid	All noise sources are concentrated at the geometric centre of the site.	Acknowledges that most site operations are located within the site, rather than at the site boundary.	May introduce additional distance attenuation to a noise prediction which may not represent a realistic worst-case assumption.
All Evenly Distributed	The cumulative sound power level of all noise sources is distributed evenly across the site area.	Acknowledges that site noise does not necessarily come from a specific location and that noise sources could be mobile.	Assumes all plant/equipment would evenly cover the site area during the assessment period, which may be difficult to justify for larger sites and 15 minute assessment periods.

3 AGENT BASED MODELLING

An agent-based model (ABM) is a simulation method that uses autonomous, heterogenous 'agents' governed by microscale rules to evaluate the performance of a wider system. These models effectively show how simple and predictable local interactions within a defined system can generate system wide patterns. The emergence of complex phenomena from the accumulation of simple interactions means that it is possible to model systems with

non-linearities that could be difficult to describe at a macro scale (Macy and Willer 2002). ABMs can be combined with Monte Carlo methods to further understand the system’s response to stochastic parameters.

However, since ABMs are defined by the specific interactions and operations programmed into the system’s agents, they run the risk of becoming an artificial world without relevant application to real-world phenomenon. Since ABMs rely on a bottom-up approach, the dynamics of the whole system can only be understood as an outcome of the micro-interactions between its basic agents (Tesfatsion 2002). There are multiple methods to verify emergent behaviours, and within the ABM community it is difficult to settle. Each of these validation techniques have different efficiencies, limitations, considerations, and accuracies proportional to specific applications (Darvishi and Ahmadi 2014). However, within the limit of geospatial time series data, comparing autoregressive models estimated from both simulated data and real world data is an effective method of validating policy and management oriented ABM models (Guerini and Moneta 2017).

Construction sites can be described as a complex system defined by discrete operations and interactions between project resources and equipment which can change over time and bring about emergent changes in the whole system. This contrasts with simulating discrete events, since the emergent behaviours of ABMs can better represent the changing and dynamic processes happening on a worksite (Zankoul et al. 2015). As such, ABMs have been utilised in construction research to understand management, operations and environment impacts (Zhang et al. 2014). ABMs can simulate the interactions between workers, vehicles and machinery on a complex construction site to develop a simulated system and allow managers to better understand site operations and plan accordingly (Sorbi et al. 2024). ABMs can be combined with other existing information systems, like site specific geospatial information systems, to model project waste output and emissions, and to model effective management solutions (Ding et al. 2022).

4 **MODEL SETUP**

4.1 **Bulk excavation ABM**

To illustrate the applicability of ABMs to noise modelling, a simulation was developed representing bulk excavation that may be encountered in an urban setting. ABMs representing earthmoving operations have been found to produce macro scale phenomena that align well with real-life examples (Jabri and Zayed 2017). Specific rules apply to each agent type depending on their role, which are described in Table 2. Simulation-level concepts and rules are outlined in Table 3 which describe agent initialisation and completion conditions.

Table 2: Agent descriptions and rules

Agent type	Description	Instantaneous sound power levels, dB(A)	Rules and assumptions
Land	Represents a small parcel of land within the site.	N/A	- Excavation to 1m depth. - Volume to be excavated is initially all rock and no spoil.
Excavator	Represents an excavator with bucket attachment whose role is to collect spoil and deposit it in a truck.	- Handling spoil: 104 - Rotating: 104 - Tracking: 107 - Idle: 95	- Representative of a 35 tonne excavator. - Footprint dimensions 5 x 3.2 m. - Bucket capacity of 1.5 m³. - Max reach of 9.1 m. - Rotates at 3.6 rpm. - Speed limit 5 km/h. - Takes 10-15 s to change load (i.e. picking up or dropping spoil). - Must rotate to face target before working. - Must rotate to face direction of travel before moving. - Target must be within 5 degrees of agent’s heading, otherwise agent must rotate to face target.

Agent type	Description	Instantaneous sound power levels, dB(A)	Rules and assumptions
Rockbreaker	Represents an excavator with rock-breaker attachment whose role is to break rock on the site, resulting in the creation of spoil.	- Hammering: 118+5=123 - Rotating: 104 - Tracking: 107 - Idle: 95	- Representative of a 35 tonne excavator. - Footprint dimensions 5 x 3.2 m. - Hammer breaks 0-0.5 m³ rock per timestep. - Max reach of 9.1 m. - Rotates at 3.6 rpm. - Speed limit 5 km/h - Must rotate to face target before working. - Must rotate to face direction of travel before moving. - Target must be within 5 degrees of agent's heading, otherwise agent must rotate to face target.
.Truck	Represents a dump truck hauling spoil from the site. Arrives empty and departs when fully loaded.	- Moving: 108 - Idle: 96	- A Truck's capacity is representative of a four axle dump truck with a load limit of 12.5 tonnes. - Footprint dimensions 9.7 x 2.5 m. - Speed limit 10 km/h (forward), 2 km/h (reverse). - When moving, agent will select the longest path that gets it the closest to its target. - Can turn within 45 degrees of agent's heading. - Reverse movements only considered if no forward movements available. - Will idle if no forward or reverse movements are possible.

Note: A +5 dB(A) penalty is applied to instantaneous sound power levels if the activity is identified as 'particularly annoying' in the ICNG.

Table 3: Simulation concepts and relevant rules

Aspect	Description	Rules
Rock and spoil	Rock is a resource which requires processing by a Rockbreaker before it can be transported by an Excavator or Truck. Spoil represents broken rock and/or soil and is a transportable resource.	- Excavator and Truck capacities are calculated assuming sandstone with a density of 2000 kg/m³. - Rock cannot be moved between agents. - Rock must be converted into spoil by a Rockbreaker. - Trucks must be provided with spoil by an Excavator. - Spoil can be moved by Excavators and Trucks.
Truck limitations	Trucks can only enter site under specific conditions, representing real-world limitations on the number of trucks in a fleet and a site's capacity.	- A new Truck can only spawn if there are no other Trucks on site, or the only Trucks on site are marked as 'ready to leave'. - The simulation assigns Trucks to the loading spot that is closest to the Excavator. - Trucks will move towards their target and idle once reaching it. - Trucks do not drive through the excavation area. - Trucks will be marked as 'ready to leave' when their payload is equal to their maximum capacity. - Trucks marked as 'ready to leave' will be assigned to a site exit and move towards it. - Trucks will despawn (i.e. leave the site) once reaching a site exit.

Aspect	Description	Rules
Agent targets	A target is a location or another agent that is the subject of an agent's actions. Agents will follow a process to assign itself a target, unless there is a simulation-level rule that gives the agent a specific target.	- Excavators have two targets: a collection target (i.e. something it loads spoil from) and a dumping target (i.e. something it loads spoil into). - Excavators' collection targets can only be Land, and dumping targets can only be Trucks. - Rockbreakers can only target Land. - Trucks can be assigned to a specific location (namely a loading spot) or, when loaded, to a site exit.
Agent movement	Certain moving agents, such as Excavators, Rockbreakers and Trucks, may change their position to reach a target if they are unable to work.	- Agents have a speed limit. - Agents will try to move where possible, but are not required to do so. - Agents will attempt to work before considering a movement. - Moving agents must not move through obstacles. - Other agents count as obstacles. - Certain areas of the site cannot be traversed by certain agents. - All agent movements must occur within the site bounds.
Rockbreaker and Excavator limitations	The simulation controls the randomised placement of Rockbreakers and Excavators. The potential locations of these are uniformly randomly distributed across the excavation area subject to the simulation's interaction rules.	- Rockbreakers will randomly spawn anywhere on top of a Land agent, provided it does not overlap with an obstacle. - Excavators will randomly spawn anywhere on top of a Land agent, provided it is not already occupied by an obstacle (such as a Rockbreaker). - Rockbreakers spawn first.
Simulation performance	Noise source locations and instantaneous sound power levels are recorded alongside macroscale metrics (in this case, number of trucks successfully loaded and departed).	- The number of despawned trucks (i.e. have successfully been loaded and left site) is recorded for grouping simulation iterations. - The centroid of each agent that generates noise, and its instantaneous sound power level, are recorded for post-processing.

4.2 Model setup

Four representative receiver points were placed at distances in the order of 10-15 m from the site boundary and approximately 25-40m from the excavation area within the site, which could be expected in urban or suburban contexts. Figure 1 shows an overview of the site and its key features.

To assist in comparisons with the noise source placement heuristics described in Table 1, instantaneous sound power levels for plant were kept constant for each operating setting. This decision was made to assist in locating an agent carrying out a certain task during post-processing. However, instantaneous sound power levels for a given operating setting could be further varied as a function of the agent's state and/or by drawing values from a probability distribution.

A comparison of the simulation's predicted noise levels with the heuristics in Table 1 were simplified by omitting excess attenuation and considering only geometric divergence. This should not be interpreted as a limitation of the ABM, as predicted noise levels including excess attenuation could be readily obtained by direct calculation or with reference to a noise model.

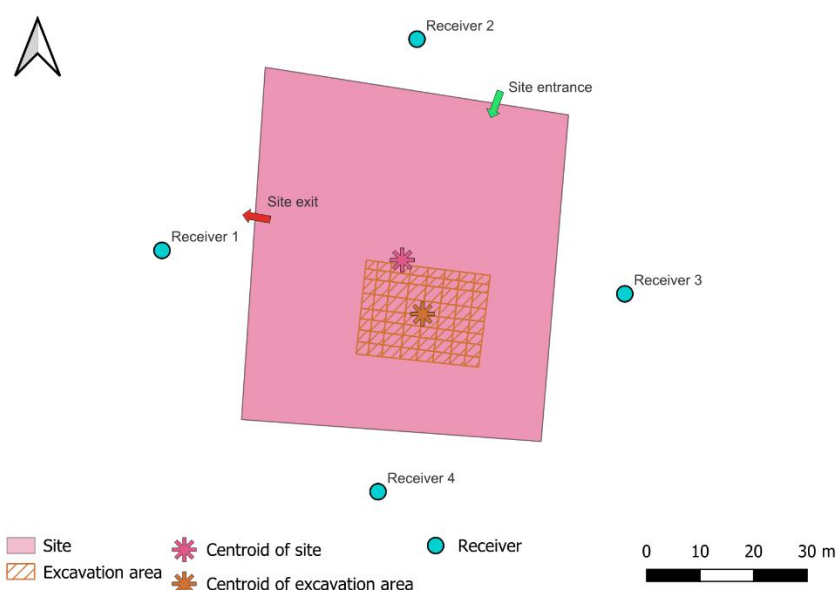


Figure 1: Bulk excavation site considered in the ABM

4.3 Model result processing

A Monte Carlo analysis of the ABM with 15,000 iterations was conducted to identify the effects of randomised placement and assignment of work activities, and potential random variations in truck loading duration and broken rock quantity per timestep. At the conclusion of each tick in a simulation iteration, the location and instantaneous sound power level of all agents were recorded.

In the authors' discussions with construction contractors, a bulk excavation site similar to the one represented in Figure 1 would aim for 3-5 trucks to be loaded in a 15 minute period. For this reason, the number of trucks successfully loaded and removed from the site is recorded for each simulation iteration and used to compare the emergent behaviour of the ABM with reality.

5 RESULTS

Each iteration of the ABM described above yielded a truck output between zero and six trucks. The most common value was zero (28.5% of simulation iterations) and the most common non-null value was three (23.1%). 43.1% of the simulation iterations were within the expected truck output range of 3-5 trucks per 15 minutes. Figure 2 shows the distribution of ABM outputs for 15,000 iterations using truck output as the assessment metric.

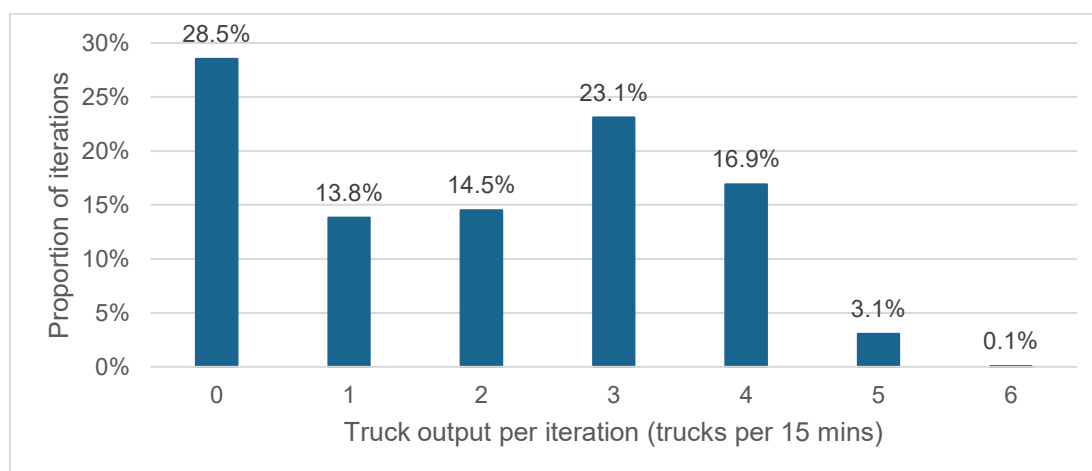


Figure 2: Distribution of simulation output (truck output per 15 mins), $n = 15,000$

Using the location and instantaneous sound power level of each source at each timestep, a cumulative noise level from all site noise sources at each representative receiver was calculated. Distributions of these site noise levels

from all ABM iterations, grouped by the truck output, are shown in Figure 3. The probability densities of the Rock-breaker and Excavator agents' locations are shown below and depict the simulation outcomes for truck outputs of zero (Figure 4) and four (Figure 5).

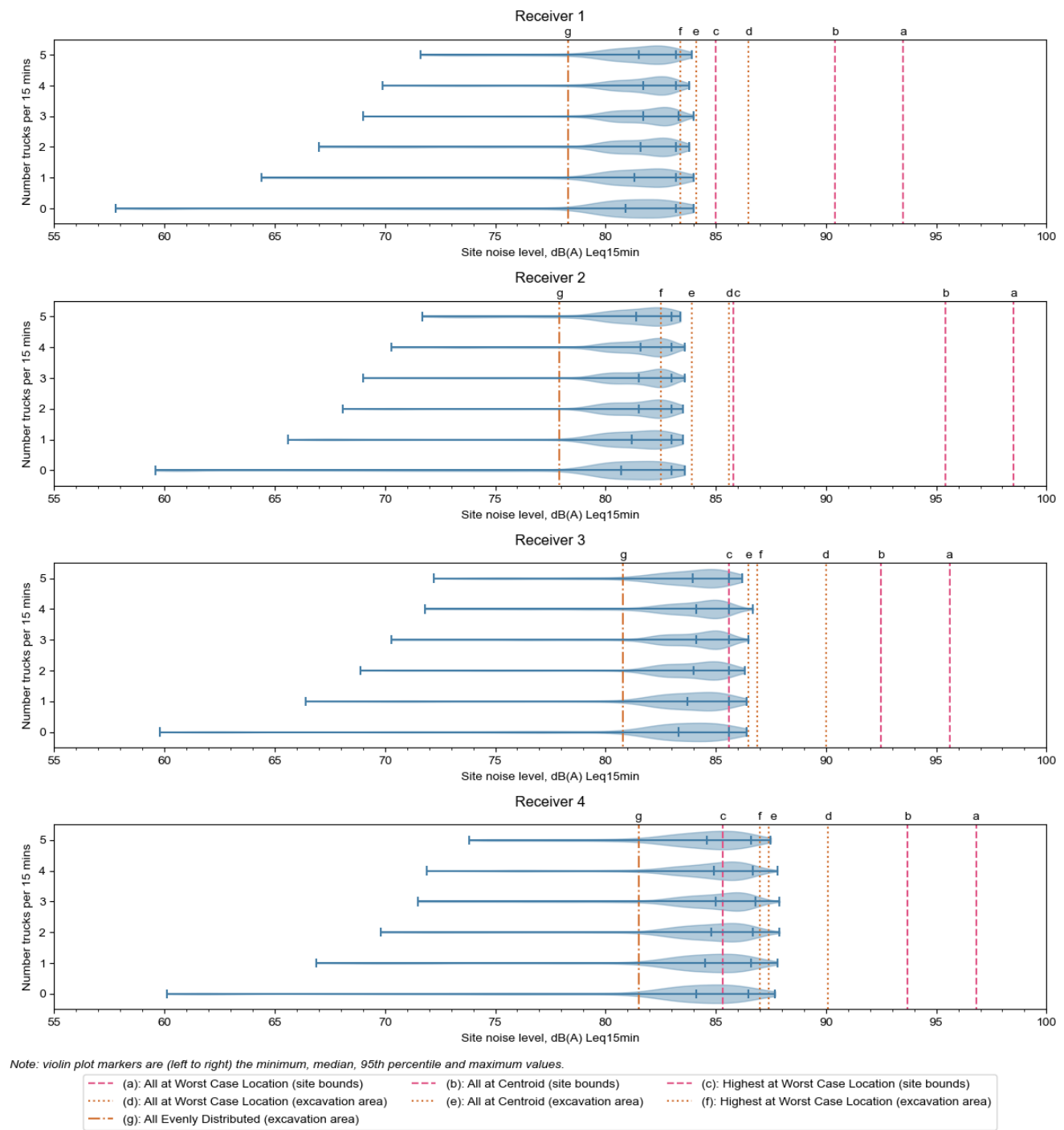


Figure 3: Site predicted noise levels

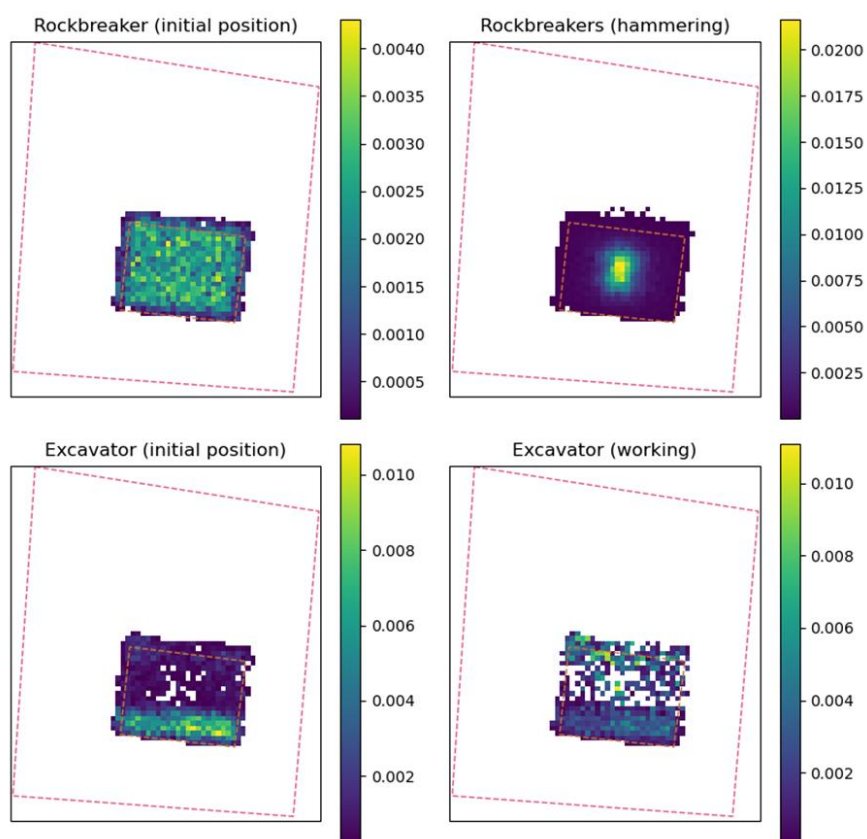


Figure 4: Spatial distributions of Rockbreaker and Excavator agents, zero trucks per 15 minutes

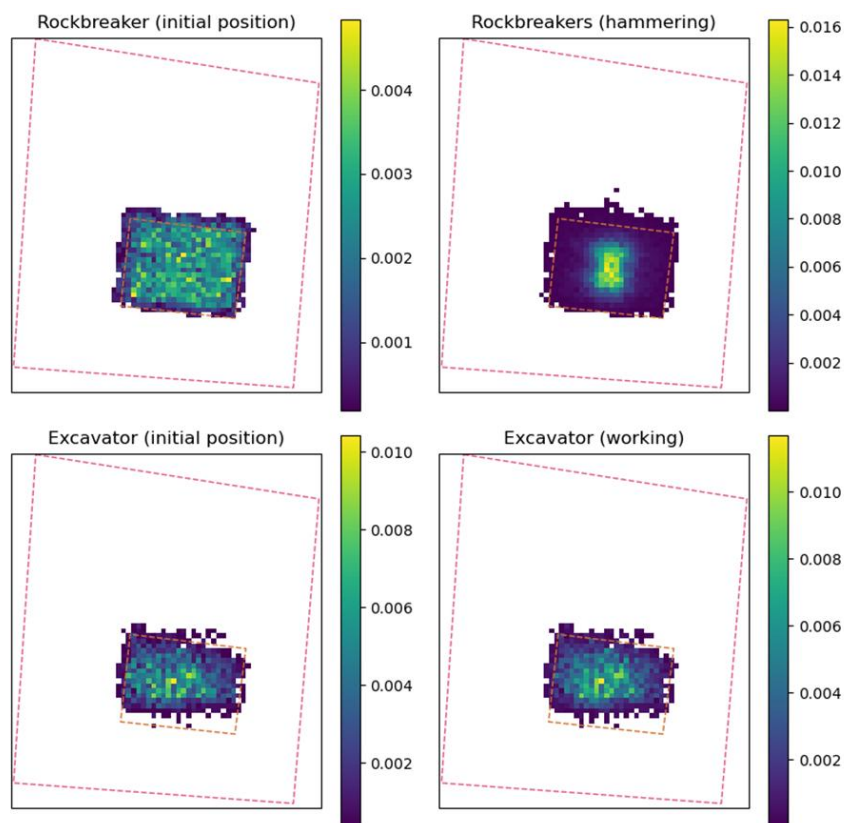


Figure 5: Spatial distributions of Rockbreaker and Excavator agents, four trucks per 15 minutes

6 DISCUSSION

6.1 Distribution of noise sources assuming a uniform distribution of work activities

The ABM was designed to randomly place noise sources within the excavation area. However, the simulation results shown in Figure 4 and Figure 5 suggest that the uniform spatial distribution of work activities across a designated area does not necessarily result in a uniform spatial distribution of the noise sources comprising that activity. In this ABM, the excavator with bucket is the prime example of a noise source which exhibits this behaviour. The Rockbreaker agents' location was primarily governed by the convolution of two uniformly distributed variables (the initial location and the target location), which would explain its tendency to operate in the middle of the excavation area in this simulation.

The requirements in the ICNG for a noise assessment that considers the realistic worst-case scenario implies the maximum value from a distribution of potential results should be adopted in a noise assessment. To avoid adopting a potentially unrealistic assessment assumption, careful consideration should be given to the potential locations of key noise sources within an activity, rather than viewing the overall activity as a single noise source.

6.2 Accuracy of noise source placement heuristics

As shown in Figure 3, the All Evenly Distributed method resulted in significant underpredictions at the representative receivers compared to the simulation's most likely, 95th percentile and maximum values. This would be due to the ABM's noise-intensive activities being generally stationary with limited and slow movement. Work activities that are inherently mobile and aim to cover larger areas (such as scraping or levelling land) could be better represented by evenly distributing the sound energy across a reasonably defined area.

Generally, the two heuristics that appeared to align well with the simulation's most likely values were the Highest at Worst Case Location and All at Centroid methods, provided the excavation area was used instead of the site boundary. Deviations between these prediction methods and the simulation were in the order of <1 to 2 dB(A).

Overall, and with consideration of the observations in Section 6.1, further investigation into the spatial distribution of noise sources is required with the aim of refining or developing heuristics that agree with site constraints. It is envisaged that ABMs could be used to inform or validate new methods, alongside real world observations.

6.3 Applicability to industrial sites and other activities

At a higher level of abstraction, the ABM could be described as a set of agents transferring a resource amongst other agents, subject to specific conditions depending on the agent's class. With varied rules through minor modifications to the source code, new agent classes could be employed to represent alternative work activities, including industrial processes during the operational phase of a project.

7 CONCLUSIONS

The combination of an ABM with Monte Carlo methods could be used to determine noise source locations and instantaneous sound power levels per model timestep, which may facilitate an improved understanding of the potential noise emissions from a work site. Existing methods of estimating noise source locations in environmental noise modelling were outlined and compared to the simulation results. These methods each have benefits and limitations, depending on the activity being modelled.

Simulation conditions can be formulated using relatively simple microscale interaction rules that can be derived from observations of similar activities. This approach reduces a practitioner's dependence on detailed knowledge of site operations that is generally not provided by a client in time for an environmental noise assessment. Employing a statistical approach to process results from multiple simulations means that a reasonable worst-case scenario result can be presented which adheres to physical and operational limitations of the site.

Future work aims to use ABMs to assist with the development of heuristics that could be incorporated into environmental noise assessments, which in turn should reduce the discrepancy between predicted noise impacts and subsequent measured noise levels.

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