# DESIGNING THE QUIET SITE: A PROPOSED METHOD FOR MODELLING, ANALYZING AND MITIGATING NOISE HARM FROM CONSTRUCTION ACTIVITIES

Oriana Albertini[1], Daniel M. Hall[2], and Renate Fruchter[3]
[1]ETH Zurich, Zurich, Switzerland
[2]Delft University of Technology, Delft, Netherlands
[3]Stanford University, Stanford, California, USA

## Abstract

Noise emission is a problem on construction sites, affecting the health and productivity of on-site workers and the well-being of nearby residents. The paper proposes a method to model, assess and reduce noise impact. The method includes determining noise goals, assembling input data, scheduling with integrated noise data, simulating peak noise days, and implementing mitigation solutions such as sound barriers, electric equipment and vegetation. The method was validated through a case study using the software platforms Autodesk Revit, ALICE, Fuzor VDC VR, and CadnaA. The study highlights opportunities for integrated information flow between BIM models and construction noise simulation software.

## Introduction

Noise on construction sites is inevitable and occurs regularly. It affects not only the health and the productivity of the workers but also the surrounding environment of the construction site such as the well-being of the people living and working in the nearby buildings. In general, noise exposure can cause hearing loss, stress, annoyance, and performance reduction (United Nations Environment Programme, 1980).

Although health and safety administrations define standards and guidelines for noise exposure in urban areas and the work environment (Berglund et al., 1999; United States Occupational Safety and Health Administration Office of Science and Technology Assessment, 1995), these regulations do not consider the implementation of noise assessment during the design phase of a construction project.

In order to deal with noise exposure, acoustic data and noise mitigation strategies are needed. However, acoustic measurements on the construction site are performed only in a few cases. Noise exposure is difficult to predict be-cause it is caused by simultaneous activities, noise sources can either be intermittent, variable, or constant, and con-struction sites are large, complex and constantly changing (Ballesteros et al., 2010; Seixas et al., 2005).

Previous studies focused on the prediction and mitigation of construction noise. These studies provide complex noise simulation techniques and noise management models (Kwon et al., 2016) to give recommendations for optimizing the location and dimension of noise sound barriers (Gannoruwa and Ruwanpura, 2007), improving the planning of the construction site as well as the transport network (Ning et al., 2019; Hammad et al., 2017).

However, an actionable noise simulation method that is user-friendly and specific to construction site noise is not widely available. Additionally, the process to integrate information from design models created using Building Information Modelling (BIM) into noise simulation software is unknown. Furthermore, there are no established standard or procedures to conduct noise analysis and implement proactive mitigation measures during the project design phase.

To address this, we have developed a method for addressing noise emissions from a construction site during the design phase. The proposed method facilitates the flow of information from design models to noise simulation software, guides professionals through necessary preparation and analysis steps, and evaluates the impact of various noise mitigation solutions. The method analyzes the noise impact of construction sites, assesses the effectiveness of different mitigation strategies, establishes targets for noise emission levels in surrounding areas, and evaluates the impact on project costs and duration.

To demonstrate the effectiveness of the proposed method, we implemented it for a case study of an interdisciplinary student project. The resulting data and mitigation strategies are presented in the results section, followed by a brief discussion and conclusion.

## Background

Noise is typically unwanted, unpleasant, or annoying. It is characterized by its level of intensity (measured in decibel (dB)), the duration of exposure, the noise spectrum, the impulsivity, and the psychoacoustic parameters such as loudness and sharpness of the noise (Fernández et al., 2010). Often the sound level is expressed in decibels A (dBA) that is one of the filters used to represent the hearing response of the human ear (Heutschi, 2021).

Noise has a large impact on human comfort and health. The World Health Organization (WHO) describes seven categories of adverse health effects of noise: interference with speech communication, hearing loss, disturbance of sleep, stress, annoyance, effects on performance, and miscellaneous effects ( United N ations Environment Programme, 1980). Because of the high impact of noise on human well-being, safety and health administrations set guidelines and standards for exposure limit values and exposure action values, such as, 55 dB for outdoor living, 45 dB for indoor areas, and 70 dB for commercial areas (Berglund et al., 1999). For the work environment, the Occupational Safety and Health Administration (OSHA) Technical Manual sets the limit for the action level at 85 dBA and the permissible exposure limit at 90 dBA (OSHA 1995). Nevertheless, 40% of the workers in the manufacturing and construction industry are exposed to excessive noise (European Communities, 2004). The problem of noise at work is additionally enhanced by the fact that workers are often not aware of the gravity of this problem. They do not use personal hearing devices as much as they should and many companies are not persistent addressing regulations against noise (Fernández et al., 2009).

### Acoustics in Construction

Acoustics is defined as the science of sound and it deals with the generation, propagation, and interaction with matter as well as the perception of sound (Heutschi, 2021). Noise emission at a construction site results from the construction equipment and activities. It depends on the construction schedule, method, and equipment type.

Acoustics measurements on the construction site are performed only in a few cases: in case a determination of noise exposure at the engineering level is required, such as for detailed noise exposure examinations, or in case studies of noise-induced adverse effects on the human health are necessary. The International Organization for Standardization (ISO) provides an engineering method for measuring occupational noise exposure in a working environment and for calculating the loudness level of noise (9612, 2009; 532-1, 2017). The ISO 9612 proposes a variety of instruments and procedures to measure the noise in the working environment. However, there is not a defined measure-ment procedure for noise on construction sites, where ad-ditional challenges such as high background noise and si-multaneous activities increase the complexity of the mea-surements.

Consequently, research has been carried out focusing on this topic. Ballesteros et al. (2010) established a procedure to measure the noise of construction activities, allowing the analysis of the sound emission of each stage of the construction process and the characterization of the construction set as a noise source. For the study, in-situ measurements were regularly performed and information about the noise emission of the different construction activities was obtained. The results were used to assess the noise pollution and the worker's risks. Based on these results, appropriate noise control criteria were established. The study emphasizes the difficulty in measuring single activities in a noisy environment where simultaneous activities are performed (Ballesteros et al., 2010).

Another study used a task-based approach to collect the noise exposure data of selected construction tasks. The assessment of the task-based measurements and the task reference duration facilitate the recognition and communication of excessive noise levels, therefore helping the planning of the administrative controls and personal protective equipment to reduce the noise exposure to and below the threshold limit value (Kerr et al., 2002).

The main gap on the acoustic in construction is the missing guidelines and procedure to conduct noise measurements on construction sites. Guidelines would provide more clarity and therefore, more measurements on the site would be performed.

### Noise Mitigation Strategies

The National Institute for Occupational Safety and Health (NIOSH) recommends the use of the hierarchy of control to implement feasible and effective controls (Centers for Disease Control and Prevention, 2018). A similar approach can be applied to reduce noise on the construction site. Sound is a form of energy and the mitigation solutions can be summarized in source control, path control, and receptor control. The source control is the most effective way to control the noise generation and it includes the elimination and substitution of the noise source. Complete elimination of the noise source is hard to achieve on a construction site, hence the substitution of the loud noise sources is the next best suitable alternative. The choice of less loud equipment such as new or electrical machinery can reduce the noise impact. In the engineering control, the noise propagation path can be controlled. This step requires physical changes to the workplace that can be in form of redesigning equipment, optimizing the construction site layout, or the installation of sound barriers that prevent noise from reaching the receivers. Noise barriers provide a substantial reduction in noise level, however, they might be cost-effective and limit the accessibility to the site. Furthermore, in the receptor control, the administrative controls and the personal protective equipment can be implemented. The administrative controls include making changes in the schedule to avoid too much noise simultaneously. The requirement of personal protective equipment, such as ear plugs or other hearing protection devices is the last and least effective solution mainly because it relies on human actions to implement the control (Centers for Disease Control and Prevention, 2018; Gilchrist et al., 2003).

Mitigation solutions to control the noise come often with additional costs, their optimal implementation is key for a successful project. Therefore, research has been carried out focusing on the prediction and mitigation of construction noise. Kwon et al. (2016) developed a noise management model based on active noise control techniques that create a specific sound that cancels the undesired noise resulting in reduced noise perception. Gannoruwa and Ruwanpura (2007) applied simulation language (Symphony software) to predict the noise levels on

a construction site at given reception points and then provided the optimized location and dimension of sound barriers. (Gilchrist et al., 2003) used a deterministic model for predicting the noise levels using the Monte Carlo simulation method, providing additional suggestions of the optimal type and location of noise barriers.
Other research has focused on improving the planning of the construction site to reduce the noise pollution for the on-site workers using hybrid genetic algorithm-ant colony (Ning et al., 2019). Additionally, functions for minimizing the noise threshold violations and the traffic interruption on the transport network were determined for an urban region (Hammad et al., 2017). However, there is a lack of research on the level of administrative controls since most of the mitigation solutions are considered and applied only during the construction and not during the design phase.

## Proposed Method

The goal of the proposed method is to integrate the noise emission analysis into the design phase of a construction project, so that stakeholders can analyze the impact of the project on the surrounding environment and explore mitigation solutions in consideration of project schedule and cost. The method consists of the following six steps (see Figure 1):

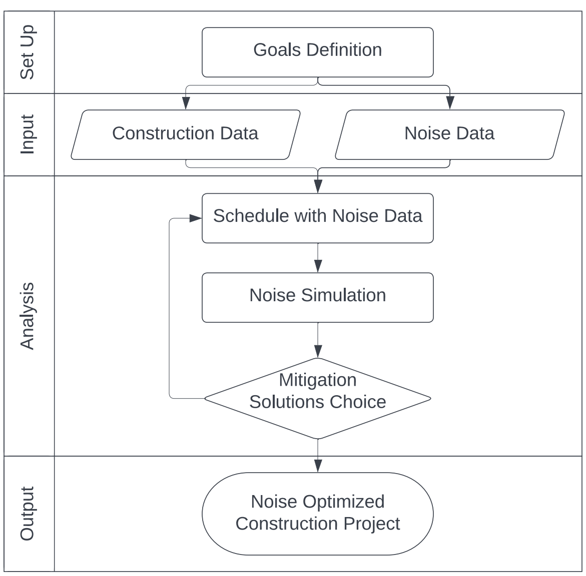


*Figure 1: The framework for the proposed method to integrate the noise emission in the design of a construction project.*

1. Determine the performance goals of the simulation.
2. Input the construction and noise data.
3. Integrate the planned construction schedule with noise data.
4. Perform a noise simulation.
5. Analyze when and where noise exceeds the performance goals, assess possible strategies for noise mitigation, and return to step 4 for each possible mitigation approach.
6. Compare the outcomes among possible mitigation solutions, and modify the design or construction plan in consideration of an appropriate noise mitigation approach.

The final output is a noise-optimized construction project. Each step of the method is further described below.

### Goals Definition

The first step of the method is to define the desired goals, including which stakeholders are considered and what the acceptable dB level will be. The construction noise influences both the on-site workers and the surrounding environment. Therefore, the goals depend on the client, the occurring activities, the location, the construction time, and the limit values defined by the regulations. The client might define goals with regards to the surrounding environment, while the contractors might define goals with regard to worker safety.

### Input Construction and Noise Data

Next, the input data required for the method includes construction data and noise data must be defined and collected. The construction data should include the building information, such as construction methods, number, dimensions, and position of the elements as well as the selected construction equipment. The use of an integrated BIM model is advantageous because it includes all the necessary information from the different disciplines. The noise data should include the planned construction activities and the equipment planned to be used for these activities. Most of the noise information about the machinery is provided directly by the manufacturers. Data about the construction activities can be taken from previous research studies or from the noise database provided by administrations such as OSHA (1995) and the Department for Environment Food & Rural Affairs (DEFRA, 2022).

### Integrate Schedule with Noise Data

The schedule provides information about the location, time, duration as well as equipment and material needed for each activity. Therefore, the noise data of each operation and equipment can be integrated with each activity and location. The result is a construction schedule with integrated noise data that can be used for the noise simulation in the next analysis steps.

### Conduct Noise Simulation

The simulation is computed using noise simulation software, where the construction activities are defined as noise sources with a determined decibel level that is generated for a certain time and duration. Depending on the defined goals, various receivers can be determined and located. At those receiver locations, the noise levels are computed for different periods of the day, week, or project phase. Depending on the noise simulation software, the received sound may or may not be computed from the simulation of noise originating from parallel activities. Because of the complexity of the noise sources in construction, an advanced noise simulation software that can calculate multiple noise sources and create 3D noise propagation is recommended for the method.

#### Determine Possible Mitigation

Once the noise simulation is performed, the noise levels resulting at the receivers can be analyzed and compared to the desired outcome. If the levels exceed the limit values defined by the noise goals, mitigation solutions need to be implemented. Possible mitigation strategies include:

- Replace heavy equipment with alternative machinery such as equipment that is newer, electric, and/or specifically noise-optimized. Heavy equipment is the main source of noise emission during construction.
- Install active sound barriers as temporary installations that absorb and reflect the sound. They can be installed in areas with an expected high noise emission or be attached to external scaffolding of the building.
- Use objects that are already on the construction site as passive sound barriers. For instance, strategically postponing the demolition of on-site elements or avoiding the relocation of trees might reduce the propagation of the sound.
- Reschedule activities to avoid simultaneous tasks that emit high noise levels can reduce the resulting overall noise. If the performance goal is to minimize disturbance to the nearby environment, high noise activities can be scheduled for less disruptive times. For example, if the nearby environment is a university, noisy activities can be rescheduled from exam week to spring break.

#### Implement and Analyze Mitigation Strategies

Once the mitigation solutions are applied, the analysis needs to be repeated to ensure that the noise goals defined at the beginning are met. The input data should be revised according to the chosen mitigation solutions. The simulation is performed again, and the noise emission levels are determined. The resulting analysis is multi-criteria optimization problem (regarding trade-offs between noise, project cost and project duration), it might take several attempts to identify the solutions that can mitigate the construction equipment and activities causing the most disruption. The method is therefore intended to be applied as a tool to enable discussion among the project participants regarding possible mitigation strategies. The final output of the method should be a noise-optimized construction project with the updated schedule and costs according to the implemented mitigation strategies.

## Implementation

A case study is used to illustrate the proposed method. The first author participated from January-May 2022 as part of the AEC Global Teamwork offered by the PBL Lab at Stanford University in collaboration with university partners worldwide (`http://pbl.stanford.edu/AEC\%20projects/projpage.htm`). The AEC Global Teamwork course implements a project-based learning approach, where students learn to collaborate in multidisciplinary teams to virtually design and build university buildings in challenging locations. Each team is composed of architects, engineers, construction managers and facility managers collaborating using technologies such as cloud-based BIM platforms and virtual reality.

The first author played the role of construction manager. The project team was responsible to design a new building for the University of Puerto Rico in the city of San Juan, Puerto Rico. The final design of the building is shown in Figure 2. A complete overview of the project is available at `https://www.youtube.com/watch?v=BSlTF_Wjyu4`.

*Figure 2: Rendering of the final design*

The proposed method was implemented using a num-ber of software platforms as illustrated in Figure 3.

#### Goal De inition

The first step of the proposed noise mitigation method is to define the goals to be achieved through the optimization process. The overall goal was to limit the noise level received at the surrounding buildings that was generated from the construction site. Here the recommended limit value is 55 decibels (United States. Office of Noise Abatement Control, 1974). In addition, a lower acceptable decibel level (45 dBA) was defined for certain period of time (in this case, the University's exam period.

#### Input Data

The construction data needed for the analysis was included in the central model created in Autodesk Revit and BIM360. During the project, the team made construction plans including the choice of equipment, the optimization of the construction site logistics, construction sequence, and schedule. The noise data needed for the analysis were sourced from the equipment sheets of the considered construction equipment and activities. The equipment was chosen according to the utilization during the construction. An abbreviated example of the selected noise data for the equipment is visible in table 1.


*Figure 3: Software architecture diagram used for the implementation of the method.*

*Table 1: Noise level (dBA) used for construction activities (Berger et al., 2015)*

| Noise source | dBA | Operation |
|---|---|---|
| Concrete mixer truck | 85 | Concrete pouring |
| Concrete pump | 99 | Concrete Pouring |
| Haul truck | 81 | Excavation |
| Excavator | 90 | Excavation |
| Small excavator | 90 | Excavation |
| Concrete poker vibrator | 98 | Concrete pouring |

### Integrate Schedule with Noise Data

The construction schedule was selected from the schedule solution space generated by ALICE (From ALICE Technologies), the world's first artificial intelligence-powered construction simulation platform. The platform delivers feasible construction schedules which do not over-allocate resources and violate physics laws. ALICE generates a schedule solution space illustrated in a time-cost graph.

Currently, there is no automatic way to integrate the noise parameters in ALICE. Therefore, the noise had to be added as a costless reusable material with infinity availability, giving the user the possibility to track it throughout the project. The amount of "noise material" for each construction operation was defined by the decibel level gener-ated by the equipment or the workers (see Table 2). Once the noise sources were incorporated in ALICE, the sched-ule with the noise data could be exported.

### Noise Simulation

The software platforms used for the simulation were Fuzor VDC VR and CadnaA. Fuzor VDC VR, developed by Kalloc Studios, is a Virtual Design and Construction (VDC) virtual reality platform that gives a detailed simulation of the construction process and the option to simulate the noise of the equipment in use. Furthermore, an avatar can be used to walk around the building and the surroundings and to listen to the noise generated from the equipment. CadnaA by Datakustik is a software specialized in sound simulation and prediction where the noise sources and the receivers can be modeled. CadnaA provides quantitative results of the noise levels and the noise propagation in 2D and 3D.

For each analysis iteration, different CadnaA models were created in which the noise sources (i.e., construction operations) with their respective heights and dBA levels were inserted. The surrounding buildings were defined as receiver elements so that the decibel levels were computed on the building's facade. By computing the noise simulation the effect of the noise emission on the surrounding buildings was analyzed. The Fuzor VDC VR was used to optimize the construction site logistics preventing the creation of bottlenecks or disruptions for the material and vehicle flow. Fuzor does not provide numerical results for noise emission and perception. Using Autodes Revit, ALICE, and CadnaA provided the necessary noise and schedule coordination analysis. ALICE was used to generate the schedule with the integrated noise data. Since the concept on which the software is based is simple, the incorporation of additional factors such as the noise data is facilitated. Therefore, ALICE offered a way to define the noise and provided automatic tracking of the noise emission. The quantitative noise analysis of days with exceeding noise levels was simulated with CadnaA, computing the noise propagation in 2D and 3D. Thanks to the 3D simulation, the impact of the noise sources and their height was detected on the receivers' facades emphasizing the differences in results given by the noise propagation in all directions.

### Implement Mitigation Strategies

To reduce the noise emission on the surrounding buildings, active and passive mitigation strategies were applied. The considered strategies for the analyses were sound barriers at the perimeter of the construction site, sound barriers on the building's scaffolding, the vegetation surrounding the construction site, and the choice of electrical equipment.

## Results

### Goal 1: Limit Noise below 55 dBA

Once the noise sources were incorporated in ALICE, the schedule with the noise data could be exported and analyzed, such as exporting a CSV of the different resource

*Table 2: Noise data considered for the project construction activities (Berger et al., 2015)*

| Noise source | ID | dBA | Operation |
|---|---|---|---|
| Carpenters: stripping form work | N_a_stripping_forms | 95 | Remove form work |
| Carpenters: setting forms | N_a_setting_forms | 87 | Install form work |
| Concrete Crew: placing concrete | N_a_placing_concrete | 88 | Concrete pouring |
| Iron Workers: tying + placing rebar | N_a_placing_rebar | 96 | Install rebar |
| Laborers: install drains + roughing concrete | N_a_roughing_concrete | 100 | Concrete finishing |
| Laborers: interior finishing | N_a_interior_finishing | 85 | Interior floor finishing |
| Drywaller: install drywall | N_a_install_drywall | 90 | Install glazing and wall panels |
| Roofer: cutting + installing roof deck | N_a_roofing | 94 | Install roof |
| Electricians: panel wiring + installing fixtures | N_a_wiring | 87 | Install PV system |

consumption over the project. Therefore, the consumption of the ”noise material” was exported into Excel. In order to detect the days with a lot of noise on the construction site, the decibel levels for each day were linearly summed. Figure 4 shows the graph of the summed decibel levels throughout the project.

The analysis of the construction noise emission focused on half-days with an excessive decibel level (linear sum exceeding 900 dBA) caused by multiple simultaneous activities. Since most of the construction activities are not performed for the entire day, the morning and afternoon of the working days were analyzed separately. Thereafter, the half-day with the highest noise emission was chosen and the noise simulation was performed with the corresponding noise emission values. As shown in Figure 4, there were four days where the linear sum of the noise levels exceed 900 dB:

- 16 January 2025.
- 11 February 2025.
- 18 February 2025.
- 21 March 2025.

Three mitigation strategies were attempted. First, the effectiveness o f *s ound b arriers* a t t he c onstruction site perimeter as well as on the building’s scaffolding were analyzed. Overall, the sound barriers at the construction perimeters provided an average noise emission reduction of 5 dB throughout the entire project. Combined with sound barriers installed to specifically reduce noise emission of certain operations, an additional average reduction of 1.2 dB was observed. Nevertheless, the installation and dismantling of the sound barriers are time-consuming and costly. Further analyses was needed to define if the temporary installation is more reasonable than the permanent installation.

The next mitigation strategy was using *alternative equipment*. Electrical equipment generates approximately 6 dB less than fuel equipment. We considered possible alternative electrical equipment selection. A combination of alternative equipment with the sound barriers at the construction perimeter reduced the noise at the facades of the surrounding buildings by 1.5 dB.

The final mitigation strategy was the use of *vegetation* in front of the surrounding buildings and around the construction site. This is a passive mitigation solution where neither the cost nor the duration of the project is impacted. By reducing the construction site area, fewer trees have to be relocated, hence the noise emission improved. In some parts of the facades, a dense vegetation between the façade and the construction site led to a noise reduction of up to 3 dB. However, the reduction of the site area also had impacts on the on-site workflow (e.g., vehicles, workers, material, etc.)

**Goal 2: Limit Noise during Exams**

The second goal defined for the analysis was to minimize the annoyance during the university exam phase by setting the decibel limit at 45 dB. The considered week, was the one from the $9^{th}$ to the $15^{th}$ of December 2024. On the $9^{th}$ of December, several activities were occurring contemporary. Space limitations means that we cannot describe the implemented mitigation in detail. However, the overall approach was to assess when construction activities generate a noise emission that results in a noise level of over 45 dB at the surrounding buildings, and to reschedule these activities to the previous or the following week.

## Discussion

The findings, and specifically the noise analyses in CadnaA, demonstrate that the equipment noise cause the main part of the noise emission. Therefore, the optimization of their position that might lead to a noise emission reduction was analyzed using Fuzor. However, detecting such dif-ferences was minimal, and the expected reduction of the noise barriers or other elements could not be observed in this preliminary case study. The presented implementation required significant manual data extraction and data entry between the different software plaforms.

An additional limitation was the limited flexibility of thecurrent software platforms used to extend data types,

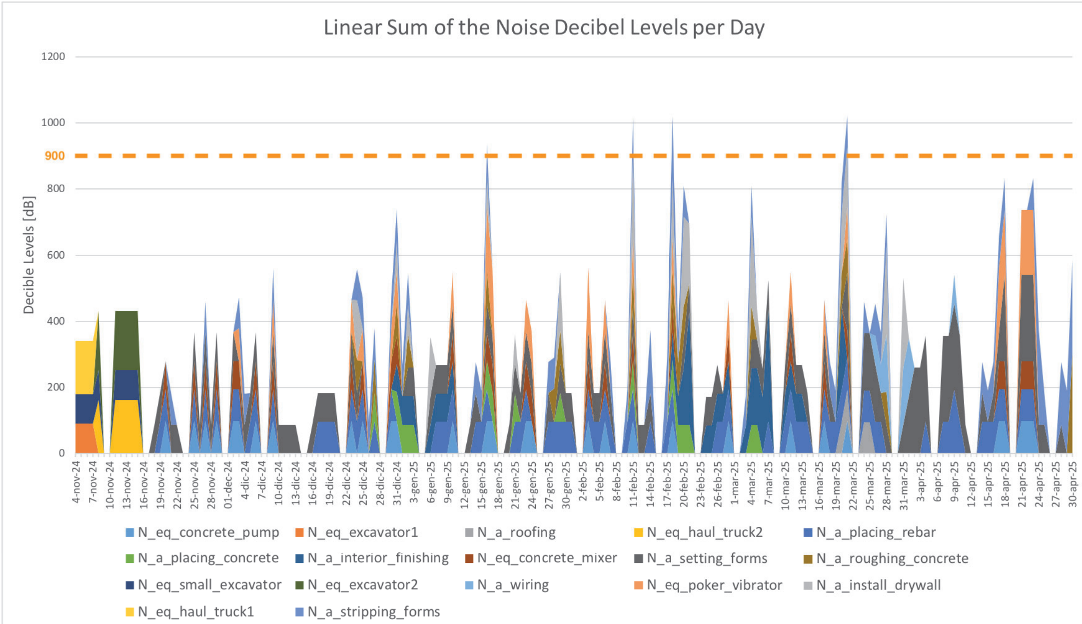


*Figure 4: Graph of the linear sum of the decibel levels daily generated. The dashed line indicates the dB level set by Goal 1.*

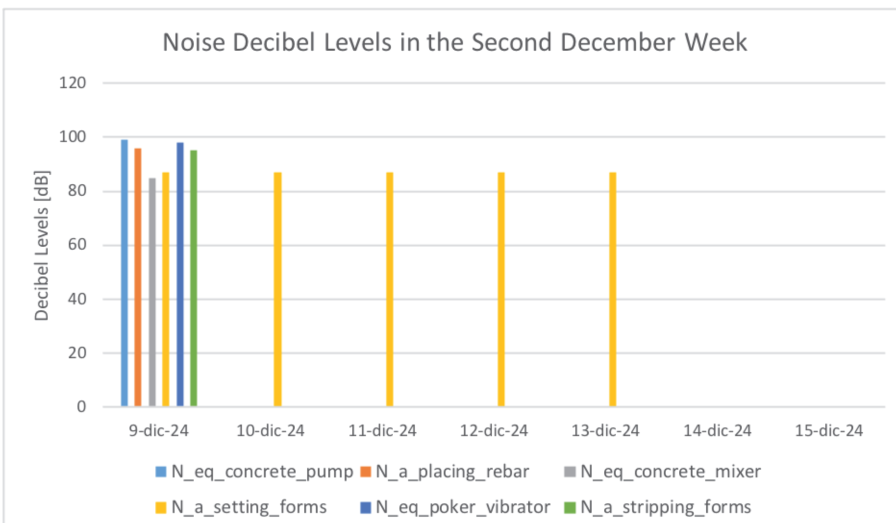


*Figure 5: Noise levels during exam week. Activities above 45 dB should be rescheduled to meet Goal 2.*

attributes, or functionalities related to noise characteristics and equipment performance. A key future development could be a more automated approach, and the use of an expert system to quickly conduct multi-criteria optimization across cost, schedule and project duration that might be required for noise mitigation.

One advantage of the method is the avoidance of the current complex and time-consuming practice of using on-site measurements to account for noise impacts. Such methods are often reactive, such as when neighbors make complaints about the noise levels of ongoing work. Our proposed method enables a proactive exploration and assessment of different noise mitigation strategies. This helps to improve the prediction of the necessary duration and location of the mitigation solutions and minimize the additional costs and duration of such intervention. It enables optimization of the construction site area and logistics, and considers low-cost passive alternatives such as delaying or avoiding removal of trees and vegetation that can reduce the noise emission caused by the construction.

Such approaches could facilitate project teams to rapidly prototype what-if scenarios in the conceptual development phase. Future information integration studies might consider construction-related factors like local hazards, weather impacts, and schedule delays.

## Conclusion

This paper presents a method to model the noise impact of construction activities and analyze noise reduction strategies. It is intended to be used during the design or preconstruction stage in order to mitigate the negative impacts of noise on construction workers and/or nearby environments. Various data inputs were required in order to perform the analysis, such as, the BIM model, the construction equipment types, the construction activities, and the associated noise levels for equipment and activities.

To demonstrate a basic implementation, a use case for an interdisciplinary student project identified how specific noise emissions can exceed project objectives, and how the method can be used to implement and analyze potential mitigation strategies. This implementation focused on noise emission and its impact on surrounding buildings. The basic implementation showed that the proposed method can be an effective approach to address noise mitigation. Future work is needed to better integrate the method with many different data sources. Future implementations could also be done to consider different impacts, such as the impact to on-site construction workers.

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