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Prediction of Noise from a Construction Site

Cover Page Footnote

First of all, I thank Allah, the Most Merciful, who guided me, and helped me throughout this research work. I would like to express my deep gratitude to Emeritus Prof. Adel I. Eldosouky , Civil Engineering Department, Faculty of Engineering, Tanta University, and Prof. Nashwa M. Yossef , Civil Engineering Department, Faculty of Engineering, Tanta University, for their wise guidance, continuous advice, and constructive criticism throughout this research work.

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Prediction of Noise from a Construction Site

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Abstract- **Construction activities significantly contribute to environmental noise pollution, affecting workers' health and the surrounding community, posing significant challenges to human well-being and productivity. This research aims to investigate the factors affecting noise levels in construction sites. Previous research has often lacked comprehensive models that accurately predict construction site noise, considering the complex interplay of various influencing factors. This study addresses this gap by focusing on the identification of key variables influencing noise generation and propagation and by developing a probabilistic prediction method using the Monte Carlo technique.**

The study is motivated by the need to understand the impact of noise pollution on construction activities and to provide a practical tool for selecting appropriate noise mitigation measures. The research relies on data collected from previous studies and codes of practice for construction noise to build a robust prediction model.

The findings indicate that equipment types, operational conditions, and site characteristics are significant factors affecting noise levels. Furthermore, strategic planning, which includes measures such as the optimal positioning of machinery and the use of sound-absorbing barriers, emerges as a key enabler for effective noise management. Additionally, the study demonstrates the effectiveness of the Monte Carlo technique in predicting construction site noise and planning noise mitigation strategies.

Implementing these approaches can significantly reduce noise pollution, thereby enhancing the well-being and productivity of workers and the surrounding community.

Keywords- **Construction site noise; Noise prediction; Probabilistic noise modelling; Noise measurement; MATLAB.**

I. INTRODUCTION

Construction activities often contribute to noise pollution, a widespread issue across different regions. The noise levels observed at receiving points can be seen as random variables within a stochastic process, making their interactions intricate. In reality, noise generated at construction sites varies over time due to factors such as equipment operations being off, idling, or running under light loads. These differences affect the distance between the noise source and the observer and the effectiveness of noise attenuation through barriers, sound-absorbing enclosures, strategic positioning of machinery, ground cover by planting trees, and measures to limit noisy activities and equipment [9,16,17].

A probabilistic approach was developed to predict noise levels from construction sites using a stochastic Monte Carlo model. The model identifies the basic temporal distribution of noise levels for single and multiple sources, considering source location diversity, equipment power, equipment item count, and working day synchronization. The advantage of this method was its ability to predict a series of noise levels in a working day, and these noise levels were weighted by cumulative or time-distributed probabilities. The indicator was utilized to mitigate discomfort and complaints from construction workers, forming the basis for noise reduction plans to promote a more sustainable environment [9].

The basis for a stochastic model was laid using the Monte Carlo method to build the analysis and distribution of the noise level. This policy has an advantage in use because it gives information about the time distribution of noise levels. This policy has an advantage in use because it gives information about the time distribution of noise levels. The Monte Carlo approach requires the following: - an inventory of noise source variables (random variables) that influence noise, generating the variables within the sort of a specified probability distribution (standard, normal, or exponential) or units in deterministic equations. The final results are the expected average noise level plus the standard deviation and noise level associated with its probability distribution. The results obtained showed that this method is able to predict the time distribution due to either a source or a group of noise sources. This method has also been used as the basis for a simple noise management tool [17].

Research has been conducted on noise emissions from construction activities, with a particular focus on excavation, superstructure and substructure (pilings). A significant difference was found between on-site noise measurements and forecasted noise levels, with forecasted levels being higher. The research involved three stages. Where the first step involved measuring noise levels from construction activities and individual equipment operating at maximum capacity, the second stage entailed forecasting noise levels using data from the first stage and the final stage involved analyzing the discrepancies between the average measured noise levels and predicted results. Fixed machines with higher noise emission levels resulted in less variable noise levels. The difference was due to the distance between the sound source and the measurement location, the number of moving machines, and the high noise emission level of the machines [20].

The objectives of this research are to identify the factors affecting noise emission from the construction sites and to develop a probabilistic prediction method using the Monte Carlo technique. By understanding these factors, we can better assess the sources and drivers of construction-related noise pollution and propose effective noise management strategies. Previous research has often lacked comprehensive models that accurately predict construction site noise, considering the complex interplay of various influencing factors. This study addresses this gap by focusing on the identification of key variables influencing noise generation and propagation. Additionally, it aims to develop a probabilistic prediction method using the Monte Carlo approach to predict noise levels resulting from construction activities based on the specified factors. And applying the developed prediction model to a real construction project in Egypt [2,14,15].

By implementing the model in a practical setting, we can evaluate its effectiveness in accurately predicting noise levels and informing decision-making processes for noise mitigation strategies. This paper is organized as follows: Section II outlines the methodology, including data collection techniques, noise calculation steps, the probability of noise occurrence from construction equipment, modeling utilizing the Monte Carlo method, and the impact of sample size on statistical accuracy. Section III applies the developed model to analyze single source sound distribution with varying random sample sizes and duty cycle variations, as well as dual source sound distribution considering influences of position, conditions, and sample size. The findings from the application of the model are discussed at the end of each case in this section. Finally, Section IV concludes the paper with a summary of the main findings, implications for construction noise management, and suggestions for future research.

II. METHODOLOGY

The research methodology adopted for this study revolves around the development of a generalized prediction technique to serve as a noise management tool [17]. Central to this approach is the utilization of computer simulation. The methodology consists of three steps as described in “Fig.1”.

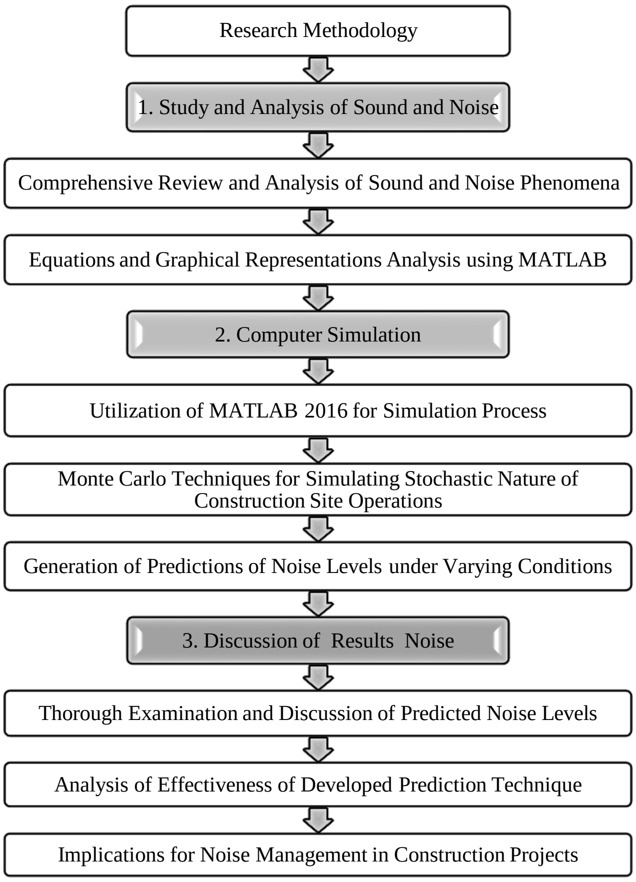

Figure 1. Research methodology for developing a noise prediction technique using MATLAB

By following this methodology, the research aims to advance the understanding of noise prediction in construction settings and provide a practical tool for noise management. The computer simulation approach offers flexibility and scalability, allowing for the adaptation of the prediction technique to diverse construction projects.

The following contents explain how MATLAB, drawing upon insights from previous studies [17], uses random numbers to determine correlated values in different distributions, with a specific focus on the relationship between a uniform distribution and the cumulative distribution of a random variable: -

1) Usually, a random number is a pseudorandom number uniformly distributed over the specified interval from 0 to 1. The random number N is selected from a uniform distribution, and this value is used to determine a value in the cumulative probability distribution F(N). This value then corresponds to a value in the assumed cumulative distribution of another random variable F(g), where g represents noise levels. F(g) represents the probability of

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a random variable (noise levels) being less than or equal to a certain value, used to determine noise levels from a uniform distribution, aiming to accurately predict total noise at construction sites.

2) The process can be visualized as the dark areas under the uniform distribution curves of P(N) and P(g). The areas under the P(N) curve from 0 to 1 and under the P(g) curve from a to b are both equal to 1 as shown in Fig. (2).
3) By selecting a large number of random numbers, we can sample a set of associated g-values from P(g) unbiasedly. These values will simulate the original function P(g).

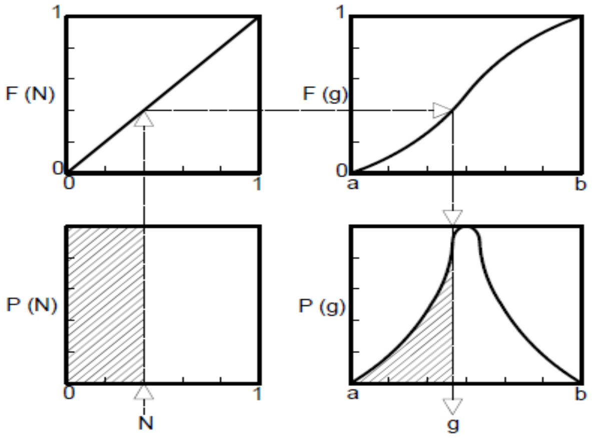

Figure 2. Relationship between the Random Numbers Generated by the Computer and the Stochastic Variable g [17].

The study focuses on predicting noise levels from construction equipment during excavation activities. Three sites were examined using loaders and excavators, and noise levels were measured using sound level meters. The data was collected during different operational states and times of the day to account for ambient noise variations (see Fig. 3).

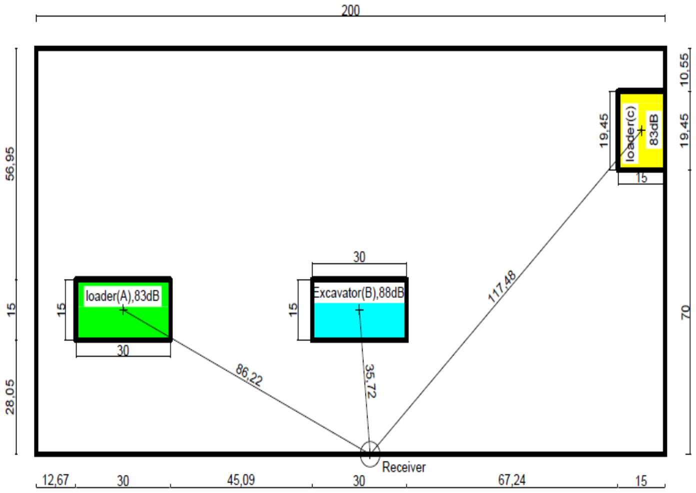

Figure 3. Site Configuration

The methodology adopted for this study involved a multifaceted approach to gather comprehensive data and analyze noise levels generated by construction equipment during excavation.

A. Data Collection Techniques

Instrumentation: To precisely quantify the noise emissions on the divided site, a noise measurement device (Sound Level Meter) was deployed in a strategic location. In order to estimate the risks of noise exposure, protect worker health, identify and mitigate high-noise areas, lessen the impact of noise on nearby residents, and track the efficacy of mitigation measures [1,8,22].

Spatial Mapping: Accurate surveying was conducted to define boundaries of the whole site and every area that was being studied [2,11,19].

Equipment Monitoring: Fixed points monitored noise emissions from the excavator and loader during different operating conditions. In the case of constant movement, the equipment remains in a fixed position, resulting in less noise generation, while in the case of fast movement, the equipment operates with sudden changes in position or speed, resulting in to increase noise [11,13,18].

Different operational states lead to varying noise and vibration levels, with stationary states generating less noise compared to rapid movements [12,17].

B. Noise Calculation Steps

These noise calculation steps are designed to model the noise impact of construction equipment on a site [9,17,21]. Below is an explanation of how each equation was proposed:

1. Machine Position Determination within Site Area

$$x_i = w\,(N_i - 0.5) \qquad (1)$$

$$y_i = d\left(N_j - 0.5\right) \qquad (2)$$

These equations are derived to randomly place construction equipment within a given site area, where (w) is the width of the site, (d) is the depth of the site, and (N_i) and (N_j) are random numbers uniformly distributed between 0 and 1 [17,21].

- (x_i) and (y_i) represent the x and y coordinates of the equipment.
- By subtracting 0.5 from the random number (N_i) or (N_j), the position is centered around the midpoint of the site, ensuring an even distribution.
- Multiplying by the site dimensions (w) and (d) scales the positions to fit within the site boundaries.

2. Calculation of Sound Intensity at Receiver Location

$$I_{ij} = \frac{w_a}{A} = \frac{w_a}{2\prod {r_{ij}}^2} \qquad (3)$$

$$r_{ij=((x_i-x_r)^2+(y_i-y_r)^2+(z_i-z_r)^2)^{0.5})} \qquad (4)$$

These equations are based on the principles of acoustic propagation and inverse-square law.

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Sound Intensity (I_{ij}): The intensity of sound at a receiver point from a source is given by the acoustic power (w_a) of the source divided by the surface area of a centered on the source with radius (r_{ij}) [17]. The formula derives from the fact that sound power disperses spherically in free space, and thus the intensity decreases with the square of the distance from the source.

Distance Calculation (r_{ij}): This equation calculates the Euclidean distance between the source coordinates (x_i, y_i, z_i) and the receiver coordinates (x_r, y_r, z_r). It follows the standard distance formula in three-dimensional space [17,21].

3. Sound Pressure Level Determination [9,17,21]

$$L_{(i,j)} = 10.\log_{10}\left(\frac{I_{(i,j)}}{I_{(i,j)\circ}}\right) \qquad \text{Eq (5)}$$

This equation calculates the sound pressure level (SPL) from the sound intensity using a logarithmic scale.

Sound Pressure Level ($L_{(i,j)}$):

- The SPL is a logarithmic measure of the ratio of a particular sound intensity (I_{ij}) to a reference sound intensity ($I_{(i,j)\circ}$).
- The reference intensity ($I_{(i,j)\circ}$) typically represents the threshold of hearing.
- The factor of 10 converts the ratio into decibels (dB), a common unit for SPL, making it easier to handle the wide range of sound intensities humans can perceive.

These equations collectively model how noise from construction equipment propagates across a site and impacts different locations. The randomness in equipment placement simulates varying operational conditions, while the intensity and SPL calculations help quantify the noise levels at specific points. These mathematical models are essential for assessing and managing construction noise impacts effectively.

C. Probability of Noise Occurrence from Construction Equipment

The study examines the probability of noise occurrence for both single and multiple sources within the construction site.

The values of A and B, which represent the proportion of time the machine spends in different operational states, are determined through a systematic process [9,17,18,19,22]:

- Data collection: Operational states of construction machinery are recorded over several days, including when the machines are off, idle, or operating at full capacity.
- Statistical analysis: Average percentages of time spent by machines are calculated by analyzing the collected data.
- Historical records and industry standards: Past equipment usage records and industry guidelines are reviewed to determine typical operating patterns.
- Expert consultation: Results are validated through input from equipment operators, site managers and industry experts.
- Iterative testing and adjustment: Initial values of A and B are applied in the noise prediction model and adjusted iteratively to match observed noise levels and operating patterns.

These conditions delineate the varying levels of sound energy produced by the machine throughout a typical working day, corresponding to its activity pattern and state. These conditions determine the source's status as follows [9,17]:

- Condition 1: If the machine is inactive for a proportion (less than or equal to) A% of the working day.
- Condition 2: If the machine is inactive for a proportion greater than A% but less than or equal to B% of the working day.
- Condition 3: If the machine is fully operational for a proportion greater than or equal to (A + B) % of the working day.

This comprehensive approach provides valuable insights into the spatial and temporal dynamics of noise emissions at construction sites, aiding in the development of effective noise management strategies. These strategies include targeted noise mitigation, operational adjustments, continuous noise monitoring, community relations improvement, and worker health and safety [9,17].

D. Modeling Utilizing the Monte Carlo Method

The model adopts the methodology introduced by Yahya and Haron [17], where simulations of the temporal progression rely on sampling noise generated from site operations throughout the relevant operational timeframe. The Monte Carlo method serves as the basis for modeling noise levels in this study. This technique involves generating random samples from probability distributions to simulate various aspects of noise generation and propagation. Specifically, it allows for considering stochastic factors like the random position of equipment and their duty cycles. By sampling these variables and integrating them into the modeling framework, the Monte Carlo approach facilitates generating probabilistic estimates for noise levels at different locations and times. This probabilistic modeling strategy offers a more holistic understanding of the inherent variability and uncertainty in noise prediction, thereby enhancing result accuracy and reliability.

a. A Noise Source with One Operating Cycle

The proposed model incorporates the site area's dimensions (width w and depth d) and positions a receiver at a distance r from the subsite's centre. It assumes that a machine operating at one location has an equal probability of operating at any other point within the site area, as influenced by the findings of previous studies conducted [9,17]. The noise source is randomly placed within the subregion, ensuring an equal probability distribution (see Fig. 4).

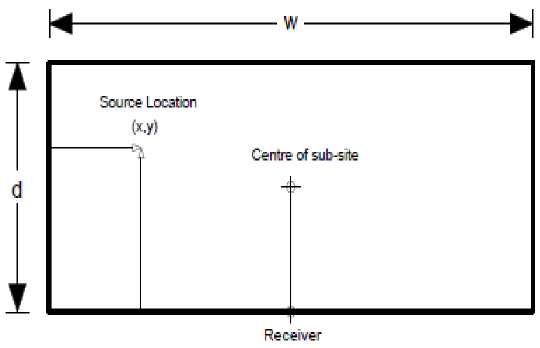

Figure 4. Placement of stochastic noise source within the operational sub-site area for Monte Carlo method.

Through acquiring numerous samples, a statistical assessment can be conducted to ascertain the temporal distribution [6], expressed through a probability distribution function (PDF) and cumulative distribution function (CDF). Moreover, the mean intensities can be calculated by aggregating the sampled intensities and dividing by the total number of samples.

b. A Noise Source with a Complicated Duty Cycle

Machinery often produces various sound power levels throughout a workday, influenced by its usage pattern. For instance, if the machine is completely turned off, producing no noise, it can be stated as (Totally Off) and their associated percentage is A% of the working day. If the machine is in an idle state, it does not produce any significant noise. It may be in standby mode or not actively functioning, it can be stated as (Inactive) for B % of the working day. However, if the machine is working at full power and producing its maximum noise level, it can be stated as (Fully Operational) for C % of the working day [1,9,17].

These tables clearly show the operational states and duty cycles of the first and second items of equipment according to their respective percentages per working day.

Table 1. Operational States, source: [1,9,17]

Operational State	Percentage of Workday (%)
Totally Off	A%
Inactive	B%
Fully Operational	**C%**

Table 2. Duty Cycles for First Item of Equipment, source: [1,9,17]

Operational State	Percentage of Workday (%)
Totally Off	0 %
Inactive	20 %
Fully Operational	**80 %**

Table 3. Duty Cycles for Second Item of Equipment, source: [1,9,17]

Operational State	Percentage of Workday (%)
Totally Off	20 %
Inactive	20 %
Fully Operational	**60 %**

To model the effect of this complex operating cycle, the Monte Carlo method can be extended to include the probability of the machine being in each of these states. Another random number, N_k can be used to determine the machine's state at a given point in time during its working day. The random number N_k is sampled from a known probability distribution that represents the probabilities of the machine being in the "Totally Off," "Inactive," or "Fully Operational" states [17].

The model incorporates noise sources from the excavator and loader operating in random conditions, considering various random variables such as location and work cycle. This approach is based on previous studies conducted by Yahya and Haron in [17], which provided valuable insights for this research. The modelling process consists of three stages: -

1) Random numbers N_i and N_j are used to determine the equipment's position, along with random power obtained from a random number N_k.
2) The noise level at the receiver is calculated based on the equipment's position and power. For multiple equipment, the first and second stages are repeated.
3) After obtaining a number of samples, noise levels are analyzed. The concept of a uniform distribution over the interval [0,1] is fundamental in generating these samples. In this context, it means that random numbers are selected uniformly from this interval to represent different noise levels. These noise levels are then analyzed using statistical techniques such as histograms and frequency analysis within a specified 1 dB range. The probability density function and proportional distribution function are then determined using a vertical axis that is standardized to a maximum value and a horizontal axis that relates to the noise levels.

E. Sample Size and Its Impact on Statistical Accuracy

Increasing the number of random samples offers several benefits that enhance the robustness of statistical analyses and experimental results [6,7,25]:

Larger sample sizes reduce standard deviation, ensuring homogeneous data and minimizing random errors, increasing confidence in results. They also improve precision and stability, accurately representing noise levels.

Larger sample sizes enable the detection of subtle differences between groups, enhancing sensitivity and understanding of underlying trends, such as construction equipment operational states.

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Considering these factors, a sample size of 25,000 random samples was utilized in this analysis to ensure robust statistical outcomes, ensuring accuracy and validity of the findings.

III. APPLICATION

A. *Single Source Sound Distribution Analysis: Impact of Varying Random Sample Sizes (one operating cycle)*

1. *Variable Definitions and sample size:*

To analyse the data, various parameters were defined to characterize the studied case. These parameters include the site dimensions, sound power, and the number of samples considered for each case.

The site width (w) was set to 100 meters, while the site depth (d) was determined as 200 meters. The sound power (w_a) of the source, which is the total energy emitted by the noise source per unit of time and expressed in decibels (dB), was specified as 100 decibels. Additionally, to explore the impact of varying random sample sizes, five different cases were considered, each with a different number of samples. These cases include case 1 with 2500 samples, case 2 with 10000 samples, case 3 with 15000 samples, case 4 with 20000 samples, and case 5 with 25000 samples.

2. *Random Coordinates Generation:*

- Use MATLAB's random function to generate random numbers within the specified range [23].
- For each piece of equipment, generate two random numbers N_i and N_j uniformly distributed over the interval [0, 1].
- Calculate the coordinates (x_i) and (y_i) using the equations (1) and (2).

3. *Receiver Location Determination:*

Specifies the coordinates and height of the receiver.

- Coordinates: $(x_r, y_r) = (31.2155136, 31.5687073)$
- Receiver height $(z_r) = 1.5$ meters

The coordinates (x_r, y_r) were measured using a Total Station, an electronic surveying device that provides high-accuracy coordinate and distance measurements. The Total Station uses advanced technologies such as laser, radar, and infrared to determine locations by receiving signals from known points and calculating the current location using trigonometry and geometric calculations. This device is widely used in engineering surveying, construction, civil engineering, and scientific research for its precise measurements.

4. *Distance Calculation between Each Source and the Receiver:*

Calculates the distance between each source and the receiver using the geometric distance formula (r_{ij}) as specified in Equation (4).

5. *Additional Conditions:*

Introduces extra parameters regarding sound levels, encompassing the range from A to B and the statuses of "totally off" and "inactive."

6. *Calculation of Sound Energy Density and Conversion to Sound Pressure Level:*

Computes the Sound intensity based on the distance between the source and the receiver using the previously mentioned equation (3), then converts it to sound pressure level (SPL) using the previously mentioned equation (5), as follows:

1) Sound Intensity (I_{ij}): Calculating the sound intensity at a specific point (i,j). This represents the energy per unit area of the sound at that location.
2) Reference Intensity ($I_{(i,j)_\circ}$): Using the standard reference intensity, which is usually ($10^{(-12)}$) watts per square meter.
3) Logarithmic Conversion: Applying equation (5) to convert the sound intensity to SPL.

7. *Plotting the Results:*

Plots the PDF (see Fig. 5) and CDF (see Fig. 6) for each case using the plot function.

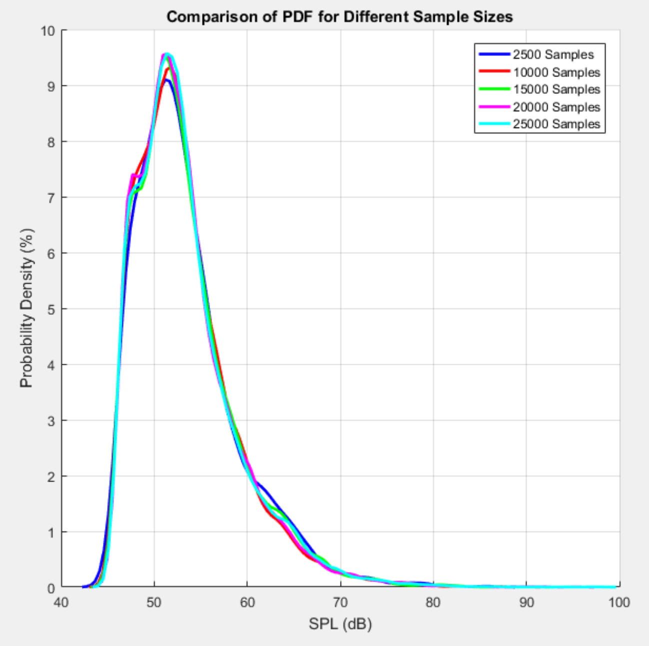

Figure 5. " PDF for comparison of Sound Pressure Level (SPL) Distribution with Continuous Operation for a Single Source: 2500, 10000, 15000, 20000, and 25000 Samples".

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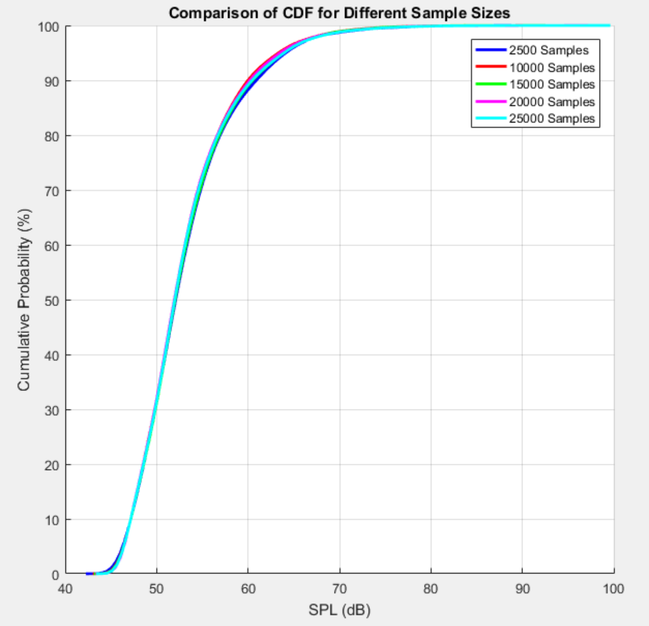

Figure 6. " CDF for comparison of Sound Pressure Level (SPL) Distribution with Continuous Operation for a Single Source: 2500, 10000, 15000, 20000, and 25000 Samples".

Based on the results presented [3], the analysis of (Fig. 5) and (Fig. 6) can be directed as follows:

1. *Common SPL values*

A set of common SPL values ranging from 46.4550 dB to 97.5646 dB was identified across different cases. The common SPL range indicates a consistent pattern of noise levels across different sampling cases, suggesting stable and predictable emissions from construction equipment. Understanding noise levels is crucial for effective construction site management, predicting noise environments, implementing mitigation measures, assessing health and safety impacts, and serving as a baseline for simulation. It also provides a benchmark for comparing noise levels across different construction sites [1,5,13].

2. *Different noise levels (Different SPL values)*

When using different sample sizes (2500, 10000, 15000, 20000, and 25000 samples), varying SPL values were observed. However, certain SPL values (e.g., 43.3583 dB, 43.3673 dB, 90.8985 dB, 93.9843 dB, and 93.9857 dB) remained consistent across all sample sizes.

3. *Standard deviation*

The standard deviation measures the extent to which the data is dispersed around its mean. The reported values of standard deviation for different samples show that there is little variation in noise levels between cases when different numbers of samples are used.

B. *Single Source Sound Distribution Analysis: Impact of Duty Cycle Variation on Random Sample Sizes*

Duty cycle variation refers to changes in the ratio of time a machine or equipment spends in active operation compared to the time it remains idle or inactive. In the context of sound distribution analysis, duty cycle variation can have a significant impact on the generated noise levels.

1. *Variable Definitions:*

To analyze the data, parameters such as site width and depth were defined as given in page 5. The acoustic power levels were characterized as follows:

w_a = 100 dB: Acoustic power level for the continuous component, declared as a constant.

w_{a1}= 100 dB: Acoustic power level for the intermittent component operating with the duty cycle shown in Table 2.

w_{a2}= 100 dB: Acoustic power level for the intermittent component operating with the duty cycle shown in Table 3.

2. *Number of Samples:*

Number of Samples = 25000: Number of required samples.

A fixed sample size of 25000 was used to analyze the impact of duty cycle variation on sound distribution from a single noise source. The focus here is on understanding how different operational states (duty cycles) of the equipment influence the noise levels, rather than the effect of sample size. Using a large, fixed sample size ensures robust and reliable results with minimal random errors, allowing clear observation of duty cycle impacts. This comprehensive statistical analysis accurately captures noise level patterns due to duty cycle variations, leading to valid conclusions about the equipment's operational states.

3. *Generating Random Coordinates:*

As given (discussed) before

4. *Receiver Coordinates:*

As given (discussed) before

5. *Calculating Distance between Source and Receiver:*

As given (discussed) before

6. *Calculation of Sound Energy Density and Conversion to Sound Pressure Level:*

Sound Intensity Calculation: Calculating the sound intensity (I_{ij}) at a specific point (i,j) using the previously mentioned equation (3):

For the Intermittent Component (20% idle, 80% on):

- Idle Mode (20% of the time): During this period, calculate the sound intensity ($I_{(i,j)\ idle}$): reflecting the lower noise levels.
- Operational Mode (80% of the time): During this period, calculate the sound intensity ($I_{(i,j)\ on}$)reflecting the higher noise levels when the equipment is fully operational.

For the Intermittent Component (20% off, 20% idle, 60% on):

- Off Mode (20% of the time): During this period, the sound intensity($I_{(i,j)\ off}$): is zero as the equipment is not operating.
- Idle Mode (20% of the time): Calculate the sound intensity ($I_{(i,j)\ idle}$)for the low noise levels.

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- Operational Mode (60% of the time): Calculate the sound intensity ($I_{(i,j)\ on}$) for the high noise levels.

Reference Intensity ($I_{(i,j)_o}$): Using the standard reference intensity, which is usually ($10^{(-12)}$) watts per square meter.

Logarithmic Conversion: Applying the previously mentioned equation (5) to convert the sound intensity to SPL for each operational state (idle, on, off).

7. *Additional Conditions:*

As given (discussed) before

8. *Plotting PDF and CDF:*

Plot the PDF (see Fig. 7) and CDF (see Fig. 8) for both cases (the first case (20% idle, 80% on) and the second case (20% off, 20% idle, 60% on)) using the computed values.

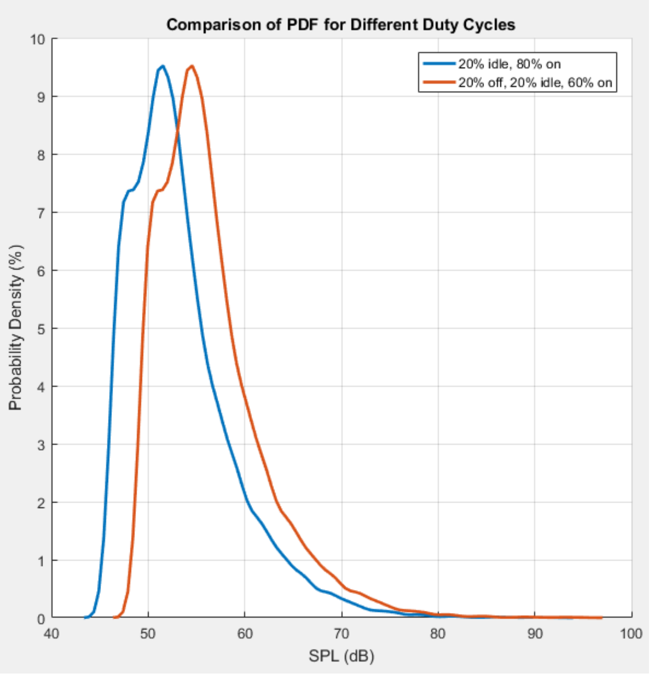

Figure 7. "PDF for comparison of Sound Pressure Level (SPL) Distribution for Different Duty Cycles: 20% Idle, 80% On vs. 20% Off, 20% Idle, 60% On".

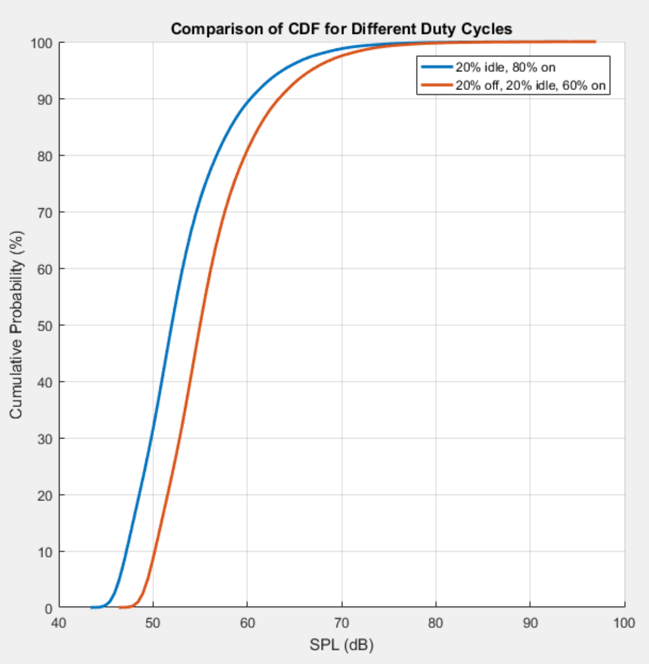

Figure 8. "CDF for comparison of Sound Pressure Level (SPL) Distribution for Different Duty Cycles: 20% Idle, 80% On vs. 20% Off, 20% Idle, 60% On".

Based on the results presented [3], the analysis of (Fig. 7) and (Fig. 8) can be directed as follows:

1. *Common SPL values*

SPL values were determined for both cases ((20% idle, 80% on) and (20% off, 20% idle, 60% on)), revealing a range from 43.3673 dB to 93.9857 dB. This range indicates the levels of noise that are consistently sensed across different duty cycle configurations.

Low-End SPL (43.3673 dB) is generally acceptable, while high-End SPL (93.9857 dB) may be disruptive or harmful, especially in residential areas. The acceptability of these noise levels depends on local noise regulations and standards. Typically, SPL levels above 85 dB may require mitigation measures to protect workers and nearby residents [1,4,12].

The contractor needs to assess construction area regulations and implement noise barriers, equipment maintenance, operational adjustments, stakeholder engagement, transparency, and ear protection to reduce noise impact, including erecting noise barriers, adjusting duty cycles, and providing ear protection for workers [1,12].

2. *Different noise levels (Different SPL values)*

Variations in SPL values were observed between the two cases ((20% idle, 80% on) and (20% off, 20% idle, 60% on)), reflecting the impact of different duty cycle configurations on noise levels. This variation suggests that changes in operational patterns result in distinct noise profiles. Consequently [1,2,12,13]:

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Customized Mitigation Strategies: Different duty cycles may necessitate tailored noise control measures to address the specific noise profiles generated during various operational states.

Regulatory Compliance: Ensuring compliance with noise regulations may require adjusting duty cycles or implementing noise reduction technologies during high noise periods.

Operational Planning: Understanding noise variations can inform better scheduling of noisy operations during times when they will cause the least disturbance.

Impact on Surrounding Areas: The distinct noise profiles can help predict and manage the impact on surrounding residential or sensitive areas, improving community relations and minimizing complaints.

Health and Safety Measures: Appropriate hearing protection and other safety measures can be implemented more effectively by understanding when and where higher noise levels occur.

3. *Standard deviation*

The standard deviation of SPL was found to be consistent across both cases ((20% idle, 80% on) and (20% off, 20% idle, 60% on)), with a value of approximately 5.4411 dB. This indicates that, despite differences in duty cycle configurations, the variability in noise levels remains relatively constant. This has several implications:

The consistent noise environment provides a predictable and uniform noise control measure, allowing for effective mitigation strategies across different duty cycles. This stability enhances the reliability of predictive models, allowing for more accurate forecasts of noise impacts. Consistent noise exposure patterns benefit workers and nearby communities, aiding in designing protection and communication strategies. The constant standard deviation also allows for clear statistical analysis and comparisons of noise levels across different duty cycles or operational states [1,9,10].

C. Analysis of Dual Source Sound Distribution: Influences of Position, Conditions, and Sample Size

Dual source sound distribution refers to the study of how noise spreads and distributed when there are two distinct noise sources operating simultaneously. In this context, factors such as the relative positions of the sources, their operational conditions, and the number of samples used in the analysis can significantly influence the noise levels and patterns observed. By understanding these influences, we can better predict and manage the impact of dual noise sources in environments such as construction sites. This analysis is crucial for developing effective noise mitigation strategies.

1. *Requirements and Variables:*

The site width (w) and the site depth (d) were determined as given in page 5. The sound power for source 1 (w_a = 100 decibels) and source 2 (w_a = 90 decibels) and number of samples = 25000.

2. *Generating Random Positions for Sources:*

As given (discussed) before

3. *Determining Receiver Location:*

As given (discussed) before

4. *Calculating Distance Between Each Source and the Receiver:*

As given (discussed) before

5. *Additional Conditions:*

As given (discussed) before

6. *Calculating Sound Density and Converting to Sound Pressure Level (SPL):*

Sound Intensity Calculation for Each Source: using the previously mentioned equation (3).

- Calculate the sound intensity (I_{ij}) for source 1 at each point (i, j).
- Calculate the sound intensity (I_{ij}) for source 2 at each point (i, j).

Reference Intensity ($I_{(i,j)_\circ}$): Using the standard reference intensity, which is usually ($10^{(-12)}$) watts per square meter.

Logarithmic Conversion: Applying the previously mentioned equation (5) to convert the sound intensity to Sound Pressure Level (SPL) for each source.

7. *Plotting the Results:*

Plotting the division of PDF for concurrent combination operation (see Fig. 9).

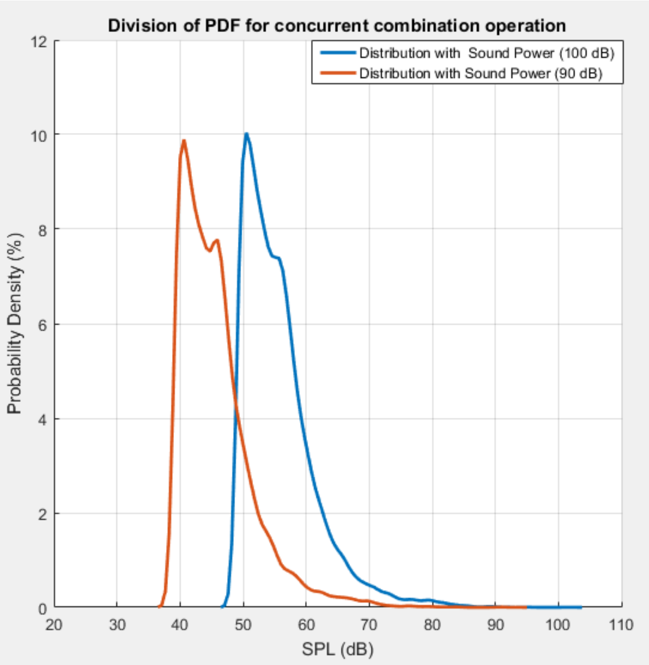

Figure 9. Division of Probability Density Function (PDF) for Concurrent Combination Operation: Source 1 Compared to Source 2 (100 dB Compared to 90 dB).

Based on the results presented [3], the analysis of (Fig. 9) can be directed as follows:

1. *Common SPL values*

The presence of common SPL values indicates consistent noise levels across different configurations of simultaneous noise sources. This indicates certain basic noise levels that persist regardless of the specific arrangement of the noise emitting sources.

2. *Different noise levels (Different SPL values)*

Differences in SPL values between cases confirm the influence of distinct acoustic forces and spatial distributions of noise sources on overall noise levels. These differences reflect the complex interaction between multiple noise sources and their combined effect on environmental noise.

Noise sources emit sound at different power levels, frequency ranges, and duty cycles, affecting SPL values at different locations. Spatial distributions, such as proximity to measurement points, barriers, and reflective surfaces, also impact SPL values. The inverse square law states that the intensity of sound decreases with the square of the distance from the source, so even small changes in distance can significantly affect SPL values [1,9,14].

The combined effect of multiple noise sources on environmental noise levels is complex and multifaceted. It involves the interference of sound waves, which can either amplify or reduce the sound, creating a complex sound field. Temporal variations in noise levels, which can be predicted by synchronized operational patterns, are crucial for mitigation strategies. High cumulative noise levels can have adverse effects on human health, and understanding these effects helps design better noise control measures and ensure compliance with regulatory standards [1,9,14].

3. *Standard deviation*

Comparable standard deviation values indicate a relatively constant dispersion of noise levels around their mean in both cases. This suggests a similar degree of variability in noise exposure despite differences in the composition of concurrent noise sources.

Concurrent noise sources create a unique acoustic environment where sounds from different origins combine. This interaction can lead to either amplification or cancellation effects, depending on the phase and frequency of the overlapping sounds. Understanding these interactions is crucial for accurately predicting and managing overall noise levels [1,9,14].

When multiple noise sources are active at the same time, their combined effect can be significantly different from the noise produced by each source individually. The cumulative impact often results in higher overall noise levels, which can exceed acceptable limits and necessitate comprehensive noise control measures [21].

The presence of concurrent noise sources generates complex acoustic patterns, making it challenging to identify and isolate the contribution of individual sources. This complexity requires advanced analytical methods and tools to effectively monitor and mitigate the noise [24].

The spatial arrangement of concurrent noise sources affects how sound propagates and interacts within the environment. Sources located close to each other may produce overlapping noise fields, while distant sources might create distinct acoustic zones. Effective noise management must consider the spatial distribution to address areas with higher noise exposure [9].

The human perception of noise is influenced by the presence of multiple sources. Concurrent noises can lead to increased annoyance and disturbance, as the brain has to process a more complex soundscape. This can have implications for both occupational and environmental health, highlighting the need for targeted noise reduction strategies [16].

D. Research Limitations

Despite the comprehensive approach taken in this study, there are several limitations. The accuracy of the prediction model is highly dependent on the quality and completeness of the input data, which were collected from a real construction project. While this reduces potential bias, the model assumes that the noise sources and environmental conditions remain constant over time, which may not always reflect real-world variability. The application of the model to a single construction project in Egypt may limit the generalizability of the findings to other regions with different environmental and operational conditions. Finally, the Monte Carlo technique, while powerful, requires significant computational resources, which may be a constraint for some practitioners.

IV. CONCLUSION AND FUTURE WORK

In conclusion, examination of noise exposure within construction sites across three distinct cases: varying sample sizes, different duty cycle configurations, and concurrent noise sources highlights essential considerations for effective noise management strategies. Firstly, the sensitivity to sample size underscores the necessity of adequate sampling to minimize variability in noise level estimates. Secondly, variations in noise profiles under different duty cycle configurations emphasize the importance of understanding operational patterns' impact on noise levels. Finally, analysis of concurrent noise sources emphasizes the complexity of noise emission dynamics and the need for comprehensive monitoring and mitigation strategies. By addressing these factors, stakeholders can develop more robust approaches to mitigate the adverse effects of environmental noise and improve overall urban living conditions.

Noise emission dynamics involve multiple sources of interference, creating complex sound fields. Frequency interference affects noise levels, and when multiple sources operate simultaneously, cumulative noise levels may exceed regulatory limits. Duty cycles, location, and physical structures also affect noise levels. Simultaneous noise sources increase disturbance and annoyance, leading to health problems like stress and hearing loss. Comprehensive monitoring strategies include real-time systems, spatial analysis, and mitigation measures like installing noise barriers, maintaining equipment, scheduling operations during less sensitive times, and providing workers with hearing protection equipment. Based on previous studies future aspects recommendations will be:

Based on the findings, it is recommended to consider the impact of duty cycle configurations on noise levels when designing and implementing noise mitigation strategies. Additionally, continued monitoring and assessment of noise levels under different operational cases are essential to ensure effective noise management practices.

Further investigation into the individual contributions of each noise source within concurrent operations can provide valuable insights for improving noise management strategies.

Continuous monitoring and evaluation of noise levels in various operational situations is essential to develop targeted mitigation measures and ensure compliance with noise regulations.

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