

CONSTRUCTION NOISE PREDICTION AND BARRIER OPTIMIZATION USING SPECIAL PURPOSE SIMULATION

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ABSTRACT

Construction projects produce serious environmental pollution and great annoyance to the neighbouring community due to construction noise. This paper presents an application of the special purpose simulation (SPS) language using Symphony software to predict the noise levels generated by construction equipment, tools and machinery at a given reception point for a certain barrier length, as well as the related cost of the barrier wall. To illustrate an application of the developed model, an example has been developed for different noise sources and different activities. The information obtained from the simulation model output will help to utilize the model as a planning tool for optimizing the length and location of noise barriers around a construction site. The tool can be useful for a contractor to develop a noise-control plan using mitigation measures that are acceptable to the owner.

1 INTRODUCTION

Over the years, an excessive number of construction projects taking place in congested urban areas create pervasive environmental pollution and insufferable noise to the neighbouring community. The major problem of the noise – any disagreeable or undesired sound or other disturbance (Harris, 1991) – that is routinely broadcast into the air is not only that it is unwanted, but also that it negatively affects health and well-being. Problems related to noise include hearing loss, stress, sleep loss, distraction, lost productivity, and a general reduction in the quality of life and opportunities for tranquility. Humans can be both the cause and the victim of noise.

“In Canada, The Environment Protection Act defines vibration and sound that can cause health ‘adverse effects’ as a contaminant. Adverse effects are defined as harm or material discomfort to any person, or an adverse effect on the health of any person, or loss of enjoyment of normal use of property” (Remmer, 2005, pp. 7). Although noise control and mitigation are a major concern within the transportation industry, there has been little interest in the

environmental impact of construction noise, due to the impermanent nature of construction projects and the fact that they are frequently conducted away from densely populated urban areas (Gilchrist et al., 2003). Construction noise covers inherently loud operations, such as building construction, pile driving, demolition, etc., which often take place in areas that are quiet beforehand and are expected to be quiet again, once the work is completed. Despite its temporary nature, construction of a high-rise structure may result in exposure of nearby residents to objectionable noise levels for a couple of years. In some cases, renewal construction, renovations and repairs can follow one upon another, making the noise a regular nuisance. The noise generated during construction and its influence vary, depending on the nature of the activities, the type and the status of equipment being used, the nature of the surrounding environment, and consideration of environmental and health regulations.

Experienced project teams may have followed the most advanced project planning techniques; however, most construction projects have been plagued with a huge cost for barriers to mitigate noise. The significance of noise control during construction in urban areas and the optimization of barrier length are extremely important in terms of noise nuisance and the cost of the project.

The paper discusses a stochastic simulation model developed using special purpose simulation (SPS) (Hajjar and Abourizk, 2002). The model is capable of predicting noise levels generated by a construction process and may help in determining the location, length and cost of the noise barrier.

2 BACKGROUND – NOISE

2.1 Noise Generators

Construction projects are commonly associated with excessive noise produced through construction activities and processes. Rock excavation, demolition works, pile-

driving and blasting operations are some of the major noise generators.

Equipment can also be responsible for noise, which can be generated by the engine, transmission, and processes of pneumatic, milling, grinding, earthmoving, etc. A list of construction equipment and their associated noise levels are given in Table 1.

2.2 Exposure Levels

Noise levels are measured in decibels (dBA). Decibels are measured on a scale much like the Richter magnitude scale for earthquakes. A small rise in the decibel level increases the noise significantly. For example, 73 decibels is twice as loud as 70 decibels. Most construction noise is generated from equipment. The decibel levels for some of the construction equipment are listed in Table 1. The following noise levels can go unprotected for the indicated lengths of time (eICOSH):

- Up to 8 hours - 90 decibels
- Up to 4 hours - 95 decibels
- Up to 1 hour - 105 decibels

Table 1: Noise levels generated by selected construction equipment (noise level measured at 15 m; used equipment >5 years old). (Wilson, 1989)

Equipment	Noise level (dBA)
Earth moving	
Excavator	85-87
Bach hoe	74-92
Dozer	70-95
Grader	72-92
Tractor	76-96
Scraper	76-98
Paver	85-90
Truck	83-95
Material handling	
Concrete mixer	74-87
Concrete pump	80-85
Movable crane	70-84
Stationary	
Pump	68-78
Generator	70-84
Compressor	64-87
Impact	
Pneumatic wrench	82-88
Jack hammer/road drills	80-98
Pile driver	94-106
Other	
Vibrator	68-82
Saw	72-82

2.3 Mitigation Strategies

Noise may reach the listener through the source, from the path where the noise barriers are located, and at the reception point. A schematic diagram of transmission of sound from a source to a reception point, who can be a person, group or a community, is shown in Figure 1.



Figure 1: Schematic diagram of transmission of sound from source to reception point

The sources may vary in numbers, and output may vary in time. The path, by which noise reaches a listener from a source, is highly uncertain. Noise can be controlled at the source, on the transmission path and at the reception point. Source control reduces noise emissions in all directions. When the source control does not provide significant reduction in noise, reduction of noise energy transmitted to listeners can be achieved along the transmission path, through building layout, enclosures, absorptions, barriers, etc. Use of noise protective measures controls the noise at the reception point.

The paper discusses controlling noise on the transmission path through barriers because, if cost-effective, they are an efficient means for substantial reduction in noise levels. A physical barrier can destroy some of the sound energy by absorbing the sound and/or redirecting the sound. The three strategies for path mitigation are distance, absorption and reflection. When a sound wave encounters a barrier, three interactions take place: (i) transmission through the barrier, (ii) absorption by the barrier, and (iii) reflection back towards the source.

3 PROCESS OF MODELING NOISE

A stochastic model for predicting resultant noise level at the reception point and optimizing the length of the noise barrier has been developed. The model takes into account a parent element and four child-level activity elements. The parent element provides stochastic and deterministic values of barrier height, type of barrier, dollar value per square meter of wall, length correction and the allowable noise limit. Each activity element consists of equipment noise emission level and source, reception point height and location, equipment frequencies, number of equipment in use, etc. The model basically applies the following seven equations.

3.1 Calculation of resultant noise level at the reception point (Gilchrist et al., 2003):

$$L = f_s \sum (S_o - A - B) \quad (1)$$

3.2 Calculation of parameters used in (1).

3.2.1 Calculation of air attenuation value (A) using equation of dissipation (Harris, 1991):

$$A = A_{div} + A_{air} + A_{ground} + A_{miscellaneous} \quad (2)$$

3.2.2 Calculation of attenuation due to geometrical divergence (Wilson, 1989):

$$A_{div} = L_1 + 20 * \log (r_1/r_2) \quad (3)$$

3.2.3 Calculation of attenuation due to ground absorption (Harris, 1991):

$$A_{ground} = 4.8 - (2h_m/r_2)*(17 + 300/r_2) \quad (4)$$

3.2.4 Calculation of attenuation due to foliage, reflection due to differential heights, and attenuation due to surrounding housing (Harris, 1991):

$$A_{miscellaneous} = A_{reflection} + A_{foliage} + A_{housing} \quad (5)$$

3.2.5 Calculation attenuation of reflection due to differential heights (authors' representation based on graphical illustration of Harris, 1991):

$$A_{reflection} = - 0.0053*x^4 + 0.12*x^3 - 1.1596*x^2 + 4.465*x - 6.4484 \quad (6)$$

3.2.6 Anticipated reduction of noise due to the proposed sound barrier (Thumann et al., 1976):

$$B \approx IL = f_s \sum \{10 \log [3 + (20 * f *(j-d)/342)] - A_{ground}\} \quad (7)$$

Definitions for equations are explained further:

In (1),

- f_s - Synchronization function of construction equipment noise levels
- i - Number of pieces of construction equipment operating simultaneously

- S_o - noise emission from a given piece of equipment (dBA)
- A - Attenuation of noise due to the distance traveled by the sound energy in open air (dBA)
- B - Anticipated reduction of noise due to the proposed sound barrier, if any (dBA)
- L - Anticipated resultant noise level (dBA) which should be $\leq L_{max}$, the maximum allowable noise limit as defined by the local noise ordinances or the construction documents. For the equipment noise emission level (S_o), range value from table 1 is considered.

In (2),

- A_{div} - attenuation due to geometrical divergence,
- A_{air} - attenuation due to air absorption,
- A_{ground} - attenuation due to ground absorption,
- $A_{reflection}$ - reflection due to differential heights.

In (3),

- geometrical divergence (A_{div}) is the spherical spreading of acoustic energy in a free field (unobstructed) from a point source. (Wilson, 1989)
- L_1 - noise level at the source
- r_1 - calibration distance for $L_1 = 15.2$ m
- r_2 - distance between source and receiver where $r_2 \geq r_1$

Air absorption (A_{air}) is likely to be quite small, except for very high frequencies, and can be neglected at short distances (e.g. distances less than several hundred metres). Thus, for the case of construction projects in urban environments A_{air} can be considered negligible.

In (4)

- h_m - mean height of the propagation path (meters)
- r_2 - distance between the source and the receiving node (metres).

Ground absorption (A_{ground}) largely depends on the type of ground surface over which the noise is traveling. When calculating the attenuation due to the ground surface, it is important to consider the hardness of the ground surface and the distance traveled by the noise and is obtained from an equation (Harris, 1991).

Three assumptions were made in reference to ground absorption:

- (i) the propagation occurs over ground that is nearly all acoustically soft;
- (ii) the noise spectrum is particularly broad and smooth, as frequently is the case for a major noise source that consists of many different contributing sources (e.g. construction project); and,
- (iii) only the A -weighted sound level at the receptor is of interest. (Harris, 1991)

Attenuation of reflection ($A_{\text{reflection}}$) is the noise increment or reduction due to the relationship between the source height (h_s) and the height of the receiving node (h_r) and can be calculated using the values given in Figures 2, 3 and 4:

- r_d - direct distance from the source to the receiving node (meters)
- r_r - length of the reflected sound path (i.e., in case a noise barrier exists).

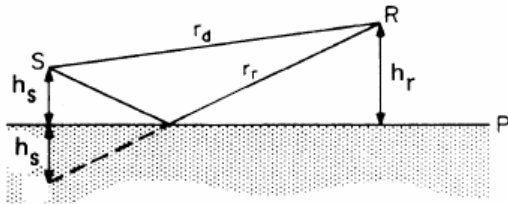


Figure 2: The terms h_s and h_r for determining $A_{\text{reflection}}$ (Harris, 1991)

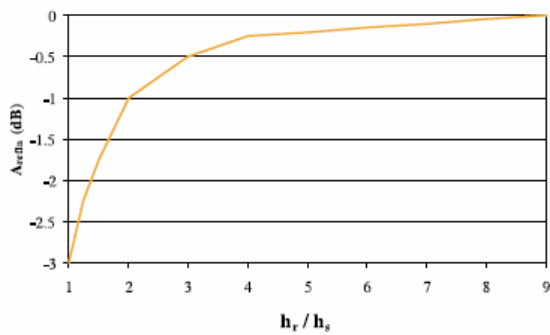


Figure 3: The terms h_s and h_r for determining $A_{\text{reflection}}$ (Harris, 1991)

In developing the model, the graph in Figure 3 was created in Microsoft Excel to find the representative equation.

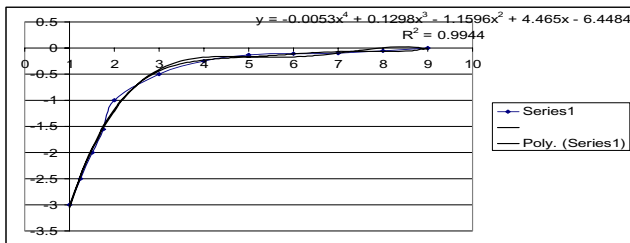


Figure 4: Developed graph using Microsoft Excel for Figures 2 and 3

In (6), x is the ratio of receiver height (h_r) to source height (h_s).

A noise barrier stops part of the energy that reaches it as noise, and the other portions pass over and around the barrier. Noise reduction by passing through the barrier is called transmission loss (TL), whereas noise reduction over and around is considered as insertion loss (IL). Noise reduction due to the barrier can be used approximately, neglecting the contribution of noise through the barrier because of its order of magnitude, as follows (Thumann et al., 1976):

In (7),

- B - Anticipated reduction of noise due to the proposed sound barrier, if any (dBA)
- f_s - The synchronization function
- f - Equipment noise frequency (Hz),
- j - Length of the transmission path over or around the barrier (paths a , b , or c in Figure 5),
- d - distance between the receiving node and the source.

Equation (6) is applied to transmission paths a , b , and c to obtain B and the three transmission paths are then synchronized at the receptor using the branch method. (Gilchrist et al., 2002)

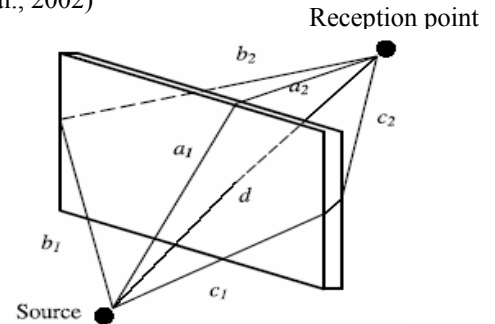


Figure 5: Sound paths used for the insertion loss calculations

The length of the transmission path above the barrier is equal to $a_1 + a_2$. The length of the transmission path around the barrier's left side is $b_1 + b_2$; and, the length of transmission path around barrier's right side is $c_1 + c_2$. The direct distance between the source and the receiver is d .

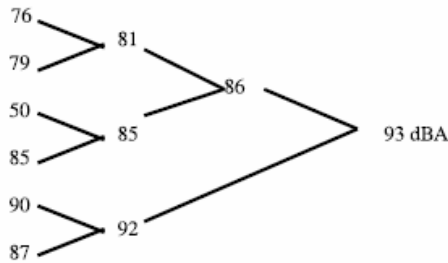


Figure 6: Example of calculating resultant noise (Thumann et al., 1976)

3.3 Synchronizing Noise Levels using the Branch Method

The synchronization function (f_s) is found by pairwise comparison of two noise levels at a time by adding a predetermined value (Table 2) to the highest noise level between the two sources (Thumann et al., 1976).

Table 2: Values to be added to the height noise level of a pair (Gilchrist et al., 2002)

Difference between sound source (dBA)	Correction factor to be added to higher decibel sound source (dBA)
0-1	3
2-3	2
3-7	1
7-9	0.5
10 and up	0

Each construction machine is checked for its motionless, in operation and active but static status. The model uses noise levels as shown in Table 3.

Table 3: Status of equipment

Status of equipment	Noise level used (dBA)
In operation	Generated by the model
Active but static	Operating level - 10
Motionless	0

It is assumed that attenuation due to air absorption (A_{air}) is neglected at distances less than several hundred metres, except for very high frequencies. Urban areas provide insignificant values of air attenuation. Noise attenuation due to foliage ($A_{foliage}$) is also insignificant because trees and bushes provide poor barriers for noise transmission. Attenuation due to neighboring housing ($A_{housing}$) is also not considered, due to its situational dependency.

$$A_{housing} = 0.1 * B * Sb \tag{8}$$

where,

B is the housing density which is defined as the $\frac{\text{Total ground floor area of the houses}}{\text{Total area of the ground}}$

Sb is the length of sound path through the housing area.

Wind and temperature effects are also considered insignificant, because propagation close to the ground for horizontal distances less than about 100m does not depend on atmospheric conditions.

4 STRUCTURE OF THE SIMULATION TEMPLATE

Simulation is a powerful technique for supporting the decision-making process (AbouRizk et al., 2000). The noise control simulation template is a special purpose simulation tool designed to predict noise levels, optimize barrier length and cost. The template has five modeling elements that depend on the number of activities to be processed during construction. The modeling elements are the starting element, site cleaning, excavation, concreting and roofing, as shown diagrammatically in Figure 7.

The parent element, developed using Symphony 1.05 (Symphony, 2000) coding language, allows the user to input common data that are applicable to all elements at the child level. The user can change the values of the elements in Figure 7, according to the actual situation. This feature generalizes the use of the template in construction work in any area. Input, output and statistics windows are shown in Figures 8, 9 and 10.

The child level comprises activities that are being processed during construction, as shown in Figure 13.

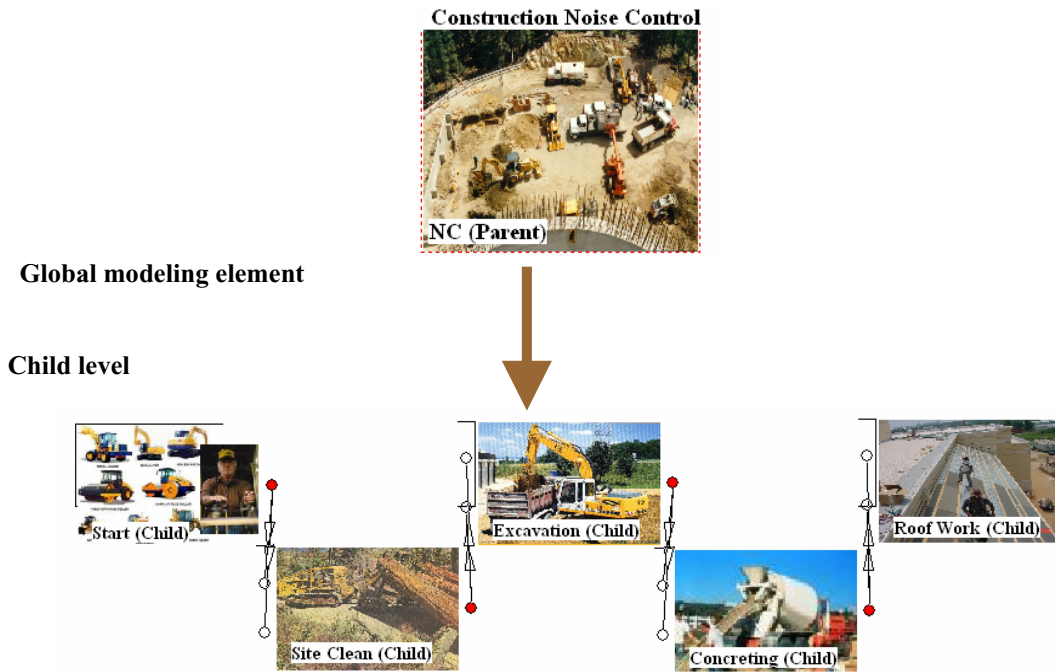


Figure 7: Sample layout of elements

Parameters	Outputs	Statistics
Parameter		Value
Barrier height		Uniform (10.00,22.00)
Type of Barrier		Concrete
\$ per square meter of wall		Uniform (90.00,150.00)
Length_correction		Uniform (1.10,1.30)
allowable_noise_level		70.00

Figure 8: Input screen (parent)

Parameters	Outputs	Statistics
Output		Value
Resultant_noise_levelSC		38.5440916425139
Resultant_noise_levelEX		54.3514364878459
Resultant_noise_levelCO		42.7060612958496
Resultant_noise_levelRF		41.4285562719441
Overall_noise_level		54.3514364878459
Barrier_Length_SC		39.958665785601
Barrier_Length_EX		43.1834139531063
Barrier_Length_CO		26.6854692119415
Barrier_Length_RF		37.2458416842257
Effective Barrier Length		53.5562611931001
Cost_of_wall_SC		58473.3798585448
Cost_of_wall_EX		112941.855218558
Cost_of_wall_CO		48431.9574683956
Cost_of_wall_RF		88015.5746912824
Cost_of_wall		112941.855218558

Figure 9: Outputs (each activity's noise level, barrier length and the cost of the barrier (parent))

Parameters		Outputs			Statistics		
Statistic	Runs	Mean	First StdDev	Global StdDev	Minimum	Maximum	Graphs
Overall_noise_level	1000	58.20	0.78	2.52	45.47	70.94	View
Cost_of_wall	1000	100619.87	11945.79	12436.05	52695.12	148483.95	View
Effective_Barrier_Length	1000	54.13	2.50	1.87	45.27	62.89	View

Figure 10: Statistic - overall noise level, cost of wall and the effective barrier length (parent)

Parameters		Outputs	Statistics
Parameter		Value	
Buldozer noise emission		Uniform	(70.00,95.00)
source heightBL/ hs(m)		Constant	(5.00)
source heightDT/ hs(m)		Constant	(5.00)
receiver height/ hr(m)		Constant	(5.00)
distance from source To barrierBL/ r3(m)		Constant	(20.00)
distance from source To barrierDT/ r3(m)		Constant	(13.00)
distance from receiver To barrier/ r4(m)		Constant	(18.00)
frequency in Hz for BL		Uniform	(125.00,1000.00)
frequency in Hz for DT		Uniform	(125.00,1000.00)
Status of buldozer		operating	
Status of dump truck		operating	
dump truck noise emission		Uniform	(83.00,95.00)
Tran_distance_above(S side)		Constant	(23.00)
Tran_distance_above(R side)		Constant	(23.00)
Tran_distance_left(S side)		Uniform	(22.00,29.00)
Tran_distance_left(R side)		Constant	(20.00)
Tran_distance_right(S side)		Uniform	(22.00,32.00)
Tran_distance_right(R side)		Constant	(20.00)
Tran_distance_above(S side)		Constant	(20.00)
Tran_distance_above(R side)		Constant	(14.00)
Tran_distance_left(S side)		Uniform	(24.00,29.00)
Tran_distance_left(R side)		Constant	(18.00)
Tran_distance_right(S side)		Uniform	(23.00,27.00)
Tran_distance_right(R side)		Constant	(18.00)
Number of bulldozers		2.00	
Number of barriers		1.00	
Number of receivers		1.00	
Number of dump trucks		3.00	

Figure 11: Input screen (child) for the activity EXCAVATION

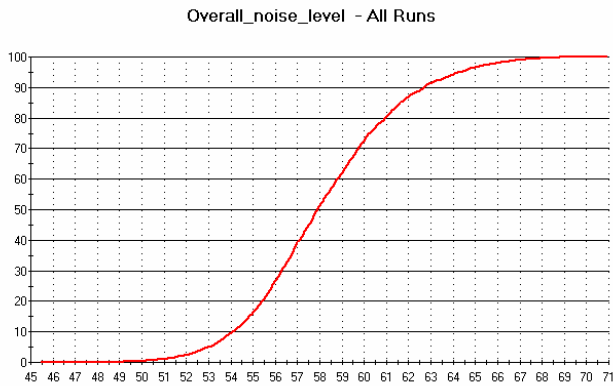


Figure 12: Variation of overall noise level throughout the project

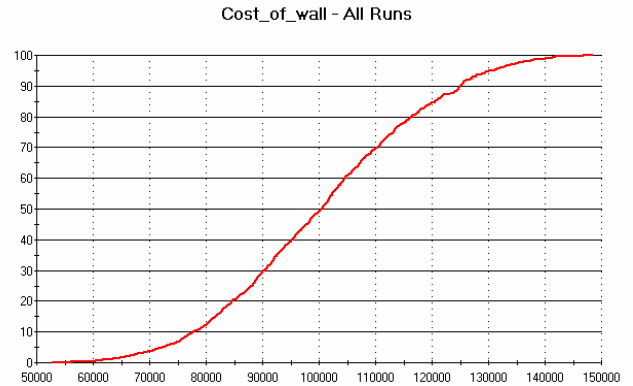


Figure 13: Variation of overall cost of the barrier throughout the project

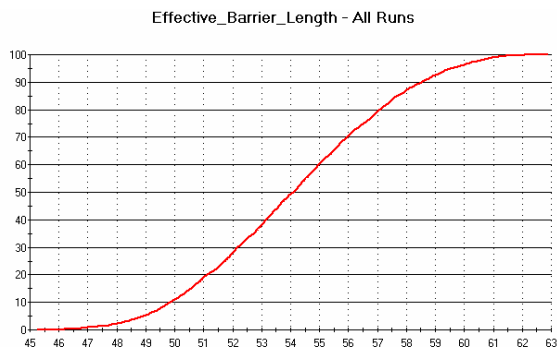


Figure 14: Variation of barrier length throughout the project

Figure 12 expresses the probability of getting a certain noise levels at the reception point. Receiving maximum allowable limit (70 decibels) is 100%. The maximum overall cost and the length of the barrier illustrated in Figure 13 and 14 help making firm decisions at the planning stage.

5 APPLICATIONS OF SIMULATION TEMPLATE AND CHALLENGES

Once noise is generated from two noise sources (source 1 and source 2) for an activity, the noise level at the reception point is calculated separately, the results of which are influenced by the barrier employed. Next, the resultant noise is found by synchronization (Thumann et al., 1976) for the specific activity. The branch method allows the resultant noise level from each activity of the construction process to be obtained. The overall noise level is then calculated similarly, by synchronizing all the activity noise levels through the branch method.

If the level is greater than the maximum permitted noise level outlined by municipal bylaws where the construction is taking place, the model provides a warning, by prompting a message “overall noise level exceeds allowable limit”. At this stage, barrier length dimensions and location can be changed, thereby making changes to the transmission paths of source 1 ($a_1, b_1, c_1, a_2, b_2, c_2$) and source 2 ($a_{11}, b_{11}, c_{11}, a_{22}, b_{22}$ and c_{22} , as shown in Figure 6); and, the model is reapplied. When calculating A_{div} , if the source to reception point distance is not greater than calibration distance (15.2 meters), a message will be prompted. The same procedure can be applied to different positions of the reception point for more reliable outputs.

6 LIMITATIONS OF THE MODEL

The model does not contain data for different barrier material co-efficients (concrete only) and for the geometry of the barrier. It is also important to differentiate among residential, industrial and commercial zones and to specify different daytime and nighttime maximum noise levels.

7 CONCLUSION

The simulation template can be applicable in places where there is a lack of resources and time to conduct research to investigate the noise impact. The model provides a platform that can be applied to various construction projects, particularly if hospitals, courts, etc. are in the vicinity of the construction sites. The model can assist in optimizing the required barriers, which will be beneficial for construction planners and managers to ensure that projects are completed without complains from neighbours. The model requires less resources and less expertise to operate and test. The graphical representations of outputs are also easier to understand and analyze.

The simulation model uses coding and the common template in Symphony 1.05 for elements. Use of the common template with the aid of user elements for modeling is relatively challenging; however, it is a flexible approach. The main challenge of any computer tool is the ability to identify wrong input data that will generate incorrect results. Precise data input, which yields reliable results, is extremely important when using a computer tool.

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