Noise Prediction for Outdoor Cooling Systems; Case Study

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Abstract: Outdoor noise analyses are commonly required to estimate the sound levels at the property line of adjacent buildings. Outdoor cooling units, such as cooling towers, air-cooled chillers and rooftop units, all create noises at different levels that can disturb neighbors or occupants inside the building itself. Creating a comfortable acoustic environment in most of Heating, Ventilating and Air-Conditioning, HVAC, applications falls on the mechanical engineering disciplines because most background noise sources are generated by the mechanical apparatuses and cooling devices. This paper investigates the prediction of sound pressure levels emitted from outdoor HVAC systems. The sound level of outdoor units in various applications is dependent upon several significant factors. These factors include equipment location, directivity of the source, barrier shielding, sound path, and attenuation due to distance, atmospheric sound absorption and ground attenuation. A developed simplified model called "Outdoor Modeling Acoustic Code, OMAC" has been utilized taking into consideration the influences of previously mentioned parameters. This OMAC code has been used to analyze and predict the noise level emitted from roof-top air-cooled chillers located on office building as a case study. Predicted noise regimes were compared with the collected field measurements for the validation and verification purposes. Detailed analyses and comparisons between predicted and measured noise spectrums were carried out based on the local and international standards. These comparisons show a good agreement among predicted noise criterions, measured data and dedicated standard thresholds. It was concluded that it is mandatory to utilize such prediction "modeling" tool during the early stages of HVAC design process to allow the authority having jurisdictions to predict the impact outdoor noises within the new development urban.

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1. Introduction

Noise is usually regarded as one of the factors threatening our living environments. Occupants are surrounded by numerous sources of noise that create pervasive environmental pollution and insufferable noise to the neighboring community. The major problem of the noise is not only that it is unwanted, but also that it negatively affects health and well-being[1]. Problems related to noise include hearing loss, stress, sleep loss, distraction, lost productivity, masking speeches and a general reduction in the quality of life and opportunities for tranquility. Humans can be both the cause and the victim of noise.

HVAC equipments are the dominating source of noise in buildings and it can even disturb people in the nearby surrounding, therefore it is importance to consider acoustic criterion and actions at the early stage of the design process. Accurate predictions for the sound pressure level emitted from HVAC equipments are needed to evaluate the noise reductions values required to meet local regulations; then the determination of each unit noise limits shall be obtained to select suitable noise controls method; and finally to confirm that the plant will comply with applicable noise threshold as stated by Frank H. Brittain, Marlund E[2].

Two quantities are needed to describe the strength of noise source, its sound power level and its directivity. The sound power level is a measure of total sound power radiated by the source in all directions. The directivity of a source is measure of the variation in its sound radiation with direction. Directivity is usually stated as a function of angular position around the acoustical center of the source and also as s function of frequency. Some sources radiate sound energy nearly uniformly in all directions. These are called nondirectional sources. Generally, such sources are small in size compared to the wave length of the sound radiated. Most practical sources are somewhat directional that is they radiate more sound in some directions than in others[3,4] .

Propagation of outdoors sound shall consider meteorological effects, the attenuation effects of ground coverings, atmospheric sound absorption, and the sound attenuation associated with barriers, and the effects of reflecting surfaces. Precious acoustical analyses associated with all of these can be rather complicated. However, the accuracy is not often justified because the acoustical effects of the above factors are extremely fluctuated. Acoustical analysis presented herein will be simplified to give an estimate of outdoor sound pressure regimes and levels associated with HVAC equipment that are affected by spherical spreading , reflecting surfaces and barriers[5] .

The successful outdoor noise consultant needs five things:

- Measurement equipment (octave band sound level meter, perhaps a long term monitor)
- Noise control techniques (such as barriers, damping materials, enclosures, mufflers and silencers)
- A goal – what is a "good" level (from regulations, resident opinions, etc.)
- A good understanding of the physical mechanisms and a basic prediction model

2. Sound Propagation Outdoors

Normally if the equipment sound power level spectrum and ambient sound pressure level spectrum are known, the contribution of the equipment to the sound level at any location can be estimated by analyzing the sound transmission paths involved. When there are no intervening barriers, the principal factors outdoors are reflections from buildings near the equipment and the distance to the specific location. The following equation may be used to estimate the sound pressure level of the equipment at a distance from it and at any frequency when given the sound power level[6]

$$L_P = L_W + 10\log_{10} Q - 20\log d - 11 \qquad (1)$$

where

Lp = sound pressure level at distance d (m) from the acoustic center of the sound source, dB

Lw = sound power level of sound source, dB

Q = directivity factor associated with the way sound radiates from sound source (refer to figure 1)

This equation does not apply where d is less than twice the maximum dimension of the sound source. Lp, may be low by up to 5 dB where d is between two and five times the maximum sound source dimension[6].

If the source is directional, an additional term, the Directivity Index DI, is needed to account for the uneven distribution of the sound intensity as a function of direction. The Directivity Index is the difference between the actual sound pressure, and the sound pressure from a non-directional point source with the same total acoustic power. It can be determined experimentally, or calculated for a limited number of analytical cases, such as a piston in a baffle (a decent approximation of a loudspeaker), a piston in the end of a long tube (engine exhaust)[4]

$$D_I = 10\log_{10} Q \qquad (2)$$

For an omni-directional source radiating into free space, DI = 0 dB. If that same source is situated directly on a perfectly reflecting surface (hemispherical radiation), DI = 3 dB.

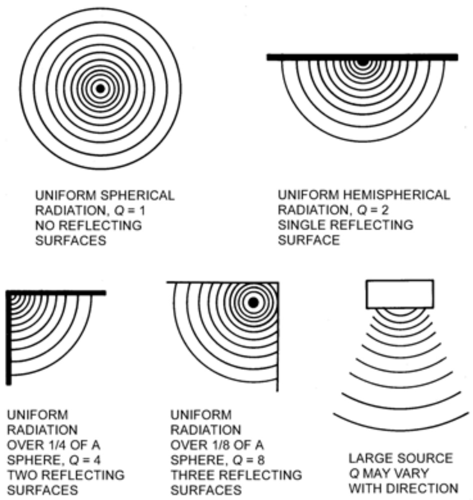

Figure 1 Directivity factors for various radiation patterns

3. Excess Attenuation Model

Including absorption of sound in air, non-uniformity of the propagation medium due to meteorological conditions (refraction and turbulence), and interaction with an absorbing ground and solid obstacles (such as barriers). Equation 1 will be extend to account for atmospheric absorption and all other effects by introducing the concept of excess attenuation, A_E is defined as: - the total attenuation in addition to that due to spherical divergence and atmospheric absorption[5,7], [ISO 9613 PART 2]. So equation (1) will be as follows:

$$L_P = L_W + 10\log_{10} Q - 20\log d - 11 - A_{abs} - A_E \ \text{(dB)} \qquad (3)$$

Where A_{abs} = atmospheric absorption,

A_E = excess attenuation (dB)

The total excess attenuation A_E (dB) is a combination of all effects:

$$A_E = A_{Weather} + A_{ground} + A_{turbulence} + A_{barrier} + A_{vegetation} + \text{any ether effects}\ldots \qquad (4)$$

where

Meteorological conditions attenuation – $A_{weather}$

Attenuation due to ground interaction – A_{ground}

Atmospheric turbulence attenuation – $A_{turbulence}$

Attenuation due to vegetation – $A_{vegetation}$

Attenuation due to barrier

Attenuation due to meteorological conditions $A_{weather}$ such as wind, that can all bend sound waves and influence sound levels at large distances. Their effects are short term and generally not included in acoustic evaluations[6,8] .

Sound energy is dissipated in air by two major mechanisms [9, 10]

- Viscous losses due to friction between air molecules which results in heat generation (called "classical absorption")
- Relaxation processes – sound energy is momentarily absorbed in the air molecules and causes the molecules to vibrate and rotate. These molecules can then re-radiate sound at a later instant (like small echo chambers) which can partially interfere with the incoming sound.

These mechanisms have been extensively studied, empirically quantified, and codified into an international standard for calculation: ANSI Standard S1-26:1995, or ISO 9613-1:1996. For a standard pressure of one atmosphere, the absorption coefficient α (in dB/100m) can be calculated as a function of frequency *f* (Hz), temperature *T* (degrees Kelvin) and molar concentration of water vapor *h* (%) by:

$$\alpha = 869 \bullet f^2 \left\{ \begin{array}{l} 1.84 \bullet 10^{11} \left[\frac{T}{T_0}\right]^{1/2} + \left[\frac{T}{T_0}\right]^{-5/2} \\ \left[0.01275 \frac{e^{-2239.1}}{F_{r,0} + f^2 / F_{r,0}} + \right. \\ \left. 0.1068 \frac{e^{-3352/T}}{F_{r,N} + f^2 / F_{r,N}} \right] \end{array} \right\} \quad (5)$$

where

$$F_{r,0} = 24 + 4.04 \bullet 10^4 h \frac{0.02 + h}{0.391 + h}$$ Oxygen relaxation frequency (Hz) (6)

$$F_{r,N} = \left[\frac{T}{T_0}\right]^{-1/2} \left[9 + 280 h e^{\left\{-417\left[\frac{T}{T_0}\right]^{-1/2} - 1\right\}} \right]$$ Nitrogen relaxation frequency (Hz) (7)

$$T_0 = 293.15^{O} K \left(20^{O} C\right) \quad (8)$$

To calculate the actual attenuation due to atmospheric absorption A_{abs} (dB) for a given propagation range for use in equation 3:

$$A_{abs} = \alpha r / 100 \quad \text{(dB)} \quad (9)$$

where :

α = absorption coefficients (dB/100m)

r = range (meters)

4. Estimation of Sound Pressure Levels

When investigating the propagation of sound outdoors, it is necessary to take into account the attenuation effects of ground coverings, atmospheric sound absorption, and the sound attenuation associated with barriers, and the effects of reflecting surfaces. Accurate acoustical analyses associated with all of these can be rather complicated. However, this accuracy often is not justified because the acoustical effects of the above factors are extremely variable.

The acoustical analysis presented in this section will be simplified to give an estimate of outdoor sound pressure levels associated with HVAC equipment that are affected by the directivity of a source , reflecting surfaces, barriers and air absorption. Air absorption is likely to be quite small, except for very high frequencies, Thus, for the case of construction projects in urban environments air absorption can be considered[11]. The simplified outdoor sound pressure levels can be estimate as follows:

$$L_P = L_W + 10\log_{10} Q - 20\log d - 11 - A_{ground} - A_{abs} \quad \text{(dB)} \quad (10)$$

Calculation of attenuation due to ground absorption[1]

$$A_{ground} = 4.8 - \left(\frac{2h_m}{r_2}\right)\left(17 + \frac{300}{r_2}\right) \quad (11)$$

where

*A*ground - attenuation due to ground absorption

*h*m - mean height of the propagation path (meters)

r_2 - distance between the source and the receiving node (meters)

If the sound source is near a vertical reflecting surface, the sound pressure level at a distance r from the sound source is given by:

$$L_P = L_W + 10\log_{10} Q - 20\log d - 11 - A_{ground} - A_{abs} + \Delta L \quad \text{(dB)} \quad (12)$$

where

ΔL is the correction term associated with the vertical reflecting surface[1].

Figure 2 shows a sound source near a hard reflecting surface. The effect of the reflecting surface can be modeled by placing an image sound source on the side of the reflecting surface opposite the sound source. As the figure indicates, these are two paths between the sound source and the receiver. One is the path of the directly radiated sound wave between the source and receiver. The distance of this path is r_s.

The other is the path of the reflected sound wave between the sound source and the receiver. The distance of this path is r_i also is the distance between the image sound source and the receiver.

If the reflecting surface is a vertical surface, the effects of this surface and the corresponding values of ΔL are a function of the distance between the sound source and the reflecting surface and the distance between the sound source and the receiver. This relation is expressed by[12]

$$\Delta L = 3.00 - 9.29\log_{10}\left[\frac{r_i}{r_s}\right] + 10.13\left[\log_{10}\left[\frac{r_i}{r_s}\right]\right]^2 - 3.84\left[\log_{10}\left[\frac{r_i}{r_s}\right]\right]^3 \quad (13)$$

$$\Delta L = 0 \qquad \text{for} \qquad \frac{r_i}{r_s} > 10$$

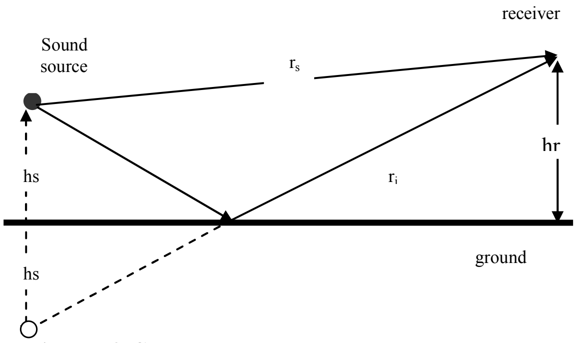

Figure 2 Sound paths between the sound source and the receiver

5. Influence of Obstructions and Barriers

When the line of sight between a source and receiver is obstructed by a rigid, non-porous wall or building, appreciable noise reductions can occur. Sound waves must diffract around the obstacle in order to reach the receiver. This phenomena is used to great advantage in the attenuation of highway noise by barriers in congested urban areas. An observer in the vicinity of a rigid, infinitely long barrier (Figure 2), for sound from a point source, will experience an excess attenuation[13] of:

$$\Delta A = 20\log\frac{\sqrt{2\pi N}}{\tan ch\sqrt{2\pi N}} + 5(dB) \text{ for N} \geq \text{-0.2} \quad (14)$$

$$\Delta A = (0) \text{ otherwise}$$

$$\nabla A_{Total} = -10\log\left[\Sigma 10^{\nabla A_i/10}\right] \quad (15)$$

$$N = \pm\frac{2}{\lambda}\partial \quad (16)$$

where

λ is the wave length (m) that corresponds to the center of the frequency band being analyzed. ∂ is called the path length difference (m) and is given by

$$\partial = A + B - D \quad (17)$$

where

A, B, C as shown in figure 3

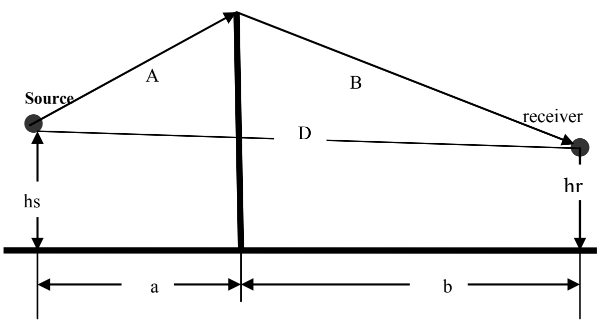

Figure 3 geometry of sound propagation path over or around a barrier

Equation (16) is based on optical diffraction theory and was developed by Z. Maekawa[14]. The dimensionless quantity N is called the Fresnel number and is a measure of how far below the line of sight (relative to a wavelength) the receiver lies. A negative sign for N indicates that the receiver can see the source, while a positive sign denotes that the receiver is in the shadow zone[15]. More complex models are needed to account for line sources, finite length and absorptive barriers. The barrier should be as tall as possible. The effectiveness of a barrier depends on how far below the line of sight the receiver lies.

When the excess attenuation for a barrier is taken into account equation (12) becomes

$$L_P = L_W + 10\log_{10} Q - 20\log d - 11 - A_{ground} - A_{abs} - \Delta A \text{ (dB)} \quad (18)$$

Many practical situations exist where barriers are of finite length. If the sound source is a point source, the sound level at the receiver location is obtained by first calculating the individual sound pressure levels for sound traveling over the barrier and around each end of the barrier. After the individual sound pressure levels at the receiver location have been calculated, the overall sound pressure level is obtained by adding the three individual sound pressure levels. For most situations where a barrier is used to attenuate noise from HVAC equipment, the barrier will enclose the equipment on three sides. When this is the case the barrier can be considered an infinite barrier with respect to barrier design, the following usually applies. Excess barrier attenuations of 10 dBA or less are easily attainable. Excess barrier attenuations up to 15 dBA are difficult to obtain. Excess barrier attenuations over 20 dBA are nearly impossible to obtain[11,16].

6. Experimental Work

Outdoor Modeling Acoustic Code, OMAC has been created to estimate the sound pressure level emitted from outdoor HVAC equipments. This program based on the mathematical equation (3). Figure (4) shows the flow chart of OMAC to predict the outdoor sound pressure level at the receiver. Outdoor Modeling Acoustic Code, OMAC includes the following steps:

- Define the sound power from the catalogue of the equipment (measured by standard method)
- Calculate the directivity of the equipments.
- Calculate the attenuation factors.
- Calculate the effect of vertical surface.
- Calculate the effect of barrier.
- Calculate the combined sound pressure level from multiple sources.

OMAC has been used to predict the sound pressure level emitted from 2 air-cooled scroll chillers that is installed on a roof at residential areas in which commercial building are located. The predicted sound pressure level has been compared to the field measured sound pressure levels at octave band frequencies. The installed air-cooled scroll chillers have the specification as given in table (1):

Table 1 - Specification of Outdoor Chiller

Type	Capacity	Power	No of comp.	No of fans
Air-cooled scroll	60 Ton/ref	110 KW	2/each	6/each
Sound power in dB				
63	103			
125	103			
250	102			
500	99			
1000	99			
2000	97			
4000	90			
8000	84			

Outdoor sound analysis is closest to a free field analysis. The sound pressure level will depend on equipment location, directivity and the attenuation factors. For instance, an air-cooled chiller sends a significant amount of sound vertically from the condenser fans. The air-cooled scroll chiller is on the roof of a 4-story building. The horizontal distance from the chiller to the receiver was 10 m. The receiver measurement at point is 1.5 meter above grade. The source is directional and situated directly on a reflecting surface (hemispherical radiation) so the directivity index DI equal 3.

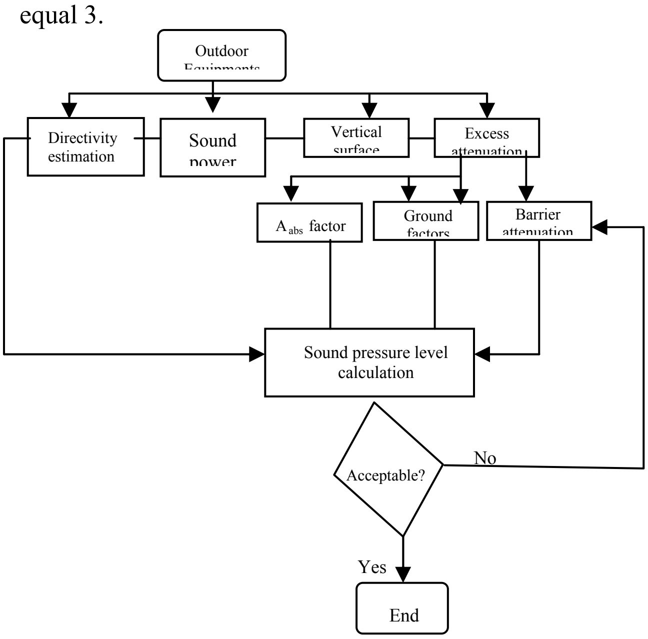

Figure 4. Flow chart of OMAC Acoustic Code

Figure 5 shows the comparison between the measured sound pressure levels with predicted sound pressure level at octave band without consider the absorption of the air.

It can be noticed that the difference between the measured and the predicted value increase at the high frequencies this may be due to fluctuation of atmospheric absorption of sound and its effect on sound propagation especially at high frequencies greater than 1000 Hz. The new ISO-DIS 9613 (parts 1 and 2) standard contains a detailed method for computing the sound propagation outdoors, taking into account the effects caused by the air absorption. So the absorption coefficient α (in dB/100m) calculated again as a function of frequency *f* (Hz), temperature *T* (degrees Kelvin) and molar concentration of water vapor *h* (%) by equation 5, 6, 7, 8 and recalculated the outdoor sound pressure.

Figure 6 shows the comparison between the measured and predicted sound pressure level adding correction for atmospheric absorption.

It can be noticed that the predicted sound pressure level is higher than the permissible sound pressure limit according to the environmental low (table 3). So sound barriers can be installed to reduce the sound levels and hide equipment from view. The barrier creates an "acoustic shadow" that reduces sound pressure levels on the opposite side of the source. The reduction in sound level, or *Insertion Loss,* is based on the path length difference. The path length difference equals the path around the barrier minus direct path from the source to the receiver in feet (or meters). If nonporous barriers placed between the sound source and the receiver can result in significant excess attenuation of sound pressure level.

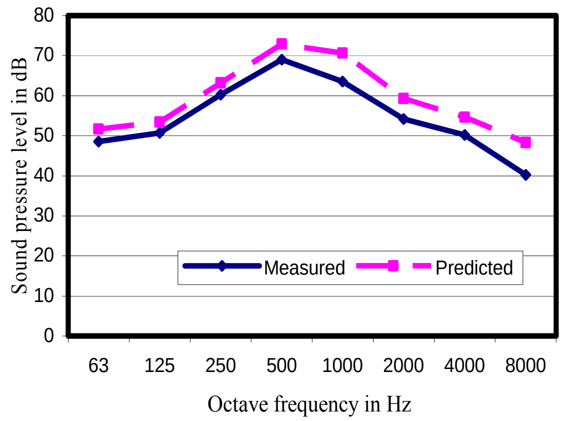

Figure 5. Measured and Predicted Outdoor Chiller Sound Pressure Level

Table 2 - Measured and Predicted Outdoor Chiller Sound Pressure Level

Octave frequency	Measured SPL (dB)	Predicted SPL (dB)
63	48.5	51.7
125	50.7	53.4
250	60.2	63.2
500	69	72.9
1000	63.5	70.6
2000	54.2	59.3
4000	50.2	54.6
8000	40.2	48.3
dBA	70.7	75.4

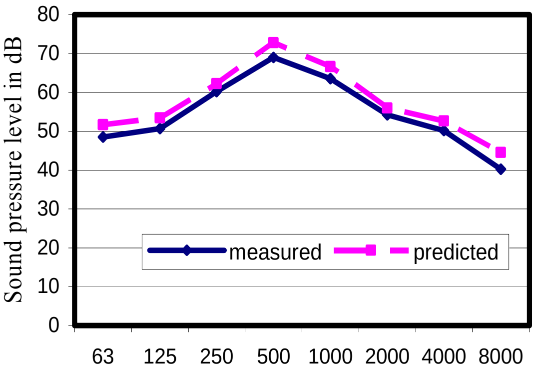

Figure 6. Measured and Predicted Outdoor Chiller Sound Pressure

Table 3 Comparing the measured SPL with Predicted SPL

Octave frequency	Measured SPL	Predicted SPL
63	48.5	51.7
125	50.7	53.4
250	60.2	62.2
500	69	72.8
1000	63.5	66.6
2000	54.2	56
4000	50.2	52.6
8000	40.2	44.5
dBA	70.7	74

OMAC has been used to predict the sound pressure level for the same building. A barrier has been added at three sides around the chiller. It was 5 m from the chiller and 2 m taller than the chiller. The new sound pressure level in dBA has been predicted at point 1.5 meter above grade. Where the excess attenuation (*Insertion Loss*); ΔA, is determined. Table (4) shows the predicted attenuation; ΔA

Table 4 predicted attenuation; ΔA sound pressure level

Octave frequency	Predicted ΔA	Predicted SPL In dB
63	12.5	39.2
125	15.2	38.2
250	19.6	42.6
500	22.3	50.5
1000	21.5	45.1
2000	20.6	35.4
4000	23.1	29.5
8000	19.6	24.9
dB		52.6

The barrier TL (Transmission Loss) must be at least 10 dB greater than the insertion loss in each band[6]. Therefore the predicted transmission loss of the barrier must be at least as shown in the figure (6).

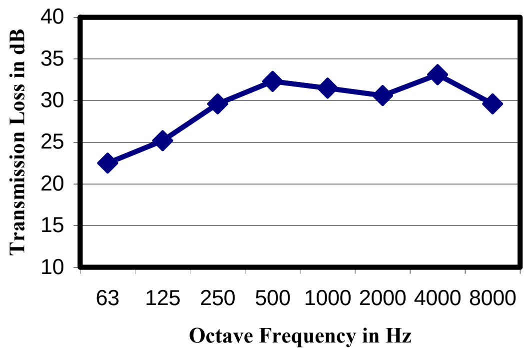

Figure 6. Transmission Loss of the Barrier

7. Conclusions

A developed simplified model called "Outdoor Modeling Acoustic Code, OMAC" has been utilized based on the measured sound power and taking into consideration the influences of equipment location, directivity of the source, barrier shielding, and attenuation due to distance, atmospheric sound absorption and ground attenuation. The OMAC code has been used to analyze and predict the noise level emitted from roof-top air-cooled chillers located on office building as a case study. The predicted sound pressure level has been compared to the field measured sound pressure levels at octave band frequencies. These comparisons show a good agreement among predicted noise criteria, measured data and dedicated standard thresholds. It was concluded that it is mandatory to utilize such prediction "modeling" tool during the early stages of HVAC design process to allow the authority having jurisdictions to predict the impact outdoor noises within the new development urban.

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8. References

1. Cyril M. Harris, Handbook of acoustical measurements and noise control. New York: McGraw-Hill, Inc, 1991.
2. Frank H. Brittain, Marlund E. Hale, Some Limitations of Ray-Tracing Software for Predicting Community Noise from Industrial Facilities, NOISE-CON 2008 July 28-30
3. L. Beranek, Noise and Vibration Control, New York: McGraw-Hill, 2005
4. L. Beranek, Acoustics, New York: McGraw-Hill, 1954
5. Lamancusa. J. S., Outdoor Sound Propagation, 2009,www.mne.psu.edu/lamancusa/me458/10_osp.pdf
6. ASHRAE Handbook, HVAC Applications, 2007- Ch. 47
7. ISO 9613-2, Acoustics- attenuation of sound during propagation outdoors- Part 2: General method of calculation
8. Application Guide *AG 31-010*, HVAC Acoustic Fundamentals, Engineered for flexibility and performance, ©2004 McQuay International (800) 432-1342 www.mcquay.com
9. ISO 9613-1, Acoustics- attenuation of sound during propagation outdoors- Part 1: Calculation of the absorption of sound by the atmosphere, 1996
10. ANSI 1995. S1-26, Method for the calculation of the absorption of sound by the atmosphere
11. Anupama Gannoruwa, Janaka Y. Ruwanpur, Construction Noise Prediction And Barrier Optimization Using Special Purpose, Simulation Proceedings of the 2007 Winter Simulation Conference
12. Douglas D. Reynolds, Jeffrey M. Bledsoe, Algorithms for HVAC acoustics, 1991, ASHRAE Special publication
13. J.E. Piercy, T. Embleton and L. Sutherland, Review of noise propagation in the atmosphere, JASA 61(6), June 1977, pp 1403-1418.
14. Z. Maekawa, Noise reduction by screens, Applied Acoustics, Vol 1, 1968, pp 157-173
15. L. Beranek; Noise and Vibration Control, McGraw-Hill, 1971
16. Pallet, D. S., W. Robert, R. D. Kilimer, 1978, Design guide for reducing transportation noise in and around building, building science 84, U.S. department of commerce, national bureau of standard
17. ASHRAE 1987 HVAC Systems and Applications Handbook, Sound and vibration control, Chapter 52
18. Simpson, Myles A., Noise Barrier Design Handbook, Report No. FHWA-RD-76-58. Arlington, VA: Bolt Beranek and Newman, Inc., February 1976.
19. Cyril M. Harris, 1979, Handbook of Noise Control, McGraw-Hill
20. Tom Paige, P. Eng, Outdoor Noise Barriers: Design and Applications Products Application Engineer, Kinetics Noise Control, Inc. Mississauga, Ontario, www.enoisecontrol.com

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