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Sound insulation of fenestration systems: a comprehensive web-based simulation program and validation

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ABSTRACT

Aluminum framed fenestration systems are becoming a leading choice for modern buildings. They provide a superior aesthetic appearance, a higher degree of weathering reliability, and quicker installation. At the same time, they offer more transparency and environmental efficiency. However, because of the complexity of the framing systems, the estimation of sound insulation of such systems for preliminary design or analysis becomes time-consuming and difficult. Currently, there is no efficient tool available for convenient and reliable estimation of the sound insulation performance of fenestration systems. To this end, the engineering team led by the authors conducted extensive studies on various fenestration systems consisting of different glazing and aluminum frames. Based on our research outcomes, a comprehensive web-based simulation program, the so-called Digital Acoustic Lab (DAL), has been developed recently. This program can provide a quick analysis and accurate prediction of sound insulation of window, door, and façade systems consist of various aluminum frames and glazing infills. A series of laboratory tests were conducted to validate the predictions by the DAL. The goal of this program is to provide designers, engineers, and architects an effective and economical tool to facilitate the design.

Keywords: Sound, Transmission Loss, Framed Window, Façade, STC, OITC, Acoustic Simulation

1. INTRODUCTION

The need for acoustical enhancements of exterior envelops while maintaining cost efficiency is an ongoing topic of research. This need has become more prevalent with the advent of highly intricate thermally-isolated and light-weight aluminum framing systems, which are the norm for most of the modern commercial and multi-unit residential constructions of today.

Even though aluminum framing has a smaller exposed area; it is made of various cavities and often contains orifices for drainage and air circulation. These features can alter the acoustical characteristics of glazing elements. Also, aluminum extrusions thicknesses are frequently optimized to archive a higher degree of economy, while mechanical interlocking systems are employed to reduce field labor costs. All these factors can contribute to the degradation of acoustical performance of the overall system.

In the past few decades, the main metric for evaluation and comparison of facade products has been the use of a single number rating (R_w in Europe and STC/OITC in the USA). These numbers are calculated based on “Sound Transmission Loss (STL)” measurements conducted at certified laboratories (1-3).

The municipalities or the building design team usually dictate the acceptable range of the sound transmission classification or the acceptable noise criteria. The numerical value of the classification is mainly a measure of comparison, and not necessarily the true indicator of the acoustic behavior. On occasion, the required ratings are augmented by a set of STL’s at the octave or one-third octave band frequencies.

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These ratings are either published by manufacturers or conducted at the request of building owners or developers for custom projects. This practice, however, has its drawbacks. Although the cost and the duration associated with the testing are in general reasonable, the overall process requires the need for the fabrication and assembly of the final product, which require weeks or sometimes months of preparation. Seldom these amounts of lead time are afforded in construction schedules. Furthermore, in the event of unsatisfactory results, the possibility of any modification or redesign is severely compromised.

This article addresses the need for a computational tool to estimate the acoustic performance of fenestration elements in buildings. We will examine the current estimation practices and will present "Digital Acoustic Lab" a cloud-based software tool, for the estimation of sound transmission loss of framed glazing systems.

2. SINGLE NUMBER RATING

The single number rating to measure the acoustic performance of architectural demising walls and interspatial spaces has been the norm for the building industry for the past half-century. The practice started in 1970, with the introduction into ASTM standards, and although the testing and measurement procedures have gone through several revisions, the fundamental concept behind the methodology has remained the same.

The original metric "Sound Transmission Class (STC)" was designed to calculate a weighted average of the sound transmission loss through interior partitions. It is based on the amount of sound attenuation required to reduce each octave-based level of a somewhat arbitrary "standard household noise" spectrum (a composite of live speech, radio and television music and speech, vacuum cleaner noise and air conditioning noise) to match the NC-25 curve. NC or "noise criteria" curves are a set of curves established by the American Society of Heating Refrigeration and Air-Conditioning Engineers (ASHRAE), to classify the various levels of background noise for the design of building facilities.

Even though STC (and its ISO approximate equivalent Rw) is not strictly appropriate to evaluate the sound transmission through exterior envelopes, it has been widely adopted as a means of performance measurements for windows. In 1990 a new metric OITC (Outside-Inside -Transmission Class) was introduced. The OITC rating system (and its ISO equivalent Rw+ Ctr) is designed to measure the transmission of urban sounds (such as car horns, sirens, construction, and low-flying airplanes) through exterior walls, windows and façade elements. Urban noise tends to be more dominated by lower frequencies, so the OITC rating system tends to emphasize this range more in its calculations. The test procedure for both these metrics is the same.

Although the OITC rating is a more reliable means of evaluation of façade elements than STC, it is still abstract and lacks enough information needed to evaluate a robust performance of the exterior barriers. Also, there are two distinct drawbacks with the use of this approach.

First, the loss of resolution by eliminating the frequency dependent nature of sound in the STC/OITC metric can create inconsistencies in the noise response predictions. For example, elements with similar acoustical behavior can have different ratings, or in reverse, products with similar ratings can have different characteristics. The graph in Figure-1 demonstrates the laboratory tested STL of three different glass compositions. The deviation of STL's at different frequencies are shown in the bar diagram. As it can be seen the overwhelming majority of the deviations are within a 3dB range which is indistinguishable by human ears, while the OITC rating differs up to five points and STC differs up to two points. One can argue that OITC predicted this anomaly. However, a more in-depth analysis might eliminate the significance of one particular frequency, in favor of either a more economical solution or a more realistic design.

The second concern with single number rating is the differences in laboratory test results. All testing facilities have some level of voluntary government sanction accreditations. The facilities are required to follow stringent procedures and quality equipment to guarantee as much uniformity as possible. However, no two facilities are identical. This observation is especially true for the size of chambers, location, and application of diffusers, as well as the positioning of the speakers and microphones. So, there is some level of flexibility as to the variations allowed on the results. In general, these tolerances have always resulted in fairly uniform ratings for the tested products, especially when it comes to STC ratings. However, the popularity of high performing glass and glazing products, as well as the greater need to consider the low-frequency range of STL response, make the laboratory attributes a more important factor. This aspect can be seen in the test results of a very high performing triple layer insulated laminated glass, tested in three different laboratories. These results are presented in Figure 2 and are summarized in Table 1. As can be seen, there can be a discrepancy of three to five points in the value of the OITC. It is important to note that the specimen with the highest rating also was the one with the smallest area, which is another factor that is lost in the single number rating of windows and facades. The discrepancies in results happen mostly in lower frequencies, where there may be more of an interaction between room acoustic modes and the test specimen. The testing labs in this experiment all met the size requirements of the ASTM-E90, but all were of different dimensions. Also, the lower frequency response is more susceptible to mounting technique and positioning of the specimen in the chamber's demising wall that is less standardized among the different testing laboratories.

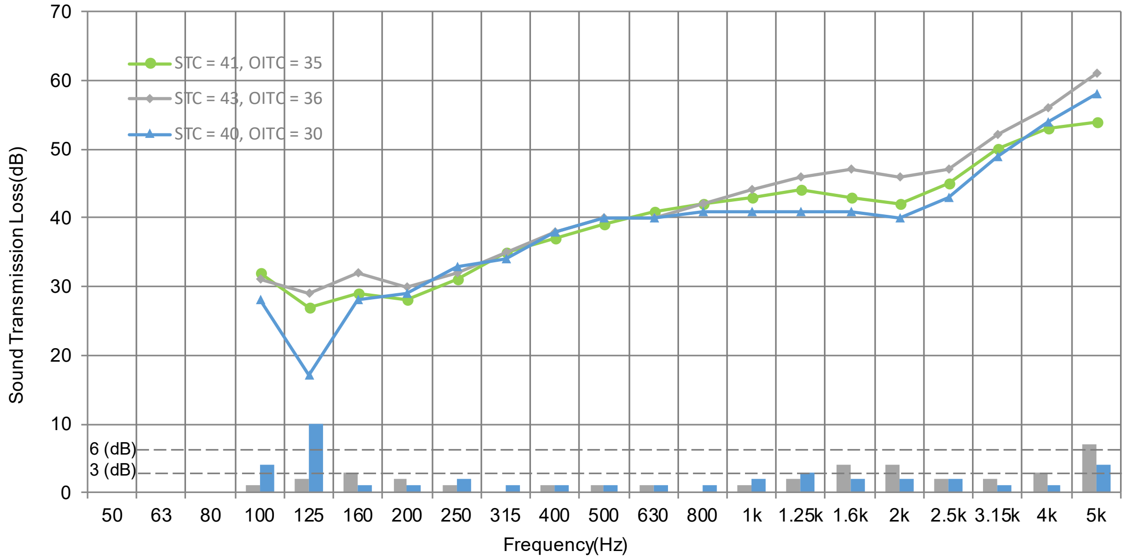

Figure 1 – Comparison of the laboratory STL of three glass compositions. Green – 6.37 mm outer glass / 12.7 mm airspace / 4.76 mm+1.52mm PVB + 4.76 mm inner glass, Gray– 6.37 mm outer glass / 12.7 mm airspace / 6.37 mm+1.52mm PVB + 6.37 mm inner glass, Blue– 6.37 mm outer glass / 12.7 mm airspace / 6.37 mm+1.52mm PVB + 3.17 mm inner glass.

All these factors highlight the need for a more detailed criteria to be used for evaluation of the acoustic performance. Especially in cases that the cost implication is significant, such as commercial or residential high-rise buildings, or cases where human health and comfort are more critical, such as hospitals, and educational facilities. These criteria also need to be used in the design process as well as the certification. To this end a more accurate and practical computational tool is needed for rapid evaluation and assessment of acoustical characteristics of windows and facades. More importantly the computational approach will need to address the frequency dependent nature of façade acoustics and not rely on single number ratings only.

Table 1 – Test results for triple layer laminated glass

Laboratory	STC	OITC	Glass Area (m^2)	Glass Density (kN/m^2)	Temperature C°	Relative Humidity
E	45	36	3.33	0.75	24	51%
C	45	38	2.02	0.74	22	51%
W	46	33	3.33	0.75	24	51%

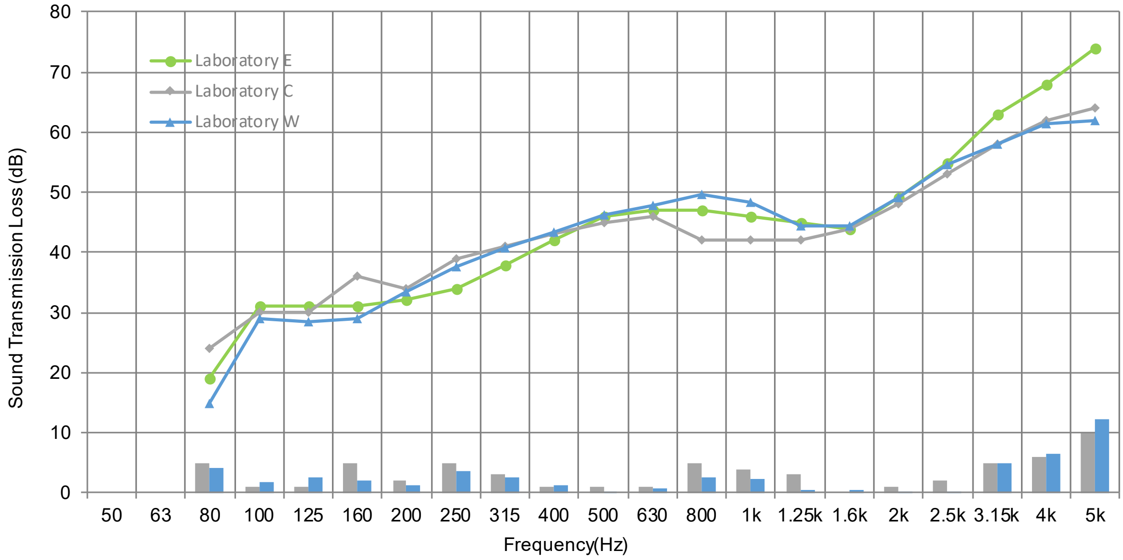

Figure 2 – Comparison of the sound transmission loss frequency response of identical glass composition at three different testing laboratories.

3. SIMULATION METHODS

Without a doubt, the laboratory testing of windows and curtainwalls are the most accurate means of evaluating the acoustical performance of the building envelopes. However, as mentioned before, analytical or empirical means for preliminary and comparative evaluation of these building component is of significant pragmatic value. The design and manufacture of façade components could take months, which severely hinder the opportunity for corrective measures as well as fine-tuning and optimization of the final design.

Several mathematical, closed formed solutions are derived for the solution of multilayer sound barriers with cavities (4,8). However, none corroborate favorability with the test results for bounded and sealed, and laminated glass.

The current practice heavenly depends on results of tests from existing or similar products. The in-house testing facility is highly desirable, but not within reach of many designers and engineers. There is some commercial software (6,7) that can provide quick analysis for designers, but there are limitations when it comes to multilayer glazing components with framing surrounds.

The use of general propose multi-physics Finite Element Analysis (FEA) software packages can help with modeling of complex material geometries, especially the ones encountered in window framing. These packages (8,9) can efficiently model both air-borne, structure-borne, and the linked fluid-structure interaction behavior of window frames and glazing. The user can model both the chambers and specimen with great accuracy. FEA methods, however, are more accurate in the low-frequency range where the mesh counts are reasonable, and solution times are practical. Also, the creation of a true defused sound filed require some level of expertise and fine-tuning of the models. The newer versions of FEA packages have attempted to solve this problem. The vibro-acoustic behavior of the simulation can also be modeled using FEA tools. This factor is important for the understanding of the realistic behavior of attachment mechanisms and the interaction between glass and the framing systems.

Another approach is the use of Statistical Energy Analysis (SEA) technique (5). SEA has been the method of choice among automotive and aircraft industries, and some attempts have been made to extend this approach in architectural acoustics. The main concept in SEA is that a structure (i.e., a window or a curtain wall system) is partitioned into coupled "subsystems" and the stored and exchanged energies are then analyzed. The original theory is based on the study of the interactions between, and relative behaviors of, the various subsystems. While this concept is clever from a mathematical point of view, it is not very practical for quick insight into the acoustic behavior of a given system.

The most important step in SEA is to segment the structure to be analyzed into rational subsystems. This is often a challenge, as the underlying theoretical assumptions must be satisfied while at the same time, several practical considerations must be accounted for. Moreover, for any given structural system, there may be several possible model constructs, each potentially yielding different behavior characteristics of the various subsystems. The challenge is to develop a model that most accurately reflects the true behavior of the tested system. On the other hand, the SEA is very efficient for the computation of sound transmission loss in the high-frequency range.

To remedy this limitation of SEA, one might consider a hybrid approach (11). Here, the primary concept is to determine parametric properties of the various components of the window by FEA or perhaps experimental means. Then the appropriate relationship can be established between the components using SEA modeling. Once the parametric model is established, the assembly of the subsystems can be used to predict the response of the overall structure to various input conditions.

In essence, rather than subdividing the field equations (models, boundaries) into elements (the approach used by FEA method), the system is subdivided into a series of sub-systems with interacting properties. The authors have performed simulation analysis utilizing this technique with some mixed results.

Figure 3 presents a comparison of laboratory test results for a triple layer insulated glass, with FEA and SEA approach. Although some promising trends can be established at the two ends of the frequency spectrum, it is very hard to establish a substantiating argument in the appropriateness of the technique. The other shortcoming of this approach is the tedious nature of the modeling work as well as the need for the utilization of multiple platforms to obtain the solution.

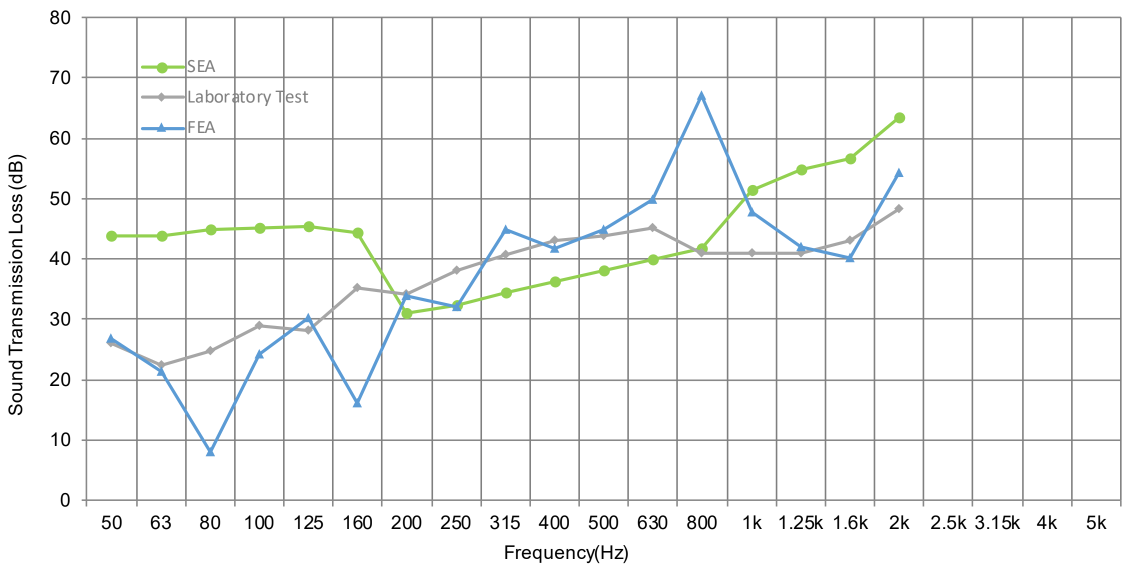

Figure 3 – Comparison of the sound transmission loss frequency response of a triple layer glass using SEA and FEA simulation analysis. The glass was made form 10 mm outer layer 19 mm argon gap, 10 mm laminate middle pane, 19 mm argon gap, and 10 mm laminated inner pane.

The limitations discussed above is the motivation behind the development of the Digital Acoustic Lab (DAL) program. The primary objective of this software is to create an easy platform for the estimation of the sound transmission loss of fenestration products. It combines sound theoretical methodology with the myriad of laboratory test results to create an accurate and reliable computational approach for the evaluation of the acoustic properties.

4. DIGITAL ACOUSTIC LAB (DAL)

The purpose of the developed Digital Acoustic Lab (DAL) program is to provide a platform for users, such as architects, building owners, and other stakeholders, to design, analyze and report a project-specific configured window, door or curtain wall façade system. It consists of three basic components, which are system designing module, theoretical analyzing module, and output/reporting module. The “Design Module” provides a simple and user-friendly interface for users to perform acoustical analysis of Schüco products. The “Analysis Module” integrates the accurate theoretical models to quickly evaluate the sound transmission loss of various glass panels, aluminum frames, and their coupling effect between them. The "Output Module" offers a smooth way to post-processing the results, builds an interface to visualize the processed data, and automatically generates an informative product report.

4.1 Design Module

In the design module, users can design a window, door or curtain wall with any customized design by inputting the dimension of the glazing panels, the size of the frame and possible split pane as shown in Figure 4 (a window system illustrates the usage). After the overall size of the window is defined, available window frames and various glazing panels such as single or multiple monolithic, insulating or laminated. For multiple laminated glazing panels, as shown in Figure 5, combinations of individual glass, interlayer, and cavity gap of most common practices are provided for users selection. The combination of the farming system, geometry, and glass composition will complete data preparation.

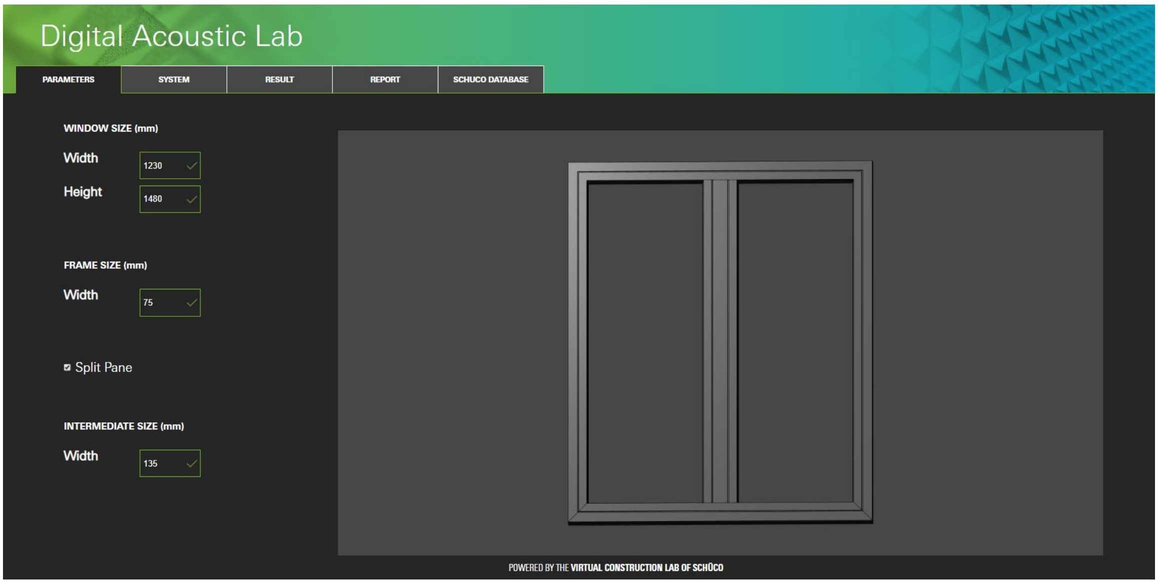

Figure 4 –Design Module: System definition

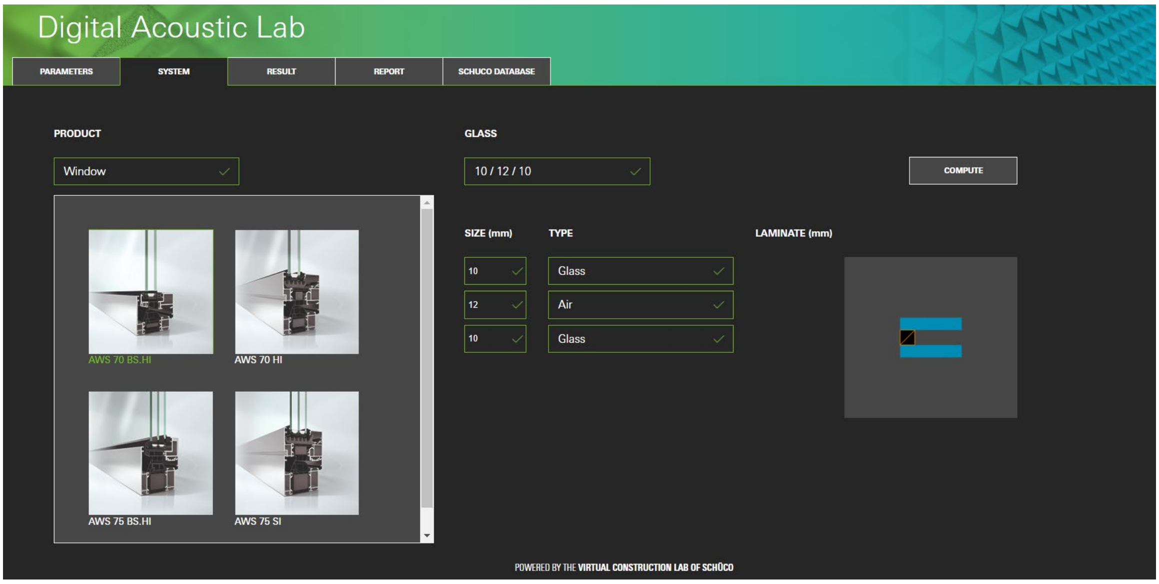

Figure 5 –Design Module: System configuration

4.2 Analysis Module

The configuration of the designed window, door, or curtain wall assembled in the design module will be transferred to the back end of the analyzing module and analyzed by clicking the compute button shown in Figure 5. The recently developed theoretical formulation by the authors (12-14) is the basis of the analysis module. The application first computes the sound transmission loss of the glazing system. The applied theoretical models provide an accurate and reliable evaluation of the acoustic performance of single or multiple laminated glazing panels. The overall STL spectra and the single number ratings is computed with the incorporating the aluminum framing contributions by using the area-weighted logarithmic average.

4.3 Output Module

The output/reporting module post-processes the results computed in the analyzing module and provides an interface for users to visualize the processed data. As illustrated in Figure 6, the sound transmission loss of a configured system is shown in 1/3 Octave band from 50 Hz to 5000 Hz, from which the STC/OITC/R_w (C, C_{tr}) classifications are obtained for the designed system. Also, the program provides comparisons of different window configurations, which offers the user a convenient approach to specify the configuration that performs the best at any interested frequency regions.

Figure 6 – Output/reporting module

Also, DAL provides an audio track to help user perceive the acoustic performance of the designed window with realistic soundtracks. The program has several preload environmental noise types (traffic noise, airplane takeoff noise, fire siren noise). Users can change the window opening percentages through a sliding bar, and the program will calculate the window sound transmission loss result at each opening percentage and process the original audio track accordingly. The audio simulation is based on one third octave band graphic equalizer in the range of 50 Hz to 5000 Hz. Comparing fully opened position with closed window position, the user will hear a clear difference due to the sound.

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