Noise as a Risk Factor in Elementary Classrooms – Applicability of Life Cycle Value Tradeoff of Noise Mitigating Measures using Multi Criteria Decision Modeling

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ABSTRACT

Research shows that noise is detrimental to developing children from many perspectives, cognitive, social, behavioral, and psychological; yet noise levels in classrooms are far from recommended standards. Studies suggest that the problem of poor acoustics exists for many reasons including lack of acoustics education for architects and engineers; lack of perception of the problem and its solution on the part of the professionals involved. Furthermore, these features are often discarded during value engineering or simply removed from the project to meet a predetermined budget. The issue is how we bridge the gap between research results, acoustics standards, and real practice of classroom design and construction.

The problem of classroom acoustics involves multiple criteria, multiple decision makers, multiple stakeholders, and multiple alternatives; therefore, it is a valid problem for applying the theories and principles of multi criteria decision making (MCDM). Consequently, the hypothesis of this study is that a robust structured decision making framework to facilitate choice of optimal classroom acoustics can be developed. This decision making framework is expected to facilitate decision-makers implementing new standards and policies; as well as provide professionals who are involved with school design and construction with decision rules for making informed choice about classroom acoustics within a specific decision context rather than just being guided by cost-effectiveness.

INTRODUCTION

It is a fact that in a classroom with optimal acoustics, learning is easier, deeper, more sustained, and less fatiguing. Studies around the world, whether in USA, Europe, or Asia, have shown that classrooms fall far below the acoustic standards established by research and standards for classrooms (Astolfi and Pellerey 2008; Kotus, Szczodrak et al. 2009). Lin, Chaing et al. in (2006) reported average school noise measured in 12 schools of sixth-grade children to be greater than 60 dB(A). Furthermore, studies have shown that the youngest children are the most vulnerable to unfavorable acoustic conditions than adults (Yang and Bradley 2009).

The bearings of poor acoustics on children are not only limited to learning disruption, but also have its influence on their overall well-being, including emotional balance, social behavior, stress levels, anxiety, fatigue, and frustration, to name a few. In the next section on theoretical background, these non-auditory effects of noise on children are discussed in detail followed by a discussion on how MCDM approach to value evaluation of noise mitigating measures is expected to help address the problem
of poor classroom acoustics. The remainder of this paper is structured as follows: theoretical background leads to discussion on the application of MCDM life cycle approach to the problem of selection of noise mitigating measures followed by illustration of acoustics advisor for elementary school classrooms (AAESC), conclusions, and future research pathway.

THEORETICAL BACKGROUND

Detrimental effects of noise on children

There is no dearth of research showing the detrimental impacts of noisy surroundings on children. In classrooms, inadequate acoustics (Zannin, Zwirtes et al. 2012), i.e., background noise, signal to noise ratio, speech transmission index, and reverberation time (RT), can affect speech intelligibility (Anderson 2004; Yang and Bradley 2009), student concentration (Kujala and Brattico 2009; Shield, Greenland et al. 2010), reading comprehension (Anderson 2004), and overall learning (Dreossil and Momensohn-Santosll 2005). National Research Council reports that the younger children under the ages of 13 to 15 are most susceptible to background noise because their listening skills are not yet matured to be able to differentiate the spoken word from the background sound (NRC 2006).

The cognitive processes of primary school children play an important role in their academic growth. Cognitive processing deals with how information is received, processed, modified, and remembered. Several research studies have examined the effects of noise, i.e., unfavorable listening conditions, on various aspects of children’s cognitive processes such as attention, listening comprehension, phonological processing, and memory, to name a few. “These effects have been attributed to a reduction of the cognitive resources available for storage and processing of the information due to increased listening effort or to the background sounds specific interference with short-term memory representations” (Colvin 2006).

Klatte, Lachmann et al. (2010) conducted study to compare the effects of unfavorable acoustics - classroom noise, background speech, and reverberation - on speech perception and listening comprehension in children, 1st graders, 3rd graders, and adults aging between 19-40 years. In line with former findings, the authors showed that speech perception and listening comprehension are severely impaired for children than adults in unfavorable acoustic conditions. Even shorter RT’s also evoked a reliable disruption in children’s speech perception.

Other well documented non-auditory impacts of irrelevant speech and sound on children include: fatigue (Persinger, Tiller et al. 1999), annoyance (Zannin, Zwirtes et al. 2012), botheration (Klatte, Lachmann et al. 2010) and raised blood pressure (Evans and Lepore 1993). Yet the noise levels and reverberation times in elementary classrooms are far from acoustical performance standards recommended by American National standards Institute (ANSI) for classroom acoustics (ANSI 2010). Perego, Bertoni et al. (1996) reported that “the daily sound levels in kindergartens is equivalent to the sound levels generated by a roaring traffic boom and exceeds the maximal value of noise admitted by the World Health Organizations (WHO) to enter the School from the outside, which is 40 Leq dB(A)”. Children in these schools, with higher levels of surrounding noise, have reported higher degree of
annoyance when compared to children from quieter schools. Furthermore, Klatte, Lachman et al. (2010) had discussed that in noisy environment children are tired sooner, may feel they are treated unfairly by their teacher, are less motivated, overall creating an environment of tension and reluctance to learn. These studies show that there are many causal paths between different sources of noise and varying impacts.

Why unfavorable acoustics in classrooms

Studies suggest that unfavorable classroom acoustics continue to exist due to lack of acoustics education for architects and engineers; lack of perception of the problem by educators, and lack of sensitivity of the professionals involved during the decision making stage of design (Thibault 2005; Zannin, Zwirtes et al. 2012). To make the situation worse, most times acoustical features are often discarded during value engineering or simply removed from the project entirely to meet a predetermined budget based on previous school designs (Thibault 2005). “In 1998, an incredible $7.9 billion was spent on school buildings nationwide. For only a fraction more, all these spaces could have been designed or renovated to provide good listening conditions” (ASA 2000). The result is perpetuation of substandard acoustical performance where students and teachers end up in classrooms that are either too noisy or so reverberant that speech becomes nearly unintelligible when the separation between the speaker and listener exceeds a nominal distance (Klatte, Lachmann et al. 2010; Lilly and Wowk 2010).

The field of acoustics is advanced enough to suggest many alternatives to the problem of poor acoustics in classrooms. The problem is how we bridge the gap between research results, ANSI standards and real practice of classroom design and construction. Many interventions have already been identified including acoustics requirements for classroom in Leadership in Energy and Environmental Design (LEED) certification. However LEED certification is a prescriptive approach. As an important next step, studies are needed with a focus on performing the life cycle value evaluation of noise mitigating measures and for assessing the direct and indirect costs of noisy classrooms such that an informed tradeoff is made between the ecological impacts and economics of classroom design. The life cycle value evaluation approach is expected to help offset the current practice of initial-cost decision making, because, “the additional cost per new classroom for good acoustical performance is not high, ranging from $1500 to $4500” (Perego, Bertoni et al. 1996). But the problem is that what gets measured gets taken care of during the cost-cutting business when a new school comes in over budget.

For the critical and complex issue of noisy classrooms, choosing the best action requires thinking about more than just the immediate effects of the actions. The problem of classroom acoustics involves multiple criteria, multiple decision makers, multiple stakeholders, and multiple alternatives; therefore, it is a valid problem for applying the theories and principles of multi criteria decision making (MCDM). The expected MCDM for classroom acoustics will guide decision-makers implementing new standards and policies; as well as provide professionals who are involved with school design and construction with a tool that details decision rules for making informed choices about classroom acoustics within a specific decision context. The ultimate goal is to develop and validate a robust structured life cycle
value evaluation framework which can be used to facilitate the choice of optimal classroom acoustics during planning and design phase. The expected outcome of this study is Acoustics Advisor for elementary school classrooms (AAESC) that will facilitate strategic alignment between classroom acoustics and classroom objectives of learning, psychological development, physiological development, and positive social development.

METHODOLOGY: MCDM MODEL DEVELOPMENT

There are three primary goals of this research study: model building; model application; model validation. These are discussed in details in the following sections.

Model building: step 1

The first step in building an MCDM evaluation model is always to represent and structure the objectives (criteria that are of key importance) that decision makers want to achieve (for example, increase profitability, reduce damage to the environment, reduce negative impacts of noise on academic performance, social behavior, etc.). Mostly the objectives are organized as a value tree that decomposes the overall broad objective of an evaluation into sub-objectives and ultimately into operational objectives, which can be more easily employed to assess the performance of decision alternatives. A work in progress illustration of such a value tree for the problem of classroom acoustics is shown in Figure 1. This value tree will be generated using cognitive maps that will represent ends decision makers want to achieve and means available to them connected by links showing perceived influence (Montibeller and Franco 2010).

The obvious knowledge sources for this step are experts from various disciplines working in the educational setting, such as audiologists, speech-language pathologists, reading specialists, regular and special education teachers, and psychologists. 15–20 experts in the related fields will be identified and invited to participate in the study. The key question that will be asked during this structuring process is: why acoustical performance standards, i.e. background noise levels = 35db, RT = 0.4 seconds, and S/N = +15db, are important for elementary school classrooms. Consequently, this step will provide answers to the following research question: How the auditory and non-auditory effects of noise on the youngest (k-5) children can be modeled into a value tree such that the problem of optimal classroom acoustics is addressed using the MCDM approach of decision making?

![Figure 1. Value tree for choice of noise mitigating measures in elementary school classrooms](image-url)
The (James 1984) within group inter-rater agreement index ($r_{wg}$) will be used to find consensus among the experts for the objectives and the structure of the value tree. $r_{wg}$ is a measure of agreement among a single group of judges who have rated a target item on a single dimension. Based on the heuristics in psychology, $0.7 \ r_{wg}$ will be considered a consensus. In general, $r_{wg}=0.7$ suggests that there has been a 70% reduction in error variance. Therefore, only 30% of the observed variance among judge’s ratings is due to random sampling. The number of judges is critical to affect the magnitude of the $r_{wg}$ index. Literature suggests 10 or more judges should be used to prevent attenuation (James 1984; Lindell and Brandt 1999). Consequently, 15-20 experts for this study correspond well with the methodological requirements of calculating the agreement index among a group of experts.

Model building: step 2

The next step in developing MCDM evaluation model for noise mitigating measures is identifying and defining attributes. Attribute is an index that measures the performance of each alternative on the criterions of the value tree; and thus on the overall objective of the decision problem. The structure of a value tree is such that all the lowest level criterions should be measurable, i.e., have a qualitative or quantitative attribute.

An attribute can be direct, indirect, natural, or constructed. However, independent of its type each attribute in MCDM evaluation model should possess the following properties: be unambiguous, comprehensive, operational, and understandable. Many methods exist for defining attributes, such as (Keeney and Gregory 2005) decision model for selecting attributes and (Parnell 2007) preference ranking for selecting attributes. For this study (Keeney and Gregory 2005) decision model is adopted for selecting among the different types of natural, proxy, and constructed attributes. This model is well-based in theory and provides comprehensive guidelines for developing attributes. Table 1 show the constructed attribute designed to measure quality of speech comprehension, where the subjective criterion of performance measurement is measured in terms of objective acoustical properties of classrooms. Such attributes will be designed for all the lowest level criterions in the value tree for choice of noise mitigating measures. The attributes will be validated by the expert panel selected in step 1. The James’s (1984) within group inter-rater agreement index ($r_{wg}$) will be calculated to find consensus. And based on the heuristics in psychology $0.7 \ r_{wg}$ will be considered a consensus.

<table>
<thead>
<tr>
<th>Table 1. Constructed attribute for quality of speech comprehension</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quality of Speech Comprehension</td>
</tr>
<tr>
<td>Excellent (5)</td>
</tr>
<tr>
<td>Good (4)</td>
</tr>
<tr>
<td>Fair (3)</td>
</tr>
<tr>
<td>Poor (2)</td>
</tr>
<tr>
<td>Bad (1)</td>
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</tbody>
</table>
Model building: step 3

Selection of appropriate MCDM methodology is the step in succession. Literature suggests more than 70 decision making methods that have been developed and applied to different decision making problems. Consequently, selection of appropriate MCDM methodology in itself has become a complex decision making problem because use of inappropriate methodology can result in misleading solutions to the decision making problem. Even if the structuring of the problem is carried out perfectly, the use of an inappropriate method can provide a decision recommendation that cannot be justified.

One of the most important requirements of a method to be used in selection of noise mitigating measures or acoustics design, is that it should be quick, simple, and easy to use and understand. For this critical step, (Eldrandaly, Hadi et al. 2009) framework for selection of the most appropriate MCDM technique will be utilized. The framework recommends a set of MCDM techniques based on the characteristics of the decision problem, the decision maker and the solution technique. In order to select an appropriate technique, the characteristics of both the decision problem and the decision maker must be studied against the characteristics of the solution technique so that the best match can be identified.

Model building: step 4

Typically MCDM models provide overall preference values of alternatives that depict the preference of one alternative over the other among a finite set of alternatives. The overall preference score in any MCDM method is obtained by adding marginal contributions from each criterion as shown in Table 2, where \( A_1, A_2, \ldots, A_n \) are \( n \) alternatives and \( C_1, C_2, \ldots, C_m \) are \( m \) criteria. The relative importance of the criteria \( C_1, C_2, \ldots, C_m \) towards the decision is represented by weights \( W_1, W_2, \ldots, W_m \), which are obtained by questioning decision makers involved in the process. Decision makers then evaluate the alternatives \( A_1, A_2, \ldots, A_n \) on individual criterion \( C_1, C_2, \ldots, C_m \). The process results in local preferences for each alternative, \( X_{11}, X_{12}, \ldots, X_{mn} \), respectively, which are then aggregated to find the overall value of each alternative \( V_1, V_2, \ldots, V_n \). The validated OWA (ordered weighted averaging) or OWG (ordered weighted geometric) operators for aggregation will be employed depending on the additive or multiplicative characteristics of the criterions.

<table>
<thead>
<tr>
<th>Alternatives</th>
<th>C1</th>
<th>C2 Model</th>
<th>C3 Color</th>
<th>Overall</th>
</tr>
</thead>
<tbody>
<tr>
<td>Car A1</td>
<td>( X_{11} )</td>
<td>( X_{12} )</td>
<td>( X_{13} )</td>
<td>( V_1 )</td>
</tr>
<tr>
<td>Car A2</td>
<td>( X_{21} )</td>
<td>( X_{22} )</td>
<td>( X_{23} )</td>
<td>( V_2 )</td>
</tr>
<tr>
<td>Car A3</td>
<td>( X_{31} )</td>
<td>( X_{32} )</td>
<td>( X_{33} )</td>
<td>( V_3 )</td>
</tr>
<tr>
<td>Car A4</td>
<td>( X_{41} )</td>
<td>( X_{42} )</td>
<td>( X_{43} )</td>
<td>( V_4 )</td>
</tr>
<tr>
<td>Car A5</td>
<td>( X_{51} )</td>
<td>( X_{52} )</td>
<td>( X_{53} )</td>
<td>( V_5 )</td>
</tr>
<tr>
<td>Criteria Weight</td>
<td>( W_1 )</td>
<td>( W_2 )</td>
<td>( W_3 )</td>
<td></td>
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</tbody>
</table>
**Model application: step 5**

Fifteen to twenty school board decision makers will be identified in the Charlotte, NC region. MCDM analysis and evaluation will consist of the following steps.

*Identification of alternatives*

Generation of alternatives is critical to effective design process and MCDM evaluation. In other cases the time and resources is wasted on evaluating alternative solutions that are far from fulfilling the goals of the stakeholders. ANSI standards and research has already established the optimal values for background noise levels, RT and S/N ratio in classrooms. These standards will be used to design the best alternative and five alternatives will be generated with varying distance from the best.

*Weighting scores for each criterion*

In many MCDM models criteria weights play an important role in estimating the overall preference values of alternatives. Proper interpretation of criteria weights is influenced by the manner they are used in the aggregation rule of the MCDM model. Usually, these weights are normalized to add up to one such that the issue of different scales is taken care of. Depending on the MCDM aggregation rules, which use the criteria weights in different ways, many methods for eliciting criteria weights have been suggested in the literature. Generally in most MCDM problems, the criteria weights represent marginal contributions, criteria trade-offs, scaling factors, and criteria importance. Choo, Schoner et al. (1999) determined the appropriate questions that should be posed to the DM for eliciting information on criteria weights. These questions will be used to elicit weights for each criterion from decision makers. The individual criteria weights provided by different decision makers will be aggregated to obtain group weights for all criteria. According to (Saaty 1995) for a group of decision makers taking the Geometric mean of weights is the most appropriate method to obtain group weight. The Geometric mean of group of weights is calculated as shown in equation 1 (Saaty 1995):

\[
W_j = \sqrt[|m|]{w_{1,j} \times w_{2,j} \times \ldots \times w_{m,j}}, \quad j = 1, \ldots, n
\]  

Where \( w_j \) is the weight of \( j^{th} \) criterion, \( w_{1,j} \)------\( w_{m,j} \) is the weights provided by \( m \) decision makers to the \( j^{th} \) criterion.

*Performance evaluation of alternatives*

Performance of each alternative solution on each criterion will be measured using the attributes identified in Step 2. The aggregation model identified in step 4 will be used to evaluate the overall performance of alternative solutions. According to the multi criteria value theory (MCVT), the variant which is awarded the highest overall performance should be the best one in a given decision context.

**ACOUSTICS ADVISOR FOR ELEMENTARY SCHOOL CLASSROOMS**

Acoustics advisor for elementary school classrooms (AAESC) will be a software tool aimed at making advice in a complex, challenging, and subtle real-life
Maximize the value of classroom acoustics
Maximize the quality of speech recognition
Minimize Annoyance
Maximize cognitive performance
Maximize psychological performance
Maximize physiological performance
Maximize social performance
Minimize early fatigue
Minimize impact on blood pressure
Maximize impact on memory
Maximize the quality of speech recognition

A1 = \[0.25 \times (3 \times 0.5) + (3 \times 0.5)\] + \[0.25 \times (4 \times 0.5) + (4 \times 0.5)\] + 0.25 (3) = 3.25

A2 (Best Alternative Scenario) = \[0.25 \times (5 \times 0.5) + (5 \times 0.5)\] + \[0.25 \times (1 \times 5)\] + \[0.25 \times (5 \times 0.5) + (5 \times 0.5)\] + 0.25 (5) = 5.0

Figure 2. AAESC illustration for selection of classroom acoustics

CONCLUSIONS
The life cycle value decision making model is expected to provide benefits throughout the life cycle of elementary school classrooms from policy making to designing and operating. The literature also recognizes this approach as Life cycle management (LCM), “which is an integrated approach to minimizing environmental burdens throughout the life cycle of a product, system or service” (Jensen, Hoffman et al. 1997). By providing a big picture, the life cycle value approach ensures that a school doesn’t create improvement in one area at the expense of another. Rather than looking at specific indicators in isolation, life cycle value analysis is the most appropriate approach to quantify and compare the ecological and economic impacts together in one model over the life of a product. Moreover, the better acoustical
performance building envelopes that result from the process produce energy savings over the life of the building.

FUTURE RESEARCH

Building on the AAESC, the next phase of the study will focus on developing an interface to integrate AAESC with classroom building information model (BIM). There are two objectives: one, integration with BIM will provide the advantage of effortless generation of various possible alternatives and what if scenarios such that the decision makers can virtually see the implications of ignoring establishment of optimal acoustical conditions. In addition, this integration will meet the future quality assurance needs of the building industry where each building from its conception to its useful life will be captured as a model.

REFERENCES


