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Acoustics and sustainable design in exposed structures

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Two very important emerging architectural trends in the USA are 1) to 'open up' the space design into an exposed structure, and 2) to incorporate sustainability into the design of building interiors. We, as acoustic designers, would like to know the consequences of both trends on acoustic performance, and on occupant satisfaction and work performance. The first concern is addressed in a study by CISCA evaluating the effects of ceiling plenum vs. exposed structures in both office and retail spaces. And the second concern relative to the compatibility of sustainable design objectives with acoustic performance is addressed by a pertinent field survey by the Center for the Built Environment (CBE at Univ. of CA, Berkeley) on occupant satisfaction and performance. The issues of availability and use of 'green' acoustic building materials, which not only meet sustainability and energy goals, but also serve to ensure that our buildings actually work for the intended purpose, are also addressed. Finally, the increased awareness of the acoustic impact of 'green' design on occupant satisfaction is being seen in the evolution of LEED and other 'green' rating systems.

1 Exposed Structures

The architectural design referred to as "Exposed Structure" is becoming increasingly popular for a couple reasons. In some cases the desire is to expose the overhead mechanical systems and roof deck thus providing a feeling of spaciousness and economy, Figure 1a. In other cases, the desire for openness is facilitated by the installation of under-floor air distribution (UFAD), in which case a traditional overhead ceiling is not needed to 'cover' plenum mechanicals, Figure 1b. The architects and building owners must, however, be reminded that the occupant safety, satisfaction, and performance will be negatively impacted by these architectural design decisions, if alternative fire safety strategies and acoustical treatment are not considered.

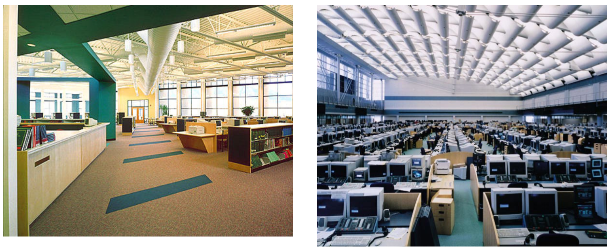


Figure 1a. Warehouse Look, 1b. Open Plenum Look

1.1 Life Cycle Cost Study – CISCA [1]

A life cycle cost study was funded by CISCA, and published by Barry Donaldson & Associates in 2007[2]. This study looked at the differences in construction costs, as well as the operating costs, for a building with a traditional suspended ceiling compared to an open plenum design, for several geographic (climatic) regions within the USA. The operating costs included the BOMA categories for: utilities, maintenance, repair, cleaning, roads/grounds, security, administration, energy, etc.

This study found that the initial construction cost of a prototypical office building with a traditional suspended ceiling design was almost 15-22% higher than for the open plenum design. According to Donaldson, "However, the energy and maintenance savings justify the use of a suspended ceiling plenum, with extremely short simple paybacks of one to eight months for the office design…"[2].

Since office 'churn', meaning relocation of furniture and workspaces, is a significant issue, the choice of suspended ceiling vs. exposed structure design will have an impact. "One of the primary reasons for the use of suspended ceiling systems is that they provide an architectural finish that provides acoustical performance and a fire rated assembly to create a plenum for the systems above, with the ability to reconfigure those systems above the ceiling as office workstations below are moved and relocated" [2].

Additionally, a suspended ceiling provides both enhanced acoustical and fire safety performance, which may not be available with a typical exposed structure design. To achieve an acceptable level of acoustic comfort and satisfaction in an exposed structure will require that alternative acoustical materials and systems be used in place of the non-existent traditional ceiling – this factor was not included in the life cycle cost study – and would serve to further reduce the 'payback' time stated above.

1.2 Acoustic Design – Exposed Structures

Surveys of the indoor environmental quality (IEQ) of buildings indicate that acoustic comfort and occupant satisfaction may be compromised when the ceiling element is removed. One of the most comprehensive studies of building IEQ is the ongoing research program at UC Berkeley's Center for the Built Environment [3]. Post-Occupancy Evaluations have been conducted in over 300 buildings inquiring about the occupant's satisfaction with building IEQ. The CBE survey shows that acoustics is 'on average' the least satisfactory environmental factor in buildings as shown in Figure 2 below [4, 5].

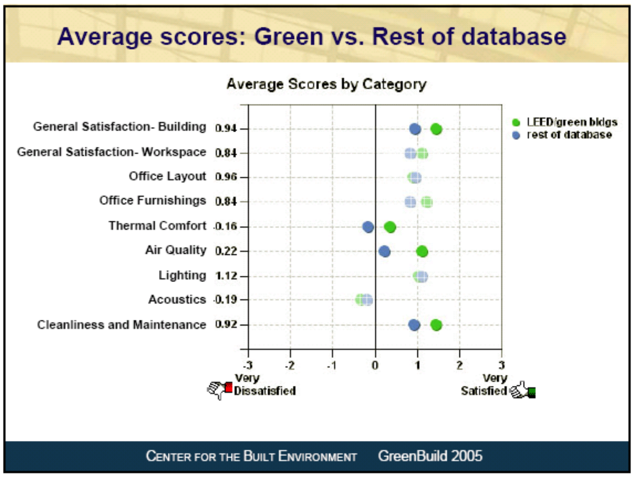


Figure 2. Acoustic performance an overlooked factor

Further analysis [6] of the CBE database indicates that the primary acoustic issue is related to speech privacy more so that to mechanical equipment noise, as shown in Figure 3.

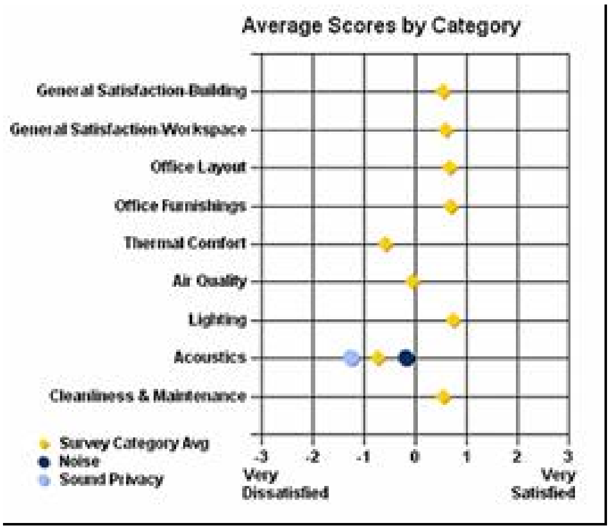


Figure 3, Details of Acoustic Satisfaction

Dissatisfaction with the interior environment, specifically noise and speech privacy, can lead to other issues, with one important factor being work performance. An ASID (American Society of Interior Designers) study [7] found that 71% of the workplace distractions in open plan offices could be attributed to noise intrusion. A study of the effects of work distractions on performance reported [8] a productivity loss of 8% for typical 'knowledge workers' yearly.

1.2.1 Acoustic Design Solutions

Many of our newer buildings are designed with areas of exposed structures in a least some portion of the building. Occupant requirements relative to acoustics generally encompass a need for speech intelligibility within a space, speech privacy between spaces, and low noise annoyance and distraction [6]. The primary contributor to achieving the above needs is the sound absorbing performance of the architectural surfaces, specifically the ceiling and wall surfaces. When a 'no ceiling' design is anticipated, then an alternative source of sound absorbing material must be considered to control the room reverberation (reflected sound) and room noise level.

Since continuous acoustical ceilings are not an option, we must instead consider alternatives such as baffles, canopies, and clouds to control the reflected sound within large open spaces, while at the same time keeping true to the architectural vision of what an 'exposed structure' space should look like.

A traditional solution (most often used in industrial situations) is the installation of vertical 'hanging baffles' as shown below Figure 4a. More recently there have been more innovative approaches such as the application of 'canopies' Figure 4b, or 'clouds' Figure 4c.

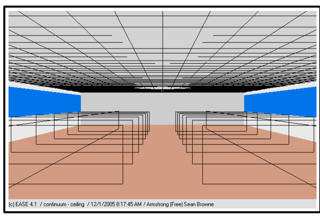
Figure 4a. Acoustic Baffles

Figure 4b. Acoustic Canopy, 4c. Acoustic Cloud

These types of products or systems are often referred to as a "space absorber", and are generally suspended from the deck above such that they can be installed in regular or irregular patterns and at various heights and inclinations. The acoustic performance rating for a 'space absorber' is usually taken as the total sound absorption provided by the product, and this is given in terms of a Sabin rating. For example, a canopy that provides 20 Sabin would be twice as effective as one that provides 10 Sabin of absorption, and this of course includes the effects of both sides of the product (if both sides exposed to sound).

By comparison, the rating used for a full suspended ceiling is the NRC, which is a material rating measure on a per square foot basis.

The product effectiveness can be compared on the basis of Sabin/sq. ft., which for the case of a traditional ceiling Figure 5a, is approximately 0.84 with a high performance mineral fiber tile, and for a ceiling cloud Figure 5b, is approximately 1.35 with a fiberglass tile.



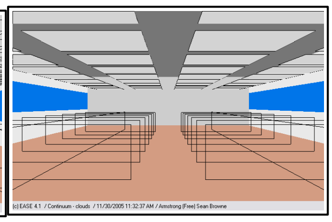


Figure 5a. Traditional ceiling 5b. Acoustic Cloud

Obviously, since space absorbers (assuming that both sides are absorptive) tend to have exposure to sound on both the front side and the backside, the resultant overall effectiveness will be higher than for a full suspended ceiling. This then allows for the exposed structure look while also providing high levels of sound absorption, thus keeping the room reverberation from getting 'out-of-hand'.

1.3 Fire Safety Design

The elimination of suspended ceilings in buildings has become a popular design trend, especially in public buildings such as restaurants and retail spaces. However, architects must recognize that their choices for the 'visual environment' can have an adverse consequence on the fire performance of the space.

Although building codes and insurance interests do not prohibit open or no ceiling concepts, the case can be made for going beyond the code to provide an extra margin of building fire safety. A suspended ceiling can delay a building fire which starts in the occupied spaces from reaching potentially combustible materials located in open areas overhead. Most building fires originate in the occupied space and not in the concealed space above the ceiling.

Fire models show that for a ceiling installed at a typical height that smoke detector and sprinkler systems activate faster, thus providing increased time for escape, and also allowing the sprinklers to react to a much smaller fire – both of which serve to increase the effectiveness of the sprinkler system [9].

1.3.1 Discontinuous Acoustic Elements

A suspended ceiling is defined as a typical grid-supported continuous ceiling with traditional mineral fiber acoustic tile. Some of the specialty ceilings that have lineal open joints and other features that create an open passage to the concealed space above the ceiling may not provide the same functionality with regards to fire safety.

Although ceiling clouds may offer some of the advantages, it is difficult to generalize on this application because the area covered by these discontinuous ceilings will vary greatly. In situations where the ceiling cloud covers a very high percentage (90%), the ceiling may function in a fire as if it were wall-to-wall. However, where large areas remain without a ceiling, the functionality would be more like a no-ceiling situation.

The point of crossover is not defined, and attempting to model the detector/sprinkler performance of discontinuous ceilings is beyond the capability of current mathematical fire models.

2 Sustainability and Green Buildings

Sustainable building programs such as supported by the US Green Building Council (USGBC) are aimed at transforming the approach to building design and operation, with more sensitivity to energy and environmental design implications. The first concern for the acoustic community is the issue of the compatibility of 'green' objectives with acoustic performance. A second concern is the availability and application of 'green' building materials that not only meet sustainability and energy goals, but also serve to ensure that our buildings actually work for their intended purposes. So, the design, application, and 'end of life' considerations of 'green' building materials all need to be considered. And finally, with the increased awareness of the impact of acoustics in 'green' design on occupant satisfaction, the evolution of LEED and other 'green' rating systems are now beginning to include acoustics.

2.1 LEED and IEQ

Acoustic standards are now starting to be addressed by a few of the rating systems (LEED for Schools, Green Guidelines for Healthcare, Australia's Green Star), so the question is how well are we doing 'right now' with the acoustic outcomes such as speech intelligibility, speech privacy, noise distraction, and annoyance?"

An indication of this was given in Figure 2 previously, which showed the outcome of the IEQ study from CBE. Approximately 10% of those buildings are either LEED certified or "self-nominated" green buildings; in total CBE has surveyed over 25 green buildings, including 16 LEED-certified buildings.

On average as shown in Figure 2, LEED buildings have been found to be 'higher performing' in terms of factors such as IAQ, Figure 6a, which are directly addressed by LEED, but slightly 'lower performing' on acoustics, Figure 6b, possibly since LEED (until recently) did not directly address this issue. Actually, in all buildings surveyed, the level of acoustic satisfaction is the lowest performance factor of all the surveyed interior environmental factors.

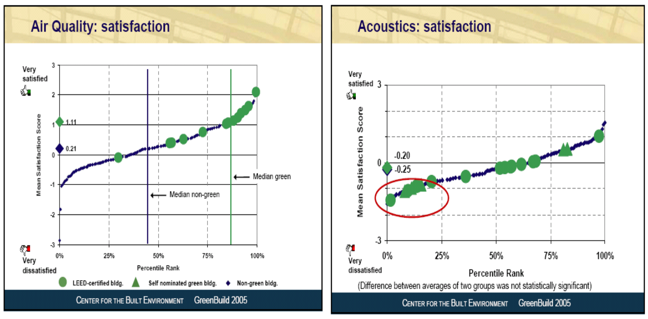


Figure 6a. IAQ results, 6b. Acoustic results

This is not surprising, but it is something that has got to change if we truly intend to design and build buildings that foster healthy and productive environments.

2.2 Acoustic Design and Green Materials

Architectural design and acoustics are interrelated since the three basic factors that define the visual environment - size, shape, and surfaces - also establish the "acoustic signature" of that space. The acoustical treatments used on the surfaces, such as ceiling tile, window drapery, furniture cushioning and fabrics, and carpet all affect the reflected sound and thus both the speech intelligibility and background noise level within the space.

Since the ceiling and wall surfaces are the largest exposed areas, they not only have a significant effect on the acoustic signature of the architectural space, but the composition of the materials themselves should also be considered relative to indoor environmental quality and sustainability to address the LEED (or other green building) criteria.

2.2.1 Sustainability and Acoustic Materials

Not only must we consider the performance features of interior products, but also the composition and complete life cycle of whatever we plan to install in high performance green buildings. Materials and resources comprise 20% of the available LEED credits as shown in Figure 7.

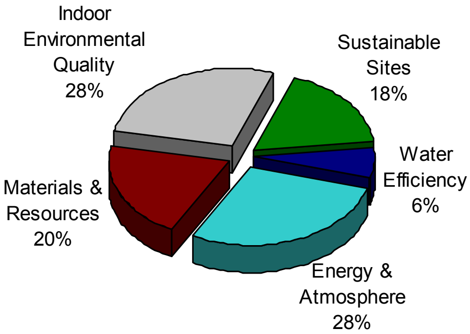


Figure 7. LEED credit areas

One of the most effective means of reducing the environmental footprint of products is to use post consumer waste as a raw materials in the production of new products. An example of this is the use of reclaimed acoustical ceilings from renovation projects being returned in a closed loop cycle to make new products. Every pound of returned tile (as practiced by some manufactures) displaces the virgin material and energy required to process those materials, as well as the waste associated with the extraction and processing of those virgin raw materials. This closed loop process also raises the post-consumer recycled content in new ceilings. Through the use of LCA (Life Cycle Assessment), manufacturers have been able to quantify the environmental impact associated with the recycling of ceiling tile and the displacement of those virgin materials indicating a reduced environmental impact by approximately 15 percent when compared to virgin raw materials.

The use of recycled materials, and specifically the introduction of ceiling tile recycling, has had a positive impact on the sustainability of buildings while also serving to provide architectural materials that satisfy acoustical requirements within the built environment.

Another area to consider in product selection and indoor environmental quality is product emissions. Careful selection of interior products can be made to reduce the concern of high levels of VOC emissions. These emissions, one of which is formaldehyde, can be lowered by specifying products with little or no added formaldehyde in their production and installation.

Manufacturers take great care to ensure that the primary purpose of their products, including the acoustical attributes, are not compromised. For example, the UL listing of acoustical performance must be present to give the specifier the confidence that these properties have been met.

2.2.2 Energy Savings and Lighting Benefits from High Light Reflectance Acoustic Materials

One of the sustainable performance features that contribute directly to energy savings and lighting performance is high light reflectance ceilings. When a high light reflectance ceiling [10] is used in conjunction with an indirect lighting system, the ceiling enhances the benefits of indirect lighting by improving overall lighting uniformity, returning 90% of light back into the space, Figure 8b, compared to 75% with standard ceilings Figure 8a.

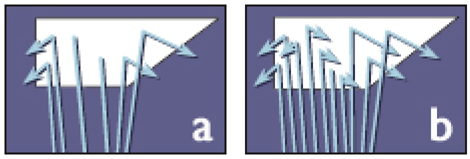


Figure 8a. Standard LR, 8b. High LR

This improves the effectiveness of the lighting system and increases the foot candles in the space. The following example, Figure 9, shows the relationship of ceiling reflectance (LR) and the increase in light level for a 60'x60'x10' open office space with 12' luminarie spacing.

Ceiling Reflectance	Work Plane illuminance (footcandles)	Increase in light level
75%	52.0	Reference
78%	54.3	4%
81%	56.6	9%
84%	59.0	13%
87%	61.6	18%
90%	63.3	22%

60' x 60' x 10' open office, 12' luminaire spacing

Figure 9. Effect of LR on light level

An extensive study performed by Brinjac Engineering [11] evaluated the energy cost and environmental advantages of combining high light reflectance ceilings and indirect lighting.

The results of this study show that by increasing the light reflectance value of the ceiling from 0.75 to 0.90, the following benefits can be realized with indirect lighting:

- ✓ Total building energy savings up to 11%
- ✓ 23% reduction in lighting energy at same light level, results in fewer fixtures and lamp/ballast replacements
- ✓ 7% savings in cooling system energy
- ✓ Increased occupant satisfaction and productivity
- ✓ Ability to secure tax credits for energy efficient design
- ✓ Ability to secure LEED credits for Energy savings

3 Conclusion

Architecture, acoustics, and sustainable design are all interrelated as they affect building IEQ and thus the resultant comfort, satisfaction, and performance of the occupants. The designer needs to be sensitive to the following issues:

- Beware of the 'Less is Better' approach, since removal of critical finishes from a space can result in an environment that is uncomfortable, unhealthy, and underperforming
- Beware of 'exposed structure' designs, acoustics and fire safety still need to be addressed, but in a different way, if suspended ceilings are not being used
- By carefully selecting surface finishes, the acoustical performance, energy usage, and lighting comfort of the space can be significantly enhanced
- When making material selection choices, consider the balance between architectural design factors and all performance criteria
- Remember that acoustical products, like typical ceiling and acoustical wall treatments are inherently 'green' materials due to the nature of their composition

As demonstrated, the careful selection and optimal design of the interior can deliver multiple benefits from productivity of the occupants, cost savings, and energy efficiency…. all of which lead to a sustainable interior with superior acoustical performance.

Acknowledgments

The authors would like to acknowledge contributions on the topic of fire safety research which was conducted by Tom Fritz, and which is referred to in this paper.

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