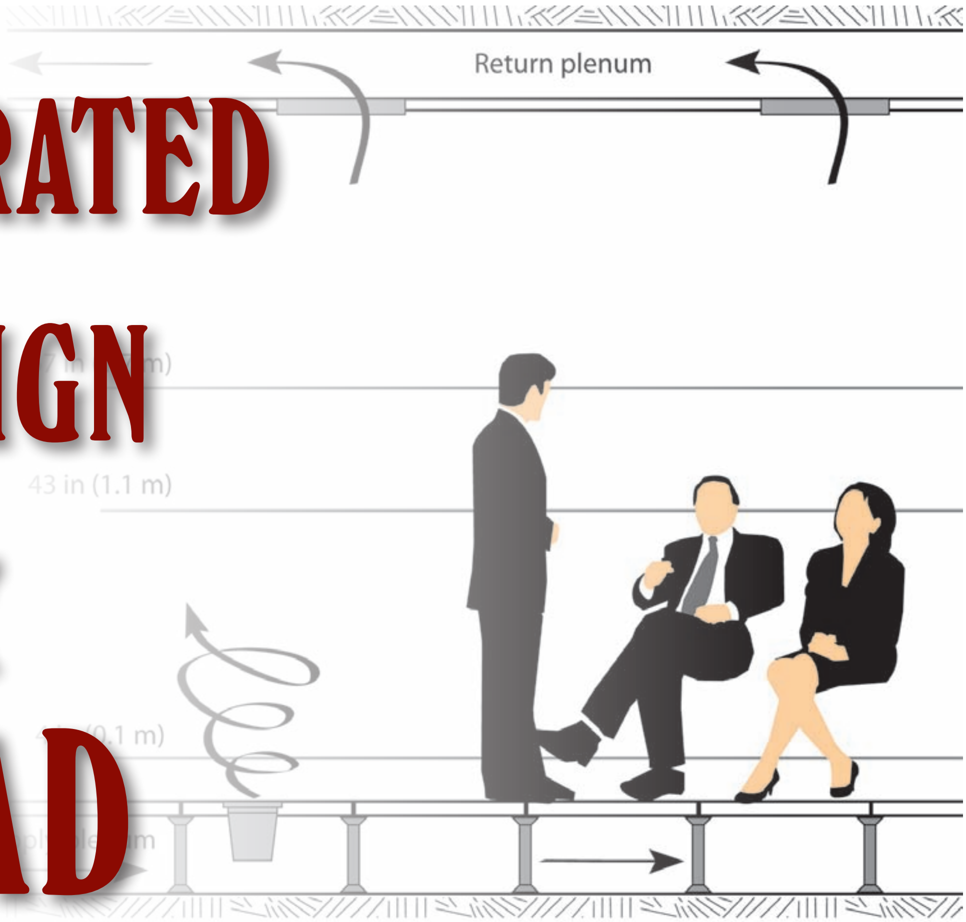
Integrated Design & UFAD



By **Eduard Cubi Montanya,** Student Member ASHRAE; **David Keith, Ph.D.;** and **Jim Love, Ph.D., P. Eng.,** Member ASHRAE

The potential benefits of underfloor air-distribution (UFAD) systems have been identified as improved ventilation effectiveness, occupant satisfaction with thermal comfort and energy performance, as well as increased ease of reconfiguration.[1] However, further research is needed to provide a better understanding of performance.[2,3] Achieving these benefits depends on the installation, operation and use of the system, as well as the underlying design – "the only downside to UFAD and DV is learning how to properly implement and construct them."[4]

Key differences between UFAD and conventional overhead systems include:

- Improved energy performance and ventilation effectiveness with UFAD depend on vertical air stratification in the space, while conventional overhead systems are designed to create uniform mixing.[1]
- Obstruction of diffusers by furniture is rarely an issue with overhead systems but is a key consideration with UFAD.
- While conventional overhead systems have fixed diffusers, most UFAD diffusers are occupant-adjustable.[1]

These differences mean that (unlike "drop-in" innovations, such as higher efficiency motors) success with UFAD depends on many participants other than mechanical engineers. The authors identify the roles of important participants, and suggest a design and construction approach, including commissioning provisions, that addresses these differences to provide greater assurance of achieving the potential benefits of UFAD. While this article focuses on the specifics of UFAD, other advanced building technologies face similar performance challenges associated with coordination among project participants.

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UFAD Can Improve IAQ & Comfort While Saving Energy

In theory, UFAD can improve IAQ through better ventilation effectiveness than overhead systems.* Lab tests by Jung, et al.,[5] found local air change effectiveness (ACE) ranging from 1.2 to 2.0 with UFAD. However, the only published field study of a UFAD system that reported both ACE and pollutant removal efficiency (PRE) found typical ACE values around 1 (comparable to overhead systems) and PRE of 1.13 (only slightly better than overhead systems).[6] Pending further research, Standard 62.1-2007 states that the ventilation effectiveness of UFAD is 1.0 in cooling mode, comparable to overhead systems. According to Standard 62.1-2007, Table 6.2, UFAD systems with low supply air velocity (lower than 150 fpm [0.8 m/s]) would fall under the displacement ventilation category, for which nominal ventilation effectiveness in cooling mode is 1.2.

The Center for the Built Environment (CBE) found that occupants appreciated having control over their thermal conditions (even if they seldom adjusted the diffusers). In addition, the increased air motion near the occupants avoids the sensation of stagnant air.[7]

Several mechanisms contribute to hypothesized energy use reductions with UFAD. First, UFAD supply air temperatures of 62.5°F to 64.5°F (17°C to 18°C) versus 55°F to 57°F (13°C to 14°C) for overhead systems extend the upper temperature range for free cooling, reducing hours of cooling plant operation (this strategy may increase fan energy use if higher airflows are used to increase cooling in variable flow systems, and should only be used if it provides a net energy use reduction.)[2] Second, the aforementioned increase in supply air temperature allows higher coil leaving temperatures under low humidity conditions, improving instantaneous cooling plant performance.[1] (In recirculation mode, the effect of slightly higher return air temperatures with UFAD should be considered in terms of cooling offsets and return air bypass performance.) Third, the room air temperature stratification attributed to UFAD systems may "shrink" the space volume requiring cooling by removing convective loads nearer the ceiling (especially lighting) from the zone load, reducing total required space air supply and fan power.[1,8] (However, recirculation of air in the air-handling unit somewhat offsets cooling plant load reductions.)

Heat transfer patterns in open plenum systems differ from those of ducted systems. In open plenum systems, heat gains from slabs and floors result in diffuser supply air temperatures (SAT) that may be several degrees higher than the air handler discharge temperature (thermal decay). As stated in ASHRAE's *Underfloor Air Distribution Design Guide,*[1] "While the amount of heat entering the underfloor plenum will not change the magnitude of the cooling load… at the system level, it does… [reduce] the… heat [to be removed]… by airflow through the room." This affects air-handling unit supply airflow sizing and temperature requirements, and the associated fan and cooling plant energy use. An additional (and major) source of energy use reductions in open plenum systems derives from the lower static pressures relative to ducted systems, which may reduce fan power and its associated energy use.[1,2]

UFAD diffusers in open plenum systems are installed in the floor tiles without the "hard" connections to ducts as in overhead systems. In addition, the underfloor plenum provides an accessible space for other building services such as secondary electrical distribution and communications cabling.[9] These characteristics theoretically ease reconfiguration. However, sealing floor panels and/or covering joints with carpet to reduce air leakage from the underfloor plenum may complicate reconfiguration.

Some of these benefits could have positive economic consequences. Energy use reductions would lower energy bills, the increased flexibility could reduce reconfiguration costs,[2] and improved comfort could improve productivity.[7,10]

*ANSI/ASHRAE Standard 62.1-2007, *Ventilation for Acceptable Indoor Air Quality,* defines zone ventilation efficiency as the efficiency with which a system distributes outdoor air from the intake to an individual breathing zone. The two indicators of ventilation effectiveness are air change effectiveness [ACE] and pollutant removal efficiency [PRE].

Integrated Design

While further research is required to better characterize the potential benefits of UFAD, achieving them depends on a comprehensive approach from the early stages of a project. In an integrated design approach, building stakeholders collaborate at the beginning of the project to set the owner's project requirements: performance goals (often summarized in a owner's project requirements or schematic design document) that the design team (typically architects and engineers) would address throughout the design process. Clear performance goals help the design team coordinate its efforts to optimize the global design and identify synergies when they make design decisions that affect more than one discipline. In reality, this is often complicated by conflicts between goals such as maximizing performance while minimizing cost, coping with shortages of experienced personnel, and responding to the influence of stylistic trends on the approaches of the architects and interior designers.

Cooling capacity in air-based systems is a function of supply air temperatures and flow rates, so it is more limited for UFAD systems than for overhead systems.*

* A recent comparison of UFAD and overhead systems[3] showed that UFAD systems were near the limit of comfort and diffuser flow limits at a cooling load of 14 Btu/h·ft² (44 W/m²). The overhead system flow rates at this cooling load were about 0.7 cfm/ft² (3.6 L/s·m²). Overhead air systems are routinely designed with airflow capacities of 1 cfm/ft² (5.1 L/s·m²) and higher, which would provide additional cooling capacity.

UFAD systems supply air closer to the occupants, so velocities must be lower and temperatures higher to maintain comfort. Increasing supply velocities to meet high cooling loads may break down the temperature stratification that provides the energy performance benefits described previously.[1] Another option to increase cooling capacity with UFAD would be increasing the number of supply diffusers (i.e., increasing the airflow by increasing supply area rather than velocity). However, coverage of floor surface by furnishings and occupants allows fewer diffuser placement locations than with overhead systems. Keeping cooling loads in perimeter zones within the range suitable for UFAD application depends on the architects' envelope design, particularly the window area exposed to direct gain.[11] Interior loads (lights, people, and equipment) depend on the occupant-to-floor-area ratio and equipment use, as well as the lighting design (e.g., task versus ambient).

Oversizing air supply systems is especially problematic with constant air volume (CAV) UFAD because it may jeopardize the stratification that is key to achieving the potential performance benefits.[9] A post-occupancy study by Fisk, et al.,[6] revealed that "low internal thermal loads and moderate supply airflow rates" contributed to lower than expected thermal stratification and ventilation effectiveness. Therefore, particular attention should be paid to "normal" loads, as well as peak design loads of CAV.[12] (Oversized variable air volume [VAV] systems would reduce airflow rates to meet the actual cooling loads, which would increase stratification.) Often, these matters must be resolved in a compressed time frame, so the interactions that are a desirable part of integrated design may be curtailed. If the interior is to be fitted out by tenants, information on loads may be vague.

Figures 1a and *1b* contrast the information flow between architects and engineers with linear versus integrated design approaches. The potential benefits of UFAD are less likely to be achieved in the linear approach.

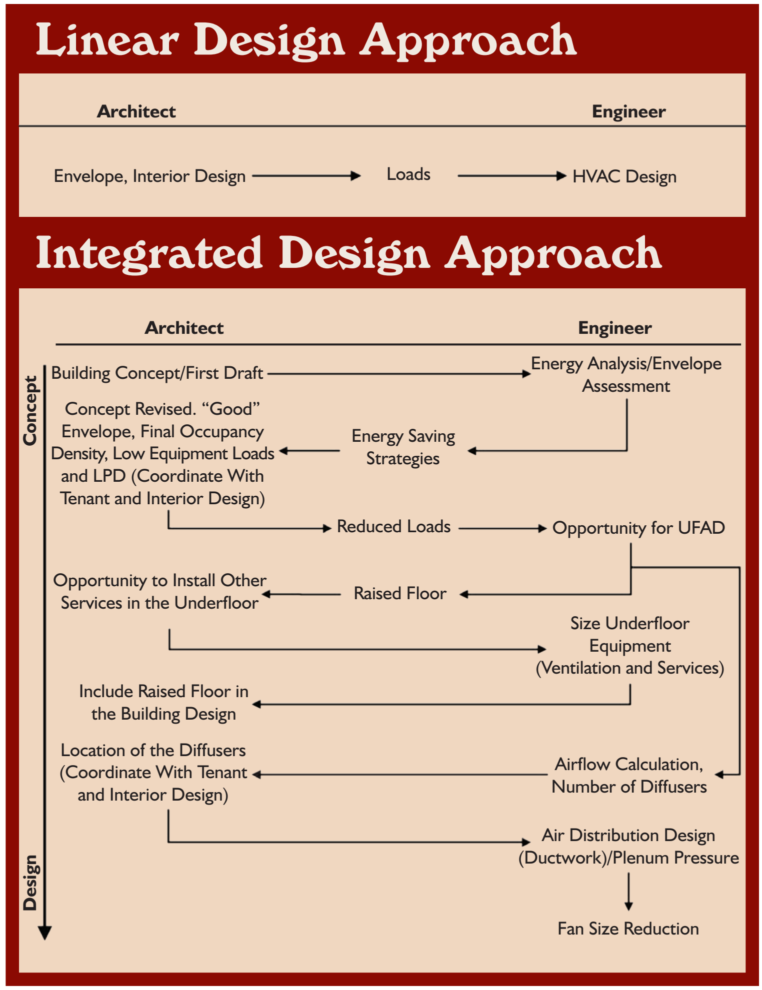

Figure 1a (top): Information flow. Linear design approach. Figure 1b (bottom): Information flow for integrated design and UFAD.

Implementation: The Importance of Details

While integrated design is necessary to achieve the potential benefits of UFAD, installation and operation are at least equally important. Sealing joints in the raised floor (especially around floor penetrations such as columns) is key to avoid air leakage with open plenum UFAD systems.[9] On the other hand, a ducted UFAD system designed with features such as extra flex duct length to diffusers to ease reconfiguration may be handicapped by unnecessary sealing of floor tiles and/or intentional misalignment of carpet and floor tiles to reduce plenum leakage. Location of heavy furniture and interior partitions above equipment that may require access for regular maintenance also reduces the advantages of UFAD.

Although overhead air-distribution system components require coordination with other elements such as partitions, structure, and piping, UFAD installation must address furniture placement to a much greater degree. Obstruction of diffusers by furniture may cause distortion of desired airflow patterns. In addition, the proximity of diffusers to occupants may drastically reduce air temperature at foot level, increase the vertical temperature difference between head and foot, and cause discomfort.

For these reasons, achieving the potential performance benefits of UFAD is affected by a larger number of design disciplines and trades than with overhead systems. Design teams should work closely with contractors and facility managers to inform them of their substantial influence on system performance and the details requiring particular attention.

System Setting and Operation

In addition to more comprehensive design and construction practices, the satisfactory performance of UFAD depends on system operations and, ultimately, on the user. Operators, facil-

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ity managers and occupants should be educated regarding the special features of UFAD.

Webster, et al., found that many occupants are unaware of the ability to adjust UFAD diffusers.[13] As well, occupant deployment of blinds at windows receiving direct sunlight increases stratification, among other thermal effects that remain to be fully understood.[14]

Building operators must be aware that, in a stratified environment, temperatures shown by thermostats may fail to represent the air temperature in the occupied zone. Occupants are often seated at a lower height than the thermostat, and therefore, at a lower temperature in the stratified environment provided by UFAD. To maintain the comfort of building occupants, the thermostat setpoint should be increased by up to 1°F to 2°F (0.5°C to 1°C) relative to settings with overhead systems.[1,15]

Whether the UFAD system is constant or variable air volume, supply air temperature should be around 62°F to 65°F (17°C to 18°C) to maintain stratification and avoid discomfort,[1,7] and airflow rates should be near instantaneous space cooling requirements and within the range recommended by the diffuser manufacturer. These building operator-managed parameters control air stratification and comfort conditions in the space. Furthermore, it is the supply air temperature setpoint (higher than with overhead systems) that reduces chiller energy use by extending the economizer cycle and improving instantaneous cooling plant performance.

The lifetime of an office building is far beyond the tenure of specific occupants. Ongoing training of new operators and occupants is important to ensure satisfactory long run system performance with UFAD than with conventional systems. Because UFAD is a new technology[1] with fundamental differences, operation and maintenance manuals should highlight key differences with UFAD.

New Systems are New to Everyone

Table 1 summarizes the roles of the individual participants in realizing the potential benefits of UFAD. It is a simplification of reality, and misses some participants who may affect UFAD performance (e.g., other engineers/consultants, the controls contractor, the testing and balancing contractor, and building owner-tenant relationship). However, it is sufficient to show that achieving the potential benefits of UFAD depends on more collaboration than conventional systems. While it is true that mechanical engineers play a crucial role in making the benefits achievable, collaboration with other participants is required to achieve any of them.

The newness of UFAD means that it is likely to be a novelty to all participants in a project. In the simplified model shown in *Table 1*, mechanical engineers are most likely to have knowledge of UFAD. Without some form of training, the rest of the design team (two participants), contractors (four participants) and users (two participants) would likely only learn about UFAD through guidance the mechanical engineer might provide. Eight of the nine participants in *Table 1* likely would lack training on UFAD, and even awareness of the role they play in system performance. Yet, their roles in system performance are as important as the mechanical engineer's role.

Since UFAD systems are new to many of the participants (including some mechanical engineers), and coordination of so many elements is required for successful performance (e.g., furniture placement, diffuser use, supply air temperature setting), a UFAD consultant/coordinator may be a valuable addition to a project team lacking prior experience with UFAD to ensure that these issues are adequately addressed throughout the project.

Cost/Benefit of Integrated Design

The integrated design approach and increased communication among participating disciplines and trades are necessary requirements for the proper functioning of advanced systems, such as UFAD, where multiple participants affect performance. The integrated design and construction approach should provide performance benefits, but also demands greater initial efforts, study, and design cost. The flow of information among participants becomes more complicated (compare, for example, *Figures 1a* and *1b*), requiring communication among participants who may lack experience in working with some of the other types of participants. With the integrated design paradigm, the concept and schematic-design stages are estimated to consume up to 35% to 40% of total design time and fees where experience is lacking.[16] In addition, advanced systems such as UFAD may require particular training of project participants.

Design and construction teams must be aware of the larger scope with systems such as UFAD before undertaking projects that require this integrated approach, and must be willing to handle it. *Table 2* illustrates the consequences in performance and cost of linear and integrated approaches for conventional and advanced systems.

As suggested in the table, under the linear design and construction approach a conventional system is more likely to perform satisfactorily than an advanced one. In the case of UFAD, the lack of coordination in the linear approach could easily turn some of the potential benefits into problems, if for example, the supply diffusers are located incorrectly, or the wrong thermostat setpoint is used.

Potential Benefits of UFAD		Participants		
		Design		
		Architect	Interior Design	Mechanical Engineer
Improved Indoor Air Quality				Design outdoor air quantities to meet occupant needs (ASHRAE 62.1). Diffuser airflow range should span normal to peak loads. Do not oversize. Avoid complete mixing.
Improved Thermal Comfort		Design diffuser location to minimize conflicts with furniture (coordinate with interior design) and components in the underfloor space (coordinate with mechanical engineer), while maintaining the recommended minimum distance to occupants.	Leave room for diffusers in the furnishing design.	Select an easily adjustable diffuser type (i.e., "salad spinner"). Avoid overcooling by using VAV or thermostatically controlled diffusers in potentially unoccupied spaces. Design diffuser airflow to allow temperature stratification and avoid draft. In open plenum, use design guidelines by Bauman, et al.[3] To account for air leakage, heat transfer through floor and ceiling and thermal decay.
		Welcome the maximum amount of diffusers. This increases temperature stratification and reduces thermal decay in open plenum systems (coordinate with mechanical engineer).		
Reduced Energy Use	Extended Economizer Use			Design air-side economizer control (if applicable). Design water-side economizer (if applicable).
Reduced Energy Use	Higher COP			
Reduced Energy Use	Reduced Cooling Loads	Reduce cooling loads to allow use of UFAD (prerequisite): good envelope thermal characteristics (walls, windows, shading) and low lighting power density and plug loads (coordinate with electrical engineer and interior design).	Reduce interior heat gains in the occupied zone: select light colors and efficient light fixtures to allow low lighting power density, reduce use of task lamps, and use occupancy sensors.	Design airflow to limit conditioning to occupied zone through temperature stratification.
Reduced Energy Use	Reduced Fan Power			Reduce static pressure: minimize duct work in the plenum and use multiple vertical shafts (coordinate with architect).[10]
Easy Reconfiguration		Leave room in the underfloor plenum to allow for changes in equipment (coordinate with mechanical engineer). Consider likely future space distributions when laying out wall partitions.	Provide easy access to underfloor equipment that will require maintenance access (coordinate with mechanical engineer).	Design equipment in the underfloor to allow easy reconfiguration: open plenums, flexible ducts (ducted systems), mobile terminals.

Table 1: Role of participants in the achievement of UFAD benefits. Table 1 continued on facing page.

Either could drastically reduce comfort levels and energy performance, which UFAD is supposed to improve. A poorly implemented UFAD system will cause more problems than it will provide benefits. A greater risk exists with technology that is new to many participants.

Commissioning UFAD

Most of the requirements shown in *Table 1* would be missed in a conventional commissioning process. Commissioning must evolve to address the coordination of the raised floor system, carpet and furnishings, as well as nuances in control such as temperature stratification, comfort and ventilation. This is a larger scope than for conventional systems, which will increase commissioning costs, but is required to realize the benefits of UFAD. Since avoiding errors is usually cheaper than fixing them over the first few years of operation, there could be a net saving. For example, early review of the floor design and construction could reduce later corrections and associated costs.[16]

Finally, one should consider commissioning cost relative to the overall building cost to put things in perspective. In an office building that costs tens of millions of dollars, a commissioning process costing tens of thousands of dollars is three orders of magnitude smaller. Investing a small percentage of the total building cost could greatly improve performance.

Potential Benefits of UFAD		Participants			
		Contractors			
		Raised Floor	Mechanical	Furniture	Carpet
Improved Indoor Air Quality		Install diffusers and underfloor equipment as per design unless problems are apparent. Coordinate resolution with other participants. Avoid covering diffusers with furniture.			
Improved Thermal Comfort		Install diffusers relative to occupants and furniture as per design unless problems are apparent. Coordinate resolution with other participants.			
Reduced Energy Use	Extended Economizer Use				
Reduced Energy Use	Higher COP				
Reduced Energy Use	Reduced Cooling Loads	Install diffusers relative to furniture as per design to allow stratified temperature profile and "upward" air motion.			
Reduced Energy Use	Reduced Fan Power	Seal edge details around the floor plenum to avoid leaks outside the plenum and short circuits that would increase fan energy use.			
Easy Reconfiguration		In open plenums leakage is a major problem: seal floor panels and edge details around the floor plenum to avoid floor leaks, leaks outside the plenum and short circuits.[10] In ducted plenums leakage is not an issue: do not seal floor panels or use sealing on what can be easily removed to ease access.		Locate furniture and interior partitions as per design.	In open plenums leakage control has top priority: overlap carpet and floor panel joints. In ducted plenums ease of access can be the priority: align carpet with floor panel joints or use nonadhesive carpet tile.

Potential Benefits of UFAD		Client	
		System Operator	User
Improved Indoor Air Quality		Set outdoor airflow to meet occupant needs (ASHRAE 62.1). In VAV–Maintain SAT to the recommended minimum (65°F [18°C]) to reduce airflows and avoid air mixing.	Change thermostat setpoint instead of having the diffuser permanently closed, which could compromise IAQ.
Improved Thermal Comfort		Adjust thermostat setpoints based on UFAD characteristics of temperature stratification and higher supply air temperature. Increase SAT in periods of low cooling loads.	Adjust diffuser to suit thermal comfort preferences. Report complaints to the designated operations contact.
Reduced Energy Use	Extended Economizer Use	Use economizer. Increase SAT in periods of low cooling loads. Maintain supply air temperature (to the space) about 65°F (18°C). Account for thermal decay (4°F to 8°F [2°C to 4°C]) in open plenum.	
Reduced Energy Use	Higher COP	Maintain supply air temperature about 65°F (18°C). Account for thermal decay 4°F to 8°F (2°C to 4°C) in open plenum.	
Reduced Energy Use	Reduced Cooling Loads	In VAV–Maintain SAT to 65°F (18°C) to avoid higher airflow settings that break down temperature stratification.	Reduce unnecessary heat gains in the occupied zone: select energy efficient equipment, use the window blinds, turn off computers and task lights when they are not in use.
Reduced Energy Use	Reduced Fan Power		
	Easy Reconfiguration		

Table 1 (continued from previous page): Role of participants in the achievement of UFAD benefits.

		Design/Construction Approach	
		Linear	Integrated
HVAC System	Conventional	Business as usual. Satisfactory performance. (*Business as usual.*)	Minor performance improvements. (*Higher design costs.*)
	Advanced (UFAD)	Poor performance. Not satisfactory. (*Waste of money.*)	Optimal system's performance. Benefits achieved. (*Investment. The benefits pay off the higher design costs.*)

Table 2: Design approaches and system types. Performance and financial (in italics) consequences.

UFAD and LEED®

With the increasing popularity of the LEED rating system, some designers use UFAD systems to achieve higher scores.[17] UFAD can contribute to a few LEED-New Construction credits. First, the energy benefits can be reflected in the building energy model, and enhance the energy optimization score in the energy and atmosphere (EA) category. Second, finer-grain control of airflow is a requirement of environmental quality credit EQc 6.2: Controllability of Systems (enhanced lighting controllability is another requirement).

Third, individual control of supply diffusers widens the comfort window (i.e., ranges of temperature and humidity) to comply with the requirements of environmental quality credit EQc7.1: Thermal Comfort. A wider comfort window makes it easier for the system to achieve this credit.[17] On the other hand, ANSI/ASHRAE Standard 55-2004, *Thermal Environmental Conditions for Human Occupancy*, limits temperature stratification and draft, both of which require special care in the design and implementation of UFAD systems, and depend on the system settings as much as they do on diffuser location relative to occupants. However, while the requirements of the standard encourage system designers to pay attention to temperature stratification and draft, this should not endanger the achievement of credit EQc7.1, since stratification and draft depend on factors beyond the design.

As discussed previously, realization of the potential benefits of UFAD that contribute to LEED credits depends on many participants, most of whom are outside the design team and the LEED terms of reference. The LEED commissioning prerequisite is limited to energy and atmosphere issues (EAp1), and fails to address comfort and ventilation. Considering that projects applying for LEED certification are likely to include advanced systems, LEED should extend the scope of the commissioning prerequisite to include all the performance features of these systems. In addition, LEED should enforce ongoing review of system operation and performance. With these two provisions, LEED could help ensure that green designs become green buildings.

Conclusions

Underfloor air-distribution systems offer the potential for improved indoor air quality and thermal comfort, reduced energy use, and easier reconfiguration compared with conventional overhead ventilation systems. However, achieving these benefits depends on the participation of architects, interior designers, contractors, facility managers, system operators, and occupants, as well as those working on the mechanical design. These participants require training on UFAD to understand their role in helping to achieve the full benefits of this system.

Advanced building technologies vary in the range of participant types whose actions affect success. A rooftop photovoltaic system may operate seamlessly without occupant or operator intervention. An active solar water heating system may require more operator expertise. Achieving good performance is most challenging with systems that involve the largest number of participant types (designers, contractors, operators and occupants), such as UFAD. The increased number of participant types increases the complexity of design and implementation, and therefore, the risk of problems.

A change in commissioning practices would help to mitigate the risk of poor performance. Commissioning should reflect the full range of performance goals, and ensure that all the benefits sought from the technology are achieved in reality. LEED should expand the scope of commissioning requirements and enforce ongoing review of system performance. Since long-term attainment of performance objectives makes a building green, performance should be the criterion to obtain or maintain certification.

Realizing the benefits of advanced systems such as UFAD requires integrated design and enhanced commissioning, which are processes that cost time and money. Design teams must be aware of the extra initial design costs, and use advanced systems only if they can afford them. UFAD should only be an option for design teams willing to change their design approach and commissioning practices to avoid problems that can rival the benefits.

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