Enhancing Productivity While Reducing Energy Use in Buildings

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Indoor air quality (IAQ) and air temperature (T) have powerful effects on the efficiency with which work can be performed in schools and offices. Huge amounts of energy are used to keep these parameters constant at levels which represent a compromise between group average requirements for subjective comfort and energy conservation. Human requirements change with task requirements and from hour to hour, so the levels at which T & IAQ are maintained are at best a crude approximation to what would be the most efficient use of energy in buildings. Different individuals have very different requirements for health, comfort and efficient performance—the three ascending levels of the human criteria hierarchy. Symptoms of ill health and discomfort have powerful effects on the efficiency with which work can be performed in schools and offices, so even a narrow economic focus requires that indoor environmental effects at all three levels be considered.

The national economic interest would best and most rapidly be served by the establishment of a virtual institute to actively apply and orchestrate three very different lines of research to establish the viability of any proposed solution to the conflict between energy conservation and productivity: (1) scientific studies of the chain of cause and effect at all three levels of the above hierarchy; (2) engineering development of innovative solutions; and (3) solution-oriented field intervention research in schools and offices, with users in the loop. Current practice is to start at (1) with a scientific breakthrough in the laboratory, proceed to (2) with engineering development of viable products, substituting marketing for (3). This is a slow, expensive and uphill road to follow. Scientific understanding has often followed engineering optimization of solutions that emerged empirically in the field. The advantage of reverse-flow field-to-laboratory development is that it provides the "pull" that is needed to develop

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successful products. A field trial of an innovative solution creates facts that must be scientifically explained, such as why it did or did not work, and if it did, justifies engineering effort and a subsequent return to the field to demonstrate in a wider context the applicability of the scientific explanation and the acceptability of the engineering solution. A national "IEQ Institute" would take an entrepreneurial approach to the introduction of new solutions.

In this paper, a range of potentially very effective solutions to the conflict between energy conservation and productivity are proposed. They have synergy, in the sense that they work towards the same end and would work very well together, but the claim that they would help to solve the conflict is sometimes based on experience and insight rather than on established facts. Some represent a "technological fix" that users would not even notice, while others affect users noticeably. In both cases, the field-to-laboratory approach would advance knowledge and accelerate the "idea-to-widespread adoption" process while ensuring rapid failure of ideas that either do not work or would be unacceptable to users even if they did work. A technological fix of the problem should include pollution source strength reduction by selection of materials and by point exhaust, increased ventilation rates using energy recovery from exhaust air, and efficient sub-micron filtration to remove respirable airborne particles. Users must be involved in solutions involving energy storage in the building structure and in solutions requiring user empowerment, such as individual control of microclimate, redistribution of energy between individual microclimates, openable windows, natural ventilation and closed-loop building operation with users in the loop. In all of these cases, field intervention experiments by the proposed IEQ Institute would be an appropriate first step.

Some key concepts discussed in this paper

- IEQ (Indoor Environmental Quality): Temperature, IAQ, humidity, draft, noise, lighting, daylighting, space, etc.
- IAQ (Indoor Air Quality): Gaseous and particulate metrics of air pollution.
- PAQ (Perceived Air Quality): Based on subjective judgments of the acceptability of odor and irritation effects.
- The Human Criteria Hierarchy for indoor environmental effects on people: Health, comfort & performance (in ascending order) must all be considered, as the limiting criterion may be found at any level of this hierarchy.
- The 3.I principle of User Empowerment:
- Insight, Information and Influence are all essential if learning is to take place.
- The Idea-to-Widespread Adoption process:

1. Scientific studies to establish cause and effect
2. Engineering optimization
3. Field intervention trials of applicability and acceptability

- Energy conservation or productivity?

The problem addressed in this paper is the conflict between the undoubted need to reduce energy use in buildings and the reasonable economic requirement that energy conservation initiatives should not impact indoor environmental quality in offices and schools in such a way as to cause negative effects on productivity. The bulk of the energy used in offices and schools is for ventilation and thermal conditioning. It is therefore logical to begin by documenting the extent to which productivity is affected by air quality and by temperature.

Indoor Air Quality Effects on Productivity

Recent research at the International Centre for Indoor Environment & Energy in Denmark has demonstrated conclusively and for the first time that the efficiency with which office work can be performed is decreased by poor air quality (Wargocki et al. 2000a). In three independent experiments in real offices, removing a source of pollution (Wargocki et al. 1999, Lagercrantz et al. 2000) and increasing the supply of outside air when the same source of the air pollution, a well-used carpet taken from an office, was always present (Wargocki et al. 2000b) have both been shown to significantly increase the objectively measured performance of simulated office tasks. The subjects did not know the ventilation rate or whether the source was present behind a screen. Each exposure lasted almost five hours and the subjects were young women. The tasks included typing text onto a computer screen, numerical calculation, proof-reading text and responding in their own words to open-ended questions. They thus represent a cross-section of the tasks that are commonly performed in offices and schools, and may confidently be claimed to predict the likely effect of air quality on productivity in these types of building.

The mechanism by which performance was reduced is believed to be the inducement of several Sick Building Syndrome symptoms such as headache and fatigue, as the subjectively reported intensity of such symptoms was significantly affected by the exposures, and in the expected direction. Field studies have shown that SBS symptoms of this kind are more prevalent in poorly ventilated rooms, as indicated by measured CO_2 levels during occupation (Apte et al. 2000). Exactly how this occurs and what aspects of indoor air chemistry are involved is not known. The observed effects on performance are large enough to be economically significant—a 6.5% decrease in performance in indoor air that was no more than realistically polluted, in comparison with indoor air that was unpolluted by the carpet but still polluted by bioeffluents from six occupants, all using VDUs that are themselves believed to be a source of indoor air pollution, as discussed in later sections of this paper.

Prior to these experiments, the prevalent belief among indoor environment professionals was that while poor indoor air quality might reduce productivity by affecting health and thus absenteeism, there were no direct effects on productivity (Fisk & Rosenfeld 1997). This view can be traced back to experiments by the New York State Commission on Ventilation (1923), in which no effects on typing or other simulated office tasks could be shown even when ventilation rates were reduced so that CO_2 levels reached 5000 ppm. These negative results seem likely to have dissuaded other researchers from undertaking experiments to demonstrate effects of air quality on performance at the much higher levels of outside air ventilation rate which occur in modern offices and schools. However, Nunes et al. (1993) showed that Canadian office workers reporting Sick Building Syndrome (SBS) symptoms performed computerized diagnostic tests less well than did subjects reporting no SBS symptoms, and Myhrvold et al. (1996) showed that Norwegian school children performed a diagnostic test of mental performance less well in classrooms with lower air change rates.

The most recent experiment cited above (Wargocki et al. 2000b) provides reliable evidence that increasing the outdoor air supply rate from the 3.0 Liters/second /person that is typical of home offices, to the 10.0 L/s/p that is now recommended for commercial office buildings in most countries would significantly improve the performance of office work. A further improvement occurred when the outdoor air supply rate was increased to 30 L/s/p. The quantitative relationship was a 1.8% increase in performance for each two-fold increase in the outdoor air supply rate expressed per unit of pollution load (i.e. per person or per olf) over this range, or a 1.6% increase in performance for each two-fold decrease in pollution load. On a national scale, assuming there are 95 million full-time workers paid an average of $36k per year in the USA, a two-fold increase in ventilation would cause an increase in performance worth $61.6 billion per year. Against this saving must be set the running costs for conditioning the additional outside air used to increase the ventilation rate. At least part of the benefit of improving the ventilation is the removal of airborne particles. Supply air filtration performs this function in systems with recirculation, but filters in themselves may be a source of airborne particles (Croxford et al. 2000). Replacing a used supply air filter with a clean one was shown by Wyon et al. (2000) to cause office workers to feel better and also to improve their self-estimated productivity by 5.7%. The use of air cleaners to remove airborne particulates in schools and offices is suggested in a subsequent section of the present paper.

Milton et al. (2000) will show in a forthcoming paper that the risk of sick leave was significantly associated with local rates of ventilation in a large enterprise employing 3720 people in Massachusetts, USA. The relative risk of short-term sick leave was 1.5 among the 600 office workers. The mechanism for this effect is believed to be the increased cross infection that occurs at low outdoor air supply rates, particularly for upper respiratory tract (URT) infections. Increased ventilation lowers the density of airborne bacteria and virus molecules. Sick leave constitutes a cost on any enterprise and thus reduces productivity. Without assuming any effect of the increased URT infection rate on the performance of employees who are not absent on sick leave, the authors calculate that net savings of $400 per employee would result from improving outdoor ventilation rates from 12 to 24 L/s/person, yielding annual savings of $22.8 billion per year on a national scale in the USA. National savings of $6 to $16 billion annually had been predicted by Fisk and Rosenfeld (1997) on the basis of earlier studies of cross-infection rates for URT at different ventilation rates, making conservative assumptions. It should be noted that these savings due to reduced sick leave for URT infections would be in addition to the direct effect of increased ventilation on performance that was estimated above.

Thermal Effects on Productivity

Personal experience is sufficient to convince most people that it is difficult to study or perform office work effectively when it is even slightly too hot or too cold. That there is a direct effect of the thermal environment on mental work is supported by a wealth of published experimental results, extensively reviewed by Wyon (1993, 1994, 1996a) and by Fisk and Rosenfeld (1997), who have conservatively estimated that improving the thermal environment in US office buildings would result in a direct increase in productivity of 0.5% to 5%, worth $12 to $125 billion annually. While the distracting effect of thermal discomfort is obvious, other thermal effects in offices and schools are equally important but not intuitively obvious or perceptible by personal experience, as discussed below.

Many symptoms of environmentally induced distress, including many that are conventionally included in the Sick Building Syndrome, are experienced more intensively at mildly elevated temperatures, even within the range providing thermal comfort for more than 80% of the population, i.e. 20-24 C (68-75 F). The effect has been reported in several field intervention experiments (Krogstad et al. 1991, Mendell et al. 1999) but is not apparent in cross-sectional studies, most probably because indoor temperatures change continuously—they are not a permanent characteristic of a given indoor volume. By exacerbating SBS symptoms, elevated indoor temperatures can have an additional, indirect effect on school and office productivity.

Perceived air quality is much lower at moderately raised indoor temperatures and humidities (Fang et al. 1999). A change from 18 C and dry to 28 C and humid can increase the proportion dissatisfied from 10% to 90%, and the thermal effect is greater for clean air than for normally polluted indoor air. It has been shown in field intervention experiments that the performance of office work decreases by 1.5% for every increase by 10% in the percentage dissatisfied with indoor air quality (Wargocki et al. 2000b), and although the experiments on which this estimate is based involved manipulating pollution sources or ventilation rates, not temperature or humidity, it is quite possible that thermal effects on perceived air quality (PAQ) constitute a further mechanism by which thermal effects on productivity may be occurring.

There are large individual differences in preferred air temperature, as much as 10 K (= 18 F degrees) in standard clothing. Wyon (1996b) reviewed estimates of inter-individual variation in neutral temperature and estimated that individual control of 3 K about the group average neutral temperature, i.e. a range of 6 K (= 11 F degrees) would be necessary for 99% of office workers in their preferred clothing to achieve thermal neutrality. People use clothing adaptively to compensate for individual differences if they are allowed to do so. Individual differences are lower when no dress code is in effect, as people who have a low neutral temperature tend to dress lightly, and vice versa, up to the limits imposed by convention and decency. Altering clothing insulation is a rapid and effective means of altering the whole-body rate of heat loss to the environment by a few multiples of 10 watts, which is sufficient to adjust for most individual differences, but conventional clothing is unevenly distributed over the body surface and adjustment of the insulation value often results in “thermal asymmetry”, i.e. some parts of the body being too cold, while others are too hot. This is not always acceptable. The development of clothing that could more easily and comfortably adjust to a range of room temperatures would contribute enormously to energy conservation in buildings, assuming that users were in the control loop, as discussed in later sections. The thermal insulation of seating can also be used adaptively, and should be regarded as an additional clothing item.

Productivity is reduced when many individuals have to occupy the same indoor volume with no individual means of adjusting the temperature they experience, as thermal effects progressively reduce the performance of those whose neutral temperature is not exactly equal to the group average—the neutral temperatures of 40% of any group of office workers differ by at least 1 K (1.8 F degrees) from the group average, while those of 9% differ by at least 2 K (3.6 F degrees). Wyon (1996b) has estimated that individual control equivalent to being able to select air temperature in a 4 K range (plus or minus 2 K, or 3.6 F degrees) would lead to an increase of about 3% in the performance of both logical thinking and very skilled manual work, and to a 7% increase in typing performance, relative to performance maintained at the group-average neutral temperature. Tsusuki et al. (1999) have recently shown that desk-mounted devices are easily capable of providing this degree of individual control. The advantage of controlling the microclimate is that it can be achieved in minutes with only about 100 watts of installed power per person, whereas controlling room temperature requires about 1000 watts of power per person and can still take hours. The rate of metabolic heat production per person is about 100 watts, and the time constant of the body is 20-30 minutes. Microclimate control is better matched to this human scale than is room temperature control.

There are many reasons why individuals differ in terms of preferred air temperature, the thermal parameter that is most often controlled by HVAC systems in the US, followed by humidity. The most influential individual differences are in the rate of metabolic heat production, which is largely determined by activity, and in clothing insulation and vapor diffusion resistance, as discussed above. Age and gender differences in these factors can lead to systematic differences in thermal preference between groups, but in real buildings as opposed to laboratories, the variance between occasions for the same person is as large as the variance between randomly selected individuals (McIntyre 1980). This is more because activity and clothing may differ between occasions than because subjective preference is unstable. Humidity, air velocity and thermal radiation exchange with hot or cold surfaces that are close to a person will obviously bias preference for air temperature, and these may differ spatially within a building as well as over time. Desk-mounted devices usually provide individual control of thermal comfort by altering air velocity and surface temperatures close to a person, as this can be done without affecting other occupants of the same space, while air temperature differences induced locally will rapidly have an effect on the rest of the space.

Energy Efficiency

HVAC systems in conventional buildings provide thermal background conditions of air temperature and humidity and are designed to maintain these factors as uniformly constant as possible within each control zone, which may be a whole floor of a multistory building with several hundred occupants. The set points for different zones are in principle the same. Division into zones is to reject the influence of external disturbances, such as solar gain, and internal disturbances, such as changing lighting power or occupancy, which may be expected to differ systematically between zones. Although large amounts of energy are used to maintain air temperature and humidity at the set points in each zone, these represent crude approximations to the thermal conditions that would most enhance individual health, comfort and productivity. As the ultimate purpose of using energy in buildings is not to maintain conditions as close as possible to set points, but to enhance the health, comfort and productivity of the occupants, current practice is not an efficient use of energy.

The same is true of air quality. Individual differences in sensitivity to air pollution are much larger than individual differences in thermal preference. This is true for sensitivity to inorganic gaseous and particulate materials in indoor air and particularly true for sensitivity to allergens, which are usually organic. Both inorganic and organic air pollution can enter with outdoor air or originate from indoor sources such as building materials, mold or bacterial growth. Hypersensitive individuals may have thresholds of sensitivity—the airborne pollution concentration that will cause irritation—that are 100 000 times lower than those of normally healthy people, and people who have developed true allergies may have thresholds of sensitivity 10 times lower than this (SOU 1989). It is believed that repeated exposure to allergens can lower thresholds of sensitivity, leading to the development of allergic symptoms where none occurred before, so it is important for all occupants, not just for particularly sensitive individuals, to maintain good IAQ, with low concentrations of gaseous and airborne particulate pollution. The traditional approach is to ventilate indoor spaces with large volumes of outside air. While in modern offices and in cool weather this can sometimes serve to remove excess heat and thus to reduce the cooling load and save energy that would otherwise have to be used for this purpose, so that maintaining good IAQ is “free”, during hot weather thermally conditioning the outdoor air flow required to maintain acceptable IAQ represents the largest use of energy in buildings. Proof that IAQ affects productivity provides an economic justification for using energy to maintain acceptable IAQ, but energy conservation goals mean that more efficient ways of doing so will have to be developed. Compromising health and productivity to save energy is both unimaginative and unacceptable.

In the following sections some new ways of enhancing productivity in school and office buildings while reducing the energy used to optimize thermal and IAQ conditions for their occupants will be introduced. Technical improvements in the efficiency with which energy is used to meet conventional HVAC goals, such as more efficient compressors or better insulation, will not be addressed.

Technological Fix Solutions

Conserving energy by means which do not affect health, comfort or productivity, do not alter occupant behavior and in the ideal case are not even be noticed by occupants, is popularly called a "technological fix". The following solutions come under this heading.

Pollution Source Strength Reduction

International ventilation standards of minimum ventilation are in the process of being altered to take account of the fact that the flow of outside air must not only remove bioeffluents generated by the occupants, but also other forms of air pollution originating from indoor sources. The source strength of non-human sources of indoor air pollution, in terms of their contribution to degrading perceived air quality (PAQ), may exceed that of the occupants (Fanger 1988). Their source strength in terms of how they affect health and productivity may be greater still, as bioeffluents are considerably less toxic and irritating than the other air pollutants found in indoor air. The energy used to condition the outside air that is needed to dilute and remove air pollution from these other sources can be radically reduced by selecting materials with low emission. This applies not only to building materials, but also to furnishing materials such as floor and wall surfacing, carpets, rugs and curtains, and to equipment such as business machines. At present, manufacturers in some countries can voluntarily submit samples of their products for emission testing with respect to PAQ, and architects are encouraged to select materials found to have low emission by using this criterion, but there is no legal obligation for manufacturers to document emissions or for architects to take account of them. If selection of materials with a low impact on PAQ would increase the first cost of a building, only clients with a long-term interest in the running cost are likely to follow this good practice. Field trials which document the impact of materials selection on HVAC costs, the acceptability of low-emitting materials to occupants and the additional economic benefit in terms of the impact of better IAQ on health and productivity are urgently required before this potentially huge new avenue for energy conservation can be properly exploited. Augustin and Black (2000) report on a workshop at the recent conference “Healthy Buildings 2000” which dealt with current labeling schemes for materials emissions, but even this group did not deal with evaluating the benefits of materials selection for energy conservation in buildings or the likely impact on health and productivity. In view of the very large energy savings which could result, with nothing but benefits for health, comfort and productivity, this whole area should be a high priority for DOE-funded R&D, deployment initiatives, demonstration projects and validation.

Point Exhaust

That air pollutants should be removed at source wherever possible is the basis for materials emission testing and materials selection. Where the source must be physically present in a building for some reason, the principle still applies. Point exhaust is routinely used in industrial buildings to remove dust and fumes at their source, in fume cabinets in chemical laboratories and even in operating rooms in hospitals, to reduce the exposure of operating room staff to the anaesthetic gases administered to the patient, but not in schools or offices. This represents another massive opportunity for energy conservation, as follows.

Office machinery such as copiers and laser printers are sources of volatile organic compounds and ozone, which are now known to react with each other to form more aggressive but short-lived daughter products in indoor air (Wolkoff et al. 1993, Wolkoff 1995, Knudsen et al. 2000, Lam & Lee 2000). The hot components in all electronic equipment such as PCs and other types of printer are coated with flame retardants which are emitted when the equipment is operated, at a rate which is highest in new equipment. The most commonly used flame retardant chemicals, organophosphates and polybrominated compounds, are extremely toxic and have been shown to be pervasively present in samples of office dust (Pardemann & Salthammar 2000). All electronic equipment, whether or not it needs a fan, takes in room air for cooling temperature-sensitive components. Room air contains airborne dust, which is deposited on the component boards and is heated to temperatures well above 70 C (158 F) when the equipment is operated. Dust which is heated above 70 C undergoes three changes: it becomes more finely divided and dry, it emits the air pollutants it has absorbed, and it becomes a source of unpleasant odor (Hirvonen et al. 1990). These changes, particularly the increase in the number of sub-micron and therefore respirable particles, have been shown to significantly reduce lung function (Raunemaa & Sammaljärvi 1993). It is clear from the above that the air which has entered the casing of electronic equipment, and particularly copiers and laser printers, represents a source of air pollution, is not fit to breathe and should leave the building as rapidly as possible. Point exhaust from the casing of all electronic equipment would achieve this, and it would also remove the heat they generate, which amounts in offices to at least as much as is generated by occupants (100 W per occupant). Removing it at source would have several beneficial effects: 1) it would reduce the cooling load on the building, by an amount many times larger than the energy required for the point exhaust system; 2) it would raise supply air temperatures, eliminating complaints of draft; 3) historic buildings which cannot be used as modern offices because their cooling and ventilation capacity is not able to deal with larger heat loads than occupants plus lighting could be brought into use again as offices; and 4) the exhaust air flow would be very suitable for energy recovery and preheating of outside air, as it will be well above room temperature. Field experiments to demonstrate and validate the usefulness of point exhaust are required.

Energy Recovery from Exhaust Air

Whenever the temperature or humidity of the exhaust air rejected from an office or school differs from that of outside air, it represents an in-house energy source that is currently underused. In the simplest case it could be used in counter-current heat exchangers to condition the incoming supply air, utilizing even the latent heat of more humid air by allowing outgoing moisture in warm air to condense on conducting surfaces separating incoming from outgoing air. This can be done centrally, zone-by-zone or even room-by-room. Counter-current heat exchangers have no moving parts and are extremely cheap to install and run. They work well in summer and in winter. They are applicable in the simplest classroom and would permit greatly increased ventilation rates at a very low first cost. They would pay for themselves very quickly in terms of reduced running costs. The reason they are not used may simply be that they are low-tech and the profit margin on them would therefore be very small. They do not impact the occupant in any way.

Heat pumps can be used to alter the temperature of the energy flow that is recovered from exhaust air. By this means the recovered energy can be used for other purposes than conditioning incoming outside air, e.g. to heat hot running water or to heat or cool the water circulating in radiant heating or cooling systems. Heat pumps similar to the ones in domestic refrigerators can be mass-produced at a very low unit cost and are suitable for distributed use in buildings, where they can recover energy from exhaust air and either use it immediately or store it as described. Large heat pumps located in the central HVAC plant room are more expensive but also more efficient. In Sweden energy recovery from exhaust air is mandatory in all buildings except in dwellings with two or fewer apartments. A typical apartment building easily recovers enough heat from exhaust air to heat all the hot water that is used by the occupants. In schools and offices too little hot water is required for this to be the sole repository of the recovered energy. Low temperature heating and cooling systems in which the floors, ceilings or walls are heated or cooled represent the perfect repository for this kind of recovered energy (Olesen & Petras 2000). In winter they raise the radiant temperature and make it possible to achieve thermal comfort at a lower air temperature. This increases the perceived air quality, as demonstrated by Fang et al. (1999), saving more energy by reducing the outside air flow required to provide subjectively acceptable air quality when this is the dimensioning criterion for the ventilation rate, as is most often the case. In summer they are used for radiant cooling.

Heat recovery systems and low-temperature radiant systems are already available, but unbiased field experiments to demonstrate their effectiveness are required.

Air Cleaners

Air cleaning devices can remove airborne particles from room air, delivering clean room air at a fraction of the energy cost of using outside air, since room air is already conditioned. Electrostatically-enhanced air cleaners have high rates of efficiency in the sub-micron region, retaining particles small enough to pass straight through the nose. They do not have the high fan power and unacceptable noise levels of conventional HEPA filter units. Free-standing units of this kind have been shown to reduce airborne particle density in working offices (Croxford et al. 2000) and to reduce nasal congestion (Skyberg et al. 2000). There is no reason why air cleaners could not become an integral part of office design, graduating from the status of appliance to that of system component. Ventilation air will still be required to remove heat, CO_2 and other gas-phase pollutants, and to provide oxygen, and it will still need to be filtered to remove particles originating outside, but air cleaners can greatly reduce the amount of outside air required for the purpose of removing airborne particles. Many different kinds of air cleaner are available, but unbiased field experiments to determine and demonstrate their relative advantages are required.

Solutions That Affect Building Occupants

The "technological fix" solutions discussed above do not inconvenience users and will conserve energy, but they also involve a modest increase in the first cost or retrofit cost of a building. These increased costs can be recovered over time from the reduced running costs. They are economically justifiable over the complete life-cycle of a building, but if first cost is an insuperable barrier, energy conserving strategies which involve occupants and may inconvenience some of them must also be considered. A number of solutions of this kind are discussed below.

Energy Storage in the Building Structure

Energy can be very effectively conserved at no first cost by storing it in the building structure, transferring heating or cooling power that is available cheaply or free in one period to another when it is needed but would be more expensive, e.g. by using night air to cool the building structure and so reduce the amount of active cooling required during the day, or by allowing a building to warm up during the day to reduce the energy required for heating it at night. Cheap off-peak energy can be stored in the same way. Energy storage is such a cost-effective means of conserving energy that it is becoming economically justified to install and run water or ice storage systems as components of the HVAC system, even though they are huge, costly and complex to run. Energy storage in the building structure has been used throughout history because it is has none of these disadvantages, but it is now regarded as unacceptable because it does inconvenience occupants to some extent—room temperatures cannot be maintained exactly constant and this results in increased complaints. It is very likely that a compromise between energy conservation by this means and thermal discomfort is acceptable under some conditions, but it will be necessary to demonstrate in field experiments that this is so before building controls can be reprogrammed to conserve energy at virtually zero first cost.

Solar energy can be stored in the building structure over a 24-hour cycle. Architects have traditionally used this possibility at the expense of maintaining thermal comfort, and in recent years have increasingly begun to use heavy internal walls and floors exposed to solar gain as passive heat storage components, often in spaces such as corridors or atria that are occupied only intermittently. Radiant heat exchange with occupants close to these walls or floors is always increased, and without expensive means of distributing the heat throughout the building, air temperatures will also be higher, resulting in thermal discomfort in the heat of the day. In buildings with raised floor ventilation, the load-bearing floor below can be used to store energy by causing it to become hotter or colder than room temperature. This does not affect the radiant temperature experienced by the occupants but will inevitably affect supply air temperatures at some points in the storage and recovery cycle.

Workstation-mounted devices that permit some degree of individual control of the microclimate experienced by each occupant can increase the range of acceptable supply air temperatures. They are discussed in the following section.

Individual Control

Simple devices at each work station can alter the thermal environment experienced by each occupant, compensating for air temperatures that are too high by raising the air velocity, thus increasing convective cooling, and compensating for air temperatures that are too low by locally raising the radiant temperature. Tsusuki et al. (1999) have shown that such devices can maintain thermally comfortable conditions over a considerable range of air temperature. Their primary purpose is to permit individuals with widely different thermal requirements to be thermally comfortable at the same room air temperature, but they are also an effective means of maintaining thermal comfort when room air temperature is above or below what would be ideal at any given time. They are thus a key factor in making it acceptable to store energy in the building structure as described in the previous section.

Wyon (1996b) has shown that individual control of the thermal microclimate can increase productivity by a considerable amount even when the room air temperature is at the group average neutral temperature, and still more when it is below or above. Given that this is desirable, the additional energy used to achieve individual control would be greatly reduced if individual work station units could transfer energy between them, occupants who were too hot transferring heat to those who were too cold, and vice versa. This could be achieved by using small heat pumps to cool or heat the air that is delivered to each work station, linking them together by means of a circulating energy transport medium that might be either water or air. The net energy requirement is zero when the air temperature is equal to the group average neutral temperature, and consists only of transfer losses—a zero-sum energy deployment to achieve 100% thermal comfort instead of the usual 80% in conventional buildings. If air temperatures were permitted to rise in one part of a zone to conserve energy in the building structure, e.g. by deliberately allowing solar gain to affect air and radiant temperatures on one side of a building, energy transfer between work stations would be an effective way of cooling the occupants affected by solar gain while heating the occupants who were unaffected, with no additional energy input except to compensate for transfer losses when the building was in cooling mode overall. Transfer losses become heat, reducing the heating required when the building is in heating mode. A system of this kind could easily be constructed. Field experiments to demonstrate applicability and acceptability would be required.

User Empowerment

Individual control of the microclimate at each workstation is a form of user empowerment. As described above, each user can utilize the cooling or heating power that has been delegated to the workstation unit, and the only compromise involved is that background conditions will not always be ideal for every user. This is the normal situation in conventional buildings for all users except those who happen to have thermal requirements equal to the set temperature. Energy-conserving solutions that store energy in the building structure and result in cyclical changes in the set temperature can thus be deployed with very little impact on any individual. With energy transfer between workstations, users do not need to consider the energy consequences of exercising their preference, but this is not always the case. In the following sections, openable windows and natural ventilation require user empowerment, and user choices have a direct effect on energy conservation. It is therefore necessary to consider whether it is energy-efficient to empower users to this extent.

The purpose of most of the energy used in buildings is to improve environmental conditions for users. This process is only energy efficient if it promotes user health, comfort and productivity, whether or not it achieves the usual engineering goals of maintaining constant indoor environmental conditions. As user requirements depend on task demands and on user activity, fatigue and health, all quantities that change from minute to minute, only the users themselves can respond to them to continuously optimize energy use. Anything else is a gross approximation and so inefficient. It is thus axiomatic that "Empowerment Enables Energy Efficiency", although most building operators will claim the reverse.

This "4.E" axiom will only result in energy conservation when users are properly motivated and informed. As in all cases where learning must take place, the 3.I Principle applies: users must be given sufficient Insight, Information and Influence. Providing any two of these will fail to ensure that learning can take place. For example, users with insight and influence but no information cannot respond intelligently, while users with insight and information but no influence cannot respond at all. A good illustration of these two unsatisfactory situations is in learning to play darts. i.e. being unable to see the board or having no darts. Insight into how to throw darts and how the scoring system works is similarly essential for success. Insight in the case of a building user is an understanding of how the building HVAC system works and which actions would conserve energy. Information is continuous feedback on relevant indoor and outdoor conditions, on what the HVAC system is doing right now and the current rate of energy use. Influence might consist of an openable window, a personal heating or cooling system, a personal air supply that can be increased or decreased, perhaps equipped with personal supply air filtration, a list of telephone contact numbers to HVAC operations personnel, or a two-way Internet connection to the HVAC system and its operators. Users in conventional buildings have none of these essentials, not even a handbook, a thermometer or access to a thermostat.

The Center for the Built Environment (CBE), established 1997 at the University of California, Berkeley (UCB) by the NSF has developed an Internet home-page linked to a building's HVAC system that can provide both Information and Influence. Users can obtain on-line information from the building system and alter their recorded preferences. Field experiments in which short courses for building users provide a degree of Insight are required to demonstrate how the 4.E axiom and the 3.I Principle apply to building occupants.

Openable Windows

Building occupants are very keen on openable windows, for a wide variety of reasons, some practical, some psychological. They are prepared to put up with considerable disadvantages to retain the advantages, one of which is that they represent user empowerment. Their feasibility is obviously dependent on the meteorological climate and on local air quality and noise conditions. They are much more common in Europe than in the USA, and ways are currently being found to integrate openable windows with modern energy-efficient indoor climate control systems. In the simplest case, the system detects an open window and immediately ceases to ventilate, heat or cool the volume affected, effectively delegating control to the user who opened the window. If this action provides conditions that enhance the users' health, comfort and productivity, and also prevents energy being used to condition that part of the building, it was clearly energy-efficient. However, if users leave a window open onto an empty room, this may not be the case. The control system must monitor occupancy as well as open windows, environmental conditions and energy use in order to respond effectively. Field experiments are required to develop ways of doing so and to determine whether openable windows do conserve energy.

Natural Ventilation

Naturally ventilated office and school buildings are currently being constructed in Europe. Not all of them involve openable windows. Many of them are hybrid buildings which utilize natural ventilation when weather conditions permit, and conventional HVAC systems when they do not. Natural ventilation is only possible if building occupants are able to accept some compromises, e.g. it is quiet but it cannot provide supply air filtration, and as ventilation rates and internal temperatures are affected by wind, sun and the external temperature, users must accept this either as an advantage, as many do, or as a compromise that is acceptable to achieve energy conservation. Many parts of the USA have temperate climates comparable to or better than those of European countries. Field experiments to demonstrate the advantages and disadvantages of natural ventilation in different regions of the USA are required.

Closed-Loop Building Operation

Conventional building control systems are open-loop with respect to the target dependent variables of health, comfort and productivity. They control room temperatures and sometimes humidity but there is no feedback from occupants. This obviously has the potential for being very energy inefficient if the room temperatures and the humidity do not correspond to occupant requirements at the individual level. Massive amounts of energy are currently used to condition empty rooms, to heat occupants who are too hot, cool them when they are already too cold, and alter humidity levels to which they are insensitive. Feedback from occupants is necessary to avoid these wasteful practices. Information on occupancy can be obtained from movement sensors already built into many desk-mounted TACs (Task/Ambient Conditioning systems for individual control of the microclimate), or from CO_2 sensors in the exhaust air from each zone. Information on occupant requirements can be obtained from user interfaces of the kind developed by CBE and described above. On a longer time scale, the Occupant Satisfaction Survey developed by the CBE and administered over the Internet can provide feedback on all building operations, including lighting, cleaning and maintenance. Field experiments to demonstrate how these new possibilities can benefit energy conservation are required.

Leveraging Foreign Investment in Research

In the preceding sections some concrete proposals for new research on energy conservation in buildings as it affects occupants have been described. It will not always be possible to quantify the effects on health, comfort and productivity, but field studies of the solutions proposed should move in these directions. In 1998 a new research center for this kind of research was set up in Denmark—the International Centre for Indoor Environment and Energy (ICIE, from the Danish "Internationale Center for Indeklima og Energi"). Situated in the Energy Engineering Department of the Technical University of Denmark and based on a group of researchers with an established international reputation for research on thermal comfort and perceived air quality under Professor P.O. Fanger, who currently serves as the first Director of ICIE, the initiative will be supported for 10 years by the Danish National Science and Technology Research Council (STVF). The proposal to perform the research necessary to reconcile the requirements of energy conservation with those of building occupants was one of 40 competing proposals to establish an international center of excellence in engineering research and development. It was selected for generous support because energy conservation measures in buildings are known to have led to negative consequences for health, comfort and productivity, while conventional measures to improve indoor environmental quality in buildings, e.g. by increasing the ventilation rate, almost always increase energy use. The research currently being undertaken at the ICIE is multidisciplinary, involving experts in building, HVAC, and indoor air chemistry as well as experts in human health, comfort and performance assessment. It is carried out in advanced climate chambers, in simulated offices, and in the field. The findings are not always transferable to US buildings.

It is therefore proposed that a similar research initiative should be taken in the US. It could be a "virtual institute" rather than a bricks-and-mortar institute. The "IEQ Institute" would apply the ICIE approach to new and existing US buildings. This would be the most rapid and cost-effective way to ensure that future energy restrictions have no negative consequences for the health, comfort and productivity of the US population. The solutions outlined in this paper would be candidates for research at the new IEQ Institute. However, its brief should not simply be to undertake research, but to expedite the development of successful solutions, from idea to widespread adoption, as set out below.

Expediting the "Idea-to-Widespread Adoption" Process

There are three essential elements in developing effective solutions to the conflict between energy conservation and user requirements:

1. Scientific studies to establish cause and effect;
2. Engineering optimization;

3. Field intervention trials of applicability and acceptability.

Current practice is to start at (1) with a scientific breakthrough in the laboratory, proceed to (2) with engineering development of viable products, substituting marketing for (3). This is a slow, expensive and uphill road to follow, and in the history of science, scientific understanding has often followed rather than preceded engineering optimization of solutions that had emerged empirically in the field. The advantage of departing from the conventional sequence is that it provides the "pull" that is needed to develop successful products. A field trial of the prototype of an innovative solution creates facts that must be scientifically explained, such as why it did or did not work, and if it did, justifies engineering effort and a subsequent return to the field to demonstrate in a wider context the applicability of the scientific explanation and the acceptability of a properly engineered solution. The IEQ Institute would be able to expedite the process by iteratively applying all three stages, in the appropriate order. The research would be contracted out to national laboratories such as National Renewable Energy Laboratory, Oak Ridge, and Lawrence Berkeley National Laboratory, to university research centers, and to private industry, depending on the capability, experience and equipment required for each aspect of the work.

Existing centers for scientific research have no brief to optimize the engineering of proposed solutions, which is essential if ideas are to become reality. This is left to the private sector, which likes to market new solutions as if they were based on science but seldom funds scientific research worth the name or undertakes properly-controlled field intervention studies in schools and offices to determine whether a new solution conserves more energy than existing alternatives and is also acceptable to occupants. The process of taking an idea that would benefit the national energy economy all the way through to widespread adoption can be derailed by the omission of any one of these three stages. A nationally-funded IEQ Institute that was able to coordinate multidisciplinary research and development would serve the public interest by taking an entrepreneurial approach to the introduction of new solutions. Royalties would be earned by protecting the intellectual property that is developed at the engineering optimization stage of the idea-to-widespread-adoption process. Joint development agreements (JDAs) could make this stage in the process self-funding even if the preceding and following stages had to be funded by government to preserve impartiality in evaluating competing solutions. An IEQ Institute would pay for itself many times over in any national economic calculation.

References

Augustin R, Black M (2000) Labeling schemes for material emissions. Report of Workshop 8. In: Workshop Summaries, Healthy Buildings 2000, Helsinki, Finland, 43-48

Apte MG, Fisk WJ, Daisey JM (2000) Indoor carbon dioxide concentrations and SBS in office workers. Proceedings of Healthy Buildings 2000, Helsinki, Finland, 1, 133-138

Croxford B, Tham KW, Young A, Oreszczyn T, Wyon DP (2000) A study of local electrostatic filtration and main pre-filtration effects on airborne and surface dust levels in air-conditioned office premises. Indoor Air, 10 (3), 170-177

Fang L, Wargocki P, Witterseh T, Clausen G, Fanger PO (1999) Field study on the impact of temperature, humidity and ventilation on perceived air quality. Proceedings of Indoor Air ’99, Edinburgh, Scotland, 2, 107-112

Fanger PO (1988) Introduction of the olf and decipol units to quantify air pollution perceived by humans indoors and outdoors. Energy and Buildings, 12, 1-6

Fisk WJ, Rosenfeld AH (1997) Estimates of improved productivity and health from better indoor environments. Indoor Air, 7(3), 158-172

Hirvonen A, Savolainen T, Ruuskanen J, Tarhanen J, Pasanen P (1990) Thermal desorption of settled dust. Proceedings of Indoor Air ’90, Toronto, Canada, 3, 743-746

Knudsen HN, Nielsen PA, Clausen P, Wilkins CK, Wolkoff P (2000) Sensory evaluation of the impact of ozone on emissions from building materials. Proceedings of Healthy Buildings 2000, Helsinki, Finland, 4, 217-222

Krogstad AL, Swanbeck G, Barregård L, Hagberg S, Rynell KB, Ran A, Andersson NH, Calås B, Håkansson Y, Jorulf L, Lindberg G, Persson Å, Samuelsson G (1991) A prospective study of indoor climate problems at different temperatures in offices (in Swedish). Gothenburg, Sweden: Volvo Truck Corporation

Lagercrantz L, Wistrand M, Will U, Wargocki P, Witterseh T, Sundell J (2000) Negative impact of air pollution on productivity: previous Danish findings repeated in new Swedish test room. Proceedings of Healthy Buildings 2000, Helsinki, Finland, 1, 653-658

Lam S, Lee SC (2000) Characterisation of VOCs, ozone and PM10 emissions from office printers in an environmental chamber. Proceedings of Healthy Buildings 2000, Helsinki, Finland, 4, 429-434

McIntyre DA (1980) Indoor Climate. London, UK: Applied Science

Mendell MJ, Fisk WJ, Petersen M et al. (1999) Enhanced particle filtration in a non-problem environment: summary findings from a double-blind crossover intervention study. Proceedings of Indoor Air ’99, Edinburgh, Scotland, 4, 974-975

Milton DK, Glencross PM, Walters MD (2000) Risk of sick leave associated with outdoor air supply rate, humidification and occupant complaints. Indoor Air (in the press)

Myhrvold AN, Olsen E, Lauridsen Ø (1996) Indoor environment in schools—pupils' health and performance in regard to CO_2 concentration. Proceedings of Indoor Air '96, Nagoya, Japan, 4, 369-374

New York State Commission on Ventilation (1923) Report of the New York State Commission on Ventilation. New York, USA: Dutton

Nunes F, Menzies R, Tamblyn RM, Boehm E, Letz R (1993) The effect of varying level of outdoor air supply on neurobehavioural performance function during a study of sick building syndrome (SBS). Proceedings of Indoor Air '93, Helsinki, Finland, 1, 53-58

Olesen B, Petras D (2000) Low temperature heating—high temperature cooling of buildings. Report of Workshop 13, In: Workshop Summaries, Healthy Buildings 2000, Helsinki, Finland, 67-70

Pardemann J, Salthammar T, Uhde E, Wensing M (2000) Flame retardants in the indoor environment, part 1: specification of the problem and results of screening tests. Proceedings of Healthy Buildings 2000, Helsinki, Finland, 4, 125-130

Raunemaa T, Sammaljärvi E (1993) Changes in indoor air and human response induced by electric heating units. Proceedings of Indoor Air '93, Helsinki, Finland, 1, 265-270

Skyberg K, Skulberg KR, Kruse K, Madsø L, Levy F, Kongerud J, Djupesland P (2000) Subjective symptoms and nasal congestion after installation of electrostatic air cleaners in the office environment—a double blind intervention study. Proceedings of Healthy Buildings 2000, Helsinki, Finland, 2, 55-57

SOU (1989) The nature, prevalence and prevention of allergy. Sveriges Offentliga Utredningar (SOU76-78), in Swedish. Stockholm, Sweden: Allmänna Förlaget

Tsusuki K, Arens EA, Bauman FS, Wyon DP (1999) Individual thermal control with desk-mounted and floor-mounted task/ambient conditioning (TAC) systems. Proceedings of Indoor Air '99, Edinburgh, Scotland, 2, 368-373

Wargocki P, Wyon DP, Baik YK, Clausen G, Fanger PO (1999) Perceived air quality, Sick Building Syndrome (SBS) symptoms and productivity in an office with two different pollution loads. Indoor Air, 9(3), 165-179

Wargocki P, Wyon DP, Fanger PO (2000a) Productivity is affected by the air quality in offices. Proceedings of Healthy Buildings 2000, Helsinki, Finland, 1, 635-640

Wargocki P, Wyon DP, Sundell J, Clausen G, Fanger PO (2000b) The effects of outdoor air supply rate in an office on Perceived Air Quality, Sick Building Syndrome (SBS) symptoms and productivity. Indoor Air (in the press)

Wolkoff P, Wilkins CK, Clausen PA, Larsen K (1993) Comparison of volatile organic compounds from office copiers and printers: methods, emission rates and modeled concentrations. Indoor Air, 3(2), 113-123

Wolkoff P (1995) Volatile Organic Compounds—sources, measurements, emissions and the impact on indoor air quality. Indoor Air, Suppl.3, 9-73

Wyon DP (1993) Healthy buildings and their impact on productivity. Proceedings of Indoor Air ’93, Helsinki, Finland, 6, 3-13

Wyon DP (1994) The economic benefits of a healthy indoor environment. La Riforma Medica, 109 (N2, Suppl.1), 405-416

Wyon DP (1996a) Indoor environmental effects on productivity. In: IAQ96 Proceedings “Paths to better built environments”, Baltimore, Maryland, USA: ASHRAE, 5-15

Wyon DP (1996b) Individual microclimate control: required range, probable benefits and current feasibility. Proceedings of Indoor Air ’96, Nagoya, Japan, 1, 1067-1072

Wyon DP, Tham KW, Croxford B, Young A, Oreszczyn T (2000) The effects on health and self-estimated productivity of two experimental interventions which reduced airborne dust levels in office premises. Proceedings of Healthy Buildings 2000, Helsinki, Finland, 1, 641-646.