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Review of Health and Productivity Gains From Better IEQ

William J. Fisk

Environmental Energy Technologies Division
Indoor Environment Department
Lawrence Berkeley National Laboratory
Berkeley, CA 94720

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Indoor Environment Department, Lawrence Berkeley National Laboratory, Berkeley, CA.

ABSTRACT

The available scientific data suggest that existing technologies and procedures can improve indoor environmental quality (IEQ) in a manner that significantly increases productivity and health. While there is considerable uncertainty in the estimates of the magnitudes of productivity gains that may be obtained, the projected gains are very large. For the U.S., the estimated potential annual savings and productivity gains are $6 to $14 billion from reduced respiratory disease, $2 to $4 billion from reduced allergies and asthma, $10 to $30 billion from reduced sick building syndrome symptoms, and $20 to $160 billion from direct improvements in worker performance that are unrelated to health. Productivity gains that are quantified and demonstrated could serve as a strong stimulus for energy efficiency measures that simultaneously improve the indoor environment.

KEYWORDS: Air quality, Energy conservation, Health effects, Infectious disease, Productivity

INTRODUCTION

Based on the available literature and analyses of statistical and economic data, Fisk and Rosenfeld [1] estimated the annual productivity gains in the U.S. potentially achievable from improvements in indoor environmental conditions that reduce health effects or directly improve worker performance. An updated and much longer review will be published as a book chapter [2]. This conference article summarizes the updated analyses, incorporates additional updates, and reviews implications for building energy efficiency.

METHODS

Relevant papers were identified through computer-based literature searches, reviews of conference proceedings, and discussions with researchers. The evidence supporting or refuting hypothesized linkages of IEQ with health and productivity was synthesized. Communicable respiratory illnesses, allergies and asthma, and acute non-specific health symptoms often called sick building syndrome symptoms were identified as categories of health effects for further consideration. The economic costs of these adverse health effects were estimated, primarily by synthesizing and updating the results of previously published cost estimates. The economic results of previous analyses were updated to 1996 to account for general inflation, health care inflation, and increases in population [3]. The next and most uncertain step in the analysis was to estimate the magnitudes of the decreases in adverse health effects and the magnitudes of direct improvements in productivity that result from improved indoor environments. These estimates are based on the published data characterizing the strength of associations between indoor environmental characteristics and health outcomes, and on our understanding from building science of the degree to which relevant indoor environmental conditions could practically be improved. Nationwide health and productivity gains were then computed by multiplying the estimated potential percentage decrease in illness (or percent direct increase in productivity) by the associated cost of the illness (or by the associated magnitude of the economic activity).

Improvements in the indoor environment require changes to building design, operation, maintenance, or occupancy. Many of these changes will influence building energy use. A multi-disciplinary international committee [4] has developed a list of building energy efficiency measures and identified the most common impacts of these measures on IEQ. The committee's assessments are the primary source for the discussion of energy implications within this paper.

To make this article understandable to a broad audience, potentially unfamiliar statistical terminology has been minimized. The findings reported in this paper would generally be considered to be statistically significant (e.g., the probability that the findings are due to chance or coincidence is generally less than 5%). Fisk and Rosenfeld [1] and Fisk [2] provide the statistical information on which this conference paper is based.

RESULTS AND DISCUSSION

Communicable Respiratory Illness

A portion of the transmission of common respiratory illnesses, such as common colds and influenza, occurs via infectious aerosols containing virus. Disease transmission via airborne infectious aerosols is theoretically reduced by more efficient or increased rates of air filtration, increased outside-air ventilation, and reduced air recirculation. Air temperature and humidity, which affect the period of viability of infectious aerosols, may also modify rates of disease transmission. Additionally, indoor environmental conditions, for example high mold exposures, may influence occupants' susceptibility to respiratory infections. Field studies, summarized in Table 1, provide consistent and strong evidence that building characteristics significantly influence the prevalence of respiratory illness among building occupants.

In the U.S., four common respiratory illnesses cause about 176 million days lost from work and an additional 121 million work days of substantially restricted activity [5]. Assuming a 100% and 25% decrease in productivity on lost-work and restricted-activity days, respectively, and a $39,200 average annual compensation [3], the annual value of lost work is $34 billion. The total annual cost of providing health care for upper and lower respiratory tract infections is about $36 billion [5]. Thus, the total annual cost of respiratory infections is approximately $70 billion.

A number of existing, relatively practical building technologies, such as increased ventilation, reduced air recirculation, improved filtration, ultraviolet disinfection of air, reduced space sharing (e.g., shared office), and reduced occupant density have the theoretical potential to reduce inhalation exposures to infectious aerosols by more than a factor of two. The studies in Table 1 suggest that changes in building characteristics and ventilation could reduce indexes of respiratory illness by 15% (absence from school) to 76% (influenza in nursing homes). The amount of time spent in a building should influence the probability of disease transmission within the building. If efforts to reduce disease transmission were implemented

Table 1. Summary of studies of the association of building characteristics with communicable respiratory illness. Finding in parenthesis are adjusted for time in the building.

Setting [reference]	Populations Compared	Health Outcome	Findings (adjusted for time in building)
U.S. Army Barracks [6]	Recruits in modern (low ventilation) versus recruits in older barracks	Respiratory illness with fever	33% (12.5%) lower prevalence of respiratory illness in older barracks
U.S. Navy Barracks [7]	Recruits in barracks with UV irradiation of air versus those in barracks without UV irradiation	Respiratory illness with fever	23% (9%) decrease in respiratory illness with UV irradiation
Finnish Office [8]	Office workers with ≥ 1 roommates vs. office workers without roommates	Common Cold	Worker without roommates had 17% (17%) lower risk of > two common colds per year
Antarctic Station [9]	Residents of smaller vs. larger quarters	Respiratory Illness	50% (19%) lower incidence of respiratory illness for residents of larger quarters
NY State Schools [10]	Students in fan ventilated versus window ventilated classrooms	Respiratory illness and absence	41% (41%) less illness and 15% (15%) less absence in window ventilated classrooms
Four US Nursing Homes [11]	Residents of single nursing home with no recirculation of ventilation air and less crowding of common areas versus residents in three homes with recirculation and more crowding	Culture-confirmed type A influenza and total respiratory illness	76% (19%) less influenza and 50% (12.5%) less total respiratory illness in nursing home with no recirculation and less crowding
Gulf War Troops [12]	Troops ever vs. never housed in different types of buildings during Gulf War	Symptoms of respiratory illness	27% (10%) less cough and 16% (6%) less sore throat if never housed in air-conditioned buildings
U.S. Jail [13]	> 7.4 m^2 vs. < 7.4 m^2 space per occupant and high vs. low CO_2 (i.e., low versus high ventilation per occupant)	Pneumococcal disease	Significantly lower incidence if > 7.4 m^2 space; 49% (12%) lower incidence if not in cell type with high CO_2 concentration
40 buildings with office, trade, manufacturing workers [14]	Workers in buildings with high versus normal ventilation rate	Short term absence	35% (35%) less short term absence in high ventilation buildings
Dwellings in Finland [15,16]	168 residents of moldy apartments versus 139 residents of non-moldy apartments	Acute respiratory infection	54% (20%) reduction in number of residents with ≥ 1 respiratory infection during prior year if in non-moldy apartments

primarily in commercial and institutional buildings that people occupy approximately 25% of the time, smaller reductions in respiratory illness would be expected in the general population than indicated by the existing literature. Adjusting for time spent in buildings [2] and considering only the studies with explicit respiratory illness outcomes (i.e., excluding studies with absence or individual symptoms as outcomes) results in nine estimates of decreases in respiratory illness, adjusted for time in building, ranging from 9% to 41% with an average of 18%. The range is 9% to 20%, if the outlier value of 41% (illness in schools) is excluded. This narrower range is adopted, i.e., 9% to 20%, for the potential reduction in respiratory illness. With this estimate and statistics on the frequency of common colds and influenza (0.69 cases per person per year), approximately, 16 to 37 million cases of common cold or influenza would be avoided each year. The corresponding range in the annual economic benefit is $6 billion to $14 billion.

Allergies and Asthma

Approximately 20% of the U.S. population have allergies to environmental antigens [17] and approximately 6% have asthma [18]. Symptoms of allergies and of asthma may be triggered by allergens in indoor air including those from house dust mites, pets, fungi, insects, and pollens [17,19]. Allergens are considered a primary cause of the inflammation that underlies asthma [19]. Asthma symptoms may also be evoked by environmental tobacco smoke [19]. Viral infections, which may be influenced by building factors (Table 1), are also strongly associated with exacerbations of asthma, at least in school children [20]. In a recent review [19], the prevalence of asthma related respiratory symptoms is increased by approximately a factor of two among occupants of homes or schools with dampness problems or molds. In the same review, environmental tobacco smoke exposure, indicated by parental smoking, is associated with increases in asthma symptoms by 20% to 40%.

Based on the scientific literature, we anticipate significant reductions in asthma and allergy symptoms if moisture problems were prevented or repaired, indoor smoking was reduced, and dogs and cats were maintained outdoors of the homes of allergic subjects. However, the benefits of these and other interventions have rarely been studied. While some measures have been found effective in reducing indoor concentrations of allergens [19], except for studies with air cleaners, there are few published experimental studies of the effect of changes in building conditions on the symptoms of allergies and asthma. Measures to reduce exposures to dust mite allergen, such as improved cleaning and encasement of mattresses in non-permeable materials, have reduced symptoms in some but not all studies [19].

Overall, the evidence of a linkage between the quality of the indoor environment and the incidence of allergic and asthma symptoms is relatively strong. Additionally, the exposures that cause allergic sensitization often occur early in life and are likely to occur indoors; consequently, the quality of indoor environments may also influence the proportion of the population that is allergic or asthmatic.

Fisk [2] summarized the results of several recent estimates of the annual costs of allergies and asthma in the U.S., updated to 1996. Averaging the data from five studies yields a total estimated annual cost for allergies and asthma of $15 billion.

There are three general approaches for reducing allergy and asthma symptoms via changes in buildings and indoor environments. First, one can reduce the indoor sources of the agents that cause symptoms (or that cause initial allergic sensitization). For example, indoor tobacco smoking can be restricted, pets can be maintained outside of the homes of individuals that react to pet allergens, and changes in building design, construction, operation, and maintenance could reduce water leaks and moisture problems. Reservoirs for allergens, such as carpets for dust mite allergen, can be eliminated or modified. Improved cleaning of building interiors can also limit the accumulation of allergens. There are no major technical obstacles to these measures, but their costs and benefits are not well quantified.

The second general approach for reducing allergy and asthma symptoms is to use air cleaning systems or increased ventilation to decrease the indoor concentrations of the relevant pollutants. Better filtration of the outside air entering mechanically-ventilated buildings can diminish the entry rate of outdoor allergens. For indoor-generated particles, filtration is most effective [19] for particles smaller than a few micrometers, such as tobacco smoke particles (but not tobacco-smoke gases). The influence of particle air cleaning on symptoms of allergies and asthma was reviewed by IOM [19]. Many of the studies have important limitations such as small capacity air cleaners, a small number of subjects, or a focus on dust mite allergies which may be poorly controlled with air cleaners due to the large size and high settling velocities of dust mite allergens. Four of eleven studies of subjects with perennial allergic disease or asthma reported statistically significant improvements in symptoms or reduced use of medication when air cleaners were used. However, in six of seven studies, seasonal allergic or asthma symptoms were significantly reduced with air cleaner use.

Because viral respiratory infections will often exacerbate asthma symptoms, a third approach for reducing asthma symptoms is to modify buildings in a manner that reduces respiratory infections among occupants.

With the available data, the magnitude of the potential reduction in allergy and asthma symptoms is quite uncertain, but some reduction is clearly possible using practical measures. The subsequent estimate is based on two considerations: 1) the degree to which the relevant indoor pollutant concentrations can be reduced, and 2) the strength of the reported associations between symptoms and changeable building and IEQ factors. From engineering considerations, it is clear that concentrations of many allergens could be reduced very substantially. Filtration systems, appropriately sized, should be capable of reducing concentrations of the smaller airborne allergens by approximately 75% [19]. Source control measures, such as elimination of water leaks, reduction or elimination of indoor smoking and pets, and improved cleaning and maintenance will yield much larger reductions in the pollutants that contribute to allergies and asthma. As discussed above, several studies have found that building-related risk factors, such as moisture problems and mold or environmental tobacco smoke, are associated with 20% to 100% increases in allergy and asthma symptoms, implying that roughly 16% to 50% reductions in symptoms are possible by eliminating these risk factors. However, the complete elimination of these risk factors is improbable. Assuming that it is feasible and practical to reduce these risks by a factor of two, leads to a 8% to 25% estimate of the potential reduction in allergy and asthma symptoms. With this estimate, the annual savings would be ~$1 to ~$4 Billion. Control measures can be targeted at the homes or offices of susceptible individuals.

Sick Building Syndrome Symptoms

Characteristics of buildings and indoor environments have been linked to the prevalence of acute building-related health symptoms, often called sick-building syndrome (SBS) symptoms. These symptoms, which include irritation of eyes, nose, and skin, headache, fatigue, and difficulty breathing, are most commonly reported by office workers and teachers that make up about 50% of the total US workforce, 64 million workers [3]. The most representative data from US buildings, obtained in a 56-building survey found that 23% of office workers reported two or more frequent symptoms that improved when they were away from the workplace [21]. Applying this percentage to the estimated number of U.S. office workers and teachers (64 million), the number of workers frequently affected by at least two SBS symptoms is 15 million.

Although psychosocial factors such as job stress influence SBS symptoms, many building factors are also known or suspected to influence these symptoms including: type of building ventilation system; rate of outside air ventilation; level of chemical and microbiological pollution; and indoor temperature [22-25]. In a set of problem buildings, SBS symptoms were associated with poorer ventilation system maintenance or cleanliness [26]. For example, debris inside the air intake and poor drainage from coil drain pans were associated with a factor of three increase in lower respiratory symptoms. In the same study, daily vacuuming was associated with a 50% decrease in lower respiratory symptoms. In some, but not all, controlled experiments, SBS symptoms have been reduced through practical changes in the environment such as increased ventilation, decreased temperature, and improved cleaning of floors and chairs [22, 24, 25].

SBS symptoms are a hindrance to work and can cause absences from work [27] and visits to doctors. Calculations indicate that the costs of small decreases in productivity from SBS symptoms are likely to dominate the total SBS cost. Fisk [2] has summarized the available information on the subjectively-reported and objectively-measured relationship between SBS symptoms and productivity. The available objective data suggest that SBS symptoms are associated with decrements on the order of 3% to 5% in specific aspects of work performance averaged over the population; however, it is not clear how to translate these specific performance decrements (e.g., increases in response times and error rates, and decreases in typing performance) with an overall productivity decrement from SBS symptoms. Self estimates of productivity decreases, averaged over the entire work population, average approximately 4% due to poor indoor air quality and physical conditions at work. Although SBS symptoms are the most common work-related health concern of office workers, some of this self-reported productivity decrement may be a consequence of factors other than SBS symptoms. Also, workers who are dissatisfied with the indoor environment may have provided exaggerated estimates of productivity decreases. To account for these factors, we discount the 4% productivity decrease cited above by a factor of two, leading to an estimated 2% productivity decrease caused by SBS, recognizing that this estimate is highly uncertain. This 2% estimate is used for subsequent economic calculations.

SBS symptoms are primarily associated with office buildings and other non-industrial indoor work places such as schools. Statistical data on the occupations of the civilian labor force indicate that 50% of workers have occupations that would normally be considered office work or teaching [3]. Since the gross domestic product (GDP) of the US in 1996 was \$7.6 trillion [3], the GDP associated with office-type work is roughly half as large -- \$3.8 trillion. Multiplying the number of office workers and teachers (64 million) by the annual average compensation for all workers (\$39.2K) results in a similar estimate of \$2.5 trillion. Averaging these two estimates yields \$3.2 trillion. Based on the estimated 2% decrease in productivity caused by SBS symptoms, the annual nationwide cost of SBS symptoms is on the order of \$60 billion.

Because multiple factors, including psychosocial factors, contribute to SBS symptoms, we cannot expect to eliminate these symptoms by improving indoor environments. However, strong evidence cited by Mendell [22], Sundell [23], and Seppanen et al. [25] of associations between SBS symptoms and building environmental factors, together with our knowledge of methods to change building and environmental conditions, indicate that SBS symptoms can be reduced. Many studies have found individual environmental factors and building characteristics to be associated with changes of about 20% to 50% in the prevalence SBS symptoms. A smaller number of studies have identified building-related factors to be associated with an increase in symptoms by a factor of two or three (e.g., [28, 26]). The review by Seppanen et al. [25] suggests that a 5 L s^{-1} per person increase in building ventilation rates in the building stock would decrease prevalences of upper respiratory and eye symptoms by ~35%. In summary, the existing evidence suggests that reductions in SBS symptoms, on the order of 20% to 50%, should be possible. The corresponding annual productivity increase is on the order of $10 to $30 billion.

Direct Impacts of Temperature and Lighting on Human Performance

Indoor environmental conditions, such as temperature and light, may directly influence the performance of physical and mental work, without influencing health symptoms. Many studies have investigated the relationship of the thermal environment with aspects of work performance and there are several reviews of this topic (e.g., [29,30]). The results of many studies indicate that changes in temperature of a few degrees Celsius within the 18 ^{o}C to 30 ^{o}C range can significantly influence performance in typewriting, factory work, signal recognition, time to respond to signals, learning performance, reading speed and comprehension, multiplication speed, and word memory. However, some other studies have not found such associations. Given that the optimum temperature for work performance depends on the nature of the task and will vary among individuals and over time, some researchers have advocated the provision of individual control of temperature as a method to increase productivity [31,29]. A study in an insurance office [31] suggested that individual temperature control increased productivity by approximately 2%. Wyon [29] estimated that providing workers ± 3 ^{o}C of individual control would increase in performance for logical thinking and very skilled manual work by 3%, and increase in typing performance by 7%.

Lighting has the theoretical potential to influence performance directly, because work performance depends on vision, and indirectly, because lighting may direct attention, or influence arousal or motivation [32]. Lighting illuminance (the intensity of light that impinges on a surface), amount of glare, and the spectrum of light may theoretically affect performance. The potential to improve performance by changing the lighting normally experienced within buildings is the relevant issue for this paper.

It is expected that performance of work that depends very highly on excellent vision, such as difficult inspections of products, will vary with lighting levels and quality. The published literature, while limited, is consistent with this expectation. For example, a 6% increase in the performance of postal workers during mail sorting was recorded after a lighting retrofit that improved lighting quality and also saved energy [33]. A review by NEMA [32] provides a few additional examples.

As reviewed by Fisk [2] many laboratory studies have investigated subjects' performance on special visual tests as a function of illuminance, spectral distribution of light, and the contrast and size of the visual subject. Many statistically-significant differences in people's performance on these visual tests with changes in lighting have been reported; however, the relationship between performance in these visually-demanding laboratory tests and performance in typical work (e.g., office work) remains unclear. Several studies have examined the influence of illuminance on reading comprehension, reading speed, or accuracy of proofreading. Some of these studies have failed to identify statistically significant effects of illuminance. Other studies have found illuminance to significantly influence reading performance; however, performance reductions were primarily associated with unusually low light levels or reading material with small, poor-quality, or low-contrast type.

A few studies have examined the influence of different <u>lighting systems</u> on self-reported productivity or on cognitive task performance. In one study [34], occupants reported that some types of lighting systems better-supported reading and writing on paper and computer screens. Katzev [35] found that the type of lighting system influenced occupant satisfaction and one energy-efficient lighting system was associated with better reading comprehension. However, performance in other cognitive tasks, (detecting errors in written materials, typing, and entering data into a spreadsheet) was not significantly associated with the type of lighting system. Veitch and Newsham [36] found that the type of luminaire influenced performance of computer based work and that energy-efficient electronic ballasts, which decrease lighting flicker, were associated with improvements in verbal-intellectual task performance.

Based on this review, the most obvious opportunities to improve performance through changes in lighting are work situations that are very visually demanding. The potential to use improved lighting to significantly improve the performance of office workers seems to be largely unproved; however, it appears that occupant satisfaction and the self-reported suitability of lighting for work can be increased with changes in lighting systems. Many of the published lighting studies had few subjects, hence, these studies were unable to identify small (e.g., few percent) increases in performance that would be economically very significant.

Extrapolations from the results of laboratory studies and specialized field studies to the real work force are the only avenues available for estimating the potential values of direct productivity gains from changes in temperatures and lighting. There are reasons for estimating that the potential productivity increases in practice will be smaller than the percentage changes in performance reported within the research literature. First, some measures of performance used by researchers, such as error rates and numbers of missed signals, will not directly reflect the magnitudes of overall changes in productivity (e.g., decreasing an error rate by 50% usually does not increase productivity by 50%). Second, research has often focused on work that requires excellent concentration, quick responses, or excellent vision while most workers spend only a fraction of their time on these types of tasks. Third, changes in temperatures and lighting within many studies are larger than average changes in conditions that would be made in the building stock to improve productivity.

To estimate potential productivity gains, we consider only reported changes in performance that are related to overall productivity in a straightforward manner, e.g., reading speed and time to complete assignments are considered, but not error rates. The literature reviewed above and described in greater detail in Fisk [2] generally reports performance changes of 2% to 20%. Assuming that only half of peoples' work is on tasks likely to be significantly influenced by practical variations of temperature or lighting, the range of performance improvement would be 1% to 10%. Because research has generally been based on differences in temperature and lighting about a factor of two larger than the changes likely to be made in most buildings, the estimated range of performance improvement was divided by another factor of two. The result is an estimated range for potential productivity increases in the building stock of 0.5% to 5%. Considering only U.S. office workers, responsible for an annual GNP of approximately $3.2 trillion, the 0.5% to 5% estimated performance gain translates into an annual productivity increase of roughly $20 billion to $160 billion.

Cost of improving indoor environments

In two example calculations, Fisk [2] compared the cost of increasing ventilation rates and increasing filter system efficiency in a large office building with the productivity gains expected from reductions in health effects. The estimated benefit-to-cost ratio is 14 and 8 for increased ventilation and better filtration, respectively. Similar calculations by Milton et al. [14] result in a benefit-to-cost ratios of three to six for increased ventilation, neglecting the benefits of reduced health care costs which are about half of the total benefit. For many other measures that should increase productivity, we would expect similarly high benefit-to-cost ratios. Also, some measures, such as excluding indoor tobacco smoking or maintaining pets outdoors of the houses of asthmatics, have negligible financial costs.

Relationship to building energy efficiency

In non-industrial workplaces, the costs of salaries and benefits exceeds energy costs, maintenance costs, and annualized construction costs or rent, by approximately a factor of 100 [37]. Consequently, businesses should be strongly motivated to invest in changes to building designs or building operation if these changes improved worker performance by even a significant fraction of a percent or reduced absence from work by a day or more per year.

The responses of employers to the growing body of information indicating that productivity improvements are possible through improvements in the indoor environment are quite uncertain; however, the nature of the response has significant energy implications. In the near term, employers may not respond significantly because of the uncertainties that remain about productivity and health improvements, and due to the limited communication of research findings. However, as research is completed these uncertainties will diminish and an employer response seems likely. One potential near-term or longer-term response is for employers to implement the easy measures, such as a doubling of minimum ventilation rates, regardless of the energy consequences. Building energy use would increase, but the percentage increase will be modest (e.g., 5%) in most buildings because the energy used to heat or cool ventilation air is a small portion of total building energy consumption [2, 38]. In buildings with a high occupant density, such as schools, the percentage increases in building energy use could be considerably larger (e.g., 10-20%). Another possible response, and the most desirable one, is the preferential adoption of measures that improve productivity and simultaneously save energy. The building performance contracting industry, which finances and implements energy-efficiency measures for a share of the energy cost savings, is likely to push this option. When marketing energy-efficiency measures, energy-service companies can promise or suggest the possibility of IEQ improvements and associated productivity savings. In the ideal scenario, the productivity gains could serve as a strong stimulus for building energy efficiency. While the cost of energy is too small to garner the attention of many businesses, the promise of simultaneous productivity gains, that are financially much more significant, is less easily ignored. Institutions with a mission to promote energy efficiency could influence the response to the new information on productivity gains by supporting research and demonstration efforts on the suspected win-win measures that simultaneously save energy and improve productivity.

A multi-disciplinary international committee [4] has developed a table of the most common energy efficiency measures for commercial buildings and discussed their potential impacts on indoor environmental quality. Based on this committee, energy efficiency measures that often improve indoor environmental quality include: 1) energy efficient lamps, ballasts, fixtures; 2) outside air economizer; 3) heat recovery from exhaust ventilation air enabling increased ventilation; 4) nighttime pre-cooling using outdoor air; 5) operable windows substitute for air conditioning; 6) increased thermal insulation in building envelope; 7) improved HVAC system controls and maintenance; and 8) thermally efficient windows.

CONCLUSIONS

Based on a review of existing literature, there is relatively strong evidence that characteristics of buildings and indoor environments significantly influence the occurrence of communicable respiratory illness, allergy and asthma symptoms, sick building symptoms, and worker performance. Theoretical and empirical evidence indicate that existing technologies and procedures can improve indoor environments in a manner that increases health and productivity. Estimates of the potential reductions in adverse health effects are provided in Table 2. Existing data and knowledge allows only crude estimates of the magnitudes of productivity gains that may be obtained by providing better indoor environments; however, the projected gains are very large. For the U.S., the estimated potential annual savings plus productivity gains, in 1996 dollars, are approximately $40 billion to $200 billion, with a breakdown as indicated in Table 2. The implications of the growing knowledge about productivity gains from better indoor environments on building energy efficiency are uncertain. One scenario is that demonstrated productivity gains could serve as a strong stimulus for energy conservation measures that simultaneously improve indoor environments.

Table 2. Estimated potential productivity gains in 1996 $US.

Source of Productivity Gain	**Potential Annual Health Benefits**	**Potential Annual Savings or Gains**
Reduced respiratory illness	16 to 37 million avoided cases of common cold or influenza	$6 - $14 billion
Reduced allergies and asthma	10% to 30% decrease in symptoms within 53 million allergy sufferers and 16 million asthmatics	$2 - $4 billion
Reduced sick building syndrome symptoms	20% to 50% reduction in SBS health symptoms experienced frequently at work by ~15 million workers	$10 - $30 billion
Improved performance from thermal and lighting changes	Not applicable	$20 - $160 billion

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