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ESTIMATES OF POTENTIAL NATIONWIDE PRODUCTIVITY AND HEALTH BENEFITS FROM BETTER INDOOR ENVIRONMENTS: AN UPDATE

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1.0 ABSTRACT

The existing literature offers relatively strong evidence that characteristics of buildings and indoor environments significantly influence prevalences of respiratory disease, allergy and asthma symptoms, symptoms of sick building syndrome, and worker performance. Theoretical considerations, and limited empirical data, suggest that existing technologies and procedures can improve indoor environments in a manner that significantly increases health and productivity. At present, we can develop only crude estimates of the magnitude of productivity gains that may be obtained by providing better indoor environments; however, the projected gains are very large. For the U.S., we estimate potential annual savings and productivity gains in 1996 dollars of $6 to $14 billion from reduced respiratory disease; $2 to $4 billion from reduced allergies and asthma, $15 to $40 billion from reduced symptoms of sick building syndrome, and $20 to $200 billion from direct improvements in worker performance that are unrelated to health. In two example calculations, the potential financial benefits of improving indoor environments exceed costs by factors of 9 and 14. Further research is recommended to develop more precise and compelling benefit-cost data that are needed to motivate changes in building codes, designs and operation and maintenance policies.

2.0 INTRODUCTION

In office buildings, the salaries of workers exceed the building energy and maintenance costs by approximately a factor of 100 and salaries exceed annualized construction or rental costs by almost as much (Woods 1989). Thus, even a 1% increase in productivity should be sufficient to justify an expenditure equivalent to a doubling of energy or maintenance costs, or large increases in construction costs or rents. Productivity increases for a worker of 1% correspond to reduced sick leave of two days per year, reduced breaks from work or increased time at work of 5 minutes per day, or a 1% increase in the effectiveness of physical and mental work.

Current evidence suggests at least four major links between peoples' health and productivity and the quality of indoor environments, where we spend 90% of our lives. Three of these links involve the following health effects influenced by the indoor environment: 1) infectious disease; 2) allergies and asthma; and 3) acute building-related health symptoms commonly called sick building syndrome symptoms. The fourth link is the direct impact of indoor environmental conditions on worker performance, without any change in health. Most of the prior literature on the relationship between indoor environments and productivity has focused on the fourth link – potential direct improvements in worker's cognitive or physical performance. Possible productivity gains and savings in health care costs from reductions in adverse health effects have received much less attention despite the very high costs of adverse health effects. This paper will consider both direct productivity gains and gains associated with reducing adverse health effects.

The primary purpose of this paper is to synthesize available information pertaining to the linkage between the indoor environment and health and productivity and, based on this synthesis, to develop credible estimates of the total productivity gains that might result from better indoor environments. We recognize that existing data and knowledge are inadequate for precise estimates of potential productivity gains from better indoor environments; however, even imprecise unbiased estimates should be of considerable value to policy makers, researchers, and those responsible for decisions about the design and operation of buildings.

3.0 APPROACH

The approach used for this analysis is illustrated in Figure 1. Computer-based literature searches and personal contacts were used to identify relevant papers and the evidence supporting or refuting the hypothesized linkages was synthesized. Evidence from small studies without sufficient statistical power, or from studies judged to be of poor quality[1], was disregarded. The potential economic significance of adverse health effects linked to the indoor environment was estimated, primarily by synthesizing and updating the results of previously published estimates. The economic results of previous analyses were updated to 1996 to account for general inflation, health care inflation, and increases in population (U.S. Department of Commerce 1997). The next and most uncertain step in the analysis was to estimate the magnitude of the decrease in adverse health effects and the magnitude of direct improvements in productivity that might result from improved indoor environments. These estimates are based on findings reported in the literature (e.g., 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 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). In two example calculations, the costs of improving indoor environments are compared with the value of potential productivity gains and savings in health care costs. A final section discusses policy implications.

This article is based on the results of many studies that have used statistical models to analyze research data and that report findings in statistical terms. To make this article understandable to a relatively broad audience, the use of potentially unfamiliar statistical terminology has been minimized. For example, the odds ratio is a statistical parameter commonly used to indicate the statistical association between an outcome (e.g., a health effect) and a risk factor suspected to increase the proportion of the population that experiences the outcome. Published odds ratios plus data on the fraction of the populations that experienced the outcomes were used to calculate estimates of the percentage increase or decrease in the outcomes when the suspected risk factors are present or absent[2]. Additionally, measures of statistical

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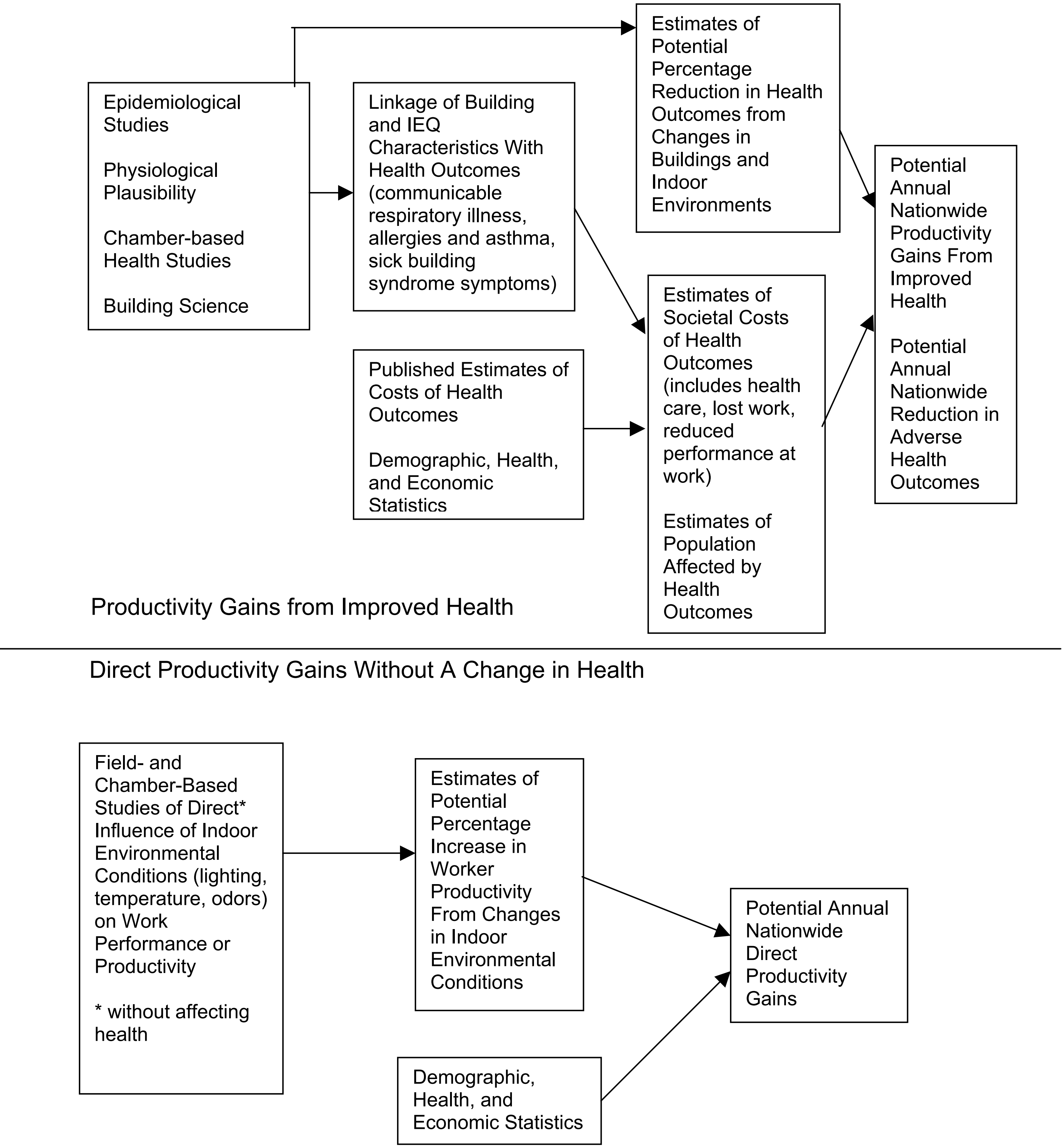
[1] Reasons for neglecting a study included: suspected major uncontrolled sources of confounding due to missing data or incomplete data analyses and very limited statistical power. Only one article from the archival refereed literature was neglected.

[2] Because of the definition of odds, the ratio of symptom prevalences is smaller than the odds ratio by an amount that depends on the proportion of the population that experiences symptoms.

Figure 1. Flow chart illustrating method of estimating health and productivity gains from better indoor environments.



significance have been excluded from the text. 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%). For the statistically inclined, measures of statistical significance are included in footnotes.

This article draws heavily on a previously published paper (Fisk and Rosenfeld 1997). Relative to the previous paper, the current article has been updated to reflect new research findings, more recent statistical data, and 1996 prices. Also, tables have been added that summarize some key published findings, and a section on odors and productivity has been added.

4.0 LINKAGE OF BUILDING AND IEQ CHARACTERISTICS TO HEALTH AND PRODUCTIVITY

In this section, the magnitude of potential productivity gains is estimated for the four previously-identified links between the indoor environment and productivity. For each link, the estimate is preceded by a synthesis of the literature.

4.1 Infectious Disease Transmission

Linkage

The relationship of building and indoor environmental characteristics with infectious disease transmission among building occupants likely depends on the mechanisms of transmission. If disease transmission occurs due to airborne transport of infectious aerosols[3] over distances of many meters between the source and the recipient, then measures that reduce or interrupt this long-range transport would be expected to reduce disease transmission. Examples of such measures include more efficient or increased rates of air filtration, increased ventilation (i.e., increased supply of outside air), and reduced air recirculation in ventilation systems. If disease transmission is primarily a consequence of short-range transport of infectious aerosols over distances of only a few meters (because the aerosols settle on surfaces or quickly become non-infectious), then measures that increase the separation between individuals may help to reduce disease transmission, e.g., reductions in occupant density and increased use of private work spaces[4] may be helpful. However, more efficient filtration of infectious aerosols in the recirculated airstreams of ventilation systems and decreased air recirculation by ventilation systems may not significantly reduce short-range airborne disease transmission. Regardless of the range of transport, disease transmission by infectious aerosols may also be influenced by environmental conditions aerosols (e.g., air temperature and humidity) that affect period of viability of infectious. Finally, if disease transmission is primarily due to direct person-to-person contact or to indirect contact via contaminated objects, many indoor environmental and building characteristics may have a very small influence on transmission. However, temperatures and humidities at surfaces may affect the survival of infectious organisms on surfaces, and the associated disease transmission.

In addition to direct effects of building factors on the transmission of respiratory infections among occupants, indoor environmental conditions may influence occupants'

[3] Examples of infectious aerosols are small aerosols produced by coughing and sneezing that contain a high virus concentration.
[4] Separating workers with walls or partitions will generally increase the path that infectious aerosols must travel between their source (infected worker) and a nearby uninfected individual.

susceptibility to these infections. For example, there is some evidence, discussed subsequently, that increased exposures to molds are associated with substantially increased numbers of respiratory infections.

Numerous laboratory experiments and field-based epidemiological studies have attempted to determine the significance of different potential routes of transmission of common infectious diseases. Most laboratory research has focused on selected viral infections, such as rhinovirus infections that are responsible for an estimated 30 to 50% of acute respiratory illness (Jennings and Dick 1987) For rhinovirus infections, laboratory experiments demonstrate that transmission is possible as a consequence of both direct and indirect contact (e.g., Gwaltney et al. 1978; Gwaltney and Hendley 1982) and also from infectious aerosols (e.g., Dick et al. 1987; Jennings and Dick 1987; Couch et al. 1966); however, there is contradictory evidence regarding the relative significance of the transmission routes. The airborne route of transport is also known or thought to be significant for a number of other respiratory infections including adenovirus infections, coxsackievirus infections, influenza, measles, and tuberculosis (Couch et al 1966; Couch 1981; Knight 1980; Sattar and Ijaz 1987; Nardell et al. 1991). In general, however, the relative importance of transmission mechanisms for many common respiratory illnesses remain controversial.

Several field studies provide evidence that building characteristics significantly influence the incidence of respiratory illness among building occupants. Most important is a multi-year study performed by the U.S. Army that involved a large number of subjects (Brundage et al. 1988). This study showed that rates of acute respiratory illness with fever (illness confirmed clinically) were 50% higher among recruits housed in newer barracks with closed windows, low rates of outside air supply, and extensive air recirculation compared to recruits in older barracks with frequently open windows, more outside air, and less recirculation[5]. This study provides strong evidence that some building-related factor(s) can have a large influence on rates of illness transmission. Because of potential confounding, this study does not prove that low ventilation rates or mechanical air recirculation increase illness transmission. However, low ventilation and recirculation are suspected risk factors because of their theoretical impact on exposures to infectious aerosols (Nardell 1991).

Another study in U.S. Navy barracks (Langmuir et al. 1948) also compared the rate of respiratory illness with fever among recruits housed in two types of barracks. One set of barracks contained ultraviolet lights (UV) that irradiated the indoor air near the ceiling – a technology designed to kill infectious bioaerosols. The second set of barracks, housing the control group, had no UV lights. An epidemic of influenza occurred during the study. Rates of respiratory illness with fever were lower in the population with UV irradiated air by 48%, 19% and 13% during the pre-epidemic, epidemic, and post-epidemic periods, respectively. For the entire study period, there was a 23% lower rate of respiratory illness in the population housed in barracks with UV irradiated air.

Several additional studies provide relevant information on this topic. In a study by Jaakkola et al. (1993), office workers with one or more roommates were about 20% more likely to have more than two cases of the common cold during the previous year than office workers with no roommates[6]. At an Antarctic station, the incidence of respiratory illness was twice as high in the population housed in smaller (presumably more densely populated) living units (Warshauer et al. 1989). In an older study of New York schools (N.Y. State Commission on Ventilation 1923), there were 170% as many respiratory illnesses[7] and 118% as many absences

[5] Adjusted relative risk = 1.51, 95% confidence interval (CI) 1.46 to 1.56.
[6] Adjusted odds ratio = 1.35 (95% CI 1.00 - 1.82).
[7] Difference more than three times probable error.

from illness[8] in fan-ventilated[9] classrooms compared to window-ventilated classrooms, despite a lower occupant density in the fan-ventilated rooms. Unfortunately, ventilation rates were not measured in the classrooms. Another study investigated symptoms associated with infectious illness among 2598 combat troops stationed in Saudia Arabia during the Gulf War (Richards et al. 1993). The study results suggest that the type of housing (air-conditioned buildings, non-air-conditioned buildings, open warehouses, and tents) influenced the prevalence of symptoms associated with respiratory illness. Housing in air conditioned buildings (ever versus never housed in an air-conditioned building while in Saudia Arabia) was associated with approximately a 37% greater prevalence of sore throat[10] and a 19% greater prevalence of cough[11]. For housing in non-air-conditioned buildings (ever versus never), which had a lower occupant density and presumably a higher ventilation rate than air-conditioned buildings, the corresponding increases in the prevalences of sore throat and cough were smaller, approximately 24% and 12%, respectively[12]. For housing in tents and warehouses (ever versus never), which presumably had much higher ventilation rates than buildings, there were no statistically significant increases in sore throat or cough.

Jails are not representative of other buildings because of severe crowding and residents that are not representative of the general public. However, disease transmission in such facilities is an important public health issue and indoor-environmental factors that influence disease transmission in jails may also be important, but less easily recognized, in other environments. An epidemic of pneumococcal disease in a Houston jail was studied by Hoge et al. (1994). There were significantly fewer cases of disease among inmates with 7.4 m^2 (80 ft^2) or more of space[13] relative to inmates with less space. The disease attack rate was about 95% higher in the types of jail cells with the highest carbon dioxide concentrations and the lowest volume of outside air supply[14].

Nursing homes are also densely populated. Drinka et al. (1996) studied an outbreak of influenza in four nursing homes located on a single campus. The total number of residents was 690. Influenza, confirmed by analyses of nasopharyngeal and throat swab samples, was isolated in 2% of the residents of Building A versus an average of 13% in the other three buildings[15] (16%, 9%, and 14% in Buildings B, C and D, respectively). After correction for the higher proportion of respiratory illnesses that were not cultured in Building A, an estimated 3% of the residents of Building A had influenza, a rate 76% lower than observed in the other buildings[16]. The total number of respiratory illnesses (i.e., influenza plus other respiratory illnesses) per resident was also 50% lower in building A. Vaccination rates and levels of nursing care did not differ among the buildings. The authors of this study suspect that architectural factors may be the cause of the lower infection rate in Building A. The ventilation system of Building A supplied 100% outside air to the building (eliminating mechanical recirculation) while the ventilation systems of the other buildings provided 30% or 70% recirculated air. The Building A ventilation system also had additional air filters. Finally, the public areas of Building A were larger (per resident), reducing crowding that may facilitate disease transmission.

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[8] Difference greater than probable error.
[9] In fan-ventilated classrooms, fans are use to bring outside air into the classrooms.
[10] Adjusted odds ratio =1.57 (95% CI 1.32-1.88).
[11] Adjusted odds ratio = 1.33 (95% CI 1.01 - 1.46)
[12] For sore throat, adjusted odds ratio = 1.36 (95% CI 1.13-1.64). For cough, adjusted odds ratio = 1.21 (95% CI 1.01-1.46).
[13] $p=0.03$
[14] Relative risk = 1.95 (95% CI 1.08-3.48).
[15] $p < 0.001$, Cochran-Mantel-Haenszel statistics
[16] $p < 0.001$, chi-square

Milton et al. (1998) investigated the association of absence from work caused by illness in 4119 workers (located in 40 buildings) with the rate of outside air supply and the presence of humidification systems. While absence is clearly not synonymous with respiratory disease, it is a useful surrogate and a substantial proportion of short-term absence from work caused by illness results from acute respiratory illness. Ventilation rates were estimated based on ventilation system design, occupancy, and selected end-of-day carbon-dioxide measurements, and buildings were classified as normal ventilation (~ 12 L s^{-1} per occupant) or high ventilation (~22 L s^{-1} per occupant). The total absence rate was 34% lower in the high ventilation buildings. The estimated rate of short-term absence, which excludes lengthy absences and those not associated with respiratory conditions, was 17% lower in the high-ventilation buildings. Absence rates were 25% and 18% percent lower, for total and short term absence, respectively, in spaces without humidification. The associations of low ventilation and humidification with absence remained significant after controlling for age, gender, work shift, seniority, and job type.

The association of mold problems in buildings with the incidence of respiratory infections has been investigated in a few studies. One study (Husman et al 1993, Husman 1996) compared the rates of acute respiratory infection in 158 residents of apartments with verified[17] mold problems to the rates of infection in 139 residents of apartments without mold problems. Approximately twice as many residents of the moldy apartments reported at least one acute respiratory infection during the previous year[18]. A complex multi-stage study examined the association of high mold exposures within day-care centers with common colds as well as other health outcomes in children (Koskinen et al 1993, 1996) with inconclusive results (i.e., one comparison suggests that mold significantly increased serious persistent respiratory infections while other comparisions found small statistically insignificant decreases in common colds with higher mold exposure.) The recent evidence that mold exposures may adversely affect immune system function (Dales et al. 1998) is consistent with the findings of a positive association between molds and respiratory infections.

Table 1 summarizes the key features and findings from these studies (excluding the inconclusive results from the studies of mold and respiratory illness in day care centers). Taken together, these studies provide relatively strong and consistent evidence that building and IEQ factors can influence rates of respiratory disease. Only one paper was identified with a null finding of no association of building factors with respiratory disease (Rowe et al. 1992), and this paper is based on a study with important methodological limitations.

[17] Visible mold growth was recorded. Also, measured airborne mold levels were higher in six moldy homes relative to six control homes.

[18] Relative risk is 2.2, 95% CI is 1.2 to 4.4, adjusted for age, sex, smoking and atopy

Table 1. Summary information from studies of the association of building characteristics with acute respiratory illness.

Setting	Populations Compared	Health Outcome	Findings
U.S. Army Barracks (Brundage 1988)	Recruits in modern (low ventilation) versus recruits in older barracks	Respiratory illness with fever	50 % higher incidence of respiratory illness in modern barracks
U.S. Navy Barracks (Langmuir 1948)	Recruits in barracks with UV irradiation of air versus those in barracks without UV irradiation	Respiratory illness with fever	23% decrease in respiratory illness with UV irradiation
Finnish Office (Jaakkola 1993)	Office workers with ≥ 1 roommates vs. office workers without roommates	Common Cold	Worker with roommates had 20% higher risk of more than two common colds per year
Antarctic Station (Warshauer 1989)	Residents of smaller vs. larger quarters	Respiratory Illness	100% higher incidence of respiratory illness for residents of smaller quarters
NY State Schools (NY State Commission On Ventilation 1923)	Students in fan ventilated versus window ventilated classrooms	Respiratory illness and absence	70% more illness and 18% more absence in fan ventilated classrooms
Four US Nursing Homes (Drinka 1996)	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% less influenza and 50% less total respiratory illness in nursing home with no recirculation and less crowding
Gulf War Troops (Richards 1993)	Troops ever vs. never housed in different types of buildings during Gulf War	Symptoms of respiratory illness	37% more cough and 19% more sore throat if housed in air-conditioned buildings
U.S. Jail (Hoge 1994)	> 80 ft^2 vs. < 80 ft^2 space per occupant and high vs. low CO_2 (i.e., low versus high ventilation per occupant)	Pneumococcal disease	Significantly higher incidence if < 80 ft^2 space, 95% higher incidence if in cell type with high CO_2 concentration (i.e., with low ventilation)
40 buildings with office, trade, manufacturing workers (Milton 1998)	Workers in buildings with high versus low ventilation and workers in buildings with and without humidification	Short term absence	17% less short term absence in high ventilation buildings and 18% less short term absence in spaces without humidification
Dwellings in Finland (Husman 1993, 1996)	168 residents of moldy apartments versus 139 residents of non-moldy apartments	Acute respiratory infection	Approximately twice as many residents of moldy apartments had at least one respiratory infection during prior year

Cost of Infectious Respiratory Illness

The obvious direct costs of respiratory illness include health care expenses and the costs of absence from work. Additionally, there is evidence that respiratory illnesses cause a performance decrement at work. In controlled experiments, Smith (1990) has shown that viral respiratory illnesses, even sub-clinical infections, can adversely affect performance on several computerized and paper-based tests that simulate work activities. The decrement in performance can start before the onset of symptoms and persist after symptoms are no longer evident.

To estimate the productivity losses associated with respiratory illness, we consider periods of absence from work and restricted activity days as defined in the National Health Interview Survey (U.S Department of Health and Human Services 1994). In the U.S., four common respiratory illnesses (common cold, influenza, pneumonia, and bronchitis) cause about 176 million days lost from work and an additional 121 million work days of substantially restricted activity (Dixon 1985, adjusted for population gain). Assuming a 100% and 25% decrease in productivity on lost-work and restricted-activity days, respectively, and a $39,200 average annual compensation (U.S. Department of Commerce 1997), the annual value of lost work is approximately $34 billion[19]. The annual health care costs for upper and lower respiratory tract infections total about $36 billion (Dixon 1985, adjusted for population gain and health care inflation). Thus, the total annual cost of respiratory infections is approximately $70 billion. This estimate may be less than the true cost, as neglected costs include the economic value of reduced housework and of absence from school. Also, these estimates reflect lost work and restricted activity from only four common respiratory illnesses.

Potential Savings from Changes in Building Factors

Without being able to substantially change the building-related factors that influence disease transmission, we cannot realize these health care cost savings and productivity gains. A number of existing, relatively practical building technologies, such as increased ventilation, reduced air recirculation, improved filtration, ultraviolet disinfection of air, and reduced space sharing (e.g., shared office) have the theoretical potential of reducing inhalation exposures to infectious aerosols by more than a factor of two. Also, occupant density can be decreased if future studies confirm that less density reduces the incidence of respiratory illness. (Attempts to reduce the costs of workspace by increasing occupant density may be counter-productive.) Changes in building codes could help to stimulate widespread adoption of technologies that have been proven to be effective.

Based on the previous analyses, each one percent decrease in the incidence of respiratory illness in the U.S. would result in approximately $0.7 billion in annual savings. The studies cited above 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), with the strongest study (Brundage et al. 1988) suggesting that a 33% reduction is possible[20].

While the evidence is compelling that the incidence of common respiratory infections is associated with indoor environmental conditions, the complexity of disease transmission makes it difficult to estimate the magnitude of practical reduction for the U.S. population. For example, reducing disease transmission in one setting, such as an office or school, should lead to reduced

[19] A similar estimate, $39 billion, is obtained based on the information in Garabaldi (1985)

[20] For example, the observed 50% increase in disease in the modern army barracks suggests that a 33% decrease in disease is possible, i.e., (1.5-1.0) / 1.5 = 0.33.

disease in other settings, e.g., at home; however, we do not attempt to account for these indirect effects.

The amount of time spent in a building should influence the probability of disease transmission within the building. The period of occupancy in the studies cited above ranged from approximately 25% time in offices and schools to 100% time in nursing homes and jails. If efforts to reduce disease transmission were implemented primarily in commercial and institutional buildings[21] that people occupy approximately 25% of the time, smaller reductions in respiratory illness would be expected in the general population than indicated by the building-specific studies. To adjust the reported decreases in respiratory illness for time spent in buildings, we estimated the percentage of time that occupants spend in each type of building (100% of time in jails and nursing home, 66% in barracks and housing, and 25% in offices and schools) and assumed that the magnitude of the influence of a building factor on the incidence of respiratory illness varies linearly with time spent in the building. After this adjustment (Table 2), the ten studies yield 14 estimates of potential decreases in metrics for respiratory illness (some studies had multiple outcomes such as influenza and total respiratory infections), ranging from 6% to 41% with an average of 16%. 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 much smaller, 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 year[22]), 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.

[21] There are no technical barriers to implementation of similar measures in residences; however, business owners will have a stronger financial incentive to take action than home owners.

[22] Averaging data from 1992 through 1994, the civilian non-institutional population experienced 43.3 common colds and 25.7 cases of influenza per 100 population (US Department of Commerce 1997)

Table 2. Percentage reduction in respiratory illness or surrogate metrics before and after adjustment for time spent in building.

Setting	Estimated % Time in Building	Outcome (observed % reduction[23])	Adjusted % Reduction in Outcome Assuming 25% time in Building
U.S. Army Barracks (Brundage 1988)	66	Respiratory illness (33)	12.5
U.S. Navy Barracks (Langmuir 1948)	66	Respiratory illness (23)	9
Finnish Office (Jaakkola 1993)	25	Common colds (17%)	17
Antarctic Station (Warshauer 1989)	66	Respiratory illness (50)	19
NY State Schools (NY State Commission On Ventilation 1923)	25	Illness (41) Absence (15)	Illness (41) Absence (15)
Four US Nursing Homes (Drinka 1996)	100	Influenza (76) Total respiratory illness (50)	Influenza (19) Total respiratory illness (12.5)
Gulf War Troops (Richards 1993)	66	Cough (27) Sore Throat (16)	Cough (10) Sore Throat (6)
U.S. Jail (Hoge 1994)	100	Pneumococcal disease (49%)	12
40 buildings with office, trade, manufacturing workers (Milton 1998)	25	Short term absence with high ventilation (17%) Short term absence without humidification (18)	17 (high ventilation) 18 (without humidification)
Dwellings in Finland (Husman 1993, 1996)	66	Respiratory illness (54%)	20

4.2 Allergies and Asthma

Linkage

In the US, approximately 20% of the U.S. population has allergies to environmental antigens (Committee on Health Effects of Indoor Allergens 1993) and approximately 6% have asthma (Rappaport and Boodram 1998). Over the last two decades, the prevalences of asthma, asthma-related hospitalization, and asthma-related mortality have risen substantially (Committee on Health Effects of Indoor Allergens 1993). The symptoms of allergies and of asthma may be triggered by a number of allergens in indoor air including fragments of house dust mites, allergens from pets, fungi, and insects, and pollens that enter buildings from outdoors (Committee on Health Effects of Indoor Allergens 1993). Allergens are considered to be a primary cause of the inflammation that underlies asthma (Platts-Mills 1994). Viral infections, which may be influenced by building factors, also appear to be strongly linked to exacerbations

[23] Some studies report the increase in the health outcome while other studies indicate the degree of reduction. All percentage increases have been converted to a percentage reduction, e.g., if some risk factor is associated with a 50% increase in illness, the percentage reduction from eliminating that risk factor is 33% [(1.5 –1.0)/1.5]

of asthma, at least in school children (Johnston et al. 1995). Asthma symptoms may also be evoked by irritating chemicals in indoor air, including environmental tobacco smoke (Evans et al. 1987). For example, in a study of children (Garrett et al. 1996), higher formaldehyde concentrations were associated with diagnosed asthma[24], asthma symptoms[25], and positive responses to skin-prick allergy tests[26]. There is evidence (e.g., Arshad et al 1992, Wahn et al. 1997) that lower exposures to allergens during infancy or childhood can reduce the sensitization to allergens.

The building factors most consistently and strongly associated with asthma and allergic respiratory symptoms are moisture problems, molds, and house dust mites. Many studies indicate that occupants of homes or schools with evidence of dampness or presence of molds have approximately a 30% to 60% higher prevalence of asthma or of lower respiratory symptoms associated with asthma (e.g., Brunekreef 1992, Bjornsson et al. 1995, Dales et al. 1991, Li and Hsu 1996, Smedje et al. 1996, Spengler et al. 1993). Bjornson et al. (1995) also found detectable levels of house dust mites and increased concentrations of bacteria were associated with asthma-related symptoms[27]. Platts-Mills and Chapman (1987) provide a detailed review of the role of dust mites in allergic disease.

Smedje et al. (1997) investigated the proportion of school children within 28 classrooms who were diagnosed as asthmatic and also had current asthma (i.e., experienced asthma symptoms or used asthma medication within the past 12 months). As shown in Table 3, several classroom and indoor environmental quality factors were associated with the rate of current asthma, suggesting that improvements in the classroom factors might substantially reduce current asthma.

Fewer office-based studies data are available for asthma and allergy associations with indoor environmental conditions. In case studies, moisture and related microbiological problems have been linked to respiratory symptoms in office workers (Division of Respiratory Disease Studies 1984). In a study of office workers[28] (Menzies 1988), higher relative humidity, higher concentrations of alternaria (a mold) allergen in air, and higher dust mite antigen in floor dust were associated with a higher prevalence of respiratory symptoms.

Various measures have been found effective in reducing indoor concentrations of allergens in buildings (Harving et al. 1991; Ingram and Heymann 1993; Pollart et al. 1987). Unfortunately, except for studies involving air cleaners, we have identified relatively 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 a non-permeable materials, have reduced symptoms in some but not all studies (Ingram and Heymann 1993; Pollart et al. 1987; Harving et al. 1991; Antonicelli 1991, Platts-Mills and Chapman 1987).

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[24] $p = 0.035$

[25] adjusted odds ratios for symptoms ranged from 1.57 to 2.21, 95% CI excluded 1.0 only for cough

[26] The reference was children in homes with < 16 ppb formaldehyde. A higher proportion of children in homes with 16 – 40 ppb had positive skin prick tests ($p < 0.05$). An even higher percentage of children in homes with >40 ppb formaldehyde had had positive skin prick tests ($p < 0.05$).

[27] For the association of asthma-related symptoms and bacteria, adjusted odds ratios and 95% CI are 5.1 (1.3 to 20). For the association of asthma-related symptoms and detection of house dust mites , adjusted odds ratios and 95% CI are 7.9 (1.2 to 55). House dust mite levels were positively associated with humidity ($p < 0.05$) and increasing age of the house ($p < 0.001$).

[28] This was a case-control study of ~ 17% of all workers in the buildings.

Table 3. Association between classroom factors and current asthma in Swedish pupils, 13 to 14 years old (From Smedje et al. 1997).

Classroom Factor[29]	**Change in Current Asthma**[30] **Associated With Increase in the Classroom Factor**	**Observed Range in the Classroom Factor**
Unit increase in shelf factor (measure of area of open shelves)	40% increase	Not provided
1.0 ^{o}C increase in air temperature	40% decrease	21.0 to 27.5 ^{o}C
10% relative humidity (RH) increase	80 % increase	22% RH to 61% RH
1 $\mu g\ m^{-3}$ increase in formaldehyde	10% increase	< 5 to 10 $\mu g\ m^{-3}$
10 $\mu g\ m^{-3}$ increase in volatile organic compound (VOC) concentration	30% increase	4 to 93 $\mu g\ m^{-3}$
100 per m^3 increase in airborne viable bacteria concentration of	40% increase	100 to 1100 per m^3
Increase in airborne viable mold concentration of 1000 per m^3	50% increase	8000 to 170000 per m^3
100 ng per g fine dust increase in cat allergen	80% increase	< 16 to 391 ng per g

Numerous studies have examined the influence of air cleaners that remove particles from indoor air on symptoms of allergies and asthma. Many of these studies have important limitations. Some studies have used small air cleaners that would not be expected to significantly reduce airborne allergen concentrations. Many studies have involved a small number (e.g., 20) of subjects so that moderate (e.g., 20%) improvements in symptoms can not be distinguished from random variations in symptoms. Many of the studies have focused on dust mite allergies, and dust mite allergens which may be poorly controlled with air cleaners due to their large size and high settling velocities.

Nelson et. al. (1988) reviewed research on the use of residential air cleaning devices to treat allergic respiratory disease. All nine of the studies reviewed indicated that air filtration devices and air conditioning reduced seasonal allergic symptoms, but the subjects of most of the studies were not blinded. For perennial allergic disease, six of eight studies reviewed by Nelson et al (1988) suggested improvement with air filtration. Despite these generally positive results, Nelson et al. (1988) indicated that current data were inadequate to support recommendations for the use of air cleaners.

Since the review by Nelson et al (1988), a few new studies of the benefits of air cleaners have been completed. In a double-blind study by Van de Heide et al. (1997), air cleaner operation combined with allergen-impermeable mattress covers was associated with an improvement[31] in a measure of lung function used as a test for asthma (but a combination of both measures was required). In a double-blind study of dust-mite sensitive individuals (Reisman et al. 1990), operation of efficient air filters (compared to placebo filters) was associated with a lower (better) score for several allergy symptoms[32] but only during the period of the study without respiratory infections. In a similar study (Antonicelli et al. 1991), again involving individuals sensitive to dust mites (but with only nine subjects), operation of filtration units did not significantly influence dust mite allergen concentrations or measures of allergic response.

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[29] Factors not associated with current asthma include age of building, type of ventilation system, air exchange rate, carbon dioxide concentration, visible signs of dampness, fleece factor, respirable dust, settled dust, total molds, total bacteria, VOC from short term sampling, nitrogen dioxide, endotoxin, dog allergen

[30] P values as follows: < 0.001 for shelf factor, 0.003 for temperature, 0.014 for RH, 0.042 for formaldehyde, < 0.001 for VOCs, 0.01 for bacteria, < 0.001 for mold, 0.001 for cat allergen

[31] $p < 0.05$

[32] several p values < 0.05 and others close to 0.05

Overall, the evidence of a linkage between the quality of the indoor environment, particularly moisture problems, molds, and dust mites, 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.

Cost of Allergies and Asthma

Table 4 summarizes the results of several recent estimates of the annual costs of allergies and asthma in the U.S., updated to 1996. The authors of these studies have generally characterized their estimates as conservative because some cost elements could not be quantified. Differences between cost estimates are due to reliance on different underlying data, different assumptions, and inclusion of different cost elements. For the purposes of this paper, the averages of the cost estimates for each outcome and cost category, provided in the last row of table 4, have been summed, yielding a total estimated annual cost for allergies and asthma of $15 billion. A significant portion of the costs of allergies and asthma reflect the burden of these diseases in children.

Table 4. Estimates of annual costs of asthma and allergic disease in billions of dollars, updated to 1996

	Cost of Asthma		Cost of Allergic Rhinitis		Cost of Other Associated Airway Diseases*	
Study	Health Care	Indirect+	Health Care	Indirect	Health Care	Indirect
Weiss et al. 1992	5.0	3.1	NA	NA	NA	NA
McMenamin 1995	3.7	2.7	1.2	1.2	2.7	0.2
Fireman 1997	NA	NA	NA	> 4.3	NA	NA
Smith and McGhan 1997	NA	NA	3.4	NA	NA	NA
Smith et al. 1997	5.5	0.7	NA	NA	NA	NA
Average	4.7	2.2	2.3	2.8	2.7	0.2

*Portion of costs of chronic sinusitus, otitis media with effusion, and nasal polyps attributed to allergies

+Components of indirect costs vary among the studies; indirect costs account for lost work, lost school days, and in some cases, mortality

Potential Savings from Changes in Building Factors

There are three general approaches for reducing allergy and asthma symptoms via changes in buildings and indoor environments. First, one can control the indoor sources of the allergens and chemical compounds that cause symptoms (or that cause initial sensitization to allergens). For example, indoor tobacco smoking can be restricted to isolated separately-ventilated rooms or prohibited entirely. Sources of other irritating chemicals can be decreased by changing building materials and consumer products. Pets can be maintained outside of the homes of individuals that react to pet allergens. Perhaps even more effective are measures that reduce the growth of microorganisms indoors. Changes in building design, construction, operation, and maintenance could reduce water leaks and moisture problems and decrease indoor humidities (where humidities are normally high). Known reservoirs for microorganisms, such as carpets for dust mites, can be eliminated or modified. Improved cleaning of building interiors and HVAC systems can also limit the growth or accumulation of microorganisms indoors. There are no major technical obstacles to these measures, but the costs and benefits of implementation 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. Many of the exposures that contribute to allergies and asthma are allergens in the form of airborne particles. Technologies are readily available for reducing indoor concentrations of airborne particles generated indoors (e.g., better air filtration). Better filtration of the outside air entering mechanically-ventilated buildings can also diminish the entry of outdoor allergens into buildings. Filtration is likely to be most effective for the smaller allergenic particles such as cat allergens. Allergens that are large particles, e.g., from dust mites, have high gravitational settling velocities and are less effectively controlled by air filtration.

Because viral respiratory infections will often exacerbate asthma symptoms, a third approach for reducing asthma symptoms is to modify buildings and IEQ in a manner that reduce viral respiratory infections among occupants. A recent study of 108 children, age 9 to 11, found a strong association of viral infections with asthma exacerbation (Johnston et al. 1995). Viral infections were detected in 80% to 85% of asthmatic children during periods of asthma exacerbation. During periods without exacerbation of asthma symptoms, only 12% of the children had detectable viral infections[33].

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 changeable building and IEQ factors have been associated with symptoms; and 2) the degree to which indoor allergen concentrations and concentrations of irritating chemicals can be reduced. As discussed, several cross-sectional studies have found that building-related risk factors such as moisture problems and mold or dust mite concentrations are associated with 30% to 60% increases or decreases in allergy and asthma symptoms. Several, but not all, studies have found that use of particle air cleaners reduced symptoms, but the magnitude of the improvement is generally not well characterized.

Significant reductions in allergy and asthma symptoms would not be expected unless it was possible to substantially reduce indoor concentrations of the associated allergens and irritants. From engineering considerations, it is clear that indoor allergen concentrations, for many allergens, can be reduced very substantially. Filtration systems, appropriately sized[34], should be capable of reducing concentrations of the smaller airborne allergens by more than 75%. Some of the source control measures, such as elimination of water leaks, control of indoor humidities, reduction or elimination of indoor smoking, and improved cleaning and maintenance are likely to result in much larger reductions in the pollutants that contribute to allergies and asthma.

Based primarily on the strength of reported associations of changeable building and IEQ factors to allergy and asthma symptoms, we estimate that a 10% to 30% reduction in symptoms and associated costs is feasible and practical. With this estimate, the annual savings would be ~$2 to ~$4 Billion. Control measures can be targeted at the homes or offices of susceptible individuals, reducing the societal cost.

4.3 Sick Building Syndrome Symptoms

[33] The difference between infection rates is statistically significant, $p < 0.001$

[34] Many of the commonly used portable air cleaners will be ineffective because they do not remove pollutants at a sufficient rate.

Linkage

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, experienced by building occupants. SBS symptoms are most commonly reported by office workers and teachers that make up about 50% of the total workforce (64 million workers[35]). SBS symptoms include irritation of eyes, nose, and skin, headache, fatigue, and difficulty breathing. In a modest fraction of buildings, often referred to as "sick buildings", symptoms become severe or widespread, prompting investigations and remedial actions. The term "sick building syndrome" is widely used in reference to the health problems in these buildings. However, sick building syndrome appears to be the visible portion of a broader phenomenon. These same symptoms are experienced by a significant fraction of workers in "normal" office buildings that have no history of widespread complaints or investigations (e.g., Fisk et al. 1993; Nelson et al. 1995, Brightman et al. 1998), although symptom prevalences vary widely among buildings. The most representative data from US buildings, obtained in a 56-building survey that excluding only buildings with prior SBS investigations, found that 23% of office workers reported two or more frequent symptoms that improved when they were away from the workplace. (Brightman et al 1998). Applying this percentage to the estimated number of US 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 the level of job stress are known to influence SBS symptoms, building factors are also known or suspected to influence these symptoms: e.g., type of building ventilation; type or existence of humidification system; rate of outside air ventilation; level of chemical and microbiological pollution; and indoor temperature and humidity (see the reviews by Mendell 1993; Sundell 1994; Menzies and Bourbeau 1997). In one set of problem buildings, SBS symptoms were associated with evidence of poorer ventilation system maintenance or cleanliness (Sieber et al. 1996). 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[36]. In the same study, daily vacuuming was associated with a 50% decrease in lower respiratory symptoms[37]. 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 (Mendell 1993, Menzies and Bourbeau 1997). Therefore, there is little doubt that SBS symptoms are linked to features of buildings and indoor environments. The building-related factors most consistently associated with increased SBS symptoms include sealed air conditioned buildings, presence of humidification, higher air temperature, and lower outside air ventilation rate.

Cost of SBS Symptoms

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[35] Based on statistical data of employed civilians by occupation (US Department of Commerce 1997), there are approximately 63 million civilian office workers plus teachers (49.6% of the civilian workforce). Assuming that 50% of the 1.06 million active duty military personnel are also office workers, the total is approximately 63.5 million.

[36] For debris in air intake, relative risk = 3.1 and 95% CI = 1.8 to 5.2 For poor or no drainage from drain pans, relative risk = 3.0 and 95% CI = 1.7 to 5.2

[37] Relative risk = 0.5, 95% CI = 0.3 to 0.9

SBS symptoms are a hindrance to work and can cause absences from work (Preller et al. 1990) and visits to doctors. When SBS symptoms are particularly disruptive, investigations and maintenance may be required. There are financial costs to support the investigations and considerable effort is typically expended by building management staff, by health and safety personnel and by building engineers. Responses to SBS have included costly changes in the building, such as replacement of carpeting or removal of wall coverings to remove molds, and changes in the building ventilation systems. Some cases of SBS lead to protracted and expensive litigation. Moving employees or students imposes additional costs and disruptions. Clearly, SBS imposes a significant societal cost, but quantification of this cost is very difficult. However, it is possible to make some estimates of potential productivity losses from SBS.

Our calculations indicate that the costs of small decreases in productivity from SBS symptoms are likely to dominate the total SBS cost. Limited information is available in the literature that provides an indication of the influence of SBS symptoms on worker productivity. In a New England Survey, described in EPA's 1989 report to Congress (U.S. Environmental Protection Agency, 1989), the average self-reported productivity loss due to poor indoor air quality was 3%. Woods et al. (1987) completed a telephone survey of 600 U.S. office workers and 20% of the workers reported that their performance was hampered by indoor air quality, but the study provided no indication of the magnitude of the productivity decrement. In a study of 4373 office workers in the U.K. by Raw et al. (1990), workers who reported higher numbers of SBS symptoms during the past year also indicated that physical conditions at work had an adverse influence on their productivity. Based on the data from this study, the average self-reported productivity decrement was about 4%[38]. In an experimental study (Menzies et al. 1997), workers provided with individually-controlled ventilation systems reported fewer SBS symptoms and also reported that indoor air quality at their workstation improved productivity by 11% relative to a 4% decrease in productivity for the control population of workers[39].

In addition to these self-reported productivity decrements, measured data on the relationship between SBS symptoms and worker performance are provided by Nunes et al. (1993). Workers who reported any SBS symptoms took 7% longer to respond in a computerized neurobehavioral test[40] and had a 30% higher error rate in a second computerized neurobehavioral test[41]. Similar findings were obtained in a study of 35 Norwegian classrooms. Higher concentrations of carbon dioxide, which indicate a lower rate of ventilation, were associated with increases in SBS symptoms and also with poorer performance in a computerized test of reaction time[42] (Myhrvold et al. 1996). Renovations of classrooms with initially poor indoor environments, relative to classrooms without renovations, were associated with reduced SBS

[38] The data indicate a linear relationship between the number of SBS symptoms reported and the self-reported influence of physical conditions on productivity. A unit increase in the number of symptoms (above two symptoms) was associated with approximately a 2% decrease in productivity. Approximately 50% of the workers reported that physical conditions caused a productivity decrease of 10% or greater; 25% of workers reported a productivity decrease of 20% or more. Based on the reported distribution of productivity decrement (and productivity increase) caused by physical conditions at work, the average self-reported productivity decrement is about 4%.

[39] $P < 0.05$ for the reduction in SBS symptoms and $p < 0.001$ for the self-reported change in productivity.

[40] $p < 0.001$

[41] $p = 0.07$

[42] Correlation coefficient = 0.1111 and P value = 0.009 for performance versus carbon dioxide. Correlation coefficient = 0.1976 and P value = 0.000 for performance versus a score for headache, heavy headed, tiredness, difficulty concentrating, and unpleasant odor. Correlation coefficient = 0.1136 and P value = 0.008 for performance versus a score for throat irritation, nose irritation, runny nose, fit of coughing, short winded, runny eyes. Correlation coefficients are controlled for age.

symptoms and with improved performance in the reaction time tests[43] (Myhrvold and Olsen 1997).

Another investigation (Wargocki 1998) providing evidence that SBS symptoms reduce productivity was a laboratory-based blinded, controlled, randomized experimental study with all indoor environmental conditions constant except for the presence or absence of a 20 year old carpet that was not visible to study participants. In this study, subjects (30 females age 20-31) rated the quality and acceptability of air, reported the current intensity of their SBS symptoms, completed a standardized performance-assessment battery, performed simulated office work, and completed a self-assessment of performance. These tests and assessments were completed several times with and without the presence of carpet. The study design and data analyses controlled for the effects on performance of learning when tasks were repeated. Due to the complexity of this fascinating study, there were numerous findings. The major relevant findings were that removing the carpet was associated with the following outcomes[44]: a) small decreases in selected pollutants; b) better perceived air quality; c) increased intensity of some SBS symptoms, particularly headache; d) 6.5% increase in amount of text typed in the simulated office work; e) a 7% increase in performance in a column addition test; f) a 4% increase in performance in a logical reasoning test; g) a 2.5% increase in performance in a serial addition test; h) a 4% increase in performance in an addition test; i) a 6.5% increase in performance in a reaction time test; and j) one conflicting finding - a 2% decrease in performance in a code substitution test. The self assessments of performance, suggested that performance increases may be a consequence, in part, of increased effort by the workers when the carpet was absent. The author's interpretation was that that performance increases in the typing test were most likely a consequence of the reductions in headache. The other performance increases were not associated with a reduction in SBS symptoms.

We must base our estimate of the productivity loss from SBS symptoms on the limited information available. The measured data (described above) of Nunes et al. (1993), the studies of classrooms in Norway (Myhrvold et al. 1996, Myhrvold and Olsen 1997), and the laboratory based studies by (Wargocki 1998) provide substantial evidence that SBS symptoms actually decrease performance; however, it is not clear how to translate the increases in response times and error rates, and decreases typing performance measured in specific tests with the magnitude of an overall productivity decrement from SBS symptoms. The self-reports discussed above suggest a productivity decrease of approximately 4% due to poor indoor air quality and physical conditions at work. Although SBS symptoms seem to be 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 will discount the 4% productivity decrease cited above by a factor of two, leading to an estimate of the productivity decrease caused by SBS equal to 2%, recognizing that this estimate is highly uncertain. The objective data of Nunes (1993) and Wargocki (1998) suggest that, for specific tasks, performance decrements from SBS symptoms may be considerably larger.

SBS symptoms are primarily associated with office buildings and other non-industrial indoor work places such as schools. According to Traynor et al. (1993), office workers are responsible for approximately 50% of the US annual gross national product. Statistical data on the occupations of the civilian labor force are roughly consistent with this estimate (US

[43] Measures of statistical significance are not included in paper.

[44] The associated p values for outcomes c through j are as follows: c) $p < 0.04$ [severe headache]; d, e, h, i, and j) $p < 0.05$; f and g) $p < 0.10$

Department of Commerce 1997), i.e., 50% of workers have occupations that would normally be considered office work or teaching. Since the gross domestic product[45] (GDP) of the US in 1996 was $7.6 trillion (US Department of Commerce 1997), the GDP associated with office-type work is approximately $3.8 trillion. Based on the estimated 2% decrease in productivity caused by SBS symptoms, the annual nationwide cost of SBS symptoms is $76 billion.

Potential Savings from Changes in Building Factors

Because multiple factors, including psychosocial factors, contribute to SBS symptoms, we cannot expect to eliminate SBS symptoms and SBS-related costs by improving indoor environments. However, strong evidence cited by Mendell (1993) and Sundell (1994) 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 SBS studies[46] have found individual environmental factors and building characteristics to be associated with changes of about 20% to 50% in the prevalence of individual SBS symptoms or groups of related symptoms[47]. A smaller number of studies have identified a few building-related factors to be associated with an increase in symptoms by a factor of two or three (e.g., Jaakkola and Miettinen 1995, Sieber et al. 1996). In a few blinded experimental studies (reviewed in Mendell 1993; Sundell 1994), specific indoor environmental conditions have been changed to investigate their influence on symptoms. Some of these studies have also demonstrated that increased ventilation rate, decreased temperature, better surface cleaning, and use of ionizers can diminish SBS symptoms, while no significant benefit was evident in other studies. In summary, the existing evidence suggests that substantial reductions in SBS symptoms, on the order of 20% to 50%, should be possible through improvement in individual indoor environmental conditions. Multiple indoor environmental factors can be improved within the same building. For the estimate of cost savings, we will assume that a 20% to 50% reduction in SBS symptoms is practical in office buildings. The corresponding annual productivity increase is of the order of $15 to $38 billion.

4.4 Direct Impacts of Indoor Environments on Human Performance

Background

The previous discussion has focused on the potential to enhance worker productivity by improving the indoor environment in a manner that reduces illness and health symptoms. However, indoor environmental conditions may influence the performance of physical and mental work, without influencing health. This section discusses the evidence of a direct connection between worker performance and three characteristics of the indoor environment: thermal conditions, lighting, and odors. Existing standards define the boundaries of recommended thermal and lighting conditions in buildings. These standards exist, in part, because conditions far from optimal have an obvious adverse influence on worker performance.

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[45] GDP is approximately equal to GNP.

[46] Most of these studies have taken place in buildings without unusual SBS problems, thus, we assume that the reported changes in symptom prevalences with building factors apply for typical buildings.

[47] Adjusted odds ratios (ORs) for the association of symptom prevalences to individual environmental factors and building characteristics are frequently in the range of 1.2 to 1.6. Assuming a typical symptom prevalence of 20%, these ORs translate to risk ratios of approximately 1.2 to 1.5, suggesting that 20% to 50% reductions in prevalences of individual SBS symptoms or groups of symptoms should be possible through changes in single building or indoor environmental features.

Research on this topic is difficult because of the complexity of defining and measuring human performance in real-world environments and because many factors influence performance. Additionally, worker motivation affects the relationship between performance and environmental conditions (e.g., highly motivated workers are less likely to have reduced performance in unfavorable environments). Indicators of human performance have included measures of actual work performance, results of special tests of component skills (e.g., reading comprehension) deemed relevant to work, and subjective self-estimates of performance changes.

A large number of papers, including many older papers, provide information pertinent to an assessment of the direct influence of environmental factors on human performance. A review of all identified papers was not possible; therefore, the following discussion is based on a review of selected papers, emphasizing more recent research with performance measures that are more closely related to actual work performance, and with environmental conditions more typical of those found in non-industrial buildings.

Linkage Between Thermal Environment and Performance

Several papers contain reviews of the literature on the linkage between the thermal environment (primarily air temperature) and selected indices of work performance. Based on these literature reviews and on original reports of research, there is substantial evidence of an association between work performance and air temperature, for the range of temperatures commonly experienced in buildings. However, not all studies have found such associations. Emphasizing the relationship of temperature to mental performance and light manual work, a brief summary of positive findings follows:

1. Laboratory studies by the New York State Commission on Ventilation (1923) found that performance of manual work was significantly influenced by air temperature but that performance of mental work was not affected by temperature. However, a re-analysis of a portion of the Commission's data (Wyon 1974) found that subjects performed 18% to 49% more typewriting work[48] at 20 ^{o}C compared to 24 ^{o}C.

2. Meese et al. (1982) investigated factory-worker's performance on fourteen tasks that simulate factory work. Workers' performance on eight of the tasks, differed significantly[49] (generally lower performance) at an 18 ^{o}C air temperature compared to 24 ^{o}C.

3. Automobile drivers of a special test vehicle missed 50% more of the signals introduced via instruments and rear view mirrors at 27 ^{o}C compared to 21 ^{o}C and response time was 22% slower at 27 ^{o}C (Wyon 1993).

4. Pepler and Warner (1968) investigated the learning performance of University students at six temperatures ranging from 16.7 ^{o}C to 33.3 ^{o}C. Students studied a programmed text and were required to respond to questions on critical points. Air temperature significantly influenced two out of four measures of learning performance: errors per unit time and times required to complete assignments. Error rates were about 20% smaller at 26.7 ^{o}C than at 20 ^{o}C or 33.3^{o}C[50]. However, the time to complete assignments was 5% to 10% higher at 26.7 ^{o}C compared to the temperature extremes. These results suggest that overall effect of

[48] $p < 0.05$
[49] $p < 0.002$ to $p < 0.01$
[50] $p < 0.05$

temperature on performance would depend on the importance of errors relative to speed of work.

5. Existing literature suggests a complex relationship between temperature and mental work performance that varies with the type of work. In a study of reading speed and comprehension, performance was superior at 20 °C and 30 °C compared to 27 °C (Wyon 1976). Similarly, based on simulated high-school classroom conditions the following findings were reported (Wyon et al. 1979): reading speed was 20% better at 23 °C and 29 °C compared to 26 °C; multiplication speed in males was ~20% higher[51] at temperatures above and below 27 - 28 °C; word memory in males was best (~20 % higher) at an intermediate temperature of around 26 °C[52]; and word memory performance for females increased with temperature between 24 and 26 °C, but did not fall as temperatures increased further to 29 °C.

The previous discussion suggests that temperature can influence mental performance in some settings. For some types of mental work (e.g., complex or creative mental work), optimal thermal comfort and optimum performance may approximately coincide. For other types of mental work, slight thermal discomfort that increases arousal (e.g., slightly cool temperatures) may increase performance. Temperatures just below the point that causes sweating may cause workers to relax and work less to prevent sweating. Given that the optimum temperature for a task depends on the nature of the task, varies among individuals (e.g., with gender, age, and clothing) and varies over time (e.g., since tasks change), some papers have advocated or investigated the provision of individual control of temperature as a practical method to increase productivity (Kroner and Stark 1992; Wyon 1993, 1996, Menzies et al. 1997). A study in an insurance office, using the number of files processed per week as a measure of productivity, suggested that provision of individual temperature control increased productivity by approximately 2%. However, studies of individual control may be criticized because these studies can not be performed blindly, i.e., occupants know if they have individual control. With assumptions about workers' use of individual control, Wyon (1996) has estimated that providing workers ± 3 °C of individual control should lead to about a 3% increase in performance for both logical thinking and very skilled manual work, and approximately a 7% increase in performance for typing relative to performance in a building maintained at the population-average neutral temperature. Larger productivity increases would be predicted if the reference building did not maintain the average neutral temperature.

Linkage Between Lighting and Human Performance

As discussed by the National Electrical Manufacturers Association (NEMA 1989) lighting has at least 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. Several characteristics of lighting, e.g., illuminance (the intensity of light that impinges on a surface), amount of glare, and the spectrum of light may theoretically affect work performance. Obviously, lighting extremes will adversely influence performance; however, the potential to improve performance by changing the lighting normally experienced within buildings is the most relevant question for this paper.

[51] $p < 0.05$
[52] $p < 0.05$ for the performance improvement between 24 and 26 °C

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, Romm (1994) reports a 6% increase in the performance of postal workers during mail sorting after a lighting retrofit that improved lighting quality and also saved energy. A review of the relationship between lighting and human performance (NEMA 1989) provides additional examples, such as more rapid production of drawings by a drafting group after bright reflections were reduced.

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. As an example, in one visual test subjects must identify the location of an open section in a circle (called a Landolt C) that is briefly shown on a computer monitor. Many of these studies have identified statistically-significant differences in people's performance on these visual tests with changes in lighting (e.g., Berman et al. 1993, 1994, NEMA 1989); 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 aspects of reading performance, such as reading comprehension, reading speed, or accuracy of proofreading. Some of these studies have failed to identify statistically significant effects of illuminance (Veitch 1990, Smith and Rea 1982). 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 (Smith and Rea 1979; Tinker 1952). Low levels of illuminance seem to have a more definite adverse influence on the performance of older people (Smith and Rea 1979, NEMA 1989), a finding that may become increasingly important as the work force becomes older.

Clear and Berman (1993) explored economically-optimum lighting levels by incorporating equations that relate illumination to performance within a cost benefit model. Their resulting recommended illumination levels varied a great deal with the visual subject (size and contrast), the age of the person, and the model used to relate illumination to performance. It is not possible to generalize from the findings; however, the variability in optimum illumination indicates that occupant-controllable task lighting may be helpful in increasing productivity.

There have been anecdotal reports of the benefits of full spectrum lighting on morale and performance, relative to the typical fluorescent lighting. However, based on the published literature (Boray et al. 1989; Veitch et al. 1991; NEMA 1989) there seems to be no strong or consistent scientific evidence of benefits of full spectrum lighting.

Berman et al. (1993; 1994) have found that changes in the spectrum of light (with illuminance unchanged) influence both pupil size and performance in visual tests. They suggest that the smaller pupil size when light is rich in the blue-green portion of the spectrum reduced the adverse effects of optical aberrations. Additionally, Berman (1992) argues that the required illuminance to maintain work performance, hence the required lighting energy use, could be decreased by 24% if standard cool-white lamps were replaced by those with a larger portion of light output in the blue-green spectrum. The associated annual reduction in energy use for the U.S. would be $4.2 billion.

A few studies have examined the influence of different lighting systems on self reported productivity or on cognitive task performance. The lighting systems compared resulted in different illuminance and also different lighting quality (e.g., differences in reflections and glare). In a study by Hedge et al. (1995), occupants reported that both lensed-indirect and parabolic downlighting supported reading and writing on paper and on the computer screen better than a recessed lighting system with translucent prismatic diffusers[53]. Katzev (1992) studied the mood and cognitive performance of subjects in laboratories with four different lighting systems (both conventional and energy-efficient). The type of lighting system influenced occupant satisfaction and one energy-efficient system was associated with better reading comprehension[54]. 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. In a recent laboratory study, Veitch and Newsham (1998) found that the type of luminaire influenced performance of computer based work. Also, energy efficient electronic ballasts, which result in less lighting flicker than magnetic ballasts, 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. Most of the studies that incorporated measurements of performance had few subjects, hence, these studies were not able to identify small (e.g., few percent) increases in performance that would be economically very significant. Also, the majority of research subjects have been young adults and lighting is expected to have a larger influence on the performance of older adults.

<u>Linkage Between Odor or Scents and Human Performance</u>

Substantial research has been undertaken to evaluate the relationship of work performance with odors or scents, e.g., pleasant odors, unpleasant odors, stimulating or relaxing odors. The rationale behind these studies is that odors may potentially affect mood, or arousal, or increase relaxation which, in turn, influences work performance. Odors, especially unpleasant odors, could also distract workers or cause workers to be afraid of health effects. Additionally, the temporal coincidence of odors, even unconscious odors, with an emotionally significant (e.g., anxiety producing) event could result in conditioning so that the emotions re-occur upon subsequent exposure to the odors.

Researchers have investigated the influence of odors on moods, attitudes, self-reported health effects, self-reported work performance, and measured task performance. Some findings of associations between odors and measured task performance are summarized below:

1. Rotton (1983) used groups of approximately 80 subjects to investigate the influence of malodors on performance in a simple mental task (arithmetic) and a complex task (proofreading). The experimental periods were 15 to 30 minutes. He found that the presence or lack of malodor was associated with significant[55] changes in the number or errors identified during proofreading. About 50% more errors were detected in the no-odor situation. Performance on the arithmetic task was not significantly changed by the presence or lack of the odor. The intensity of the odor was uncharacterized, and may have exceeded the intensity of odors normally experienced in buildings.

2. Dember et al. (1995) summarize four fascinating short-term laboratory experiments involving intermittent odors of peppermint (considered arousing), muguet (considered

[53] $p < 0.01$
[54] $p < 0.01$
[55] $p < 0.01$ to 0.1

relaxing) and normal air (for reference). In each case, the performance test was the detection of signals on a computer screen. The test was characterized as tedious and demanding vigilance, similar to the real work of air traffic controllers and other workers that must monitor displays and detect occasional events. In the first experiment (Warm et al. 1991), the percent of signals that were detected increased by approximately a factor of 1.4 with exposure to 30 second pulses of either odor[56] (the pulses occurred every 5 minutes). In the second experiment, the subjects had control over delivery of the odor, and only the performance of women improved with exposure to the odors. A third experiment found that peppermint odor significantly improved the performance of subjects judged to be inattentive (attentiveness based on a self-administered test), but that the performance of attentive subjects was not improved. The final experiment showed that exposure to peppermint odors improved signal detection and also had a significant effect on the amplitude of voltage changes measured from the scalp. The amplitude of these voltage changes had previously been linked to the extent of attention to a stimuli.

3. Knasko (1993) assessed performance on simple and difficult math and verbal tasks during exposure to pleasant, unpleasant, and no odors. The odors were rated as moderately strong. No significant influence of odors on performance was identified. Knasco (1992) also found that odors of weak-to-moderate intensity did not influence performance on a test that measured creativity.

4. Baron (1990) found that positive odors from commercial air fresheners had no significant influence on performance in a clerical coding task; however, in the pleasant-odor condition subjects more often used an efficient approach to complete the task[57].

5. In one of two sessions of a study, Ludvigson and Rottman (1989) found a significant association between exposure to lavender odor (considered relaxing) and reduced performance in a test of arithmetic reasoning. No significant associations were found between other measures of cognitive performance and lavender or clove odors. The odors were described as subjectively quite strong.

6. One additional study (Kirk-Smith et al. 1983) employed a neutral odor with low intensity so that subjects were not conscious of the odor. The odor did not significantly influence the subjects' ability to assemble a pattern from a set of blocks.

Several, but not all, studies have found that odors can influence moods and attitudes which, in turn, may influence work performance. For example, the data from the study by Baron (1990) suggests that positive scents may lead to higher goal-setting and improved methods of conflict resolution[58]. Even feigned (suggested but non-existent) odors influenced moods (Knasco et al. 1990). A significant association[59] between exposure to lemon scents and reduced self-reported health effects, such as SBS symptoms, was found by Knasco (1992) but not in a subsequent study (Knasco 1993).

Based on this review, the results of research on odors and performance range from findings of no effect to findings of large statistically-significant effects. The variability in results is not surprising, since the research has included many different odors, odor intensities, and measured

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[56] $p = 0.05$

[57] $p < 0.07$

[58] $p < 0.05$ for both goal setting and conflict resolution

[59] $p = 0.02$

or reported outcomes. Overall, the literature provides substantial evidence that some odors can affect some aspects of cognitive performance. Each of the studies cited above has relied on special laboratory-based tests of cognitive performance. The implications for the overall performance of workers in the actual workplace are not readily quantified. Also, intentionally exposing workers to chemicals that have scents could be considered unethical

Summary of Findings Regarding Direct Impacts of Environments on Human Performance

Much of the research on the direct linkage between human performance and environmental conditions is from laboratory experiments, and the relevance of laboratory findings to real-world settings is uncertain. Numerous studies suggest that the thermal environment can influence performance of some aspects of mental work by a few percent to approximately 20%, however, other studies suggest that modest changes in environmental conditions will not influence performance. There is also evidence that improved lighting quality can have a strong positive (e.g., 6%) influence on work performance when the work requires excellent vision; however, the potential to improve the performance of more typical, largely cognitive work by changing the lighting within buildings remains unclear. The literature provides substantial evidence that some odors can affect some aspects of cognitive performance.

Estimate of Potential Productivity Gains

Once again, the limited existing information makes it very difficult to estimate the magnitude of direct work performance improvements that could be obtained from improvements in indoor environments. Extrapolations from the results of laboratory studies to the real work force are the only avenues presently available for estimating the potential values of productivity gains. 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 of the 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 environmental conditions (e.g., temperatures and illuminance) 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 research literature reviewed above reports performance changes of 2% to 20% (with one outlier value excluded, a 49% improvement). 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 $3.8 trillion (as discussed above), the 0.5% to 5% estimated performance gain translates into an annual productivity increase of $19 billion to $190 billion.

5.0 EXAMPLE COST BENEFIT ANALYSES

To illustrate the costs of improving indoor environments relative to the potential productivity gains and health care cost savings discussed previously, two methods of improving indoor air quality are considered: increased outside air ventilation and improved particle filtration. These two cost-benefit analyses serve as examples. A comprehensive assessment would consider many additional changes in technologies or practices such as improved lighting, changes in air temperature, improved building maintenance, and reduced occupant density.

5.1 Increased Outside Air Supply

Increasing the rate of outside air ventilation is one obvious method of reducing indoor exposures to indoor-generated air pollutants contributing to infectious disease, allergies, dissatisfaction with air quality, and a variety of sick building syndrome symptoms. The costs of increased ventilation, estimated based on model predictions, have been reported in a variety of papers. The findings vary considerably with the type of building, type of heating, ventilating, and air conditioning (HVAC) system, occupant density, and climate. For example, if minimum ventilation rates are increased to 10 L/s-occupant (20 cfm/occupant) from 5 L/s-occupant (10 cfm/occupant), the estimated increase in building HVAC energy used for fans, heating, and cooling, varies from less than 1% to approximately 50%. In office buildings with HVAC systems that have an economizer[60], increasing the average minimum ventilation rates to approximately 10 L/s-occupant (20 cfm/occupant) from 2.5 L/s-occupant (5 cfm/occupant) is likely to change building energy use by only a few percent to 10% (Eto and Meyer 1988; Eto 1990, Mudarri and Hall 1993). The larger increases in energy use (e.g., 30% to 50%) are expected only in buildings with a high occupant density such as schools (Ventresca 1991, Mudarri and Hall 1996, Steele and Brown 1990). Since workers' salaries in office buildings exceed total building energy use by approximately a factor of 100 (Woods 1989), the cost of modest (e.g., 10%) increases in HVAC energy will be small compared to the potential savings cited above. However, to reduce adverse environmental impacts of energy use, energy efficient options for increasing ventilation (e.g., adding economizer systems where they are absent or ventilation with heat recovery) should be considered preferred options.

As an example of costs, we consider the results of analyses of Eto and Meyer (1988) involving a large 55,500 m^2 (597,000 ft^2) office building. Eto and Meyer (1988) do not indicate building occupancy; therefore, we will assume a default occupancy for offices of 7 persons per 100 m^2 (ASHRAE 1989) resulting in an estimated 3880 occupants. Results from the Washington D.C. temperate climate are used. Increasing the minimum ventilation rates from 2.5 L/s-person (5 cfm-person) to 10 L/s-occupant (20 cfm/occupant) increased the projected annual energy costs by $24,100 or $6.20 per person in 1996 prices ($20,400 in 1988 prices)[61]. The estimated incremental first cost of the HVAC system was $154,000 or 2.1% ($116,000 in 1988 prices)[62,63]. Spreading this first cost over a 15 year period using a 6% real capital recovery factor

[60] To save energy, economizer systems automatically increase the rate of outside air supply above the minimum setpoint during mild weather.

[61] Since the increased energy costs are dominated by electricity used for cooling, data on the price of electricity for commercial establishments were used to update costs (Table 752 of US Department of Commerce 1997).

[62] In many existing office buildings, there will be no incremental HVAC costs because oversized HVAC equipment will handle increased loads.

[63] Cost updated to 1996 using the ratio of the CPI (for all items) in 1996 to the CPI in 1988 which equals 1.33 (Table 752, U.S. Department of Commerce 1997)

results in an additional annual cost of ~$15,800 ($4.10 per person), thus, the total estimated annual cost is ~$40,000 or $10.30 per person. The annual total compensation for the 3880 office workers in this building will be approximately $152 million (3880 persons x $39.2K per person). If the increased ventilation leads to a 10% reduction in respiratory infections, the days of lost work and reduced performance at work will decrease by 10%. Since respiratory infections cause workers to miss work about 1.3 days per year and to have 2.2 days of restricted activity, the annual value to the employer of the 10% reduction in respiratory disease would be $117,000[64] ($30.20 per person) or three times the projected annual cost. Additionally, health care costs for the workers would be reduced by roughly $49,000 annually[65] ($12.60 per person). If the increased ventilation decreases symptoms of SBS by 25% and SBS symptoms are responsible for a 1% drop in productivity, the associated annual productivity increase is $380,000 (0.0025 x 3880 persons x $39.2K per person) or $97.90 per person. Combining the three savings elements yields an annual savings of $545,000 ($140 per person), 14 times the projected annual cost.

5.2 Improved Air Filtration

As discussed previously, improved air filtration has the potential to reduce disease transmission, allergies and asthma, and SBS symptoms. In a recent field study, high efficiency air filters were installed in an office building (Fisk et al 1998). Product literature indicates that these filters remove 95% of particles with an aerodynamic diameter of 0.3 μm and a higher percentage of smaller and larger particles. Based on measured data, the high efficiency filters reduced the total indoor concentration of particles 0.3 μm and larger by a factor of 20. Many of these particles have an outdoor origin. The estimated reduction in the concentration of sub-micron indoor-generated particles is a factor of four. The annual cost of purchasing the high efficiency filters used in this study is approximately $23 per person, assuming the filters must be replaced annually[66]. The incremental cost of labor for installing an extra set of filters once per year is negligible compared to the cost of the filters. (Upstream low-efficiency prefilters are often used to extend the life of the high efficiency filters). The increased air-flow resistance of high-efficiency filters, compared to typical filters, can increase the required fan power if HVAC air flow rates are maintained unchanged. The increased cost of fan energy was estimated to be ~$1.00 per person-year using standard relationships between fan power requirements and air flow resistance, assuming that the average airflow resistance increases by 60 Pa. However, in many retrofit applications the flow rate in the HVAC system can decrease substantially without adverse effects because existing flow rates are excessive. In these applications, installation of high-efficiency filters will actually save fan energy.

In the previous example, the total estimated annual per-person cost of improved air filtration is $24. If the improved filtration resulted in a 10% reduction in respiratory disease, the

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[64] We assume a 25% reduction in productivity on restricted-activity days. We also scale the days in bed and restricted activity days reported by Dixon (1985) by the ratio of work days to total days.

[65] The direct health care costs of respiratory infection for the U.S. population were estimated to be $36.4 billion (see prior text). The incidence of acute respiratory conditions (common cold and influenza) is approximately 63 per 100 for people of working age (18-64) and 80 per 100 for others (Tables 16 and 217, U.S. Department of Commerce 1997, estimate based on average influenza rate for 1990 - 1994). The total number of acute respiratory conditions per year is 180 million. The number of people in the workforce is 135 million and outside of the workforce is 131 million. If health care costs per respiratory infection are approximately the same for workers and non-workers (relevant data were not identified), the annual health care cost per worker per respiratory illness is $200. Multiplying by the incidence of respiratory infections for workers yields an annual health care cost per worker of $126 or $489,000 for 3880 workers. A 10% reduction is $49,000.

[66] Calculations indicate that the high efficiency filters should have a lifetime of at least a year, before they need to be changed due to an increase in air-flow resistance.

annual savings would be $43 per worker (see calculation in the previous example on increased ventilation). If the improved filtration reduced allergic symptoms experienced by the 20% of the work force that have environmental allergies and this reduction in allergic symptoms resulted in a 1% increase in the productivity of allergic workers, the annual productivity gain would be $78 per person averaged over all workers (0.01 x $39,200 annual compensation x 0.2 of workers affected). If the improved filtration decreased the productivity loss from SBS symptoms from 1% to 0.75%, the annual productivity gain would be $98 per person. If all of these benefits were realized, the annual savings of ~$220 per worker would exceed the annual cost per worker by a factor of 9.

6.0 CONCLUSIONS

1. Based on a review of existing literature, there is relatively strong evidence that characteristics of buildings and indoor environments significantly influence the occurrence of respiratory disease, allergy and asthma symptoms, sick building symptoms, and worker performance.

2. Theoretical and limited 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 5.

3. 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 $250 billion, with a breakdown as indicated in Table 5.

4. In two example calculations, the potential financial benefits of improving indoor environments exceed costs by large factors of 9 and 14.

Table 5. Estimated potential productivity gains from improvements in indoor environments.

Source of Productivity Gain	Potential Annual Health Benefits	Potential U.S. Annual Savings or Productivity Gain (1996 $U.S.)
Reduced respiratory disease	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 approximately 15 million workers	$15 - $38 billion
Improved worker performance from changes in thermal	Not applicable	$20 - $200 billion

environment and lighting		

7.0 IMPLICATIONS

Strong evidence that better indoor environments can cost-effectively increase health and productivity would justify changes in the components of building codes pertinent to indoor environmental quality, such as the prescribed minimum ventilation rates and minimum efficiencies of air filtration systems. Additionally, strong evidence of benefits would justify changes in company and institutional policies related to building design, operation, and maintenance. Health maintenance organizations and insurance companies might also be motivated to reduce rates charged to organizations that maintain superior indoor environments.

We do not presently have the specific and compelling cost-benefit data that are necessary to motivate these changes in building codes, designs, and operation and maintenance policies. The existing evidence of potential productivity gains of tens of billions of dollars per year is, however, clearly sufficient to justify a program of research designed to obtain these cost-benefit data. The primary objectives of the research should be to develop more specific and accurate estimates of the benefits and costs of technologies and policies that improve indoor environments. Wright and Rosenfeld (1996) describe the required program of research and identify research priorities.

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