

Indoor Air Quality Optimization to Increase Worker Productivity in Commercial Buildings

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Abstract

Sustainable design, construction, and operation practices have been developing rapidly. One of the criteria of building a more sustainable environment is to create a healthy and comfortable indoor air quality (IAQ). Specific levels of indoor air pollutants may affect the health, comfort, and the productivity of the occupants of a building. Many private and public entities have realized the importance of space optimization in order to increase the productivity of their employees. However, experts lack a quantitative decision making methodology to balance the trade offs between increased IAQ and worker productivity. The building industry and its clients lack the resources to identify optimum solutions for a sound commercial solution. This study introduces a decision model of linear mathematical programming for optimizing costs associated with IAQ and worker productivity in commercial buildings. This study utilizes a set of decision variables, technical, and legal constraints, as well as a sample objective function to achieve the maximum financial benefits of a better IAQ, for commercial buildings. The results of this optimization model determines the levels of outdoor and filtered air inside a commercial building by considering cost of increased or decreased worker productivity as well as other building and business specific data.

Keywords

Sustainable construction, Indoor air quality, Optimization, Worker productivity

1. Introduction

Sustainable design and construction of the buildings has become more common among the recent practices of building experts. Main reason for this increase in the awareness is due to a combination of increased environmental sensitivity, as well as the recognition of how buildings can impact its occupants' health and comfort in significant ways.

One of the areas that sustainable construction concentrates on is the Indoor Environmental Quality (IEQ) of buildings. This area has become especially important in commercial buildings where the comfort of the occupants has a direct relationship with their productivity at work. There have been a number of studies in determining the impacts of a certain IEQ of a building on how employees work on a day to day basis. These studies concentrate on many different aspects of IEQ such as indoor air quality (IAQ), illumination, acoustics, and thermal comfort. Among these different aspects of IEQ, this study concentrates specifically on determining the optimum IAQ of commercial buildings.

EPA studies of human exposure to air pollutants indicate that indoor air levels of many pollutants may be 2-5 times, and occasionally more than 100 times, higher than outdoor levels (USEPA, 1993). These levels of indoor air pollutants are significant when it is considered that people spend most of their time indoors. Indoor air contamination can become very dangerous due to the fact that the indoor air is continuously recycled. This causes the contaminants in the air to be trapped in the system and easily increase in quantities. Common indoor air contaminants include dust, volatile organic compounds (VOC), mold, pollen, pet dander and smoke. The sources of indoor air pollutants include the HVAC system itself, as well as human activities, and building materials. Controlling these sources of pollution requires measures to be taken at many stages of a building's lifetime. Design, construction, commissioning, and occupancy phases are all crucial stages that can include decisions and activities that affect IAQ.

The problems of the IAQ in buildings start with the lack of a decision mechanism besides the local and national standards when choosing a specific IAQ management option. The standards or the federal/state regulations do not always guarantee the optimum decisions. Building industry does not search for a better IAQ when they are not entirely aware of the consequences of different IAQ management methods and decisions. Another problem is that many building owners and managers do not have the resources to identify the "best" solutions to IAQ problems.

The purpose of this paper is to generate a conceptual background for developing decision models for optimizing the control of IAQ in commercial buildings. This study focuses on the use of mathematical programming to achieve a conceptual optimization study as well as determines the decision variables, and configures the technical constraints as the major steps of the optimization study. Programming also includes an objective function towards maximizing the cost effectiveness of the control techniques.

2. IAQ and True Costs

IAQ has financial consequences as well as its health affects on the building occupants. The cost of an IAQ management option can be associated with two different types of costs. These costs can be categorized as hard and soft costs. "Hard costs" in building industry is a term for the amount that includes total land costs, site clearance, grading and construction costs, and landscaping (ELI, 2005). Hard costs associated with IAQ would be the life cycle costs (LCC) of managing the IAQ in a building (i.e. energy costs, maintenance costs, etc.). Soft costs in building industry are known as architectural, engineering, and legal fees as distinguished from land and construction costs. Consequently soft costs of a specific IAQ management option include costs associated with occupant productivity, health, insurance fees, litigation, etc. Unfortunately many investors or building owners/managers usually ignore the soft costs associated with IAQ due to their stochastic natures.

One of the major soft costs that are related to the IAQ of a building is the cost associated with the variance in worker productivity in correlation with the IAQ of the building. This issue is discussed in more detail in the upcoming section. Another type of soft cost associated with IAQ is the economic loss created by health problems. In OSHA's effort to establish ventilation rules for non-industrial workers, following rationalization is used:

"....the Agency estimates that the excess risk of developing the type of non-migraine headache which may need medical attention or restrict activity which has been associated with poor indoor air quality is 57 per 1,000 exposed employees. In addition the excess risk of developing upper respiratory symptoms, which are severe enough to require medical attention or restrict activity, is estimated to be 85 per 1,000 exposed employees. These numbers are extrapolated from actual field studies and therefore show the magnitude of the problem at present."(OSHA, 1994).

Damiano (2005) estimates that the direct cost to the U.S. economy due to increased allergies, asthma and sick building syndrome (SBS) symptoms were \$7 to \$23 Billion per year. A large portion of these costs was estimated to be in the form of workmen's compensation claims, health care insurance premiums and direct health care costs. There have been many cases where poor IAQ of buildings have caused major financial, health, and even psychological problems among the building owners, managers, and occupants. Harvard's Brigham and Women's Hospital, where 47 nurses had to take disability leave in 1993 due to IAQ related health complaints; Florida's Martin County Courthouse, where mold and its affects on the IAQ of the building required a \$3.5 million for remediation; even the EPA's Washington offices, where brand-new carpets were blamed for gas emissions, are among some of the IAQ and SBS related cases (Mann, 2001).

In addition to the productivity and health related costs, IAQ can also be associated with litigation cases and their associated costs. The number of these cases is still few but is continuously increasing along with the awareness of the affects of IAQ on building occupants. One of the examples of an IAQ related litigation case is DuPage County Courthouse in Wheaton, IL. Due to SBS 25 employees in DuPage County Courthouse were hospitalized in a single day in 1992 (Bas, 1993). The \$50 million building was closed temporarily, which affected the health of more than 700 employees. The main problem with the courthouse was later determined to be inadequate ventilation. The county in this case sought \$3 million in damages for the design, engineering, and construction of the building (Bas, 1993).

The number of IAQ related litigation cases is growing continuously along with the public awareness on IAQ issues. In addition to this, there is also an increasing understanding by employees that they are owed a healthy working environment. This makes HVAC engineers, general or subcontractors, property management companies, architects, material suppliers and building owners the biggest targets of potential IAQ related law suits (Celik *et al.*, 2006).

2.1 IAQ and its Impact on Human Productivity

In 2000, three studies were conducted to determine the increase in productivity, if any, associated with added levels of OA ventilation using 90 human subjects. By increasing OA ventilation from 0.60m³ to 5.05m³ while holding all other indoor climate conditions constant, the subjects' performance of simulated office tasks were observed. Results found that doubling OA ventilation can initially increase overall performance by 1.8%. However, the rate of increase in performance benefits declines with respect to additional increases in OA ventilation beyond approximately 1.56 m³. In fact, as presented in Table 1, increasing OA ventilation another five-fold to 5.05 m³ results in only another 1.9% increase in worker productivity (Wargocki, 2000).

Table 1: OA Ventilation Rate (m³/min/person) vs. Worker Performance Index (Wargocki, 2000)

OA (m ³)	PI	OA (m ³)	PI	OA (m ³)	PI	OA (m ³)	PI	OA (m ³)	PI
0.60	0.9900	1.56	1.0220	2.51	1.0289	3.46	1.0330	4.42	1.0358
0.71	1.0000	1.67	1.0230	2.62	1.0294	3.57	1.0333	4.52	1.0361
0.81	1.0069	1.77	1.0240	2.72	1.0300	3.67	1.0337	4.63	1.0364
0.92	1.0110	1.87	1.0249	2.83	1.0305	3.78	1.0340	4.73	1.0366
1.03	1.0139	1.98	1.0257	2.93	1.0309	3.89	1.0344	4.84	1.0369
1.13	1.0161	2.08	1.0264	3.04	1.0314	3.99	1.0347	4.95	1.0371
1.24	1.0179	2.19	1.0271	3.15	1.0318	4.10	1.0350	5.05	1.0374
1.34	1.0195	2.30	1.0277	3.25	1.0322	4.21	1.0353		
1.45	1.0208	2.40	1.0283	3.36	1.0326	4.31	1.0356		

Using the Wargoeki data, the incremental performance benefit, or, performance index (PI) of each added cubic feet of OA ventilation can be determined by multiplying the worker's fully burdened labor rate or salary by PI minus one. This value (PI-1.0) represents the incremental performance "profit" index (PPI). For instance, if the average cost of the employee to the employer is \$US 30,000 per year, then increasing the employee performance index to 1.02 could improve the value of productivity \$US 600 per year per employee. By multiplying the average benefit per employee by the total number of employees, a total annualized benefit for added OA ventilation can be determined. If the total annualized benefit for added OA ventilation is greater than the total annualized cost, then a positive return on investment can be realized (Celik *et al.*, 2007).

3. Optimizing IAQ by Linear Programming

This study uses a quantitative methodology that combines LCC analysis with the soft cost analysis in order to optimize the true costs of IAQ control technologies and strategies in buildings. Linear programming (LP) is used as a preliminary option for this study.

There are basically two assumptions implicit in an LP model. One is that any relationship of two or more variables must satisfy the characteristics of a linear relationship. Second, the model uses deterministic assumptions meaning that the variances in the values are not significant enough to warrant a nondeterministic approach. In summary, an LP model may be considered as a potential tool in determining the optimal allocation of limited resources if and only if the situation under consideration adequately satisfies the linear and deterministic assumptions. In a real world situation some of the constraints and variables in a decision process may have nonlinear relationships such as the relationship between productivity and IAQ. This research simplifies these relationships into a linear level by using piece-wise linear approximations.

In order to solve the model there are many software available. Excel Solver ® is one of those alternatives and is used to solve the model created in this study.

3.1 Methodology

The optimization study includes three major parts as listed below:

- Improved ventilation by central unit
- Improved ventilation by a dedicated unit
- Air cleaning

These areas are all combined in an objective function in order to set the values for the decision variables that are subject to the constraints. In order to calculate the LCC of the parameters given above, this study utilized a preliminary methodology that is developed by the EPA (Henschel 1999). EPA's study provides a number of worksheets to help calculate the LCC of improved ventilation, and air cleaning techniques. An important factor to note is that using the preliminary methodology developed by EPA can help estimate the rough values for the input unit costs. However it is also important to evaluate the model not in terms of the actual numbers that will be constantly changing due to inflation rates and other economic, global and technological developments, but of the relationships among the IAQ control options. The model is developed as a preliminary study that is basically simplified in many terms to clarify the application of linear programming methodologies in construction management. Although more complex optimization methodologies are widely used in the engineering side of this area, construction managers and the building owners and managers are still not aware of the possibilities that optimization studies can offer in making preliminary decisions.

3.1.1 Decision variables

Decision variables are the dependent variables in LP that are subject to changing while optimizing the objective function. There are a total of eleven decision variables in this study. The units of all the variables except the binary ones and the productivity variable are cubic feet per minute per person and all the cost values in the model are annual. Decision variables of the model in this research are listed below:

X_1 = Amount of OA supplied by a central unit (cfm/person)

X_2 = Amount of OA supplied by a dedicated unit (cfm/person)

W = Profit generated by increased productivity (\$)

F_1 = Amount of air through cleaner 1 (cfm/person)

F_2 = Amount of air through cleaner 2 (cfm/person)

F_3 = Amount of air through cleaner 3 (cfm/person)

Y_1 = "1" if central unit is used, "0" if not

Y_2 = "1" if dedicated unit is used, "0" if not

B_1 = "1" if cleaner 1 is used, "0" if not

B_2 = "1" if cleaner 2 is used, "0" if not

B_3 = "1" if cleaner 3 is used, "0" if not

3.1.2 Objective function

The objective of the model in managerial terms is to minimize the true costs of IAQ management options. In more detail, it is to minimize the overall cost of providing outdoor air and cleaning air in a commercial building while maximizing the benefits of increased worker productivity. Equation below represents the summation of three major costs. These are the cost of OA by a central unit, OA by a dedicated unit, and cleaning air in three possible locations. The cost of bringing OA by a central unit includes the variable cost (VC), revenue generated by increased productivity (R), and the fixed costs (FC).

$$\text{Min } z = \sum_{i=1}^2 (A_i X_i + C_i Y_i) + \sum_{j=1}^3 (F_j D + B_j E) - W$$

\Downarrow
 \Downarrow
 VC

\Downarrow
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 FC

\Downarrow
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 VC

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 FC

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 R

- z = The total annual cost of the IAQ control (\$)
- A_1 = Marginal cost of air by central unit (\$ x person/cfm)
- A_2 = Marginal cost of air by dedicated unit (\$ x person/cfm)
- C_1 = Fixed cost for central unit (\$)
- C_2 = Fixed cost for dedicated unit (\$)
- D = Cost for cleaning air (\$ x person/cfm)
- E = Fixed cost for air cleaners (\$)

3.1.3 Decision constraints

Decision constraints of the model are a set of constraints that the model is limited with while changing the value of the decision variables to optimize the objective function. The decision constraints that the objective function is subject to are given below:

- $X_1 + X_2 \leq 140 \text{ cfm}$
- $X_1 + X_2 \geq 20 \text{ cfm}$
- $Y_1 + Y_2 \geq 1$
- $B_1 + B_2 + B_3 \geq 1$
- $X_1 - 140Y_1 \leq 0$
- $X_2 - 140Y_2 \leq 0$
- $F_i - 140B_i \leq 0$
- $F_1 + F_2 - F_3 \leq 0$
- $X_1 + X_2 - (F_1 + F_2 + F_3) \leq 0$
- $1831.02 X_1 - 1831.02 X_2 + W \leq -36620.41$
- $-851.38 X_1 - 851.38 X_2 + W \leq -11149.65$
- $-560.79 X_1 - 560.79 X_2 + W \leq -1850.81$
- $-418.36 X_1 - 418.36 X_2 + W \leq 3542.52$
- $-334.45 X_1 - 334.45 X_2 + W \leq 7256.39$
- $-278.42 X_1 - 278.42 X_2 + W \leq 10057.78$
- $-238.50 X_1 - 238.50 X_2 + W \leq 12293.41$
- $-208.61 X_1 - 208.61 X_2 + W \leq 14146.98$
- $-185.38 X_1 - 185.38 X_2 + W \leq 15726.56$
- $-166.81 X_1 - 166.81 X_2 + W \leq 17100.76$
- $-151.62 X_1 - 151.62 X_2 + W \leq 18315.65$
- All variables ≥ 0

3.2 Results

The building used in the case study is assumed to be located in Miami, FL and is a middle-sized commercial building. Cost data that is used in this case are rough estimates. These costs may significantly vary due to changes in system design and the operating and maintenance unit costs. Demographic data that is used to solve the model is given below:

- Number of occupants: 50
- Average salary of the occupants: \$20,000

The cost data are set as follows:

- Cost of OA by central unit: \$3.40 cfm/person
- Cost of OA by dedicated unit: \$3.20 cfm/person
- Cost of cleaning air: \$3.40 cfm/person
- Fixed cost for central unit: \$35,000
- Fixed cost for dedicated unit: \$40,000
- Fixed cost for air cleaner: \$8,000

According to the optimization model structured in this study, the optimum solution to the above case would require bringing 44 cfm/person outdoor air by using the central unit. Also the solution suggests using an air cleaner at the outdoor air and recirculated air combination location, and filtering 44 cfm of air/person. According to the results of the binary variables in this hypothetical situation, it is not optimal to use a dedicated unit, air filter for only outdoor air, or air filter for only recirculated air. The model's objective function for this case is calculated by the software to be \$35,988.00. This means that the cost of

the system (when the productivity increase is taken into consideration) would be approximately \$36K annually.

According to the sensitivity report of the above case, provided the coefficient (unit cost) of X_1 in the objective function lies between 248.86 and 164.45, the values of the variables in the optimal LP solution will remain unchanged. Similarly, if the coefficient (unit cost) of X_2 goes above 170, the current solution of the model will be invalid; this would require a new solution by using the new coefficient values. However it is important to note that the actual optimal solution value will constantly change as the objective function coefficient of X_1 or X_2 are changing. If the coefficient of W (profit from increased productivity) lies between -0.81 and -1.02 , values for the decision variables would remain the same.

It is also observed in this case that if the average salary of the occupants in the building does not stay between \$16,235.00 and \$20,331.00, the values for the decision variables do not remain optimal. This means the model with a new total salary beyond this range needs to be solved again in order to find the new objective value and more importantly the new values for the decision variables. This is mainly due to the shift of the optimum extreme point to a different extreme point, which happens when at least one of the constraints changes its state of being binding or not binding. In general, if the total salary of the occupants increases, the objective function (the total cost of the system) decreases due to the increase in total savings by increased productivity.

In another case study, where the number of employees and their average salaries are held constant while increasing the energy costs, the decision model suggests supplying less than 44cfm of outdoor air. This proves that in order to generate the maximum profit from an IAQ management option, it is to the building experts' best interest to increase the energy efficiency of their building to its highest extent.

4. Conclusion and Recommendation

Planning, design, and construction work should be based not on tight but on generous estimates in regards to the time required for each phase. An extensive reserve capacity should be designed and built into the building and its systems. IAQ is a crucial part of the efforts towards more sustainable systems in construction and building technologies. The benefits of a better IAQ are widely known although the quantity of potential savings has not been very clear to a majority of the audience. This problem causes the building owners and managers, architects, or the contractors to choose systems and options that decrease the hard costs, which mostly decrease IAQ in their buildings.

This study develops an optimization model that takes the operation and maintenance costs of a better IAQ into account, combines them with potential soft cost savings and quantifies the true cost of a system under different circumstances. This study demonstrates that an optimization study by using linear programming can be used to pre-screen the optimal IAQ measures in commercial building. The results show that meeting the minimum code recommendations may not always create the most optimum cost saving results for commercial buildings. It is also clear that there is an indirect relationship between the total salary and the total cost of an IAQ system when the initial cost of the system is held constant. The same indirect relationship is also observed between the number of the occupants and the total cost of the system in commercial buildings when the fixed costs are held constant.

The model uses mixed integer linear programming to generate the optimization study. One of the advantages of linear programming is the simplicity and the speed of the solution generation. However, it has been discussed earlier that there are several matters in this area that have non-linear correlations. This study mostly deals with the nonlinear functions by piece-wise linearization with underestimating. Future studies may consider configuring a nonlinear optimization problem that concentrates more on the correlations among productivity, air cleaning, and ventilation. However this would also require more

studies developing realistic data for the effects of air cleaning and ventilation on worker productivity. Future research should also concentrate on the correlation between ventilation and air cleaning; which when proved would transform a linear objective function to a non-linear function. Users with different specific cases can also consider re-evaluating the constraints provided in this study. The constraints regarding air velocity, noise, and many more can be easily integrated in the model to represent more accurate scenarios.

Future studies may also concentrate on including other soft costs introduced in this study but excluded from the model due to their stochastic nature such as litigation and health related costs. Thus stochastic modeling studies may be conducted towards an improved financial representation of the benefits of a better IAQ in commercial buildings. Integrating marginal cost calculation methodologies into spreadsheet would be a very useful contribution towards improving the proposed optimization model. Also integration of the developed optimization models for IAQ into the green building assessment tools such as LEED™ would strengthen the foundation of building assessment methods.

The significance of the presented methodology derives from its contribution to the current sustainable building research by quantifying the benefits of better IAQ. This model is also a conscious effort towards clarifying the arguments on the conflicts among IAQ and energy efficiency issues, which in return would help promote sustainable buildings.

5. References

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