AMERICAN UNIVERSITY OF BEIRUT

BUDGET OPTIMIZATION TOOL FOR OFFICE BUILDING RENOVATION PROJECTS

by
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A thesis
submitted in partial fulfillment of the requirements
for the degree of Master in Engineering Management
to the Engineering Management Program
of the Faculty of Engineering and Architecture
at the American University of Beirut

Beirut, Lebanon
April 2015

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ACKNOWLEDGMENTS

I would like to seize this opportunity to cordially thank Dr. Issam Srour for believing in my potential since the first day I stepped into this beautiful AUB; not only has he been my thesis advisor and mentor for the past two years throughout my thesis work, but also has became a sincere friend with whom working on this study was an enjoyable yet highly intellectual experience. Likely I thank Dr. Ali Yassine, who joined our team shortly after, and had fully supported me throughout my two years of thesis work. I will stay grateful to every hour we spent in his office, scratching our brains hard to ensure the best outcome. Without his input, I would not have made it as successfully as I have. Last but not least, I would like to thank Dr. Nesreen Ghaddar for her support and strong belief in our work.

AUB has carved yet another scar in my life; I will forever remain loyal to this honorable identity, that which has opened before me doors of success for a brighter future…

AN ABSTRACT OF THE THESIS OF

Wissam George Khoury for Master in Engineering Management
Major: Engineering Management

Title: Budget Optimization Tool for Office Building Renovation Projects

Recent studies acknowledge the link between Indoor Environmental Quality (IEQ) and employees‘ overall satisfaction at work, and in turn, productivity. This link led practitioners to include IEQ factors (e.g., thermal comfort, air quality, etc.) in green building standards such as Leadership in Energy and Environmental Design (LEED) and Building Research Establishment Environmental Assessment Methodology (BREEAM). The ultimate goal of this paper is to propose and validate a quantitative method to estimate employee productivity by assessing the level of occupants‘ IEQ satisfaction in office buildings. The first step in understanding this complex relation requires an understanding of the relationship between IEQ and productivity. This is achieved through a survey of corporate employees, which provides a quantitative correlation between the level of IEQ in an office setting and the overall level of satisfaction with the workplace. The latter is, in turn, correlated with the level of occupant performance and productive time. However, and by analyzing the attained results, it was found that there is yet another factor that affects 3 the level of productive time besides IEQ satisfaction; that being longevity at the workplace. profiles.

Drives behind office buildings’ renovation projects can vary widely depending on the type and purpose of the project; workplace expansion, occupants’ well-being and satisfaction improvement, infrastructure upgrade, etc. However, and no matter what target lies behind the renovation project, one factor will inevitably be affected: the Indoor Environmental Quality (IEQ) at the workplace. As noted by several recent studies, the IEQ conditions significantly affect the level of occupants’ satisfaction with their workplace, which, in turn, significantly affects their level of productivity. The target of this paper is to propose a capital budgeting tool that optimizes budget allocation for renovation projects of office buildings in a way to maximize the expected increase in productive time. This is achieved by analyzing the effect of each of the retrofit options available for the renovation on the IEQ conditions at the workplace, and in turn, on the level of productive time of the employees. The proposed tool optimizes the capital size and budget allocation necessary for renovating, as well as maximizes the expected increase in productive time for the organization as a whole.

PREFACE

This thesis study is composed of two complementary research studies that had been consecutively worked on, hereafter noted as Part I and Part II, consecutively.

Part I, titled: “An Examination of the Relationship between Indoor Environmental Quality and Productive Time at the Workplace”, aims at analyzing the relationship that exists between the Indoor Environmental Conditions (IEQ) at the workplace and the level of well-being and satisfaction of the employees towards their workplace, and relating this finding to the level of productive time of the employees. The latter, in turn, affects the overall performance of the organization. The relationship is assessed in details and a regression model is proposed that quantifies the relationship between occupants’ overall satisfaction with the IEQ conditions at the workplace and their level of productive time. This is achieved via conducting a survey questionnaire, along with one-on-one meetings with selected office-building occupants.

Part II, titled: “Budgeting Office Building Renovation Projects: Maximizing Productive Time by Optimizing the Indoor Environmental Quality”, aims at proposing a budgeting binary optimization tool that 1) helps business owners point out the areas throughout the office building that are in need for IEQ enhancement; and 2) optimizes and sizes renovation projects in a way to maximize occupants’ productive time by maximizing the IEQ enhancements that follow every renovation project, and thus occupants’ overall satisfaction with the IEQ conditions at their workplace. The budgeting proposed tool is created using Microsoft Excel, and can be used by any organization that hopes to maximize its productive time by optimizing its renovation project.

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CHAPTER I

INTRODUCTION

The overarching objective of any for-profit firm is to maximize profitability. The cost of employees is considerably larger than any other cost incurred in running most businesses. In fact, the cost of employees is more than 130 times the cost of energy in a typical workplace[1], and is 85% of the total costs incurred in a typical office building[2]. Hence, to ensure a profitable operation, the benefits associated with the employees' productivity must outweigh the associated costs. In fact, a slight increase of 0.1% in employee productivity - by enhancing Indoor Environmental Quality (IEQ) factors such as occupant comfort and satisfaction - can yield a dramatic increase in profitability[3]. Stated in short, the quality of the indoor environment reflects on the health, comfort, satisfaction and productivity of individuals in buildings[4].

Researchers have spent a great deal of effort on trying to understand the factors that govern employees' productivity[3]. Classical management theories have long studied ways through which organizations could enhance their performance[5]. Emerging with the concept of job specialization and the division of labor, as presented by Adam Smith during the early 18th century, organizations started showing an increase in performance and efficiency. With the rise of Frederick Taylor's Scientific Management theory (1856 -

1915), companies became more aware of the effect of the workplace physical conditions on their workers. Tests were conducted on different aspects of the physical environment, such as lighting, temperature, noise, etc. aiming to enhance the level of occupant performance. These efforts were followed by the Administrative Management Theory, as presented by Max Weber (1864 - 1920), which aims at creating an organizational structure that leads to high efficiency and effectiveness. The Behavioral Management Theory was then put forth by Mary Parker Follett (1868 - 1933), who studied how managers should personally behave to motivate employees and encourage them to perform at high levels and be committed to the achievement of organizational goals[6]. The Management Science Theory then followed, focusing on rigorous quantitative techniques to help managers make maximum use of organizational resources to produce goods and services[7]. Finally, the Organizational Environment Theory emerged to explain how different forces and conditions that exist outside the boundaries of the organization can influence the inside[8].

Despite advocating an understanding of the different factors that affect employees' productivity, classical management theories do not directly address IEQ at the workplace as a critical matter that could highly influence their level of productivity. IEQ is defined as "*a generic term used to describe the physical and perceptual attributes of indoor spaces. These include the indoor air quality and the thermal, acoustic and visual properties of the environment, as well as various characteristics of the furnishings, facilities and fitouts*"[9].

In reference to Table 1, fifteen different factors, classified into seven categories, can define the indoor environmental quality of a workplace, which are: thermal comfort, air quality and ventilation, amount of light, visual comfort, noise level, sound privacy, amount of space, visual privacy, ease of interaction, comfort furnishing, adjustability of furniture, colors and textures, building cleanliness, workspace cleanliness, and building maintenance[10]. Each of these factors has a unique impact on the physical and mental well-being of the occupants.

Table 1. Indoor Environmental Quality Factors[10, 11]

Main IEQ Categories	**IEQ Factors**	**IEQ Factors description and definition**
Thermal comfort	Thermal Comfort	Temperature, humidity, air velocity, controllability (operable windows, etc.)
Air quality	Air Quality and Ventilation	Environmental tobacco smoke (ETS), Indoor chemical and pollutant sources and levels,
Lighting	Amount of light	Amount of light in your workspace
	Visual comfort	Including daylight and views; visual comfort of the lighting (e.g., glare, reflections, contrast)
Acoustic quality	Noise level	side-chats, machines, office equipment, outdoor noise, etc.
	Sound privacy	Ability to have conversations without neighbors overhearing and vice versa
Office layout	Amount of space	Amount of space available for individual work and storage
	Visual privacy	Enclosed offices, Cubicles with partitions, Open offices, etc.

	Ease of interaction	Ease of interaction with co-workers
Office furnishings	Comfort furnishing	Comfort of office furnishings (chair, desk, computer, equipment, etc.)
	Adjustability of furniture	Hydraulic chairs, Adjustable curtains, etc.
	Colors and textures	Colors and textures of flooring, furniture and surface finishes
Cleanliness and maintenance	Building cleanliness	General cleanliness of the overall building
	Workspace cleanliness	Cleaning service provided to your workspace
	Building maintenance	General maintenance of the building

IEQ is regarded as one of the main categories set by most green rating systems [12], including Leadership in Energy and Environmental Design (LEED), Green Star, Building Research Establishment Environmental Assessment Methodology (BREEAM), Hong Kong Building Environmental Assessment Method (HK-BEAM), Comprehensive Assessment System for Built Environment Efficiency (CASBEE), and Haute Qualité Environnementale (HQE). Such rating systems present benchmarks and recommendations of IEQ factors that ensure sustainable development and occupant satisfaction. However, their role does not include quantifying the relationship between IEQ and the level of occupants' satisfaction, or between satisfaction and its effect on the occupants' productivity at work.

The literature includes several studies that offer quantitative post-occupancy evaluation of the correlation between employee productivity and satisfaction with the workplace. However, the results of these studies differ widely due to the different approaches used for measuring satisfaction and productivity; as will be discussed in the following sections. The purpose of this study is to redevelop this relationship using a new method that addresses these spotted differences. This method includes estimating productivity through measuring productive time, which is a more quantifiable parameter to assess in comparison to self-assessed levels of productivity; as being measured by most of the previous studies cited in this paper. Satisfaction with IEQ, on the other hand, is measured through the perceived level of satisfaction with each of the factors of IEQ, and then aggregating the assessments to estimate the level of overall satisfaction with the IEQ at the workplace, while taking into consideration the different levels of influence of each IEQ factor on the overall satisfaction at the workplace.

In the next section, a literature review on IEQ is presented and related to the well-being, satisfaction, and productivity of the occupants at the workplace. The third section presents the methodology adopted in this paper to test this relation, while taking into consideration all of the spotted gaps in the literature. A new method for measuring productivity is presented that includes on-field measurement of productive time in accordance to the unique individual capacity of each employee. The level of occupant satisfaction is measured using weighted effects of IEQ factors on the overall satisfaction at the workplace. This is achieved through a survey questionnaire, followed by one-on-one meetings with office employees, as described in the fourth section. The section begins with testing the hypothesis of the existing relationship between productive time and occupant satisfaction, and ends with a regression curve that raises another hypothesis about the effect of yet another parameter on productive time; longevity at the workplace. This leads to extending the study to include a fifth section, in which the observed effect is further analyzed and validated. In the last section of this paper, the results are discussed and compared with those of previous studies.

CHAPTER II

LITERATURE REVIEW

This section presents a literature review on the correlation between post-occupancy IEQ and three relevant constructs: Occupants' well-being, overall satisfaction, and level of productivity at the workplace. Based on the reviewed literature described in this section, the relationship among these constructs can be depicted as schematized in Figure 1.

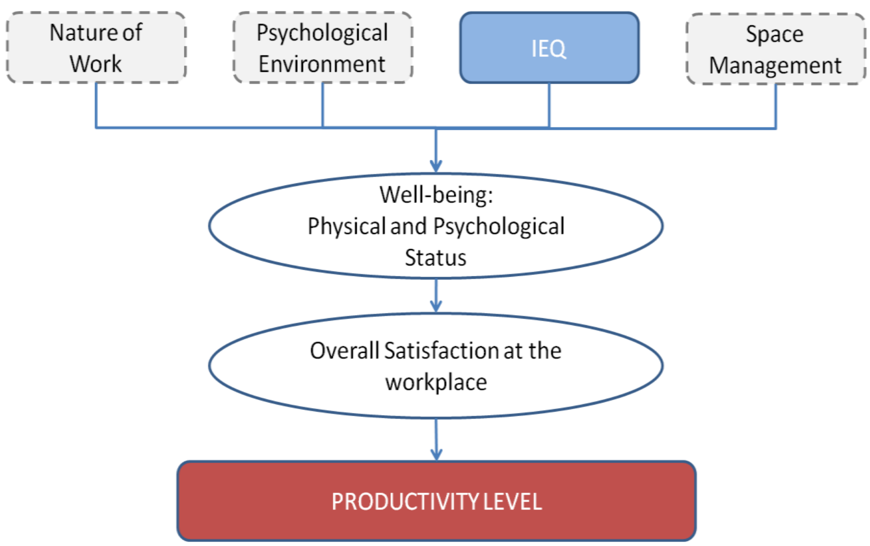


Figure 1 - The hypothesized relationship between IEQ conditions, well-being, overall satisfaction, and productivity at the workplace – Adapted from Mahbob et al.[13].

The four factors of IEQ, nature of work, psychological environment and space management, do not equally influence physical and psychological status; however, all four play a role in influencing occupants' satisfaction level, which, in turn, influences their level of productivity. It is important to note that the direct causality between all these factors as presented is only a simplified representation that is yet to be ascertained and validated, since the existing relationship among these factors is of high complexity.

A. IEQ Conditions and Occupants' Well-Being

IEQ conditions at the workplace can have physical and psychological implications on the employees. Many studies examine the health implications of each of the 15 IEQ factors on occupants' well-being[14-18]. As summarized in Table 2, many of the implications are common across several IEQ factors. This shows the complexity of the relationship between IEQ conditions and occupants well-being.

Table 2. IEQ and well-being

IEQ Factor	Health Impact (Physical and Psychological)	Reference
Thermal Comfort[a]	Fever, chills, fatigue, attention drift, dizziness and nausea	19
Air Quality and Ventilation[b]	Asthma/chest tightness, respiratory allergy, fever/chills, dizziness, nausea, headache, eye/nose/throat irritation, fatigue, dry or itchy skin, lowered cognitive	20

	performance	
Amount of light	Depression, dizziness, nausea, fatigue, headache	[19], [20], [21]
Visual comfort	Depression, Stress, headache, fatigue	[19], [20], [21]
Noise level	Stress, headache, fatigue, lowered cognitive performance	[19], [20], [22]
Sound privacy	Attention drift, lowered cognitive performance	[23], [22]
Amount of space	Stress, fatigue, headache	[19], [20]
Visual privacy	Attention drift, lowered cognitive performance	[24], [25]
Ease of interaction & IT	Stress, tension, attention drift, misconception and miscommunication	[26], [27]
Comfort furnishing	Muscle aches, de-motivation	[19], [28]
Adjustability of furniture	Muscle aches, de-motivation, stress	[19], [28]
Colors and textures	Depression, fatigue, stress, headache	[19], [20]
Building cleanliness	Stress, de-motivation	[19], [29]
Workspace cleanliness[b]	Eye/nose/throat irritation, dry or itchy skin, respiratory allergy, lowered cognitive performance, stress, de-motivation, headache	[19], [29], [24], [25]
Building maintenance	Can lead to any of the above	

[a] Canadian Centre for Occupational Health and Safety, http://www.ccohs.ca, Accessed on October 2, 2014.
[b] EPA – Indoor Air Facts No. 4 (revised), http://www.epa.gov/iaq/pdfs/sick_building_factsheet.pdf, Accessed on October 2, 2014.

A. IEQ Conditions and Occupants' Overall Satisfaction with the Workplace

Several studies examine the relationship directly between IEQ factors and occupants' overall satisfaction at the workplace[11, 30, 31]. Of particular interest is Kim and de Dear's work, which goes a step further in relating IEQ to satisfaction by giving weights to the IEQ factors listed in Table 1, expressing their degree of influence on the overall satisfaction[10]. They propose a new expression to quantify the level of overall occupant satisfaction with the IEQ conditions in the workplace by breaking it down into its 15 factors and applying the weighted effect of each factor as perceived independently by the occupants, and then aggregating the results afresh. Their study analyzes data from a web-based survey administered to more than 50 thousand office-building occupants over more than 10 years by the Center for the Built Environment (CBE)[32]. The survey uses 7-point ordered scale questions pertaining to satisfaction with IEQ parameters, aiming to gather information about the effect of perceived IEQ conditions on self-assessed comfort and productivity level. Many other researchers also benefit from this survey in studying the effect of IEQ on occupants from many different aspects. For example, Frontczak et al. analyze the data to find out which of the IEQ factors mostly affects the occupants level of satisfaction in mainly US office buildings[30]. Another example is the work of Abbaszadeh et al., which compares the effect of green and non-green buildings on the perceived level of satisfaction towards the different IEQ factors[33].

According to the results of Kim and de Dears' work, some of 15 IEQ factors, named *Proportional Factors* – such as air quality, amount of light and sound privacy, have a direct relation with the overall satisfaction; i.e. as the level of perceived satisfaction with these IEQ factors increases or decreases, the level of overall satisfaction increases or decreases respectively, each with a different magnitude. The remaining IEQ factors, named *Basic Factors* – such as temperature, noise level and amount of work space, have a non-direct relation with the overall satisfaction. When such factors are perceived negatively, they inflict a negative effect on the overall satisfaction, while perceiving them positively barely adds to the overall satisfaction; quoting, "it is not easy to impress occupants with IEQ"[10].

This classification indicates that every IEQ factor affects the overall satisfaction of the occupants differently, depending on their type and on how well they perform at the workplace. Some have linear relation with the overall satisfaction, while others do not. For this reason, it is highly important to include the weights of the IEQ factors while quantifying the overall satisfaction at the workplace.

B. IEQ conditions and occupants' productivity

Productivity, being the essential organizational outcome, forms the main indirect economical benefit of IEQ enhancements. As shown in Figure 1, IEQ is among the four main factors that describe the overall satisfaction and comfort of employees at their workplace, which in turn affects their level of performance and productivity at work.

Enhanced indoor environments in office buildings have a positive correlation with occupants' satisfaction, yielding higher levels of well-being, which, in turn, positively correlates to productivity[34]. Early studies point out a possible increase of 15% in work productivity when the occupants are satisfied with their indoor environment[13]. As stated in Lan et al.[35], improving thermal conditions increases employees' productivity by 0.5 – 5%[35]. Moreover, enhancing ventilation alone is enough to increase productivity by 2% in typical office tasks[36]. On the other hand, poor indoor air quality, which is one of the most important IEQ factors, can lead to 10% loss in productivity[13].

Several studies measure the level of productivity and compare it with the level of satisfaction, providing additional evidence on the relationship between the two[13, 37, 38]. The approaches followed in analyzing the relationship between productivity and IEQ can be categorized into three methods. The first method, such as the one used by Seppanen and Fisk[39] and Agha-Hossein[11], consists of creating frameworks for cost-benefit analysis of investing in IEQ; however, the analysis is of qualitative nature only. A detailed conceptual relation presented by Seppanen and Fisk show that health and productivity are highly improved when proper measures are taken to enhance IEQ conditions[40]. Agha-Hossein argued further that employees' levels of satisfaction with "physical conditions" and "interior use of space" form the best indicators of their perceived productivity[11].

The second method, such as the one used by Wyon[41], relies on quantitative techniques to examine the effect of IEQ conditions on productivity. This method analyzes the effect of each IEQ factor independently. For example, Wyon claims that air quality is among the IEQ factors that can highly affect office work performance by up to 9%[41]. Fisk and Seppanen[40] combines formal statistical analysis of existing studies to graphically model the existing relationship between work productivity and the indoor thermal quality and outdoor air ventilation rate specifically. For example, and under the controlled factors of their study environment (e.g. clothing, metabolism, etc.), job performance increases to its optimum as the temperature increases to 21.8 ºC, and decreases as the temperature increases thereafter. Similarly, Lan et al.[35] graph the decrease in job performance as the indoor air temperature varies from its optimum[35]. Notable increase in job performance could also be attained by increasing ventilation rates beyond current ventilation codes for most offices (10 L/s per person)[42]. Other studies include Kosonen and Tan[43] who examines productivity loss in relation to the density of occupants at different levels of air flow rate[43], and Wargocki et al. who further study the effect of ventilation on task by task basis, independently[36]. Other papers study the effect of noise on office productivity[44]. Despite the fact that segregating the many IEQ factors simplifies the analysis, the sum of their individual effects on performance would not be equal to the combined effect of all factors acting together. Moreover, altering the conditions of one factor may impact other factors[45].

The third method looks at IEQ as a whole as opposed to analyzing the effect of individual IEQ factors on productivity independently. Oseland[46] found a linear relation between productivity and both, environmental and facility factors at the workplace. However, Oseland's measuring of productivity is based on two self-assessed questions which ask the respondents about the effect of the facility and the environment on their productivity, along with several other questions of which are concerned with downtime such as waiting for lifts, walking between buildings, and other similar questions that might not link to IEQ conditions specifically[38]. Moreover, the IEQ factors are not weighted while calculating the overall satisfaction, such as the case with Kim and de Dear's study.

Contrarily, Somers and Casal[47] proposes a nonlinear relation between productivity and satisfaction. Artificial Neural Networks were used to model nonlinearity. Job performance measurements of the employees are taken from the organization's formal performance appraisal process and reflected supervisor ratings of employee job performance. Beside the possible inaccuracy and bias associated with such productivity measuring techniques, the sample is limited to nurses and psychiatric technicians drawn from a university medical center. Despite the limited sample of this study, it presents the possibility of having nonlinear relationships between IEQ and performance, and hence productivity, which could negate the generalization of Oselands' findings. The proposed regression model takes the form of a *U*-shaped curve such that higher performance is associated with low and high levels of job satisfaction. No further explanation of this outcome is presented.

It is important to note that all of the three methods described in this section use similar means for measuring job performance and productivity level. Productivity is measured by either self-assessments or by simulating office activities (typing, proof-reading, addition, etc.)[35, 41, 42]. Self-assessments are not quite accurate primarily due to the lack of reliable benchmarks. Moreover, occupants' opinions might fall for the famous Hawthorne effect, where biased self-assessments of productivity levels might be reported [48, 49]. Simulating office works, on the other hand, includes uncountable tasks to be properly measured. In addition, some tasks might not always be affected by the level of IEQ satisfaction, depending on the difficulty of the task at hand. This makes it challenging to quantify job performance and productivity, and highly lowers the accuracy of the results[37]. Moreover, simulating office work would inevitably include bias since, again, the studied sample is aware of being observed. Another important point is the fact that adding or averaging productivity measures for the sampled employees might be misleading. The level of output for the same state of satisfaction might significantly vary from one employee to another, depending on their nature of work, experience, psychological or physical status, etc.; thus employees with low satisfaction might have outputs equal to or higher than that of satisfied employees.

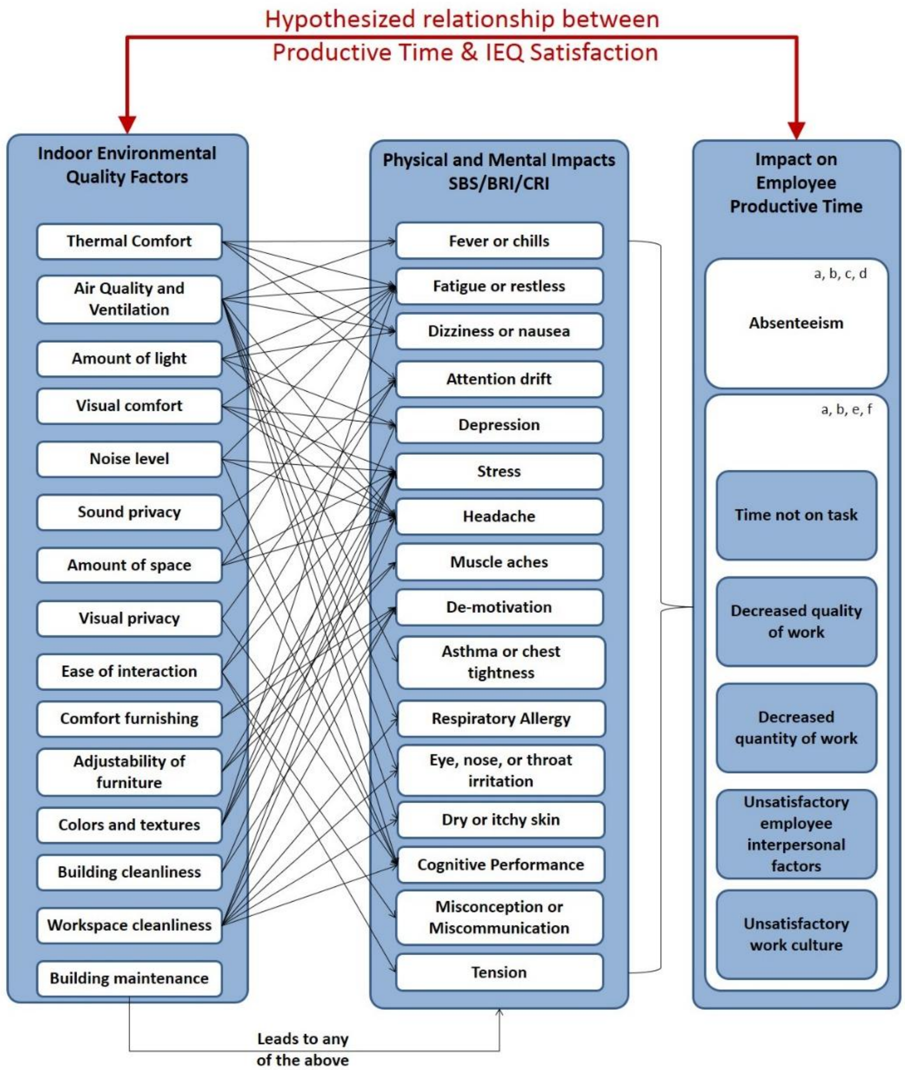
The best way to attain valid measures is by studying employees' productivity level at their own offices, while performing their routinely tasks, and without being aware of a direct assessment of their abilities[38]. Such a technique has rarely been used in a job performance versus job satisfaction study due to being practically infeasible. This fact is due to the complexity of controlling the many possible combinations of IEQ conditions if analyzed as a whole, difficulty of measuring irregular day-to-day tasks, and difficulty in studying the productivity of employees while at work without having biased results. Due to the complexity in objectively measuring the level of productivity on all its aspects, this paper focuses specifically on productive time related to IEQ conditions. Productive time, in this context, is defined as the self-reported working time perceived as wasted due to not being productive specifically because of poor IEQ conditions, subtracted from the total working time of an employee. Measuring productive time rather than productivity could give lower estimates since IEQ conditions might have an effect on productivity parameters other than productive time, such as task productivity: the amount of work done during productive time. However, the level of influence of IEQ per se on task productivity is very difficult to quantify due to the complexity of other influencing factors, and could include biasness since it directly assesses the performance of the individuals who are aware of being tested. Instead, and by asking the employees anonymously about the time lost due to external factors or due to causes out of their control, all related to IEQ, they are more likely to reply with objective and more accurate estimates, since erring seem to have neutral influence on their benefit. Moreover, measuring time rather than productive work is a much easier task to do. Several peer-reviewed questionnaires present in the literature measure productivity by focusing on quantifying productive time, such as the Migraine Work and Productivity Loss Questionnaire (MWPLQ)[50], and the Health and Performance Questionnaire (HPQ)[51].

CHAPTER III

STUDY OBJECTIVES AND METHODS

The main hypothesis addressed in this study is to test the existence of a relationship between productive time and IEQ satisfaction of the occupants at the workspace. The relationship is said to exist due to the proven influence of the different IEQ factors on the well-being of the occupants, which, in turn, influences the level of productivity as depicted in Figure 2. The level of performance of the IEQ factors at the workplace is indicated via the self-assessed satisfaction levels reported by the occupants, and the level of productivity is estimated by measuring the productive time. Accordingly, the first *null hypothesis* tested in this study is:

$$H_0^1 = \textit{The level of productive time does not correlate to the level of satisfaction with the IEQ conditions at the workplace.} \quad (1)$$



[a] Reference [52]; [b] Reference [18]; [c] Reference [53]; [d] Reference [54]; [e] Reference [14]; [f] American College of Occupational and Environmental Medicine, http://www.acoem.org/HealthTermsandDefinitions.aspx, Accessed on October 2, 2014.

Figure 2 - Hypothesized relationship between Productive Time and IEQ Satisfaction.

Figure 2 describes a detailed mapping that supports and explains the proposed relationship. The 15 IEQ factors, as categorized in Table 1, form the physical environment and facility conditions at the workplace. Poor performance of any of these 15 factors could lead to several physical or mental impacts on the occupant as presented in Table 2. Such impacts could be classified under Sick Building Syndrome (SBS), Building Related Illness (BRI) and Chemical Related Illness (CRI). The density of the arrows stretching from the first column to the second column shows the complexity of the existing relation between level of satisfaction with IEQ and the well-being of the occupants. The level of physical and mental well-being of the occupants at the workplace, in turn, impacts the employees' performance resulting in decreased productive time due to absenteeism or presenteeism. Absenteeism is the case when the employee does not show up to work, while presenteeism may include any of the following[52]:

1. Time not on task (e.g. in the workplace, but not working);
2. Decreased quality of work (e.g. increased injury rates, product waste, product defects);
3. Decreased quantity of work;
4. Unsatisfactory employee interpersonal factors (e.g., personality disorders); and
5. Unsatisfactory work culture.

A. Survey Questionnaire

In order to examine the null hypothesis and further investigate the potential relationship between occupant satisfaction with the IEQ and productive time, a survey questionnaire was proposed that measures time lost during working hours due to poor IEQ conditions as self-assessed by the occupants via expressing their level of satisfaction with IEQ conditions. The aim is to quantify the working-hours perceived as lost without performing productive work due to IEQ related causes. Productive time is measured by a set of questions that ask the respondents to estimate the time lost due to poorly performing IEQ factors or related physical and mental problems faced at work. Satisfaction is measured using the same questioning and scaling technique used in Kim's study, including the weighted parameters Kim presents for the different

IEQ factors. IEQ Satisfaction can be directly reported by asking the occupants about their level of overall satisfaction with the IEQ at their workplace, similar to several of the reviewed previous works; however, and since the respondents might not be aware of all IEQ factors, or might even base their responses on only the factors that come to their minds first, this could render highly subjective and inaccurate results. Therefore, and to better direct the occupants in self-assessing their level of satisfaction, they are asked about their perceived satisfaction towards a list of each of the IEQ factors, onto which Kim's model is applied to calculate an estimate of their overall IEQ satisfaction at the workplace.

From the findings of the survey, a statistical relationship between productive time and overall satisfaction with IEQ conditions at the workplace is inferred. The obtained relationship is then validated by comparing the results of this survey with those of Oseland's and Somer's, since these two studies address the same problem, yet yield possibly contradicting results; the latter claims a linear relation, while the former presents a nonlinear U-Shaped regression curve.

B. Questionnaire Details

The aim of the survey questionnaire is to measure the productive time in accordance to the level of overall satisfaction of employees with IEQ factors at the workplace. Thus, the participants of interest involve all employees who spend most of their working hours behind desks, specifically in single or shared offices, cubicles, and open plan office layouts. In order to ensure that the targeted sample truly reflects the characteristics of the population from which it is drawn, non-probabilistic sampling techniques were used; specifically, the judgment and snowball sampling techniques[55]. The total sample size included 102 participants divided among different types of organizations. These include white-collar workers of business, engineering, public and governmental organizations. The climatic condition in which the survey was conducted was Mediterranean and during the fall season. The proposed survey questionnaire used to test the hypothesis of the existing relationship by negating the null hypothesis H_0^1 is composed of three sections, as described below:

1. The first section is aimed at gathering background information about the years spent at the current workplace and the time per day spent behind the desk, which forms the total available time that could be used productively at the office.
2. The second section sums the time lost at work due to the physical and mental impacts associated with poor indoor environmental quality conditions at the workplace.
3. The third section measures the level of overall satisfaction towards the workplace of the respondent. The same scale and model presented by Kim and de Dear is used for this purpose.

The responses of each survey questionnaire were used to compute the two parameters under study: Percent Productive Time and Percent IEQ Satisfaction.

Percent Productive Time:

Question 2 of Section I through Question 15 of Section II of the questionnaire are used to calculate the respondent's percentage of utility of their potential productivity. For example, a *Percent Productive Time* of 70% means that the respondent is, on average, wasting 30% of their working time.

The formula used to measure the *Percent Productive Time* is:

$$Percent\ Productive\ Time = \left(\frac{T_R - T_L}{T_R}\right) \times 100\%, \quad (2)$$

where T_R is the time required to be spent working at the office (Question 2 of Section I), and T_L is the time lost at work due to absenteeism or presenteeism (Questions 1 through 15 of Section II).

Percent IEQ Satisfaction:

Section III of the survey questionnaire is used to calculate the percentage of satisfaction of the respondent with the IEQ conditions, which influences their level of overall satisfaction with the workplace. For example, a *Percent IEQ Satisfaction* of 80% means that the respondent is 20% short of being completely satisfied with the IEQ conditions at the workplace. This also means that the IEQ conditions are contributing to the overall satisfaction 80% of what they could at an ideal situation. Using Kim's weighted model as described previously, the percentage of IEQ satisfaction is computed as follows:

$$Percent\ IEQ\ Satisfaction = \left(\frac{OS-(-3.37)}{2.85-(-3.37)}\right) \times 100\%, \quad (3)$$

where *OS* is the overall satisfaction level as computed by Kim and de Dear's Model using the same scale and weights for the IEQ factors.

CHAPTER IV

RESULTS

A. Data Analysis

One response out of the 102 was eliminated since it was found to have been filled arbitrarily; the calculated lost time was greater than the reported total working hours per day. For the remaining responses, and using the previously described calculations, each questionnaire was reduced to a coordinate point (Percent IEQ Satisfaction; Percent Productive Time). Two outliers were filtered out of the data set using the ROUT method with a maximum *False Discovery Rat*e of 1%[56]. For the remaining responses (total of 99), the descriptive statistics of the complete questionnaire along with the calculated Percent Productive Time and Percent IEQ Satisfaction are summarized in Table 3.

Table 3. Descriptive statistics

Sample Size N = 99		**Measure Unit (Hours per Week)**			
Description	**Question No.***	**Minimum**	**Maximum**	**Mean**	**Std. Deviation**
Longevity - Number of years spent at workplace	I-1	.10**	12.00	3.11**	2.90**
Weekly hours spent at workplace	I-2	12.50	50.00	41.50	7.73
Time lost due to noise distraction	II-2(1)	0.00	16.67	2.70	3.17
Time lost due to visual distraction	II-2(2)	0.00	6.88	0.92	1.38
Time lost due to scent distraction	II-2(3)	0.00	4.17	0.31	0.70
Time lost due to thermal distraction	II-2(4)	0.00	9.17	0.71	1.31
Time lost due to IT malfunctions	II-2(5)	0.00	9.17	1.33	1.55
Time lost due to SBS/BRI/CRI related breaks	II-4&5	0.00	5.50	1.31	1.13

Time lost due to repeating tasks (IEQ related)	II-6&7	0.00	9.00	0.59	1.44
Time lost due to coming late to work (IEQ related)	II-8&9	0.00	5.00	0.51	0.81
Time lost due to leaving work early (IEQ related)	II-10&11	0.00	6.00	0.50	1.09
Time lost due to presenteeism	II-13&14	0.00	14.00	1.70	2.52
Time lost due to absenteeism	II-15	0.00	19.23	0.60	2.16
Percent Productive Time (Section 2)	**Section II**	**30.79**	**99.36**	**72.64**	**14.95**
Percent IEQ Satisfaction (Section 3)	**Section III**	**2.25**	**100.00**	**54.30**	**23.94**

*Section-Question(Sub-question); Refer to Appendix for survey questionnaire
**Measure unit in Years

Percent Productive Time:

The percent productive time mean of the sampled employees is 72.6% with a standard deviation of 15.0%; i.e. on average, employees are performing their jobs at 72.6% of their ability. The minimum recorded time productivity is 31%, while the highest is about 99%. This suggests that employees tend to utilize their productive time at a wide range of levels, depending on several parameters, among which, the level of IEQ satisfaction.

Percent IEQ Satisfaction:

The percentage of satisfaction with the IEQ conditions averages to 54.3%, with a standard deviation of 23.9%. The levels of satisfaction with the IEQ seem to range across the whole 100% scale, with a minimum of 2.3%, and a maximum of full satisfaction.

Table 4. 2-Tailed Pearson correlation test

		Percent Productive Time	Percent IEQ Satisfaction
Percent Productive Time	Pearson Correlation *P*-value (2-tailed)	1	.56* 0

	N	99	99
Percent IEQ Satisfaction	Pearson Correlation	.56*	1
	P-value (2-tailed)	0	
	N	99	99

* Correlation has a significance level of $P< 0.001$.

To study the null hypothesis, the sample data was first tested for normality, proving to have a normal distribution with a significance level of $P<0.01$. With the assumption of having a continuous distribution, a bivariate (Pearson) correlation test was carried out on the two inferred parameters from the survey (Percent Productive Time and Percent IEQ Satisfaction). As shown in Table 4, there is a statistically significant correlation between the two parameters, thereby enough evidence to reject the null hypothesis $\boldsymbol{H_0^1}$. This result further confirms the findings of Somers et al.[47] and Oseland[46].

A. Best Fit Regression Curve

The next step after rejecting the null hypothesis is to further investigate the relationship between *Percent Productive Time* and *Percent IEQ Satisfaction*, and try to infer a statistical model that relates the two parameters. In this section, a regression analysis is performed on the collected data to find the best fit curve that would model the relationship between *Percent Productive Time* and *Percent IEQ Satisfaction*. As summarized in Table 5, the three regression curves with the highest R-Squared values are the linear, quadratic and cubic. In addition to featuring the highest R-Square value, the cubic model offers a more logical fit especially for cases of high levels of satisfaction, since 100% productive time is practically infeasible as shown by the quadratic fit in Figure 3. Similar to the finding of Somers and Casal[47], the relation between Productive time and Satisfaction with IEQ thus appears to be non-monotonic as depicted by the U-shaped cubic regression curve. As the satisfaction increases to 25%, the productive time drops from 70% to 60%. This is a counter-intuitive result which is addressed in the following section. This value then increases at a slower rate to 95% as satisfaction increase until 100%.

Table 5. Regression analysis and parameter estimates

Parameter Estimates						
Equation	**R^2**	***P*-Value**	**b0**	**b1**	**b2**	**b3**
Linear*	0.32	0	53.5	0.4		
Logarithmic*	0.17	0	35.8	9.6		
Inverse	0.02	0.16	74	-44.3		
Quadratic*	0.36	0	64.4	-0.2	0	
Cubic*	0.38	0	71.9	-0.9	0.02	0
Compound*	0.28	0	54.3	1		
Power*	0.15	0	42.5	0.1		
S-Curve	0.02	0.23	4.3	-0.6		
Growth*	0.28	0	4	0		
Exponential*	0.28	0	54.3	0		

Regression coefficients have a significance level of $*P < 0.001$.

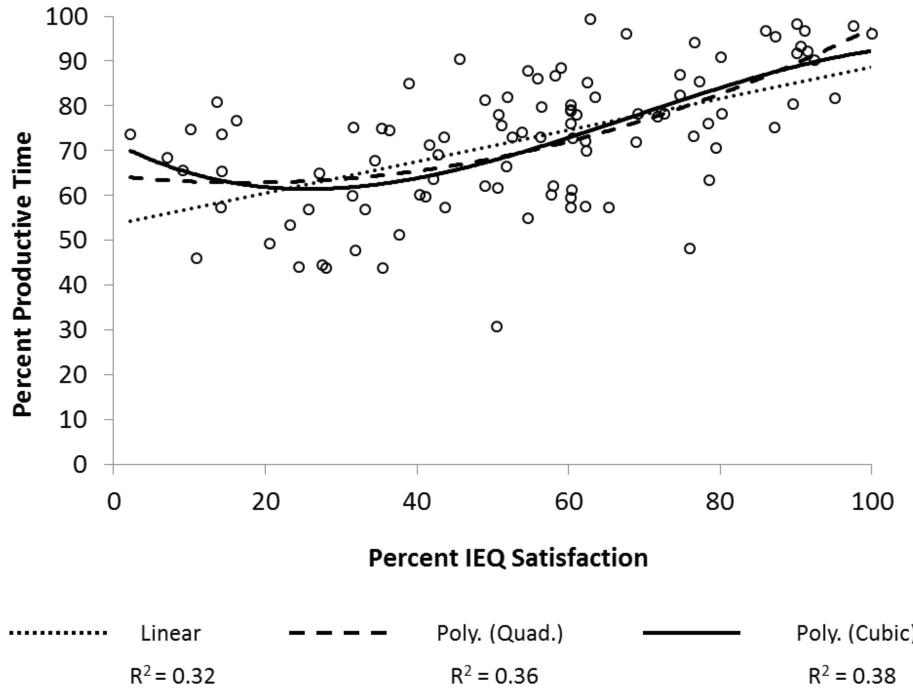


Figure 3 - U-Shape cubic relation between productive time and IEQ satisfaction.

Despite the approach used in measuring satisfaction and productivity, which is validated by previous literature to have more accurate results in comparison to other approaches used in other studies, all three regression curves show relatively low R-Squared values. A possible cause behind this outcome is the fact that productive time and satisfaction level with the different IEQ factors had been self-assessed by the respondents, who could have estimated their lost time inaccurately, or reported their level of satisfaction based on the situation they were in at the moment of assessment rather than responding in general. Another cause could be due to the complexity of the relation between IEQ conditions and occupants' comfort, well-being, satisfaction and productivity. This complex relation stretches far beyond the frame of this study, which relies on several assumptions that simplify this relation to a quantifiable dimension. For example, feeling dizzy at work and not being able to be productive could be due to reasons that have nothing to do with IEQ, such as pregnancy. A third important observation spotted in Figure 3 that could be associated with the low correlation factors attained is the scatter plot for low values of IEQ Satisfaction (below 20%). The scatter plot at that region of the graph seems to lie randomly above all three regression curves, which could influence the best-fit curves into falsely depicting the relationship between such low IEQ satisfaction levels and productive time. Unlike the first two causes presented, this is not an error in estimation or bias in assessment, but could be a phenomenon that needs to be further analyzed separately in details. The next section discusses this observed behavior in details, providing a possible explanation and an enhancement of the proposed regression model.

CHAPTER V

EXTENDED STUDY

As observed for low levels of IEQ Satisfaction, the unexpected increase in productive time as satisfaction decreases raises the need for further examination of the data. Another factor seems to significantly affect the level of productive time besides IEQ satisfaction. Referring back to the survey questionnaire responses, a new hypothesis is put forth for testing, which claims that another factor that has significant effect on productive time is the longevity. Question 1 of Section I asks participants about their time spent at their current workplace (refer to Appendix). Therefore, Longevity as presented in this context does not imply the number of years of employment, but the number of years spent at the currently occupied office, which might be much less than the total years of employment.

$$H_0^2 = \textit{For the same level of IEQ satisfaction, longevity does not affect productive time.} \quad (4)$$

To test the aforementioned hypothesis, a linear regression is conducted between the dependent variable: Percent Productive Time, and the two independent variables: Percent IEQ Satisfaction and Longevity. The summary of results is tabulated in Table 6.

Table 6. Linear regression coefficients with two independent variables

Regression Model*	**Dependent Variable: Percent Productive Time**	
Independent Variables	**Coefficients**	***P*-Value**

Constant	48.51	0**
Percent IEQ Satisfaction	0.39	0**
Longevity	1.03	0.02***

* R-Square (0.59)
Regression coefficients have a significance level of ***P*< 0.001, ****P*<0.05.

The findings of the linear regression show a significant correlation between Percent Productive Time and the two proposed independent variables, thus rejecting the second null hypothesis H_0^2. Moreover, the attained regression model has a higher R-Square value of 0.59, as compared to correlating productive time to IEQ satisfaction alone (R-Square of 0.38). In accordance to the attained coefficients, an increase in longevity is associated with an increase in productive time. This can easily be related to the fact that the higher the longevity, the more experienced and adapted to the IEQ conditions of the currently occupied workplace the employee becomes, the better the productive time is supposed to be. In fact, the effect of longevity on productive time can be well interpreted from the literature. For example, and according to Quińones et al., experience highly correlates to performance[57]. The former being a consequence of longevity, and the latter being closely related to productive time, longevity and productive time ought to correlate as well. Similar to the findings of other research studies that assess the relation between experience and performance[58, 59], productive time seem to significantly correlate to IEQ satisfaction level and longevity.

Visiting back the unexpected increase in productive time as satisfaction increases, as observed in Figure 3, longevity might be the cause behind this outcome. A possible scenario could be that dissatisfied occupants of the study sample with IEQ satisfaction below 20% could have high longevities. Despite their low levels of satisfaction, which would inevitably cause a decrease in productive time, their high longevity adds again to productive time, ending with a relatively higher net value of the latter.

To further understand and validate the proposed reasoning behind the high levels of productive time despite the decreasing IEQ satisfaction levels, one-on-one interviews were conducted with four of the highly dissatisfied employees of the previous study sample having longevity significantly higher than the mean. Interviewed participants were asked the following questions:

1. Why are you dissatisfied with your workspace?
2. Does this hinder you from performing your job productively; and to what extent?
3. What do you recommend to rectify this problem?

All four respondents provided similar responses. The respondents claimed that the reason behind their strong dissatisfaction is the fact that they have been occupying the same office, sitting on the same chair, and working on the same desk for too long, "imprisoned in this manhole for 11 years", as one of the respondents expressed. They argue that their papers and documents are piled in stacks, hosting "all kinds of dust and mites". Two of the respondents also complained that there was no privacy, and that their files and folders always get mixed up with their coworkers'. Noise and other kinds of distraction are also a common concern. Being the most experienced, they get frequently interrupted from work by questions and clarifications, "…besides the endless chitchats of the new-comers," as expressed by another. All four respondents claimed that the IEQ conditions do in fact affect their performance; however, they work hard to stay on track with their schedules, work overtime for several hours, or even come on weekends, which increasing their working-hours, and in turn, their calculated productive time.

They also stressed on the fact that they have enough experience to work efficiently and productively despite the dissatisfactory IEQ conditions. This explains why these extremely dissatisfied occupants yet manage to consume their working-time productively. When asked about listing some recommendations, the respondents insisted on enhancing their IEQ conditions, such as widening their workspaces or moving to new and enhanced private offices. Despite the fact that enhancing the IEQ conditions at the offices of such employees might not dramatically increase their productive time, which might already be acceptable, ignoring their recommended needs might lower their overall job satisfaction to an extent of quitting their jobs, which might be much more expensive than a lowered productivity level.

CHAPTER VI

CONCLUSION

In this paper, the relationship between post-occupancy satisfaction with the indoor environmental quality of office buildings and the level of productive time of the occupants is tested and related to longevity. To the contrary of most reviewed studies, productive time rather than productivity per se is measured, and it is linked solely to poorly performing IEQ or related health problems. The level of IEQ satisfaction, on the other hand, was based on Kim and de Dear’s model, which takes into consideration the weighted influence of the IEQ factors on the overall satisfaction. Moreover, longevity, a factor that has not been previously integrated in the relation between productive time and satisfaction, was also found to have significant effect on the studied relation.

A survey questionnaire was used to gather the sample data that links the level of productive time to the level of IEQ satisfaction at the workplace. Running a Pearson Correlation test on the gathered data showed a significant relationship. After the initial plotting of responses, a cubic U-shaped behavior of the relation between productive time and IEQ satisfaction was observed, similar to what Somers and Casal concluded. However, and after analyzing the causes behind this unexpected increase in productive time at lower levels of satisfaction, it appeared that there is yet another factor that significantly affects the level of productive time along with IEQ satisfaction, which is longevity. The significance of this study is that it validates the linear dependency between productive time and the two factors: IEQ satisfaction and longevity, pointing out the importance of including the latter as another significant factor in estimating productive time. The study also presents a possible explanation to the unexpected U-Shaped regression of this relation, which was similarly observe in the findings of Somers and Casal [47], and extends the work of previous studies by relating productive time to a complete range of IEQ satisfaction, in comparison to Oseland's work [46], which relates productivity to a limited range of satisfaction between 40% and 90%. Possible future work on this subject could focus on field measurements of task productivity in addition to productive time, which might lead to higher correlation factors. Also, a more extensive study of how longevity relates to productivity, and its relation with the level of satisfaction at the workplace.

The proposed relation between productive time and IEQ satisfaction can have several applications on maximizing organizational profitability and productivity through enhancing the working conditions for the employees at their workplace. The ultimate purpose of this study is to form the basis of a decision making tool that optimizes IEQ investments in office buildings to achieve an optimal increase in organizational productivity. With the increasing competition in today's business world, organizations are seeking all possible means to increase their performance and productivity. Companies, such as Google and Oracle, are continuously refining the ergonomics of their workplace to ensure the most optimal conditions for their occupants to perform better. Facing a large number of retrofit possibilities along with inevitable occupant complaints from all departments, business owners are in need of a decision making tool that would aid in optimizing retrofit projects to have the most rewarding and quantifiable gains for the organization as a whole. Moving from the proposed relation of this study that links IEQ satisfaction to productivity, an optimization tool will be presented that optimizes IEQ retrofits to ensure that organizations attain the maximum possible increase in productivity for available fixed budgets.

PART II

BUDGETING OFFICE BUILDING RENOVATION PROJECTS: MAXIMIZING PRODUCTIVE TIME BY OPTIMIZING THE INDOOR ENVIRONMENTAL QUALITY

CHAPTER I

INTRODUCTION

With the ever increasing competition in almost any business market, organizations are constantly seeking ways to enhance their productivity and performance to gain an edge over their competitors. One of the most important factors in expanding the level of performance and productivity is enhancing the comfort level of the occupants at their workplace. In fact, the cost of employees is among the highest costs incurred by any organization. Estimates of such costs are more than 130 times the cost of all energy bills paid by the organization [1]. Employers and business owners are becoming more aware of this fact, and are therefore investing a lot of efforts in ensuring a comfortable workplace for their employees to improve their performance [60]. Enhancing the comfort conditions does not only provide a better working place for the current employees, but also attracts a stronger workforce by offering a better environment to work in.

Several factors define the level of comfort of employees at their workplace, including the nature of work, the psychological environment, the space management and the Indoor Environmental Quality (IEQ) [13]. The latter, being one of the four main pillars of sustainable development [61], is defined as the physical and perceptual attributes of indoor office spaces. These attributes include “the indoor air quality and the thermal, acoustic and visual properties of the environment, as well as various characteristics of the furnishings, facilities and fitouts” [9]. The literature includes several studies that analyze the different aspects of IEQ in office buildings, and how each relates to the comfort and productivity level of the employees [11, 38, 62, 63]. Several organizations are investing in office renovations and retrofit projects aiming to improve the indoor environmental quality at the workplace for better comfort and well-being of occupants. However, most of such renovations are based on intuitive planning and barely accounts for optimality in project sizing and budget allocation. For example, a noted case scenario of an engineering firm in the MENA region carried out a complete renovation of its office building as an attempt to enhance the working environment for the employees to meet their increasing complaints and improve their productivity. Budget allocation for this project was based on the CEO's intuition, and on implementing the proposed retrofit options with the lowest cost first, until the total available budget was completely drained. Areas for retrofit were proposed based on the level of complaints received from the employees; and thus, those who complained the most, were heard the most. Despite exceeding the initially set budget for the renovation project, occupants' complaints still existed due to the fact that the budget was spent without meeting their primary needs, and also since their targeted requirements do not address the IEQ factors that have the highest impact on their overall satisfaction and productivity level.

Be it for enhancing the level of comfort, or simply for meeting the needs and requirements of the occupants, renovating existing office buildings will directly affect the IEQ conditions at the workplace, which, in turn, would affect the productivity level of the employees. Despite the intention of improving these conditions, and despite the large budgets allocated for renovation investments, the expected increase in the level of satisfaction of the employees with their workplace is barely achieved. This repeated fact can easily be explained if one would assess the minute probability of meeting the needs of the many employees involved in the retrofit, each having a different set of requirements. The main causes that make renovation projects miss their targets include a poor involvement of the main stakeholders in the planning phases of the retrofit; i.e. the occupants, a poor understanding of the effect of the IEQ factors on the satisfaction and comfort levels of the employees, and a suboptimal selection of IEQ factors for enhancement. On the contrary, and to achieve better levels of satisfaction and comfort at the workplace, the impact of the renovation on the IEQ conditions should be extensively analyzed. It is highly important to consider its influence on the employees, and accordingly, optimize the renovation project to include the retrofit options that have the highest impact on occupants' satisfaction. Improving the latter leads to the ultimate goal of every organization: an improvement in performance and productivity.

In this paper, an integer optimization program is proposed that could optimize renovation projects for office buildings on the basis of maximizing the productive time of the occupants. This is achieved via analyzing the effect of the possible IEQ enhancements that follow the possible retrofit options that could be included in the renovation on the overall satisfaction level of the occupants at their workplace, which in turn, improves their productive time. This program is a decision making tool that aids business owners in 1) spotting the areas in need for retrofit throughout the office building by quantifying the existing level of employees' satisfaction with their workplace and its impact on their productive time, and 2) optimizing a combination of retrofit options from the available set of possibilities defined by the program users, being the business owner, the employer, etc., which would optimize the IEQ conditions at the workplace, and in turn, maximize the level of employees' satisfaction and comfort level, and ultimately, their productive time. The decision making tool optimizes the selection of retrofit options in the light of several user-defined constraints: Available budget, market prices, synergy effects, etc.

The next section covers a literature review on IEQ in the context of sustainable buildings, followed by a discussion on the relationship between IEQ and productivity. In the third section, the scope and assumptions of the proposed decision making tool are presented, building up to the mathematical optimization program described in section four. In section five, the applicability of the proposed tool is validated, and the results are compared with an actual case study of an engineering firm in Beirut, Lebanon.

CHAPTER II

LITERATURE REVIEW

This section is divided into two subsections. The first characterizes the focus of this study as a quantitative analysis of one of the aspects of sustainable development: Indoor Environmental Quality. The second subsection discusses the literature on IEQ and its relation to occupant productivity.

A. IEQ Optimization and Sustainable Development

Energy, Water, Materials and Indoor Environmental Quality form the principal pillars of any sustainable/green building [61]. In fact, almost all green rating systems focus on these four pillars, such as the case with LEED (Leadership in Energy and Environmental Design) and BREEAM (Building Research Establishment Environmental Assessment Methodology). According to the definition of the Triple-Bottom Line as presented by LEED, sustainable development does not only deal with environmental conditions, but also with economic and social aspects. IEQ conditions at the workplace are closely related to the occupants' satisfaction and comfort level; therefore, improving the IEQ conditions at the workplace would have a positive influence on the social status of the occupants. The improvement that follows in productive time, on the other hand, would reflect as economical benefits on the organization as a whole.

Optimization models have been widely used in green practices and sustainable developments. However, most have been mainly used in fields such as cost and resource utilities (energy, water and materials). Castro-Lacouture et al., for example, put forth an optimization model that helps in selecting construction materials following a LEED-based green rating system [64]. Other papers present models that optimize energy consumption to minimize energy bills. Hasan et al. presented a new method for optimizing the heating system of buildings while preserving the comfort level of the occupants [65]. Asadi et al. similarly presented a multi-objective model that optimizes energy use while satisfying occupant needs [66]. Holst uses a simulation and a generic optimization program to decrease energy consumption by 22%, which not only decreased operational cost, but also improved the daylight usage and thermal comfort [67]. Wright et al. uses genetic algorithms to optimize a trade-off between energy costs of a building and its occupants comfort [68]. Realizing from what has been discussed in this section; most optimization models regard the occupants' satisfaction and comfort level merely as constraints rather than the objective to be met. In fact, and according to Evins [69], optimization models that take into account the comfort level while optimizing other sustainability aspects constitute the smallest share of the literature; about 17%. Moreover, only a few studies have directly targeted the optimization of occupants' comfort level at their workplace as an attempt to improve their performance. Among such works is that of Kroner et al., who, for example, provided office occupants with environmentally responsive workstations that could improve performance by about 2–3% [70], analyzing by that the impact of only one out of the many aspects of IEQ conditions on the occupants output. However, none of the studies within the reviewed literature proposed a decision making tool flexible to optimize all types of office building renovations by targeting occupants' satisfaction with the IEQ conditions at their workplace, aiming to improve their level of productive time.

B. The Correlation between IEQ and Productivity

1. Defining the IEQ factors

The focus of this study is to optimize office building retrofit decisions to maximize occupants' satisfaction with the IEQ conditions at their workplace, and by such, quantify the expected improvement in their productive time. In order to optimize such investments, a thorough quantitative analysis of the effect of the IEQ factors on the level of occupants' satisfaction is required. The first step towards this direction includes understanding the factors that constitute IEQ. Fifteen different IEQ factors can define the indoor environmental quality at a workplace, classified into seven main categories as shown in Table 1 [10, 11]. Each of these factors has a unique impact on the physical and mental health of the occupants, such as asthma, migraine, and other sick building syndromes [39, 71], which, in turn, can lead to a reduction in the level of comfort, well-being, and productivity of the employees [62, 72].

Table 7. IEQ Factors

Main IEQ Factors	IEQ Parameters	Parameter Description and Definition
Thermal comfort	Thermal Comfort	Temperature, humidity, air velocity, controllability (operable windows, etc.)

Air quality	Air Quality and Ventilation	Environmental tobacco smoke (ETS), Indoor chemical and pollutant sources and levels,
Lighting	Amount of light	Amount of light in your workspace
	Visual comfort	Including daylight and views; visual comfort of the lighting (e.g., glare, reflections, contrast)
Acoustic quality	Noise level	side-chats, machines, office equipment, outdoor noise, etc.
	Sound privacy	Ability to have conversations without neighbors overhearing and vice versa
Office layout	Amount of space	Amount of space available for individual work and storage
	Visual privacy	Enclosed offices, Cubicles with partitions, Open offices, etc.
	Ease of interaction	Ease of interaction with co-workers
Office furnishings	Comfort furnishing	Comfort of office furnishings (chair, desk, computer, equipment, etc.)
	Adjustability of furniture	Hydraulic chairs, Adjustable curtains, etc.
	Colors and textures	Colors and textures of flooring, furniture and surface finishes
Cleanliness and maintenance	Building cleanliness	General cleanliness of the overall building
	Workspace cleanliness	Cleaning service provided to your workspace
	Building maintenance	General maintenance of the building

2. *Defining the Relationship between the IEQ Factors and the Occupants' Overall Satisfaction at the Workplace*

Several studies have examined the existing relationship between IEQ conditions at the workplace and its effect on the occupants' comfort and satisfaction level. Wong et al. [73], for example, proposed a multivariate-logistic model that empirically expresses an estimate of the overall acceptance of the IEQ conditions in an office. Frontczak et al. [30], as another example, conducted a subjective examination of the IEQ factors that have the most effect on occupants' satisfaction mainly in US office buildings. Frontczak concluded that the IEQ factors that mostly affect occupant satisfaction are the amount of workspace and visual privacy. A third example is the work of Humphreys [31], which states that the overall satisfaction at the workplace cannot be dictated by specific IEQ factors, rather, it is the combined result of the level of satisfaction with all of the IEQ factors.

Of particular interest is Kim and de Dear's work, which puts forth a finer understanding of the level of influence that each IEQ factor has on the overall satisfaction of the occupants [10, 74]. Kim and de Dear suggest a mathematical nonlinear regression model that describes the relationship between occupants' overall satisfaction with their workplace and their perceived satisfaction with the 15 individual IEQ factors listed in Table 1. They have categorized the IEQ factors under either Proportional or Basic Factors. some of the IEQ factors directly relate to the overall satisfaction of the occupants; i.e. as the level of perceived satisfaction with these IEQ factors increases or decreases, the level of overall satisfaction increases or decreases respectively, each with a different magnitude. Such IEQ factors include indoor air quality, sound privacy, amount of light, etc. These factors are labeled as Proportional Factors. The second category of IEQ factors are labeled the Basic Factors, such as thermal comfort, work space and noise level. Such factors have a non-direct relation with the overall satisfaction; i.e. when they are perceived negatively, they inflict a negative effect on the overall satisfaction, while perceiving them positively barely adds to the overall satisfaction. This classification indicates that every IEQ factor affects the overall satisfaction of the occupants differently, depending on their type and on how well they are perceived to perform at the workplace. Kim and de Dear conducted a regression analysis that proposed two parameters for each of the 15 IEQ factors, one of which for the case when the IEQ factor is perceived as performing satisfactory, and the other when it is perceived as performing dissatisfactory. These parameters act as weights that would give a different level of importance for each IEQ factor. This weight would reflect on the estimate of the overall satisfaction at the workplace after the response on each of the 15 IEQ factors is aggregated.

3. *Defining the relationship between the occupants' satisfaction at the workplace and their level of productivity*

Optimizing the IEQ conditions at the workplace can enhance the level of satisfaction and productivity of the employees, which, in turn, can dramatically increase organizations profitability [3]. According to Mahbob et al. occupants who are satisfied with their workplace reveal a 15% increase in their productivity [13]. Lan et al. added to this discussion by proving that enhancing the thermal conditions alone within an office can lead to an increase of up to 5% in productivity [35]. Moreover, improving ventilation alone was shown to increase productivity by about 2% [36], while lack of proper ventilation can decrease productivity by up to 10% [13]. In a cost and benefit comparison between traditional and green buildings conducted by Singh [14], employee productivity was found to increase by 8% in the first 20 weeks of an office renovation project, and stabilized one year later at 6%. Singh concluded that building IEQ improvements are economically viable investments when analyzed through a life cycle cost framework. Several other studies have studied the relation between the level of satisfaction of employees with the IEQ conditions at their workplace and their level of productivity [13, 37, 38]. However, Clausen [62] also pointed out an important fact that the subjects could not agree on which of the IEQ factors should be improved when made to choose under the constraint of a limited budget . This shows that renovations must be well studied so that the IEQ enhancement involved meets the needs of the majority of the occupants, especially those whom the organization would benefit the most out of. As can be concluded, Occupants' satisfaction with the IEQ conditions can considerably influence their level of productivity, which inevitably reflects on the overall performance of the organization. Therefore, IEQ conditions must be optimized in every organization that aims to maximize its business yield.

Several studies have attempted to depict a relation that relates the productivity of employees to their level of satisfaction at their workplace. Oseland [46], for example, found that there exists a linear relation between occupants' productivity and their satisfaction with both: environmental and facility factors at the workplace. However, Oseland used self-assessed questions to measure the productivity of the occupants, along with several other downtime related questions such as waiting for lifts, walking between buildings, and other similar questions that might not link solely to IEQ conditions. Somers and Casal [47], on the other hand, proposed a nonlinear relation between productivity and satisfaction. Productivity of the employees was measured based on the organization's formal performance appraisal process and the ratings of their supervisors. One main cause behind the contradiction spotted between the two proposed regressions is the fact that each assumes a different method for the measuring of productivity. Moreover, measuring the latter in all its dimensions is almost impossible. This fact is due to the difficulty in quantifying the many factors that can affect the level of productivity, the complexity in controlling the irregular day-to-day tasks, and the inevitable Hawthorne effect involved during measuring the productivity of employees who are aware of being studied [48]. Two important requirements are needed to achieve a valid productivity measure. The first is to define a quantifiable dimension of productivity, since productivity per se is a complex product of many influencing factors, such as the nature of work, the psychological environment, IEQ and space management [13]. Measuring productive time, rather than the level of overall productivity, gives a more accurate estimate of the relation between IEQ satisfaction and productivity. Employees having the same productive time might have different levels of overall productivity, depending on their nature of work, experience, psychological or physical status, etc. Another benefit of measuring productive time is that it indirectly assesses the performance of the individuals as to reduce the margin of biased responses. Instead of assessing employees on their level of output, measuring productive time includes asking the employees about the time lost due to external factors or due to causes out of their control, all related to IEQ. Using this method, respondents are more likely to reply with objective and more accurate estimates, since erring seem to have neutral influence to their benefit. Moreover, measuring time rather than productive work is a much easier task to do. Several peer-reviewed questionnaires present in the literature measure productivity by focusing on quantifying productive time, such as the Migraine Work and Productivity Loss Questionnaire (MWPLQ) [50], and the Health and Performance Questionnaire (HPQ) [51].

In a previous study conducted by Khoury et al. (2015) for the purpose of this work, an improved correlation between IEQ occupant satisfaction and their related productive time is proposed [75]. This is achieved through a survey of corporate employees, which first provides a correlation between the level of IEQ in an office setting and the overall level of satisfaction with the workplace. This is achieved by following the same method proposed by Kim and de Dear that targets the perception of each of the IEQ factors independently, and aggregates the results for a more accurate estimate of the level of overall satisfaction. The latter is, in turn, correlated with the occupants' productive time at work. To the contrary of the concluded results reviewed throughout the literature, Khoury et al. validated the significance of including yet another factor while assessing productive time besides IEQ satisfaction; that being longevity at the workplace. Longevity in this context is the number of years an employee has spent at the office they currently occupy. The degree of influence is summarized in Table 2.

Table 8 - Linear regression coefficients with two independent variables

Regression Model*	Dependent Variable: Percent Productive Time	
Independent Variables	**Coefficients**	***P*-Value**
Constant	48.51	0**
Percent IEQ Satisfaction	0.39	0**
Longevity	1.03	0.02***

* R-Square (0.59)
Regression coefficients have a significance level of **$P < 0.001$, ***$P < 0.05$.

CHAPTER III

STUDY OBJECTIVES AND METHODS

The proposed decision making tool consist of two main phases. The first phase includes indicating the existing statuses of the offices, specifying which of the offices are in need for retrofit and which are satisfactory. By making this information visible for the end-user, the latter would be better guided through defining the possible retrofit options needed for the renovation project; i.e. the decision variables in the optimization program. This information is much more reliable and accurate in portraying the conditions of the offices, in comparison with occupants' complaints or direct visual assessment of the visible conditions at the workplace. The second phase begins after having defined all possible retrofit options that could enhance the current conditions at the offices in need for renovation. The purpose of the second phase is to optimize the selection of the retrofit options out of the previously defined based on several predefined constraints, such as budget, market prices, etc. Figure 4 present a flowchart that depicts the two phases needed to be followed to achieve a successful optimized renovation using the decision making tool proposed.

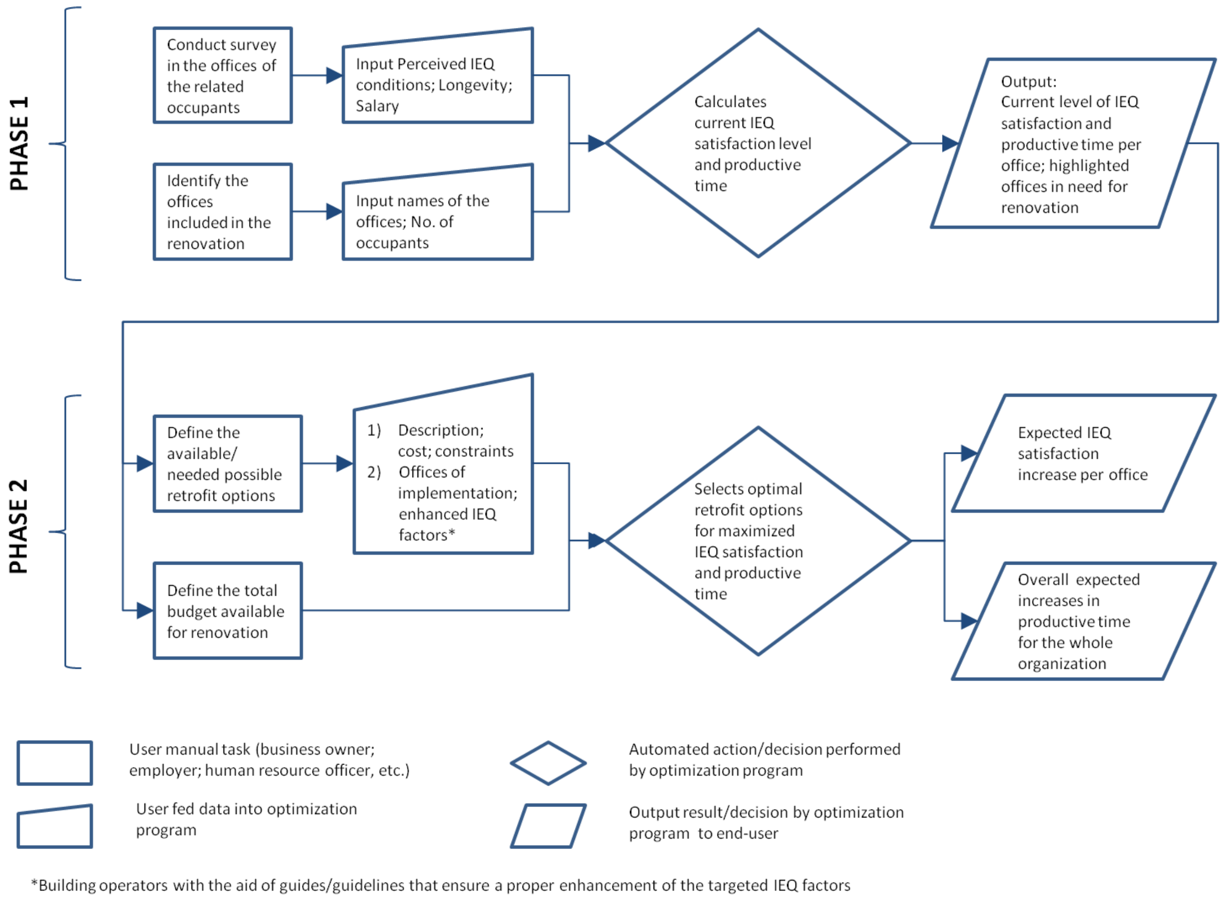


Figure 4 - Flow-chart diagram for method of use of the optimization program

A. First Phase: Guiding decision makers in spotting areas in need for retrofit

The ultimate goal of this study is to propose and validate a decision making tool that optimizes office buildings renovation projects based on maximizing occupants' satisfaction with the IEQ conditions at their workplace, and in turn, maximizing their productive time. However, the first step in this direction requires an understanding of the level of IEQ satisfaction pertaining to the current workplace status. For that matter, employees occupying the offices concerned with the renovation project are asked to fill out a short questionnaire that guides them through self-assessing their level of satisfaction towards the IEQ conditions that currently define their workplace on a 1 to 7 scale. This questionnaire consists of 18 questions; 15 of which are adopted from the CBE survey questionnaire used in Kim and de Dears study (2012), and the remaining three questions ask about the location of the office occupied, the longevity at the workplace, and the current monthly wage, respectively. Longevity, and as defined in the questionnaire, is the period of time during which the respondent has been occupying the same office, under the same IEQ conditions. Specifying the wage, on the other hand, has no margin for confidentiality risks, since this questionnaire is to be conducted by employers, business owners, human recourse officers, etc. to whom such confidential information is kept undisclosed.

Table 9 - In-house conducted survey questionnaire

IEQ CATEGORIES	IEQ Level of Perceived Satisfaction
Thermal Comfort	How satisfied are you with the temperature in your workspace?
Air Quality	How satisfied are you with the air quality in your workspace (i.e. stuffy/stale air, cleanliness, odors)?
Lighting	How satisfied are you with the amount of light in your workspace?
	How satisfied are you with the visual comfort of the lighting (e.g., glare, reflections, contrast)?
Acoustic Quality	How satisfied are you with the noise level in your workspace?
	How satisfied are you with the sound privacy in your workspace (ability to have conversations without your neighbors overhearing and vice versa)?
Office Layout	How satisfied are you with the amount of space available for individual work and storage?
	How satisfied are you with the level of visual privacy?

	How satisfied are you with ease of interaction with co-workers?
Office Furnishings	How satisfied are you with the comfort of your office furnishings (chair, desk, computer, equipment, etc.)?
	How satisfied are you with your ability to adjust your furniture to meet your needs?
	How satisfied are you with the colors and textures of flooring, furniture and surface finishes?
Cleanliness and Maintenance	How satisfied are you with general cleanliness of the overall building?
	How satisfied are you with cleaning service provided for your workspace?
	How satisfied are you with general maintenance of the building?
Office Reference	Please specify the office of your current workplace.
Longevity	How long have you been working at your currently occupied workplace?
Monthly Salary	Please specify your current monthly salary.

The second step is to input the gathered data into the proposed optimization program. For each office, the average occupants’ IEQ satisfaction level and the average productive time is computed. The program then highlights the offices in need for retrofit. The program users would then have a clearer idea over the current status of their offices performance, and would thus select the possible retrofit options to include in the renovation and the areas for their implementation on a well calculated basis.

B. Second Phase: Optimizing the selection of retrofit options

All available retrofit solutions are inputted along with their cost of implementation. For each inputted retrofit option, the offices that will be affected by the retrofit are to be defined, along with the IEQ factors that are supposed to be enhanced. IEQ specialists or engineers should be consulted while specifying the IEQ factors supposed to be enhanced to satisfactory levels by each of the defined possible retrofit options

The final step is to input the total available budget for the renovation project. With all the previous information defined, the program would solve for the optimal selection of retrofit options that promises to yield the maximum possible increase in occupants' satisfaction level and productive time by enhancing the IEQ factors within the constrained budget. The program then outputs this selection, pointing out the offices that will be retrofitted, as well as the increase in the average productive time of each of these offices. The program then interpolates the results to estimate the total increase in productive time for the organization as a whole. Figure 4 schematizes the process involved in optimizing renovation projects for office buildings to yield the maximum productive time possible by maximizing the occupants' IEQ satisfaction. Whenever the need for renovation is available and the business owners are ready to invest in it, the different retrofit options available are to be gathered and inputted in the proposed optimization program. The different constraints are then defined and the program is allowed to optimize for the optimal solution. The optimized solution will have an impact on the IEQ factors describing the workplace, along with any of the energy use, water consumption, or waste and materials constituting the office. However, the focus of the proposed program is to maximize the enhancement of the IEQ factors specifically, which will lead to an enhancement in the occupants' well-being and their overall satisfaction with their workplace, enhancing in turn their level of productive time. Ultimately, this would positively impact the performance, and thus the economic gains of the organization as a whole.

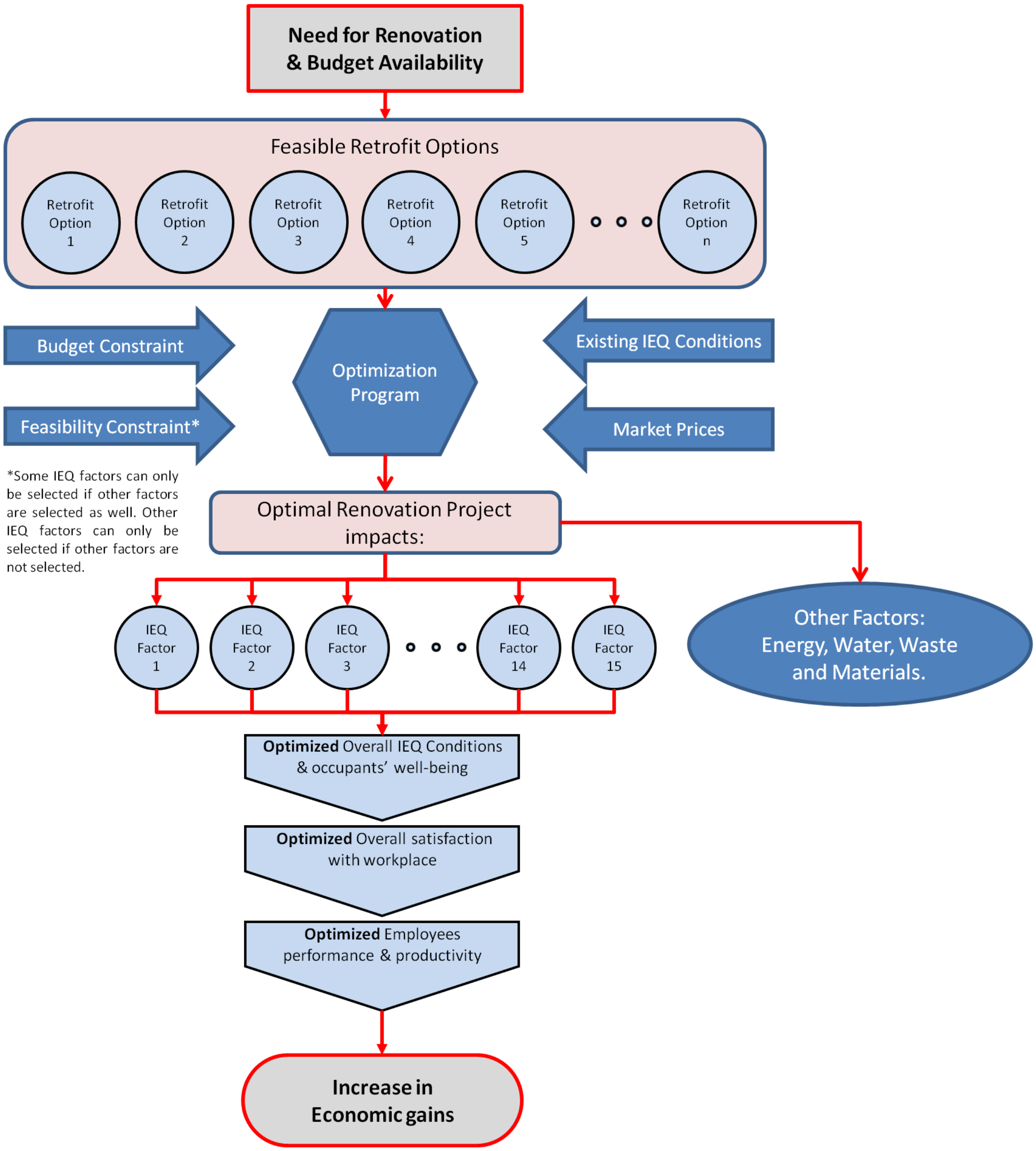


Figure 5 - Optimized budget allocation for an increase in economic gains

CHAPTER IV

OPTIMIZATION MATHEMATICAL MODEL

In this section, an optimization model is proposed that aims to maximize productive time by optimizing IEQ retrofits under limited budgets and market constraints. The section begins by describing the method for calculating the current IEQ satisfaction levels and percent productive time at the organization. The various indices, parameters, constants and decision variables used in this model are summarized in Table 10.

Table 10 - Definition of indices, parameters, decision variable, constraints and objective function

Indexes	***Description***
$\boldsymbol{i}$	Index of office unit $1 < i < I$; where *I* is the total number of office units considered for retrofit
$\boldsymbol{j}$	Index of employee $1 < j < J_i$; where J_i is the total number of employees in office unit *i*
$\boldsymbol{k}$	Index of IEQ factor $1 < k < J$; where *K* is the total number of IEQ factors (15 factors)
$\boldsymbol{m}$	Index of possible retrofit options $1 < m < M$; where M is the total number of retrofit options considered
$\boldsymbol{m'}$	Index of selected retrofit options from total set of options *M*; $m' \in M'$; where *M'* is a subset of *M.*
Decision Variables	***Description***
$\boldsymbol{X_m}$	Binary variable indicating whether to Go-or-No Go with retrofit option m
Defined Parameters[1]	***Description***
$\boldsymbol{\alpha_0}$	Baseline constant for overall satisfaction of employees at their workplace
$\boldsymbol{\alpha_k^*}$[2]	Impact parameter from the satisfied group of IEQ factor k on the overall satisfaction of employees at their workplace
$\boldsymbol{\alpha_{ijk}}$	Impact parameter of IEQ factor k on the overall satisfaction of employee j with the workplace at office i (selected from Table 10)
$\boldsymbol{l_{ij}}$	Longevity of employee j in office i; indicates the number of years the employee has spent in the currently occupied office
$\boldsymbol{s_{ij}}$	Salary of employee j in office i
$\boldsymbol{S}$	The sum of salaries of all the employees of the organization
$\boldsymbol{F_{ikm}}$[3]	Retrofit influence binary variable; indicates the offices i and IEQ factors k expected to be

	influenced by implementing retrofit option m
$\boldsymbol{C_m}$	Cost of retrofit m
$\boldsymbol{B}$	Total available budget for the renovation project
Variable Parameters[4]	***Description***
$\boldsymbol{F'_{ik}}$[5]	Retrofit influence binary variable for a feasible solution; indicates the IEQ factors k in offices i that are expected to be enhanced by the selected retrofit options of a feasible solution
$\boldsymbol{OS_{ij}}$	Overall satisfaction of employee j with the workplace at office i
$\boldsymbol{POS_{ij}}$	Percent IEQ satisfaction of employee j of office i with their workplace
$\boldsymbol{OS_i}$	Average of the overall satisfaction of the employees of office i with their workplace
$\boldsymbol{PPT_{ij}}$	Percent productive time of employee j of office i
$\boldsymbol{PPT_i}$	Average percent productive time of the employees of office i; weighted by the level of contribution of each employee to the overall productivity of the office
$\boldsymbol{MOS_{ij}}$	Maximized overall satisfaction of employee j with the workplace at office i
$\boldsymbol{MPOS_i}$	Maximized percent IEQ satisfaction of employee j of office i with their workplace
$\boldsymbol{MOS_i}$	Maximized average of the overall satisfaction of the employees of office i with their workplace
$\boldsymbol{MPPT_{ij}}$	Maximized percent productive time of employee j of office i; weighted by the level of contribution of each employee to the overall productivity of the office
$\boldsymbol{MPPT_i}$	Maximized average percent productive time of the employees of office i
$\boldsymbol{CF_i}$	Contribution of office i to the overall productivity of the organization; used as a weighting parameter while calculating the percent increase in productive time for the overall organization
Objective Function	***Description***
$\boldsymbol{OPPT}$	Objective function; maximize total increase in the percent productive time for the overall organization

[1] These parameters are to be defined for every renovation project and remain constant throughout the optimization process

[2] Example: $\alpha_1^* = 0.12$ (refer to **Table 11 -** Regression coefficients for each of the 15 IEQ factors (adapted from reference [10])Table 11)

[3] Example: If Retrofit Option 1 is expected to enhance IEQ Factors 1 and 2 to satisfactory levels in Offices 3 and 4, then $F_{311} = F_{321} = F_{411} = F_{421} = 1$; all remaining $F_{1ij} = 0$ (Assuming no other retrofit option is considered)

[4] These parameters are computed by the optimization tool using the defined parameters[1], and can vary with every feasible solution until the optimal solution is reached

[5] Example: If in a feasible solution Retrofit Option 1 is expected to enhance IEQ Factors 1 and 2, and Retrofit Option 2 is expected to enhance IEQ Factors 2 and 3, both in Office 1, then $F'_{11} = F'_{12} = F'_{13} = 1$; all remaining $F'_{ik} = 0$ (Assuming that the feasible solution consists of only these two retrofit options)

A. Defining the Current Status

In order to calculate the level of overall satisfaction of an employee with the workplace, for each respondent of the questionnaire described in Table 4, the overall Percent IEQ Satisfaction is computed by aggregating the perceived levels of satisfaction towards the 15 IEQ factors independently, taking into consideration the different influencing weight of each factor on the overall satisfaction level, in accordance to Kim and de Dear's proposed regression model[10]. Using the regression coefficients for each IEQ factor for the satisfied and the dissatisfied groups as shown in Table 11, the mathematical representation of this model is by Equation 1.

$$OS_{ij} = \alpha_0 + \sum_{k=1}^{K} \alpha_{ijk} \qquad (1)$$

Table 11 - Regression coefficients for each of the 15 IEQ factors (adapted from reference [10])

Constant	**α_0 (Neutral) = 0.38**	**α_{ijk} (to be selected from below)[1]**	
(j)	**IEQ Factor**	**Satisfied group (α_k^1)**	**Dissatisfied group (α_k^b)**
1	Thermal Comfort	0.12**	-0.21**
2	Air Quality and Ventilation	0.16**	-0.19**
3	Amount of light	0.18**	-0.18**
4	Visual comfort	0.10**	-0.14**
5	Noise level	0.21**	-0.38**
6	Sound privacy	0.15**	-0.19**
7	Amount of space	0.43**	-0.78**
8	Visual privacy	0.19**	-0.44**
9	Ease of interaction	0.21**	-0.25**
10	Comfort furnishing	0.18**	-0.23**
11	Adjustability of furniture	0.10**	-0.19**
12	Colors and textures	0.16**	-0.28**
13	Building cleanliness	0.10**	-0.08*
14	Workspace cleanliness	0.04*	-0.08**
15	Building maintenance	0.14**	-0.13**
Total		2.47	-3.75
max/min OS		2.85	-3.37
Range of OS		6.22	

R^2 of the regression model is 0.63
* Significance level of regression coefficients P < 0.01
** Significance level of regression coefficients P < 0.001
[1] $\alpha_{ijk} = \alpha_k^a$ or α_k^b based on whether employee j in office i is satisfied or dissatisfied, respectively, with IEQ factor k; $\alpha_{ijk} = 0$ if occupant is neutral

For the purpose of this study, it is important to calculate the level of IEQ satisfaction; or the percentage of satisfaction with the workplace due to IEQ conditions solely. Varying the IEQ conditions at the workplace can shift the overall satisfaction of Kim and de Dear's model between a minimum of -3.37 and a maximum of 2.85. Translating these extremities to a 0 to 100% scale would give a better interpretation of the level of IEQ satisfaction at the workplace. For example, an occupant being neutral with the IEQ conditions at the workplace has an $OS = \alpha_0 = 0.38$ on the overall satisfaction scale. Normalizing this value yields an IEQ satisfaction level of 60%. The overall satisfaction computed using Kim and de Dear's model can be normalized using Equation 2.

$$POS_{ij} = \left(\frac{OS_{ij} - (-3.37)}{2.85 - (-3.37)}\right) \times 100\% \qquad (2)$$

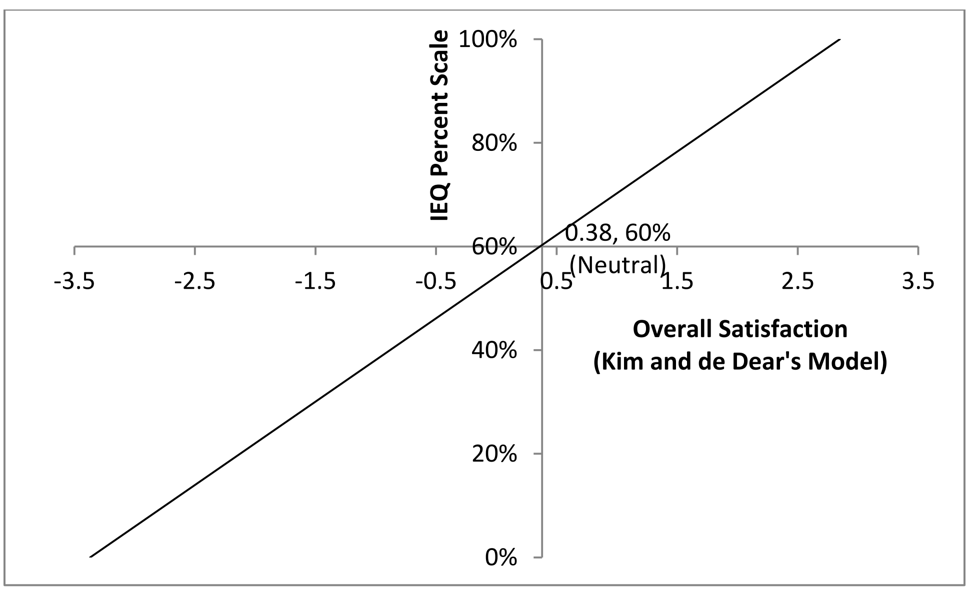


Figure 6 - Normalization of model scale

In order to estimate the average level of overall satisfaction at an office, the overall satisfaction of all employees in the related office is average using Equation 3.

$$OS_i = \frac{\sum_{j=1}^{J_i} POS_{ij}}{J_i} \qquad (3)$$

As previously mentioned, another factor besides IEQ satisfaction that influences the level of productive time of employees at their workplace is their longevity. Longevity in this context is the number of years the employee has spent in the same workplace currently occupied. Using the statistical regression model proposed by Khoury et al. [75], the relating level of percent productive time per employee is estimated using Equation 4.

$$PPT_{ij} = \left(0.39 \times POS_{ij} + 0.01 \times l_{ij} + 0.49\right) \times 100\% \qquad (4)$$

An important point to consider is that employees of a certain office contribute differently towards the overall productivity of the office they are occupying. Their quality and importance of produced work can vary along the vertical hierarchy of employment, such as the level of productivity contribution of a fresh graduate employee in comparison to an experienced manager. Generally assuming, those who perform more are rewarded more. Supposing the inverse to be likely true, it is logical to further assume that the more an employee's wage is, the more contribution this employee has to the overall productivity of the occupied office. Taking this contribution level into consideration, the average percent productive time per office is weighted by the salaries of the employees occupying it.

$$PPT_i = \frac{\sum_{j=1}^{J_i}\left(S_{ij} \times PPT_{ij}\right)}{\sum_{j=1}^{J_i} S_{ij}} \qquad (5)$$

B. Defining the Possible Retrofit Options

After defining the existing level of occupants' satisfaction and calculating the related level of productive time, it is required to specify the available budget for the whole retrofit, and define the available retrofit options by specifying there costs of implementation, areas of applicability, and the IEQ factors expected to enhance to satisfactory levels. The user of the program, such as the business owner with the aid of the building manager, assigns a value of unity for the influence binary variable F_{ikm} indicating that retrofit option m is expected to enhance in office i IEQ factor k.

For the purpose of illustration, a simple case of having three retrofit options is considered. The first option is to retrofit the HVAC system, the second option is to change all single glazed windows to double glazed throughout the building, and the third option is to transform the currently existing open-space offices into single units. Assuming that only three offices out of the whole organization are considered for retrofit, the binary matrices shown in Tables 12 and 13 should be defined.

Table 12 - Retrofit Option *m* influences Offices *i* (for illustration)

	Office *i*			
Retrofit Option *m*		**1**	**2**	**3**
	1	1	1	
	2	1	1	1
	3			1

Table 13 - IEQ factors *k* influenced by Retrofit Option *m* (for illustration)

		IEQ Factor *k*														
Retrofit Option *m*		**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**
	1	1	1			1										
	2	1			1								1			
	3	1				1	1		1							

By combining the values of

Table **12** and

Table 13, F_{ikm} can be deduced and tabulated as shown in Table 14. Table 14 includes a matrix for every office *i* that defines the IEQ factors *k* affected by Retrofit Option *m*. For example, Table 12 states that Retrofit Option 1 affects Offices 1 and 2 by enhancing the IEQ factors defined by the first row (Retrofit Option 1) of the matrix shown in Table 13. Therefore, the said row should be copied in Table 14 for Retrofit Option 1 (first row) in the matrices of Offices 1 and 2.

Table 14 - Retrofit influence binary variable (for illustration)

F_{ikm}																
Office 1	IEQ Factor *k*															
Retrofit Option *m*		**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**
	1	1	1			1										
	2	1			1								1			
	3															
Office 2	IEQ Factor *k*															
Retrofit Option *m*		**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**
	1	1	1			1										
	2	1			1								1			
	3															
Office 3	IEQ Factor *k*															
Retrofit Option *m*		**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**
	1															
	2	1			1								1			
	3	1				1	1		1							

In addition, and in several retrofit projects, two or more retrofit options might not be applicable if chosen together. For example, and taking the synergy effect into consideration, having two retrofit options that if chosen together might have a different combined effect on the IEQ conditions than the cumulative effects of each taken independently. In such cases, a third retrofit option should be created representing the case when both: Options 1 and 2 are selected. Therefore, only one of the three can be selected for retrofit: Option 1, Option 2, or Option 3; as to select the first option alone, the second option alone, or the first and the second together, respectively. In order to account for such constraints, options that cannot be selected together should be specified using Equation 6.

$$\sum X_{m'} \leq 1 \qquad (6)$$

$$where, \quad m' \in M' subset\ of\ M$$

Similarly, in the case when two or more retrofit options are to be either selected together or not selected at all, the constraint expression of Equation 7 should be used.

$$\sum X_{m'} \leq \left(\sum X_{m'}\right) \times \left(\prod X_{m'}\right) \qquad (7)$$

Table 9 illustrates how Equation 7 allows for an all-or-none selection of three retrofits.

Table 15 - Select all-or-none (for illustration)

Retrofit Option $X_{m'}$	Case 1	Case 2	Case 3
X_1	1	0	1
X_2	1	0	1
X_3	1	0	0
$\sum X_{m'}$	**3**	**0**	**2**
$\prod X_{m'}$	**1**	**0**	**1**
$\sum X_{m'} \leq \left(\sum X_{m'}\right) \times \left(\prod X_{m'}\right)$	**True**	**True**	**False**

It is important to note that some options are to be considered as a must to execute. Therefore, such options can be excluded from the decision making process, and their budgets should be reduced from the total available and will not be included in the optimization process; considering that they will be executed regardless the decision on the remaining options.

After defining the cost of each available retrofit option, Equation 8 is used to ensure that the cost of the selected options for retrofit does not exceed the available budget *B*.

$$\sum_{m=1}^{M} (X_m \times C_m) \leq B \qquad (8)$$

C. Searching for the Optimal Solution

In the process of searching for the possible solution for optimality, the possible solutions are expressed through assigning unity values for the decision variable X_m to express which of the retrofit options are selected. However, and in case one or more possible retrofit options of a feasible solution are expected to enhance the same IEQ factor in an office, that IEQ factor must be considered as enhanced only once, regardless the number of selected retrofit options enhancing it; i.e. the occupant is considered as being satisfied with an IEQ factor if at least one retrofit option is expected to enhance it. For this reason, the influence binary variable is modified to eliminate double counting by finding the union of the effect of all retrofit options considered by the feasible solution on the IEQ factors. The union of the effect of all retrofit options on the IEQ factors is defined as considering that IEQ factor *k* in office *i* has a unity value if one or more selected retrofit options of a feasible solution are expected to enhance it to satisfactory level. This is achieved by first multiplying the rows of the matrix $F_{ikm}$by X_m, canceling the effect of all non-selected retrofit options on the IEQ factors of all the offices. The union of the resulting effects of all retrofit options on every IEQ factor of all the offices is found;

i.e. the union of every column of the matrix of Table 10. The elements of the resulting matrix are defined as the retrofit influence binary variables for a feasible solution $F_{ik}^{'}$. The mathematical expression for calculating $F_{ik}^{'}$ is described by Equation 9.

$$F_{ik}' \leq \sum_{m=1}^{M} X_m \times F_{ikm} \leq 1 \qquad (9)$$

Working with the previous hypothetical example of three retrofit options, and assuming that Options 1 and 3 form a feasible solution of the proposed retrofit problem, the influence of Option 2 on the IEQ factors will be eliminated from all offices as shown in Table 16, since its related decision variable by which it will be multiplied is zero. The resulting values of $F_{ik}^{'}$ are described in Table 17.

Table 16 - Retrofit influence binary variable for a feasible solution build-up (for illustration)

F_{ikm}																
Office 1	IEQ Factor k															
Retrofit Option m		**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**
	1	1	1			1										
	~~**2**~~	~~1~~			~~1~~								~~1~~			
	3															
F_{1k}'		1	1			1										
Office 2	IEQ Factor k															
Retrofit Option m		**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**
	1	1	1			1										
	~~**2**~~	~~1~~			~~1~~								~~1~~			
	3															
F_{2k}'		1	1			1										
Office 3	IEQ Factor k															
[illegible]		**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**

	1															
	~~**2**~~	~~1~~			~~1~~								~~1~~			
	3	1				1	1		1							
F'_{3k}		1				1	1		1							

Table 17 - Retrofit influence binary variable for a feasible solution (for illustration)

F'_{ik}	IEQ Factor *k*															
Office *i*		**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**
	1	1	1			1										
	2	1	1			1										
	3	1				1	1		1							

Using the retrofit influence binary variable for a feasible solution, the expected level of overall satisfaction of the employees for the proposed possible solution is computed using Equation 10. For every employee *j* of office *i*, the impact values of the IEQ factors on the overall satisfaction are replaced by their respective "Satisfied" values, considering only the IEQ factors enhanced by the selected retrofit options of a feasible solution.

$$MOS_{ij} = OS_{ij} + \sum_{k=1}^{K} \left[F'_{ik} \times \left(\alpha_k^* - \alpha_{ijk} \right) \right] \qquad (10)$$

Similar to what was stated previously, the expected percent overall satisfaction per employee and the average level of expected overall satisfaction per office are computed using Equations 11 and 12, respectively.

$$MPOS_{ij} = \left(\frac{MOS_{ij} - (-3.37)}{2.85 - (-3.37)} \right) \times 100\% \qquad (11)$$

$$MOS_i = \frac{\sum_{j=1}^{J_i} MOS_{ij}}{J_i} \qquad (12)$$

The expected percent productive time for employee *j* of office *i* is computed for every feasible solution using Equation 13.

$$MPPT_{ij} = \left(0.39 \times MPOS_{ij} + 0.01 \times l_{ij} + 0.49\right) \times 100\% \qquad (13)$$

The expected average percent productive time for office *i*, weighted by the level of contribution of the employees to the total productivity of the office, is given by Equation 14.

$$MPPT_i = \frac{\sum_{j=1}^{J_i} \left(S_{ij} \times MPPT_{ij}\right)}{\sum_{j=1}^{J_i} S_{ij}} \qquad (14)$$

D. The Objective Function

The objective function is composed of two factors: 1) the offices *Contribution Factor (CF)*; and 2) the expected increase in productive time.

1) As stated previously, those who perform more are rewarded more, and vise versa. Therefore, it is logical to assume that the more an employee's wage is, the more contribution this employee has to the company's overall performance. Similarly, offices can also be weighted by the total salary amount of all the employees occupying them. For this model, the contribution of each office to the company's total output is reflected by the ratio of the sum of salaries of the office's occupants to the total sum of salaries of all the occupants of the company, as described by Equation 15.

$$CF_i = \sum_{j=1}^{J_i} \frac{S_{ij}}{S} \qquad (15)$$

Having a limited budget for IEQ retrofit, offices that contribute the most to the business have the priority to be retrofitted over the remaining offices. Moreover, IEQ retrofits might not scope over the whole organization, and thus might not affect all the employees at their workplace. Therefore, optimizing a retrofit project for a selected number of offices would lead to maximizing the productive time of the portion of employees of those offices only. Hence, the calculated increase in productive time should be scaled down to reflect the portion increase in the productive time of the overall organization.

2) The second factor is the expected increase in productive time of the offices included in the renovation project. This is achieved by computing the increase in value between the currently estimated percent productive time of the considered offices and the expected percent promised by the optimized renovation project.

The objective function of maximizing the increase in the productive time is thus calculated using Equation 16.

$$\text{Maximize} \quad OPPT = \sum_{i=1}^{I} CF_i \times (MPPT_i - PPT_i) \qquad (16)$$

Table 18 - Summary of equations and parameters

Category	Equations and Parameters	Description
Defining parameters of pre-retrofit status	$CF_i = \sum_{j=1}^{J_i} \frac{S_{ij}}{S}$	Contribution factor of the employees of office *i* to the total productivity of organization
	$OS_{ij} = \alpha_0 + \sum_{j=1}^{J} \alpha_{ijk}$	Occupants' Overall Satisfaction with IEQ at the workplace
	$POS_{ij} = \left(\frac{OS_{ij} - (-3.37)}{2.85 - (-3.37)}\right) \times 100\%$	Percent IEQ Satisfaction
	$OS_i = \frac{\sum_{j=1}^{J_i} POS_{ij}}{J_i}$	Average IEQ Satisfaction of the occupants of an office
	$PPT_{ij} = \left(0.39 \times POS_{ij} + 0.01 \times l_{ij} + 0.49\right) \times 100\%$	Percent Productive Time of the employees of an office
	$PPT_i = \frac{\sum_{j=1}^{J_i}\left(S_{ij} \times PPT_{ij}\right)}{\sum_{j=1}^{J_i} S_{ij}}$	Average of the percent productive time of an office weighted by the salary ratio of its employees
Defining Retrofit Options and Constraints	F_{ikm}	User-defined parameter for every retrofit option indicating which office and IEQ factor it impacts
	$\sum X_{m'} \leq 1$	Constraining for single selection among a bundle of retrofit options
	$\sum X_{m'} \leq \left(\sum X_{m'}\right) \times \left(\prod X_{m'}\right)$	Constraining All-or-Non selection among a bundle of retrofit options
	$\sum_{m=1}^{M} (X_m \times C_m) \leq B$	Budget Constraint
Solving for Optimal Solution*	$F'_{ik} \leq \sum_{m=1}^{M} X_m \times F_{ikm} \leq 1$	Parameter indicating which offices and IEQ factors will be impacted by a selected feasible solution
	$MOS_{ij} = OS_{ij} + \sum_{k=1}^{K} \left[F'_{ik} \times \left(\alpha_k^* - \alpha_{ijk}\right)\right]$	Enhanced level of occupants' Overall Satisfaction with IEQ of the workplace
	$MPOS_{ij} = \left(\frac{MOS_{ij} - (-3.37)}{2.85 - (-3.37)}\right) \times 100\%$	Expected enhanced Percent IEQ Satisfaction

	$MOS_i = \frac{\sum_{j=1}^{J_i} MOS_{ij}}{J_i}$	Enhanced weighted average of IEQ Satisfaction of the occupants of an office
	$MPPT_{ij} = \left(0.39 \times MPOS_{ij} + 0.01 \times l_{ij} + 0.49\right) \times 100\%$	Enhanced Percent Productive Time of the employees of an office
	$MPPT_i = \frac{\sum_{j=1}^{J_i}\left(S_{ij} \times MPPT_{ij}\right)}{\sum_{j=1}^{J_i} S_{ij}}$	Enhanced average of the percent productive time of an office weighted by the salary ratio of its employees
Objective Function	$\boldsymbol{Maximize}$ $$\boldsymbol{OPPT = \sum_{i=1}^{I} CF_i \times (MPPT_i - PPT_i)}$$	Increase in productive time for the whole organization due to the optimized renovation project

*All values of this category parameters vary with every trial of feasible solution until optimality is reached

CHAPTER V

CASE STUDY

A. Comparison between the Actual and the Optimized Renovation

In order to validate the importance and effectiveness of this tool in meeting its purpose, a comparison is made between the outcome of a renovation case study of a medium sized engineering firm (about 150 white-collar employees) in Beirut and the expected outcome as optimized by the proposed decision-making tool. In this section, the case study is first discussed, posing the initial problem that lead to the need for a complete office renovation, stating how the decisions were made and what were the actions taken, and concluding with the degree to which the initial target was met. The section continuous with proposing an alternative set of decisions as posed by the proposed optimization tool, and the expected outcome is compared to that of the case study, shedding light on the benefits associated.

Learning about the recently completed renovation project that took place at one of the prominent engineering firms in Beirut, an opportunity was spotted to assess the project in relation to the scope of this paper for validating the applicability and effectiveness of the proposed decision-making tool. The assessed firm is medium sized consisting of a three story building (ground, first and second floors) with 23 offices and 104 employees in total. The scope of the renovation project covered 19 offices and 83 of the employees; the excluded being the offices of the executives and their secretaries, which had already been built recently and needed not be renovated. Several interviews were conducted with the decision makers behind the renovation project. The main reasons behind the renovation project were the fact that the office building was built more than 25 years ago, and with the degrading conditions of the indoor environment, occupants' complaints are increasing notably: humidity, dusty and allergic archives, poor lighting, poor HVAC systems, and water leaks, etc. Occupants' complaints and spotted problems prior to renovation are listed in Table 19.

Table 19 - Spotted problems in need for retrofit

Problem Ref. #	Spotted problem	Description of problem	Location
1	Humidity	High occupant complaints	Ground floor offices
2	Heating/ Cooling	Split units that barely function. Most do not even work.	Ground floor offices
3	Heating/ Cooling	Split units in an open office. The blown air is directed towards nearby employees who are reporting severe headaches and sick leaves. Employees do not consent over a specific heating/cooling degree.	Engineering Department
4	Air quality	Poor air quality due to humidity. Dust and mites due to archives inside offices	In all offices
5	Lighting	Mostly incandescent lights; high electricity costs	In all offices
7	Lighting	Poor luminance	Ground floor offices
8	Day lighting	Poor day lighting; occupants complaining about feeling nausea and dizzy all day long	Accounting Department
9	Acoustic quality	Open offices despite need for high level of focusing	Engineering department

10	IT issues	Poor internet connection and old computer; too much time spent on loading software, etc.	Operations Department
11	Furnishings	Old furnishing that need replacement	Engineering Management; Operations Management
12	Furnishing	Wall paint in very poor conditions due to humidity and water leaks	Ground floor offices
13	Space	Limited workspace	Tender Department; Operations Department; Coordination Department
14	Maintenance	Water leaks	In toilets and kitchen of ground floor and second floor
15	Maintenance	Burnt light bulbs	In most offices

In Table 20, all possible retrofit options that were quoted for prior to renovation are listed along with their approximated/quoted costs of implementation. The last two columns of the table show the options that were actually selected and implemented in the renovation project, and the options that should have been selected as optimized by the proposed optimization program. The total budget allocated to the renovation project was about 100,000 USD.

Table 20 - Possible retrofit options for renovation projects; actual selection vs. optimized selection

Retrofit option Ref. #	Possible solution description	Cost of solution (USD)	Actual selection	Optimized selection
1	Replace broken AC split units	11,000	✓	✓
2	Include humidifiers in offices with high humidity levels	5,000		✓
3	Install VRV HVAC system with slot diffusers in Ground Floor offices	35,000		
4	Install VRV HVAC system with slot diffusers in First Floor offices	45,000		
5	Relocate all archives in a newly built archive areas near the company building	17,500	✓	✓
6*	Lighting replacement with LED equivalents for all the offices	22,000		
7*	Lighting replacement with LED equivalents for First Floor offices (Engineering office)	10,000		✓
8*	Lighting replacement with LED equivalents for ground floor office	14,000		
9*	Replace burnt lights with same type as existing (mostly CFL and incandescent)	500	✓	
10	Enlarge windows of Accounting Department	1,500	✓	✓
11	Renew all personal computers in Operations Department	6,000		

12	Replace old furnishing in Operations and Engineering Management offices	11,000	✓	
13[**]	Repaint whole building (internal and external)	33,000		
14[**]	Repaint ground floor only	8,500	✓	
15[**]	Repaint first and second floor	7500.0		✓
16	Expand Tender Department	13,000	✓	
17	Expand Operations Department	11,000	✓	
18	Expand Coordinations Department	23,000	✓	
19	Transform open-space offices of Engineering Department into cubical-units for more privacy and sound control	35,000		✓
20	Fix water leaks	7,000		✓

[*] Only one selection out of marked retrofit options can be selected for implementation

[**] Only one selection out of marked retrofit options can be selected for implementation

In order to assess the level of success of the renovation project, the whole decision making process was repeated using the proposed optimization tool. All the occupants affected by the renovation were asked to fill out IEQ self-assessment questionnaire based on their perceived satisfaction with the IEQ factors prior to the renovation. For confidentiality purposes, no salaries are requested to be noted; however, the contribution factor of the employees ω has been computed by the Human Resources Department and submitted in ratio form to be used for the purpose of this study. The responses along with the implemented retrofit options were then introduced into the proposed program which assessed the increased level in IEQ satisfaction and its reflection on the increase in productive time for the whole organization.

The decision making tool was then allowed to optimize the selection of retrofit options using the same initial level of occupants' satisfaction, available retrofit options, and budget. The expected level of increase in IEQ satisfaction and in productive time is calculated afresh. The difference in the results between the actual renovation decision taken and the one proposed by the decision making tool is summarized in Table 21.

Table 21 - Implemented vs. optimized renovation outcomes (IEQ satisfaction and productive time)

Offices Included in Renovation			Expected IEQ Satisfaction level		Expected increase in Productive Time	
Office	**Location**	**No. of Employees**	**Implemented Renovation**	**Proposed Opt. Renovation**	**Implemented Renovation**	**Proposed Opt. Renovation**
Operations Management	Ground Floor	2	80%	69%	7%	3%
Operations Department	Ground Floor	3	68%	87%	8%	15%
Tendor Management	Ground Floor	1	71%	69%	8%	7%
Tendor Department	Ground Floor	3	47%	53%	13%	15%
Coordinations Management	Ground Floor	1	76%	74%	3%	2%
Coordinator 1	Ground Floor	1	66%	68%	13%	14%
Coordinator 2	Ground Floor	1	56%	34%	14%	5%
Projects Development Management	Ground Floor	1	43%	38%	4%	2%
Projects Development Department	Ground Floor	2	81%	87%	6%	9%
Engineering Management	1st Floor	1	80%	85%	3%	5%
Engineering Department 1	1st Floor	10	60%	89%	9%	20%
Engineering Department 2	1st Floor	10	46%	75%	2%	13%
Senior Engineering 1	1st Floor	2	74%	79%	0%	2%
Senior Engineering 2	1st Floor	2	88%	93%	5%	7%
Senior Engineering 3	1st Floor	2	78%	84%	3%	5%
Senior Engineering 4	1st Floor	2	77%	85%	3%	6%
Senior Engineering 5	1st Floor	2	80%	88%	4%	7%
Accounting Department	1st Floor	4	67%	76%	8%	12%
Human Resources Department	1st Floor	2	68%	86%	1%	8%
Total number of employees		**52**	**Total increase in Productive Time for the organization as whole**		**5%**	**10%**
			Cost of renovation (selected retrofit options)		**$97,000**	**$94,500**

B. Discussion

In reference to Table 21, only 45% is found common between the actual selection and the optimized selection of retrofit options. An example of this discrepancy is in retrofit options referenced 16, 17 and 18 in Table 20, where in the actual case, the Tender, Operations and Coordination offices were expanded on the expense of transforming the open-space offices of the Engineering Department into cubical units; retrofit option 19. The exact opposite was selected by the optimization tool that led to a higher expected increase in productive time. Assuming that allocating the available budget over three offices rather than one misled the decision makers into spending the budget inefficiently. The actual selection was based on the degree of occupants' complaints and intuitive assessment. Another example extracted from Table 20 is how management requests had been met regardless the degree of importance of the problem in relation to the remaining offices' conditions (retrofit option reference #12). On the other hand, the optimized solution selection, and after calculating its expected effect on the overall increase in the level of satisfaction and on the productive time of the organization as a whole, considered this specific retrofit option as less important, and thus was not selected. A third notion that was concluded from the interviews made with the decision makers is that options selected for retrofit in employees offices was, and to a large extend, selected on a lower-cost basis; i.e. the solution that had a lower cost and sounded logical was selected first, reducing by such the remaining budget. An example of such a case is, and to the contrary of the optimized solution, the actual selection of the least costly option of replacing the burnt lights instead of improving the luminosity of the office to achieve true satisfaction and comfort level, which was the basic cause behind the dissatisfaction of the occupants (retrofit option reference #9). Finally, and by comparing the total expected increase in productive time for the organization as a whole reflected by the actual and the optimized renovation project is 5% and 10%, respectively. With double the expected benefit being observed, relying on the proposed optimization tool in making renovation decisions is a must in order to maximize the outcome when the budget is a limiting factor.

C. Sensitivity Analysis on Budget

In addition to optimizing the selection of retrofit options to maximize increased productive time for the organization, the optimization program proposed can be further used as a sensitivity analysis tool to help in sizing the optimal total budget for the renovation project. Setting the budget for the renovation project does not have to be based solely on availability; since increasing the budget above a certain threshold might have a small impact on the increased productive time, which the decision maker might find not worth the investment, and thus decides to limit the budget. In such cases, avoiding to perform a sensitivity analysis on the influence of the budget size on the level of increase of the productive time at the organization might lead to allocating larger budgets for renovation than the optimal amount. Moreover, and in order to avoid spending all the available budget when budget itself does not stand as a binding constraint, carrying out a sensitivity analysis can easily spot such cases. For example, when the increase in productive time seizes despite continuing with incrementing the budget, the latter should be limited to the least amount after reaching this plateau.

In order to perform the mentioned sensitivity analysis on the influence of the budget size on the level of increase in productive time, the program user can divide the maximum budget into several intervals. The maximum budget is the sum of the costs of all the available retrofit options. The budget is increased from an initial amount that is equal to the lowest retrofit cost available among the different options, up until the maximum budget using discrete increments. At each budget increment, the optimization program is made to optimize the renovation project while respecting all the constraints, including the varying budget, calculating for each case the increase in overall productive time at the organization. The results are then represented graphically for visual assessment of the outcomes; the budget size varying on the x-axis from the lease retrofit cost till the maximum available budget for renovation, and the productive time estimated for the whole organization presented on the y-axis.

To illustrate the sensitivity analysis described in this section, a factual example on the presented case study is carried out. Referring to Table 14, the lowest cost of retrofit option is 500 USD and the maximum budget is 316,500 USD. The sensitivity analysis problem is incremented by 10,000 USD. Figure 4 plots the outcome, indicating for each budget increment the optimal selection of retrofit options and the expected increase in productive time. As observed in the sensitivity analysis graph, the strongest influence on the increase in productive time happens as the budget increases to about 70,000 USD, above which the influence level increases at almost a constant rate till it reaches a plateau after 180,000 USD. A logical budgeting for this renovation project is anywhere between these two values, depending on availability and increase in production to increase in profits ratio for the firm under study.

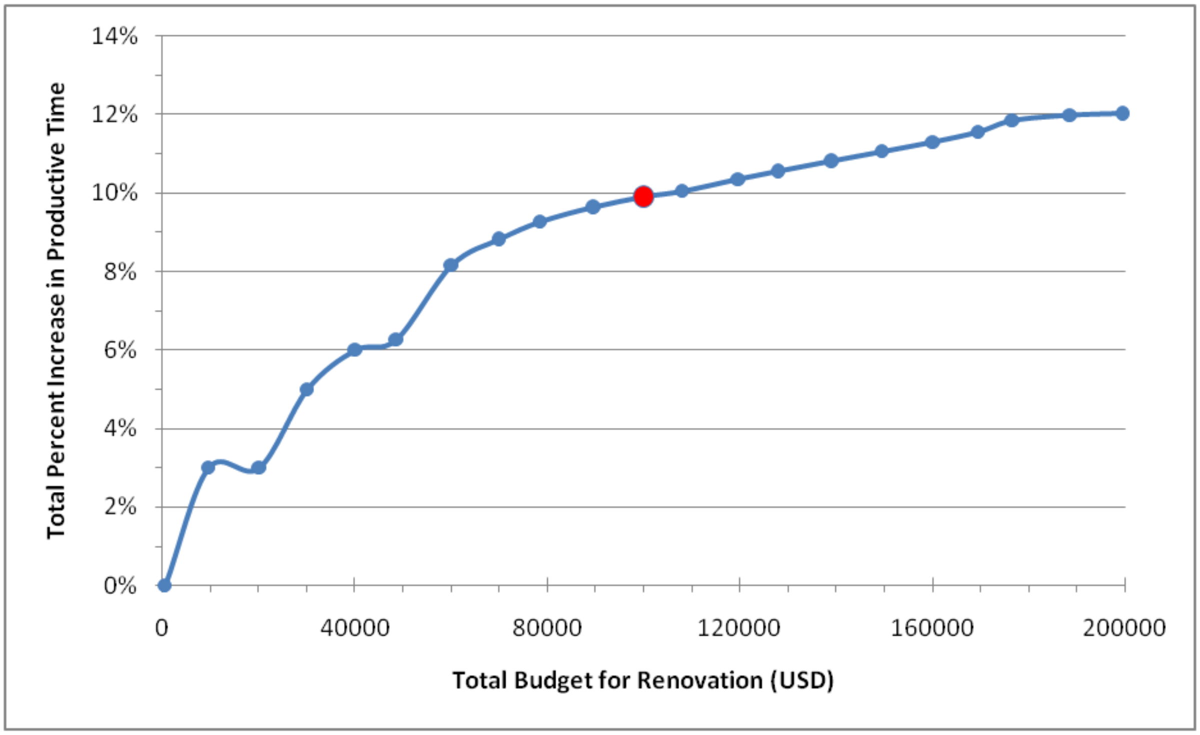


Figure 7 - Budget vs. Productive Time sensitivity analysis

Another important point to highlight is the fact that increasing the budget by the next increment does not mean adding the next best retrofit option to the last selection made; the case that is mostly followed in renovation projects that rely merely on intuition and meeting occupants' complaints. On the contrary, a completely different set of retrofit options might be selected for optimality. For example, and in reference to Table 22 that shows a sample of optimal solutions for increasing budget, most of the consecutive solutions have different options selected and not simply added retrofits to previous selections.

Table 22 - Optimal solution vs. budget

		Budget Increments					
Retrofit Ref. No.*	**Cost (USD)**	**70,000**	**90,000**	**110,000**	**130,000**	**150,000**	**170,000**
1	$11,000		✓	✓	✓	✓	
2	$5,000						✓
3	$35,000						
4	$45,000						✓
5	$17,500	✓	✓	✓	✓	✓	✓
6	$22,000					✓	
7	$10,000	✓	✓	✓	✓		✓
8	$14,000						
9	$500						
10	$1,500		✓	✓	✓		
11	$6,000						
12	$11,000					✓	✓
13	$33,000			✓	✓	✓	✓
14	$8,500						
15	$7,500	✓	✓				
16	$13,000				✓	✓	✓
17	$11,000						
18	$23,000						
19	$35,000	✓	✓	✓	✓	✓	✓
20	$7,000		✓		✓	✓	
Total Cost (USD)		70000	89500	108000	128000	149500	169500

* In reference to Retrofit Options definition in Table 20

CHAPTER VI

CONCLUSION

Renovation projects are inevitably the fate of every office building as its occupants' complaints start going high, and their productivity and competitiveness begin to drop low. At such phases of the organizations life-cycle, business owners and employers find it necessary to invest large sums of money to remedy the situation, and protect their most expensive asset: their employees. However, and to achieve promising outcomes, planning for such renovation projects requires the inclusion of several complex and interrelated factors that intuitive decision making alone fails to comprehend solely. While current renovation projects are carried out based on meeting employees' "heard" complaints as well as observed areas in need for retrofit while the available budgets are still suffice, several other important factors are left out of the decision making process, rendering such renovation projects as suboptimal or below expectations. In order to better plan for renovation projects, and ensure that the optimal benefit for the whole organization is met through proper utilization of the invested budgets, end-stakeholder, i.e. employees and other office building occupants, are to be well assessed and guided through describing their actual level of perception of their IEQ conditions at their offices. It is then important to estimate the impact level of the described conditions on their productive time; the most important factor behind successful organizations. Only after well understanding which of the offices are in need for retrofit can the decision makers list possible retrofit solutions that could improve the conditions of these offices. Moreover, it is not enough to simply propose a possible solution without specifying exactly where this solution can be implemented, which of the offices will benefit from such a retrofit, and exactly what IEQ factors will be enhanced in these offices had this retrofit option been implemented. This requires the guidance of specialists in the field of IEQ and building management. The step that follows is to optimize the selection of the retrofit options by assessing the expected increase in satisfaction levels and productive time per office, aiming to maximize that increase for the organization as a whole. Moreover, the optimization tool can also be used to size the most convenient budget based on a sensitivity analysis of the influence level the budget size has on the increase in productive time for the organization as a whole. The proposed optimization tool is a user-friendly integer optimization program designed on Excel that would guide business owners and employers through all these steps, aiding their decision making process to achieve the maximum benefits out of their office buildings' renovation projects.

The proposed tool is only a first step towards better optimizing renovation projects on the basis of improved productive time for the organization as a whole. However, this attempt can be further expanded to aid business owners and employers also in selecting possible retrofit options and in specifying the IEQ factors affected by each. Another possible limitation of this tool is that it considers enhanced IEQ factors as completely satisfactory; i.e. at least 80% of the employees are satisfied with the expected results; however, this might not be the case. Some retrofit options might improve the IEQ conditions but not to complete satisfactory levels. The proposed tool can be made more flexible to account for such cases scenarios. A third point to shed light on is renovation projects might have dimensions other than IEQ that could affect the performance of organizations, such as energy consumption, lean production, business dimensions, etc. The IEQ-driven optimization tool should be used in compliance with other requirements that the organizations might be targeting through the renovation project.

APPENDIX

Job Performance vs. IEQ Satisfaction at the Workplace

Questionnaire

<u>SECTION I: OCCUPANT BACKGROUND INFORMATION</u>

1) How long have you been working at your current workplace?

   ________________ Years ________________ Months

2) Your job description includes occupying your office for an average of:

________________ Days a week ________________ Hours a day

<u>SECTION II: LOSS IN POTENTIAL PERFORMANCE OF OCCUPANT</u>

1) Please indicate if any of the following cases of **<u>poor physical conditions</u>** describe your workplace:

□ Noisy	YES	NO
□ Tiring or depressing atmosphere due to inconvenient working space, distressing furniture and IT equipment, dull or distressing wall colors, poor lighting or visual comfort, etc.	YES	NO
□ Dusty conditions (including your desk) or throughout your office building	YES	NO

- Extreme thermal conditions due to lack/malfunctioning of the HVAC system (too cold or too hot) YES NO

- Other cases? Please specify: ________________________________

2) In reference to a typical day at work, kindly fill the table below with the number of times you feel interrupted from your work due to the listed types of distractions, and the average amount of time needed to get back to full concentration and performance after having been interrupted.

Type of distraction	Number of times distracted per day	Time needed to get back to full concentration and performance
Noise distraction (noise from street or outside, construction at or near workplace, hearing other people's conversation, footsteps, etc.)		Minutes
Visual distraction (by being looked at by others while working, by seeing others walking or working around you, chaotic environment, etc.)		Minutes
Scent distraction (unpleasant odors, strong perfumes, airborne dust, etc.)		Minutes
Thermal distraction (interrupted from work by feeling too hot or too cold, frequently stopping work to regulate the temperature, etc.)		Minutes
IT malfunction (poor internet connectivity, poor computer performance, lack of communication means, i.e. interphone, email access, etc.)		Minutes

3) On a typical day at your workplace, how many breaks do you take (other than the lunch break or other scheduled breaks) in order to refresh or gain focus due to feeling stressed, fatigue, dizzy, nausea, headache, muscle aches, chest tightness, difficulty in concentrating, etc. due to the poor environmental conditions at your workplace as indicated in Questions 1 and 2?

________________ Breaks

4) On average, how long are these breaks typically?

________________ Minutes

5) During the past month, how many times have you repeated a task that was wrongly performed because of difficulty in concentration or in understanding others due to the poor environmental conditions at your workplace as indicated in questions number 1 and 2?

________________ Times

6) On average, how long would it take you to repeat such tasks?

_____________ Minutes / _____________ Hours / _____________ Days

7) During the past week, how many days have you come late to work due to being tired or depressed, and not feeling like dealing with the poor environmental conditions at your workplace as indicated in Questions 1 and 2?

________________ Days

8) Typically on such days, how late would you come to work?

________________ Minutes / ________________ Hours

9) During the past week, how many days have you left work early due to being tired or depressed, and not feeling like dealing with the poor environmental conditions at your workplace as indicated in Questions 1 and 2?

________________ Times

10) Typically on such days, how early would you leave work?

________________ Minutes / ________________ Hours

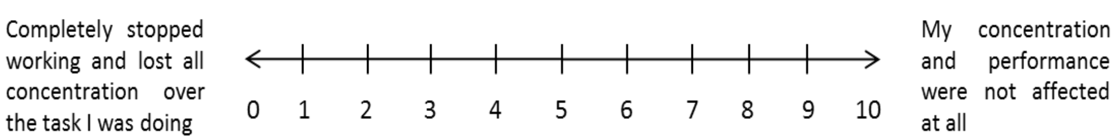
11) During a typical day at work, do you have a headache, or feel dizzy, allergic, chilled, or nausea during the day, which seem to diminish after leaving the workplace?

- ○ No, I don't
- ○ I do, during morning hours
- ○ I do, during afternoon hours
- ○ I do, almost all day long
- ○ I do, at random times

12) On average, how long would this feeling last during the day?

________________ Minutes / ________________ Hours

13) If you are asked to describe your level of concentration or performance during such times, where would you mark it on the scale below?



14) During the past 12 months, how many times have you felt that your workplace environment made you sick or too tired to work that you took a sick-leave (allergic, migraine, prolonged nausea, etc.)?

________________ Times

SECTION III: IEQ OCCUPANT SATISFACTION AT THE WORKPLACE

Kindly fill in the table below by marking the box that best describes your level of satisfaction for each of the following 15 questions.

IEQ CATEGORIES	IEQ Level of Perceived Satisfaction	Low Satisfaction						High Satisfaction
		1	2	3	4	5	6	7
Thermal Comfort	How satisfied are you with the temperature in your workspace?							
Air Quality	How satisfied are you with the air quality in your workspace (i.e. stuffy/stale air, cleanliness, odors)?							
Lighting	How satisfied are you with the amount of light in your workspace?							
	How satisfied are you with the visual comfort of the lighting (e.g., glare, reflections, contrast)?							
Acoustic Quality	How satisfied are you with the noise level in your workspace?							
	How satisfied are you with the sound privacy in your workspace (ability to have conversations without your neighbors overhearing and vice versa)?							
Office Layout	How satisfied are you with the amount of space available for individual work and storage?							
	How satisfied are you with the level of visual privacy?							
	How satisfied are you with ease of interaction with co-workers?							
Office Furnishings	How satisfied are you with the comfort of your office furnishings (chair, desk, computer, equipment, etc.)?							
	How satisfied are you with your ability to adjust your furniture to meet your needs?							
	How satisfied are you with the colors and textures of flooring, furniture and surface finishes?							
Cleanliness and Maintenance	How satisfied are you with general cleanliness of the overall building?							
	How satisfied are you with cleaning service provided for your workspace?							
	How satisfied are you with general maintenance of the building?							

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