AMERICAN UNIVERSITY OF BEIRUT

A STOCHASTIC APPROACH FOR MAXIMIZING PRODUCTIVE TIME BY OPTIMIZING INDOOR ENVIRONMENTAL QUALITY

by
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AN ABSTRACT OF THE THESIS OF

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Providing comfortable indoor environmental conditions that please most of building occupants is an essential goal of facility management. The relationship between building occupants' productivity and their level of comfort at the workplace is well established. However, this truth is frequently disregarded when renovation projects are being studied, for it is easier to focus on the direct costs of a project than it is to assign the value of improved user health and productivity. The aim of this paper is to explore the relationship between building renovation decisions and occupants' level of satisfaction with Indoor Environmental Quality (IEQ) at the workplace. The work entails developing an optimization-based framework to analyze the effect of potential building retrofit options on the improvement in IEQ conditions at the workplace, and in turn, on the level of productive time of building occupants. The framework takes into consideration the fluctuations in IEQ perception among different occupants' groups and the corresponding levels of satisfaction. For example, subgroups of employees may be classified based on three main parameters: gender, type of office, and distance to a window. Based on these parameters, the proposed framework can be used to calculate the increase in the level of satisfaction of building occupants and consequently their productivity. The framework will then be used to develop a decision-making tool which helps select optimal retrofit options, using genetic algorithms, considering several user-defined constraints such as available budget and market conditions.

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CHAPTER I

INTRODUCTION

In non-industrial work environments, the costs associated with worker salaries and benefits are much higher than the costs of providing workspaces, which in turn, are considered much higher than the costs of workspace changes to improving indoor conditions. When constructing cost-effective buildings, it seems to be normal to overlook that the success or failure of a project may rest on its indoor environmental quality (IEQ). Research shows that healthy and comfortable employees within a certain workplace are often more satisfied and productive [1], [2] and [3]. Yet, this truth is frequently disregarded, for it is easier to focus on the direct costs of a project than it is to assign the value of improved user health and productivity. Facilities should be constructed with an appreciation of the importance of providing high-quality, interior environments for all users. The recently developed estimates of how IEQ can affect workers performance enable an approximate accounting for the influence of related potential investments on productivity costs. Attention is gradually drawn to the human–work environment interaction [4]. Providing an effective and healthy workplace is a primary goal of green ergonomics [5]. As the salary of office workers is an order of magnitude higher than the cost of maintaining and operating the building [6], even small improvements in productivity can result in a substantial economic benefit. Fisk and Rosenfeld [7] estimated that improved indoor environment can bring a direct increase in productivity, ranging between 0.5% and 5%.

IEQ is simply defined as the indoor conditions of a building. It includes air quality, access to daylight and views, pleasing acoustic conditions, effective lighting and thermal comfort. It also comprises of the functional aspects of workplace's layout such as whether it provides easy access to tools and people when necessary, and whether there is sufficient space for occupants. Building managers and operators can increase the satisfaction of building occupants by considering all the aspects of IEQ rather than narrowly focusing on temperature or air quality alone. The literature outlines and analyzes how the various aspects of IEQ in workplace environment can affect the level of comfort and productivity of the employees. Thermal satisfaction associated with proper thermal conditions [8], [9] and [10] and adequate indoor air quality [12], [1], and [13] have shown to boost the performance of employees.

Providing optimal or at least comfortable indoor environment that can please most of building occupants is deemed to be essential, and it should be the main goal of buildings facilities management. However, IEQ perception varies between different occupant groups and they are believed to react with different satisfaction levels within the same indoor environment. The literature includes several studies that discuss the different psychosocial and personal factors affecting the occupant's level of satisfaction with the indoor environmental quality [14], [15]. Gender, age, height, weight, health, pattern of smoking, work category, coffee drinking, country of origin, exercising among other factors seem to have a significant effect on the level of satisfaction and the perception of the various aspects of IEQ [16], [17]. Thus, it is necessary to examine the relationships between these factors and overall satisfaction within indoor environment to improve both the service quality and occupant comfort. In addition, design of new buildings and renovation decision should take into consideration these factors to optimize indoor conditions.

The objective of this study is to present a decision support tool that optimizes renovation projects for office buildings with an objective function of maximizing the productive time, considering the demographic composition of the occupants. The tool aids business owners in 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. The tool helps select the optimal combination of retrofit options from the available set of possibilities defined by the program users, being the business owner, the employer, etc. By providing optimal IEQ conditions at the workplace, the tool maximizes the level of employees' satisfaction, comfort level, and ultimately, their productive time. The tool takes into consideration the fluctuation in IEQ perception among different occupants' groups and provides a stochastic simulation of the various levels of IEQ satisfaction. A random function will be assigned for each subgroup of employees; these subgroups will be classified based on three classes (Gender, Age and Work category). Based on these functions, the program will calculate the overall increase in satisfaction within the company and translate it into an improvement of 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.

This proposal starts with a review of the literature, and then presents the adopted methodology and preliminary results.

CHAPTER II

LITERATURE REVIEW

This section is divided into three subsections. The first subsection presents a summary of available decision support tools used to address Indoor Environmental Quality in the context of sustainable development. The second subsection discusses the literature on IEQ and its relation to satisfaction, comfort and productivity of buildings occupants. Finally, the third subsection tackles the fluctuation in IEQ satisfaction within different group occupants and presents how different personal or psychosocial factors beyond environmental parameters can influence occupants' perception of the quality of indoor environment.

A. IEQ Optimization and Sustainable Development

Green accreditation systems for assessing the environmental performance of buildings have been implemented for more than 20 years. They have been instrumental at driving innovation regarding sustainability issues within the construction industry. LEED and BREEAM are, perhaps, the two most widely recognized environmental assessment systems used worldwide in the construction industry. LEED, or Leadership in Energy and Environmental Design, is altering the way buildings are planned, constructed, maintained and operated. LEED has become the most widely used third-party verification for green buildings, with approximately 1.85 million square feet being certified every day [18]. On the other hand, BREEAM (Building Research Establishment Environmental Assessment Methodology) is the world's leading sustainability assessment method for master planning projects, infrastructure and buildings. It targets different lifecycle stages such as New Construction, Renovation and In-Use. Globally, there are more than 556,300 BREEAM certified developments, and almost 2,259,400 buildings registered for assessment since it was first launched in 1990 [19].

Projects pursuing LEED or BREEAM certification earn points across several titles that tackle sustainability. Energy, Water, Materials and Indoor environmental quality are considered the principal areas of this certification. The IEQ category rewards decisions made by construction teams about thermal, acoustic, and visual comfort and indoor air quality. Sustainable buildings with efficient IEQ provide a healthy and comfortable environment for building occupants, enhance productivity, decrease absenteeism, and reduce liability for building designers and owners [20].

Many efforts are made to support designers in sustainable building design. “Athena” [21] is abased tool for estimating the environmental consequences of material and energy use in buildings during design. Building Design Advisor [22] is a practical professional tool to facilitate both strategic and detailed decision-making throughout the design process. BDA help designers compare distinctive design alternatives based on different performance criteria. “envest2” is another tool that performs financial and environmental trade-offs during the design phase [23]. Shaviv et al. [24] presented an integrated system that combines procedural simulation and heuristic methods to assist architectural design system. This methodology was used for the design and evaluation of solar and low-energy buildings. Optimization methods represent another approach to tackle design decisions in green building. Due to great advances of computational science and mathematical optimization methods, the applications of numerical optimization began arising since the last three decades [25], many of which have been widely employed for the sake of green practices and sustainable developments.

Most of the optimization models have been used in areas such as cost and resource utilities (energy, water and materials). Yi et al., for example, presents an innovative approach for designing environmental buildings with an integrated energy–emergy (spelled with an “m”) system to study building form optimization in the schematic phases [26]. Other research studies focus on establishing optimization models that minimize greenhouse gas emissions during construction [27], [28]. Safaei established an optimization model that provides optimal operation levels and investment planning as well as the corresponding life-cycle environmental impacts for different operational strategies [29]. Asadi et al. put forth a multi-objective model that optimizes energy use while satisfying the building occupant [30]. Moreover, optimization models were used for establishing building retrofit strategies while minimizing energy use and the cost of renovation [31] and [32]. Despite the major contribution of the studies, most optimization tools do not regard occupants’ satisfaction as the main objective of their optimization process. In fact, more than 60% of the optimization models published in journals focused on building energy issues, while only 20% consider the comfort level during the optimization procedure [33]. Furthermore, a limited number of research studies focused on optimizing the comfort and satisfaction level of building occupants to improve their performance or productivity in work offices. For instance, Mofidi et al. proposed a Multi-Objective Optimization (MOOP) method for energy and comfort management in commercial buildings. The proposed MOOP method boosts occupants’ productivity, by up to $1000 per year per person, while reaching energy savings objectives [34].Also, Bachir et al. presented a computational fluid dynamics model to optimize the height of the chair fan and the fan flow rate for the best combination of indoor air quality and thermal comfort [35].However, there is a lack of studies that present an optimization tool for office building renovations that maximizes occupants' level of satisfaction with IEQ and thus their productivity and performance.

B. Perception of IEQ

The definition of occupants' satisfaction within a building is not consistent in the literature. Yet, all the studies associated occupants' satisfaction in office buildings with indoor environmental quality (thermal, visual, acoustic environment, and air quality) and.

The focus of the proposed model in this thesis is to optimize a set of retrofit choices within an office building, to maximize the level of satisfaction with indoor environmental quality and therefore the occupants' productivity, taking into consideration the demographic distribution of the employees and its effect on the level of satisfaction. Thus, this section will present the definition of IEQ, the correlation between IEQ, comfort and productivity and finally how different psychosocial and personal factors can affect occupants' satisfaction with IEQ.

C. IEQ: Definition and it's Health Effects

Human beings have endeavored to establish indoor environments in which they would feel comfortable. Since people spend around 80-90% of their time indoors [36], research has clearly established that problems with IEQ of a building has a direct effect on the comfort, health and productivity of the occupants [37]. 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 and facilities"*[39].

Fifteen different IEQ factors classified into seven key categories can define the indoor environmental quality within a work environment. These IEQ factors have various and unique effects on the physical and mental well-being of the occupants within a certain workplace. Sick building syndrome is a phenomenon that affects building occupants who report illness perceived as being building-related. The ASHRAE Position Paper on Indoor Air Quality [38] defines SBS as follows: "*The term "sick building syndrome" is used to describe a building in which a considerable number (more than 20%) of building occupants experience acute health and comfort effects that appear to be linked to time spent in a building. This phenomenon is characterized by a range of symptoms including, but not limited to, eye, nose, and throat irritation, dryness of mucous membranes and skin, nose bleeds, skin rash, mental fatigue, headache, cough, hoarseness, wheezing, nausea, and dizziness*". Table 1 presents a summary of the fifteen factors along with their health effects.

D. IEQ factors and occupants' overall satisfaction at the workplace

Occupants are the customers of the final product (the building), and therefore entitled to be comfortable and satisfied with the indoor of their product. As such, the literature provides a wide range of research papers that examine the relationship between the IEQ factors and the occupant's overall satisfaction with the workplace conditions. In addition, the adoption of "IEQ satisfaction surveys" under the rating schemes of sustainable buildings such as LEED has dramatically increased the focus on how occupants perceive the indoor environments. The 13 studies in Table 2 point out the IEQ factors that contribute to building occupants' satisfaction.

E. Occupants' overall satisfaction and their productivity at the workplace

One of the essential human desires is working in a workplace environment that allows them to execute their work tasks efficiently within comfortable surroundings. It has previously been proved that a performance or productivity increase of a minimum of

10% can be associated with improvements in the indoor environment [64, 65], which, in turn, can increase organizations profitability dramatically [66]. Singh established a cost-benefit comparison analysis between traditional and green buildings and concluded that employee productivity would increase up to 8% during the first 20 weeks of an office renovation and stabilize after one year at 6%. Furthermore, Singh reported that IEQ improvements within office buildings are economically feasible investments [67]. Nevertheless, in his paper Clausen pointed out that the subjects under study could not decide among them on which of the proposed IEQ factors should be enhanced when asked to select under the constraint of a limited budget. This can clearly imply that that renovation decisions should be well planned such that the IEQ improvement plan could meet the inquiries of most employees [68].

Several studies have tried to establish a relation that relates occupants' satisfaction with the workplace environment to their productivity level. Lan et al. depicted a quantitative relationship between thermal sensation votes and task performance. The relationship indicates that optimum performance can be achieved slightly below neutral, while thermal discomfort leads to reduced performance [69]. Jin et al. postulated that most of the current indoor environmental quality assessment schemes do not take into consideration all the IEQ factors that are relevant to façade design. Thus, a relationship relating occupant productivity and the combinatorial effects of four key façade-related IEQ factors, namely, thermal comfort, aural comfort, visual comfort and air quality, on occupant productivity [70]. Seppanen et al. collected and analyzed the studies focusing on the effect of temperature on productivity in work offices. The results suggested that task performance is not affected by temperature variation between 21 and 25 °C. However, a linear productivity decrease of 2% per degree centigrade was noticed as the temperature increased above 25 °C [71]. On the other hand, Somers and Casal, suggested a nonlinear model to address the relation between occupants' satisfaction and productivity using Artificial Neural Networks. Figure 1 presents the form of the relationship between job performance and job satisfaction or satisfaction with the work environment [72].

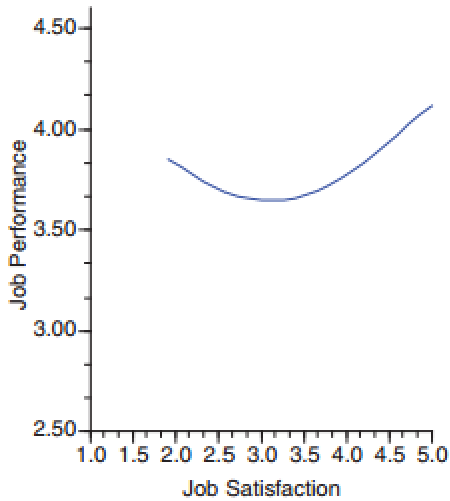


Figure 1 Job Performance versus Job Satisfaction

Khoury et al. tackled the unexpected increase in productive time as satisfaction decreases by proposing a linear regression model between the dependent variable: Percent Productive Time, and the two independent variables: Percent IEQ Satisfaction and Longevity. The findings proved that a significant correlation between Percent Productive Time and the two proposed independent variables exist. As a conclusion, the paper suggests that an increase in longevity is associated with an increase in productive time [73].

The central reason behind the inconsistency spotted among various regression models that aim at investigating the relationship between occupants' IEQ satisfaction and their corresponding productivity, is that each study assumes a different approach for measuring the productivity. Also, the ability to measure productivity in all its dimensions is relatively impossible; measuring productivity is rather a difficult task to be able to quantify the different factors affecting it. Moreover, other factors include the complexity in controlling the irregular day-to-day tasks and the unavoidable Hawthorne effect involved during measuring the productivity of employees who are alert that they are being studied [74]. To achieve a valid productivity measure, two crucial requirements are needed; the first is to be able to quantify a productivity dimension, for the productivity per se is a complex product of several influencing factors, such as the type of work, the physiological environment, space management, and IEQ [75]. A more accurate estimate of the relation between IEQ satisfaction and productivity would be the productive time. Employees can have various levels of productivity yet have the same productive time, depending on the nature of their work, experience, physiological status, etc. Another feature for productive time is its ability to indirectly evaluate the performance of the employees as to reduce the margin of biased responses. Instead of assessing employees on their level of output, measuring productive time comprises inquiring the employees about the time lost due to external factors or due to reasons out of their control that are linked to IEQ. By this method, respondents are more probable to answer with objective and more precise estimates, since erring seem to have neutral influence on their benefit. Furthermore, determining time rather than productive work is a considerably simpler task to do. Some peer-reviewed questionnaires existent in the literature measure productivity by concentrating on measuring productive time, such as the Migraine Work and Productivity Loss Questionnaire (MWPLQ) [76], and the Health and Performance Questionnaire (HPQ) [77].

F. Personal, physical and psychological factors affecting the degree of satisfaction at the workplace

Subjective assessments and objective measurement represent the main methods for the evaluation of perceived IEQ. Occupant surveys are considered the widest spread tool used for data collection. These surveys represent the backbone of post-occupancy evaluation (POE) studies across different fields, including psychology, sociology, demography, health, and building sciences [78,79 and 80]. Similarly, researchers in the field of indoor environmental quality use POE surveys to understand the relationship among the different IEQ factors, overall satisfaction and the level of productivity of occupants at the workplace. Those surveys usually collect information on the respondents' personal, physical and psychological attributes. However, not all the studies report the results based on these factors. Until now, great debates on the effect of these factors on occupants' satisfaction can be found in the literature. Most of the papers focus mainly, on the effect of gender on the perception of IEQ. Thus, a summary of papers tackling the influence of gender on the degree of satisfaction with IEQ is presented in Table 3.

Besides gender, other factors can dramatically affect IEQ satisfaction among employees in the work environment. In their paper, Kim and de Dear established an empirical analysis based on an "industry standard" POE database from CBE (Center for the Built Environment) at the University of California Berkley. CBE has conducted the survey since 2000 and it has been implemented in over 600 buildings, with over 65,000 individual occupant responses. The results of the study suggest that gender, different age groups and work categories can influence differently the occupants' satisfaction with the IEQ [81]. Indraganti et al. took the analysis one step further, to investigate the effect of other factors on the degree of satisfaction with IEQ. The paper investigated the effect of age, gender, economic group and tenure on thermal comfort. It was found that age, gender and tenure correlated weakly with thermal comfort. However, the thermal acceptance of women, older subjects and owner-subjects was higher. Economic level of the subjects showed significant effect on the thermal sensation, preference, acceptance and neutrality [82]. In addition, Lee et al. used a structural equation model to study the effects of noise on job satisfaction. A difference in the fit models for China and Korea was found which posts a robust conclusion on the effect of cultural differences on IEQ perception [83].

Table 1 IEQ factors and their corresponding health effects

IEQ Categories	IEQ Factor	IEQ Factor Description	Health Impact	Reference
Thermal comfort	Thermal Comfort	Humidity, Temperature, Air Flow, Thermostat controls, Operable windows	Sick building syndrome symptoms, Attention drift, Stress, Headache	[39, 40, 41 and 42]
Air quality	Air Quality and Ventilation	Source control, Filtration, Use of ventilation, routine cleaning of carpet and maintenance of HVAC, Tobacco smoke	Sick building syndrome symptoms, allergy and asthma, Respiratory illness, Headache	[40, 41, 42, 43 and 44]
Lighting	Amount of Light	Daylight, Artificial lighting control	Sick building syndrome symptoms, Depression, Stress, Headache	[39, 40, 44 and 45]
	Visual Comfort	Reducing glare and contrast, Provide natural views, Render appropriate color		
Acoustic quality	Noise Level	Side-chats, machines and office equipment noises, etc.	Stress, Attention Drift, Fatigue, Headache	[42, 46 and 48]
	Sound Privacy	Inability to overhear other people's conversations and the ability to have a conversation without others overhearing		
Office layout	Amount of Space	Available space for occupants' work, movement and storage	Attention drift, Miscommunication, Headache, Fatigue	[49 and 50]
	Visual Privacy	Type of offices (Enclosed or open offices, cubicles with partition)		
	Ease of Interaction	Ease of interaction with co-workers		
Office furnishings	Comfort furnishing	Comfort of office furnishing and their position in the office	Sick building syndrome symptoms, Stress, Depression, Allergy and asthma	[40 and 51]
	Adjustability of Furniture	Ease of moving some furniture pieces, adjustable curtains		
	Colors and Textures	Colors and textures of furniture and finishing (walls, doors, paint, tiles, etc.)		
Cleanliness and maintenance	Building Cleanliness	The cleanliness of the overall building	Sick building syndrome symptoms, Allergy and asthma	[42, 52 and 53]
	Workspace Cleanliness	The cleanliness of the occupant's workplace office		
	Building Maintenance	The maintenance of the overall building		

Table 2 Summary of papers studying which IEQ factors affect overall satisfaction

Study	Population Size and Description	Method of analysis	Results
Lai et al. (2009) [54]	125 occupants living in 32 typical residential apartments in Hong Kong	Multivariate logistic regression analysis	Operative temperature, CO2 concentration, equivalent noise level and illumination level all had important effects on the overall IEQ acceptance.
Zalejska-Jonsson et al. (2013) [55]	Total responses (N = 5756)	Ordinal logistic regression, Odds ratios	Air quality has the highest impact on overall satisfaction. The results indicate that if the occupant is dissatisfied with air quality, there is a 2.65 times likelihood that the overall satisfaction decreases
Geng et al. (2017) [56]	A total of 3489 valid questionnaire samples have accumulated in 8 Chinese airport terminals	Multiple regression with dummy variables	'Thermal Comfort' and 'Space Layout' have prominently negative influences on passengers' overall satisfaction when they are underperformed.
Frontczak et al. (2012) [57]	A total of 2499 questionnaires were sent to inhabitants of the most common types of housing in Denmark; 645 responses	Wilcoxon rank sum test, Multivariate linear regression analysis	An increase of acceptability with thermal, visual, acoustic environment or air quality will result in an increase of acceptability of the overall indoor environment
Xue et al. (2016) [58]	482 residents in high-rise residential buildings	Stepwise regression, Spearman rank correlation	The combined aspect of air quality and thermal comfort has the greatest influence on OES in high-rise residential buildings, followed by luminous comfort and acoustic comfort.
Frontczak et al. (2012) [59]	52 980 distributed over351 office buildings, mainly in USA	Spearman rank correlation	Overall satisfaction with the work environment was affected by the satisfaction with the 15 IEQ factors
Kim and de Dear (2012) [60]	Database from CBE (Center for the Built Environment) at the University of California, Berkeley	Multiple regression analysis with dummy variables	Overall satisfaction with the workplace correlated with all of the 15 IEQ factors, Regression coefficients for each IEQ item's satisfied occupant group and dissatisfied occupant group were calculated
Agnieszka (2014) [61]	477 responses from buildings in Sweden	Odd Ratios	Perceived sound quality, thermal quality, air quality and daylight quality are all factors that affect the overall satisfaction
Zhao et al. (2015) [62]	611 valid questionnaires distributed over 14 retail stores in Pennsylvania and Texas	Spearman rank Correlation	Employees overall satisfaction with the indoor environment was influenced by the air movement, overall cleanliness, indoor temperature and air exchange rate
Sakellaris et al. (2016) [63]	7441 workers in 167 "modern" office buildings in eight European countries	Spearman rank correlation and Proportional odds ordinal logistic regression	Overall Comfort Correlates with thermal, air quality, noise and light satisfaction

Table 3List of studies investigating gender differences in IEQ perception

Study	Population Size and Description	Effect Under Study	IEQ Factors Under Study	Method of Analysis	Results
Choi et al.(2017) [84]	188 female occupants and 223 male occupants. 196 subjects were in the Junior group (18–29 years old), 165 in the Mid-Aged group (30–49 years old), and 50 in the Senior group (50–69 years old)	Gender, Age	IAQ, Lighting, Acoustics, Thermal	Two-sample T-test analysis	Female occupants tended to feel more satisfied with air quality, while male occupants tended to respond as being dissatisfied with air quality. Junior and Mid-Aged groups, which showed higher satisfaction with higher illuminance. The senior group, however, revealed an opposite outcome.
Sakellaris et al. (2016) [85]	7441 workers in 167 “modern” office buildings in eight European countries	Gender , Age , Type of office	IAQ, Lighting, Acoustics, Thermal	OR analysis, Linear regression analysis	There were gender differences in the relations between air movement and the view from the windows and overall comfort. Slightly higher OR for noise and light in men than in women. Concerning air quality, ORs were slightly higher in the youngest and the oldest occupants as compared to the middle-aged occupants. Whatever the age subgroup, the highest association with overall comfort was found for noise. The results showed that noise seemed slightly higher in occupants’ working in private and shared offices than in open-plan offices
Xue et al.(2016) [86]	482 residents in high-rise residential buildings	Gender, Age, Window Area	IAQ, Lighting, Acoustics, Thermal	Stepwise Regression, Spearman rank correlation, Chi-square test	Gender had a great impact on air quality and thermal comfort. The results generally suggest that males tend to be more satisfied with air velocity and temperature. Age made no statistical difference to feelings about “Air quality and thermal comfort”, “Luminous comfort” and “Acoustic comfort”. Window area made statistical difference under “Luminous comfort”
Zhao et al. (2015) [87]	611 employees in 14 retail stores located in Pennsylvania and Texas	Gender	Thermal, IAQ, Lighting	Linear regression analysis	Gender makes a 31% difference in the estimated cumulative odds of rating, when comparing the ratings of female and male employees.
Schiavon et al. (2014) [88]	21,477 responses from 144 buildings (65 LEED-rated)	LEED Certification, Gender, Number of Hours Spent at the Office, Size of Building, Type of Office	15 IEQ factors	Wilcoxon rank sum test, Spearman Rank Correlation	LEED-rated buildings are effective in providing higher satisfaction in open spaces rather than in enclosed offices, in small rather than in large buildings. Males tend to express a slightly higher mean satisfaction than females with all IEQ parameters in both LEED and non-LEED buildings. The number of hours spent per week at the place of work influences the absolute difference in mean vote of occupants' satisfaction in LEED and non-LEED buildings.

Study	Population Size and Description	Effect Under Study	IEQ Factors Under Study	Method of Analysis	Results
Choi et al. (2010) [89]	40-sampled occupants and their workstations on 38 floors in 20 office buildings in the U.S.	Gender, Age	Thermal	Two sample *T*-test, one-way ANOVA	The statistical analysis of thermal satisfaction shows statistically significant results for males and females. In the cooling season, females have lower thermal satisfaction than males. Occupants over 40 years old are more satisfied than under 40 in the cooling season with marginal significance.
Choi et al. (2012) [90]	212 female and 190 male occupants, ranging in age from 18 to 69 years old. A total of 170 subjects were between 19 and 39 years old, and 230 subjects were between 40 and 69 years old.	Gender, Age, Type of Work	Thermal, Lighting	Ordinal logistic regression analysis, ANOVA, Two sample T-test	Women were significantly less satisfied with their thermal environments than men during the cooling season. Building occupants older than 40 reported higher satisfaction with their thermal environment in all seasons as compared to those under age 40. The satisfaction with workstation light levels for paper-based tasks was elevated with higher illuminance levels beyond the current minimum of 500 lx.
Frontczak et al. (2011) [91]	Data from a web-based survey administered to 52 980 occupants in 351 office buildings over 10 years by the Center for the Built Environment	Type of Office, Distance to a Window	15 IEQ factors	Wilcoxon rank sum test	Workspace satisfaction was significantly higher in private offices and close to a window than in shared offices or cubicles with high and low partitions. Satisfaction with visual and sound privacy, ease of interaction with co-workers, furniture adjustability and comfort, colors and textures of surroundings, temperature, air quality, amount of light, visual comfort, noise level, building and workspace cleanliness was significantly higher in private offices and workstations close to a window than in shared offices or cubicles and far from a window.
Zalejska-Jonsson et al. (2013) [92]	Total responses ($N = 5756$)	Gender, Age, Absenteeism	Thermal, Acoustics, IAQ	Ordinal logistic regression, Odds Ratio	The effect of thermal comfort is statistically significant, being 1.24 times the effect for women than the effect of thermal comfort on men, indicating that women are more sensitive to thermal discomfort. Occupants' age has significant impact on overall satisfaction and younger occupants are more likely to be dissatisfied. Occupants who are absent from the apartment for more than 4 h on weekdays are less likely to be dissatisfied than those who were absent for less than 4 h.
Liang et al. (2014) [93]	A total of 233 valid questionnaires were retrieved from the survey for analysis, with 134 being generated by the occupants from green buildings and 99 from conventional buildings. Onsite measurements were also done.	Gender,Green Building Vs Conventional Building, View on Energy Conservation	IAQ, Lighting, Acoustics, Thermal	Two-tailed *t*-test	Female participants were more content with the overall IEQ and the thermal status inside the investigated buildings. The respondents with a greater concern for energy expenditure were more tolerant of the IEQ in their working environment than those of a lesser concern. For all of the concerned IEQ areas as well as for the overall IEQ, the means for the green building group were greater than those for the conventional groups.

CHAPTER III

METHODOLOGY

The proposed decision-making tool consists of two main phases. The first phase includes assessment of existing status of the office spaces, 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 was coded using MATLAB. It begins after having defined all possible retrofit options that could enhance the current conditions at the offices in need for renovation. The program generates different random functions that simulate the stochastic distributions of IEQ satisfaction with the indoor environment based on the occupants' classification. The employees will be classified into smaller subgroups based on gender, type of office and distance from a window. 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.

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

The 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 -3 to 3 scale. A sample of the survey is presented in the Appendix, Table 5. This questionnaire consists of 20 questions:

The first three questions will ask the occupants to fill some demographic data that will be fed into the program. The program will categorize the occupants' population by gender (male, female), type of office (single, shared) and the distance to a window (within 4.6 m, further than 4.6 m).In their study, Kim and de Dear [81] studied the effect of gender on IEQ perception and reported the mean level of satisfaction for the different IEQ factors including both females and males. Similarly, Frontczak et al. [59] presented the mean level of satisfaction for all 15 IEQ aspects based on the type of office (single, shared) and the distance to window (Far, Close).

The next 15 questions are adopted from the CBE survey questionnaire used in Kim and de Dears study that are IEQ related [60].

The remaining two questions ask about the longevity at the workplace, and the current monthly wage, respectively. Longevity, and as defined in the questionnaire, is the period 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.

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.

The third step requires all available retrofit solutions to be entered 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 last step is to input the total available budget for the renovation project.

B. Second Phase: Optimizing the selection of retrofit options

The second phase of this tool is comprised of three main functions that were coded using MATLAB language. The first function "Main Function" uses all the previously defined information to calculate the overall satisfaction with IEQ and productivity within an office before and after renovation. Afterwards, it calculates the total expected improvement in productivity at the level of the company. This function splits the occupants according to different profiles based on the categories from the first phase. Each profile is assigned a unique function describing a distinctive pattern in assessing satisfaction with the IEQ. In addition, no two occupants within the same profile are assumed to have the same IEQ satisfaction; this is because many personal and psychological factors (random variables) interfere in the idea of satisfaction with the workplace indoor environment.

Due to the randomness involved in the "Main Function", a "Monte-Carlo Function" was introduced to capture all the uncertainty of the first function. In a Monte Carlo simulation, a random value is selected for each of the random contributors, in this case the random functions assessing IEQ perception. The expected improvement in productivity is calculated based on these random values. The result of the model is recorded, and the process is repeated. A typical Monte Carlo simulation calculates the model hundreds or thousands of times, each time using different randomly-selected values. When the simulation is complete, many results from the model, each based on random input values will be collected. The "Monte-Carlo Function" repeats the "Main Function" for a predefined number of iterations that is equal to 5000 trials.

The third function is the "GA Function" or the Genetic Algorithm Function. This function is responsible for the optimization process within this tool. GA is considered a powerful technique for spotting the global optimum. It promises to yield the maximum possible increase in occupants' satisfaction level and productive time by enhancing the IEQ factors within the constrained budget. The "GA Function" optimizes the average of the 5000 iterations conducted by the "Monte-Carlo Function" to eliminate the effect of uncertainty while locating the optimal solution.

With all the previous information defined, the MATLAB code calls genetic algorithms to solve for the optimal selection of retrofit options. The program then outputs this selection, pointing out the offices that will be retrofitted.

The program as such falls under two scenarios:

- The first is that no renovation schemes were implemented and as such the decision variable indicating whether a certain retrofit will be implemented in an office will be 0.
- The second would be the opposite, where the decision variable will be 1, indicating that this retrofit option will be implemented in that office.

If the first scenario turns out to be the case, then it is normal to expect that no improvement in IEQ satisfaction would occur within the office, thus no improvement in occupants' productivity. On the other hand, if the second scenario applies, the program then interpolates the results to estimate the total increase in productive time for the organization taking into consideration the randomness in IEQ perception between the different predefined profiles of employees.

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, the satisfaction with the workplace environment, occupants' productivity along with any of the energy use, water consumption, or waste and materials constituting the office.

The figure below summarizes the mechanism of the program.

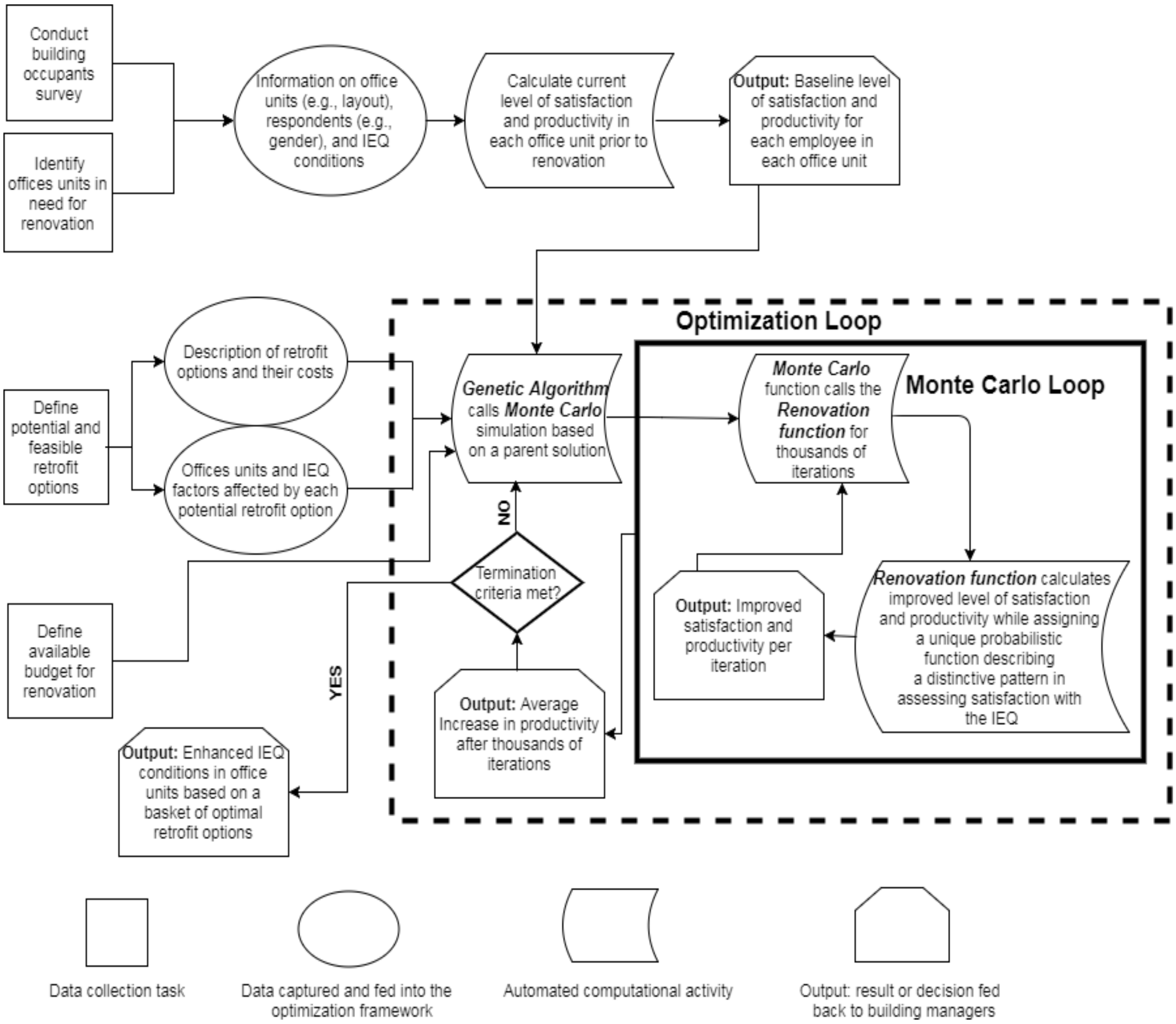


Figure 2. Program Overall Mechanism

CHAPTER IV

OPTIMIZATION MODEL BUILD UP

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 model considers the effect of gender, type of office and the distance of the worker to a window on IEQ perception and satisfaction. The section begins by describing the method for calculating the current IEQ satisfaction levels and percent productive time for each office and then for the whole organization. The various indices, parameters, constants and decision variables used in this model are summarized in Table 4.

Table 4Definition 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
$\boldsymbol{m}$	Index of employee$1 < i < M$; where M is the total number of employees in office unit i
$\boldsymbol{j}$	Index of IEQ factor $1 < j < J$; where J is the total number of IEQ factors (15 factors)
$\boldsymbol{k}$	Index of possible retrofit options $1 < k < K$; where K is the total number of retrofit options considered
$\boldsymbol{o}$	Index of different offices type; Index 1 represents a single office, Index 2 represents a shared office.
$\boldsymbol{w}$	Index of the distance of the employee to a window; Index 1 represents a distance less than 4.6m, Index 2 represents a distance more than 4.6m.
$\boldsymbol{g}$	Index representing the gender of the employee in the workplace. This index distinguishes between male and female employees.
Decision Variables	***Description***
$\boldsymbol{X_{ik}}$	Binary decision variable indicating whether to implement retrofit k in office i
Defined Parameters	***Description***
$\boldsymbol{\alpha_0}$	Baseline constant for overall satisfaction of employees at their workplace
$\boldsymbol{\alpha_{imj}}$	Impact parameter of IEQ factor j on the overall satisfaction of an employee with office i
$\boldsymbol{\alpha_j^1}$	Impact parameter from the satisfied group of IEQ factor j on the overall satisfaction of employees at their workplace.
$\boldsymbol{\alpha_j^2}$	Impact parameter from the dissatisfied group of IEQ factor j on the overall satisfaction of employees at their workplace.
$\boldsymbol{l_{im}}$	Longevity of employee m in office$i$; indicates the number of years the employee has spent in the currently occupied office
$\boldsymbol{s_{im}}$	Salary of employee $m$in office i

$\boldsymbol{S}$	The sum of salaries of all the employees of the organization
$\boldsymbol{H_{ijk}}$	Retrofit influence binary variable; indicates the offices i and IEQ factors j expected to be influenced by implementing retrofit option k
$\boldsymbol{C_k}$	Cost of retrofit k
$\boldsymbol{B}$	Total available budget for the renovation project

Variable Parameters	***Description***
$\boldsymbol{F'_{gow}}$	Net improvement in the satisfaction of employees with gender g, working in an office of type *o* and with a distance to window *w*. The degree of improvement depends on these three factors. $0 \leq F'_{gow} \leq 1$
$\boldsymbol{H'_{ij}}$	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
$\boldsymbol{IS_{im}}$	Initial satisfaction of employee *m* with the workplace at office i
$\boldsymbol{PIS_{im}}$	Percent initial IEQ satisfaction of employee *m* with the workplace at office i
$\boldsymbol{IS_i}$	Average of the initial overall satisfaction of the employees of office i with their workplace
$\boldsymbol{PPT_{im}}$	Percent productive time of employee *m* within 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
$\boldsymbol{MOS_{im}}$	Maximized overall satisfaction of employee *m* with the workplace at office i
$\boldsymbol{MPOS_{im}}$	Maximized percent IEQ satisfaction of employee *m* with the workplace at office i
$\boldsymbol{MOS_i}$	Maximized average of the overall satisfaction of the employees of office i with their workplace
$\boldsymbol{MPPT_{im}}$	Maximized percent productive time of employee *m* with the workplace at office i
$\boldsymbol{MPPT_i}$	Maximized 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
$\boldsymbol{CF_i}$	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

A. Defining Current Status

This section explains the process and mathematical equations used to calculate the initial level of satisfaction with IEQ and percent productive time for each employee and within each office unit. It also presents the tool used to input the required data.

1. *Mathematical Model*

To calculate the level of overall satisfaction of an employee with the workplace, for each respondent of the questionnaire described in Table 3, 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 [60]. Using the regression coefficients for each IEQ factor for the satisfied and the dissatisfied groups as shown in Table 5, the mathematical representation of this model is presented by Equation 1.

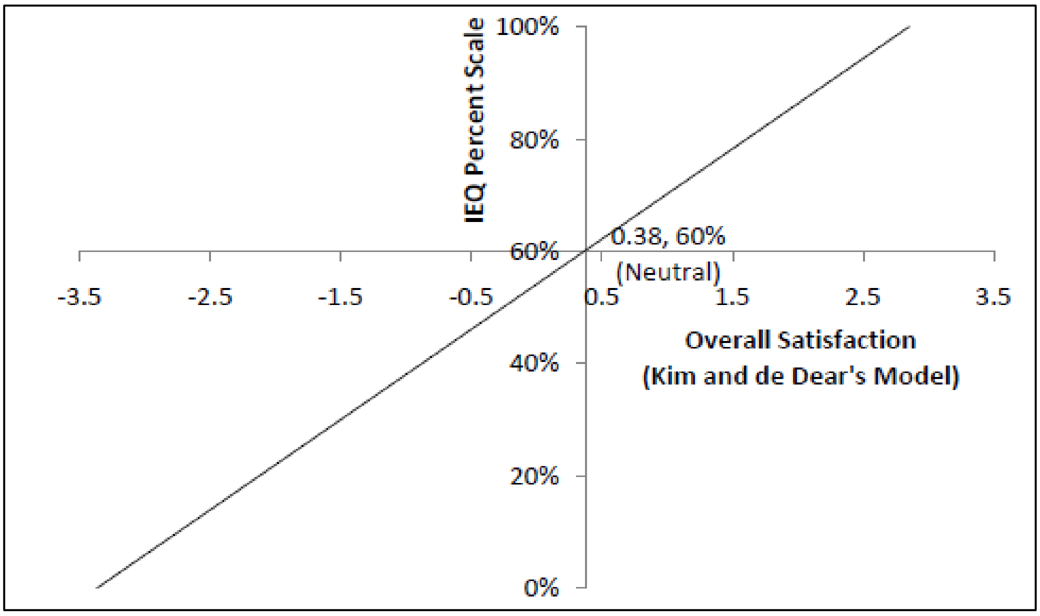
$$IS_{im} = \alpha_0 + \sum_{j=1}^{J=15} \alpha_{imj} \qquad (1)$$

Table 5. Regression coefficients for each of the 15 IEQ factors (adapted from reference [60])

Constant α_0 (Neutral) = 0.38		**α_{imj}(to be selected from below)**	
(j)	**IEQ Factor**	**Satisfied group** α_j^1	**Dissatisfied group** α_j^2
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	

For 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 72 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.

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



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.

$$IS_i = \frac{\sum_{m=1}^{M_i} PIS_{im}}{M_i} \qquad (3)$$

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. [73], the relating level of percent productive time per employee is estimated using Equation 4.

$$PPT_{im} = (0.39 \times PIS_{im} + 0.01 \times l_{im} + 0.49) \times 100\% \qquad (4)$$

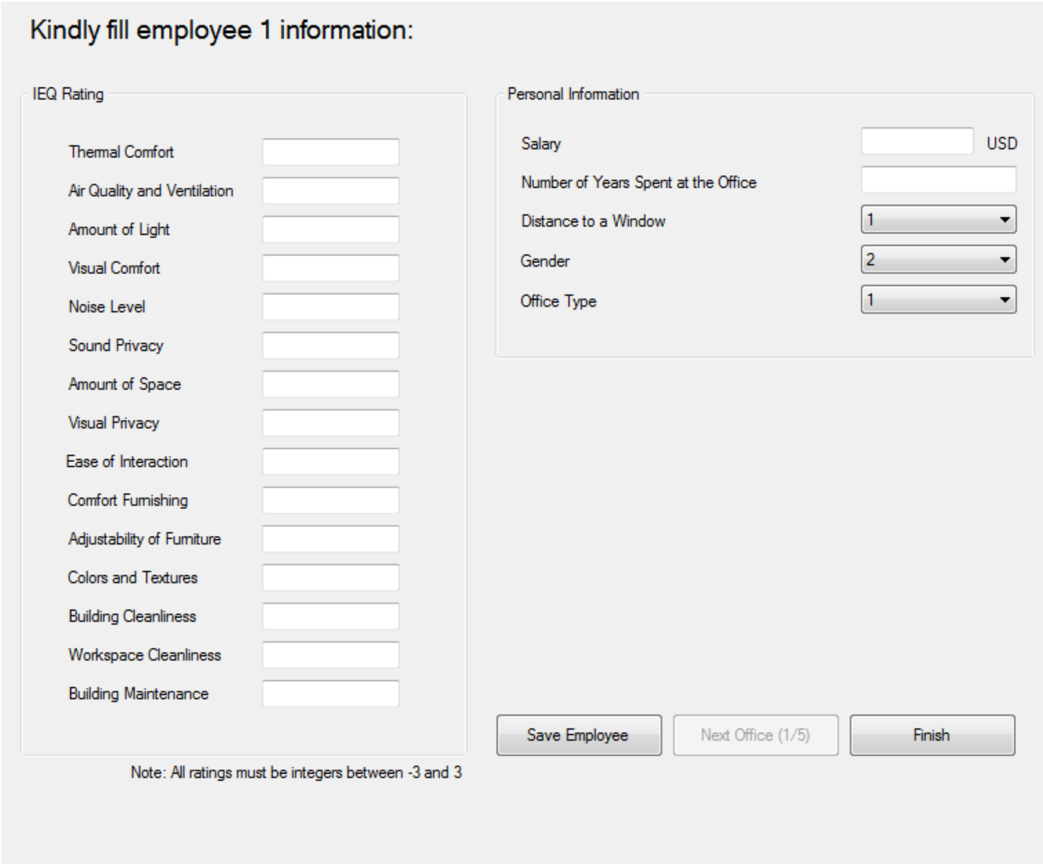
A crucial point to consider is that employees of a certain office contribute differently towards the overall productivity of the office they are occupying. Their quality and importance of produced work can vary along the vertical hierarchy of employment, such as the level of productivity contribution 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 using Equation 5.

$$PPT_i = \frac{\sum_{m=1}^{M_i}(s_{im} \times PPT_{im})}{\sum_{m=1}^{M_i} s_{im}} \qquad (5)$$

2. *Data Input Tool*

The program at hand is designed to be as user friendly as it can be. Thus, a visual basic code was established to create a "Window Form Application". The latter asks the user to input the employees' rating for each of the 15 IEQ factor for all offices. In addition, it requires the user to fill in the salary, longevity, gender, the employee's distance to a window and office type. The collected data will be exported into an excel file and then imported by MATLAB.

The figure below shows the design of the “Window Form Application” used for entering IEQ rating.



B. Defining Possible Retrofit Options

This section explains the process and mathematical equations used to define the possible retrofit options, the affected offices and IEQ factors by each renovation process. It also presents the tool used to input the required data.

1. Mathematical Model

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 H_{imk} indicating that retrofit option *k* is expected to enhance in office *i* IEQ factor *j*.

For 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. If only three offices out of the whole organization are considered for retrofit, the binary matrices shown in Tables 6 and 7 should be defined.

Table 6 Matrix M: Retrofit Option *k* influences Offices *i* (for illustration)

M		Office *i*		
Retrofit Option *k*		**1**	**2**	**3**
	1	1	1	
	2	1	1	1
	3			1

Table 7Matrix N: IEQ factors *j* influenced by Retrofit Option *k* (for illustration)

N		IEQ Factor *j*														
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							

Table 8expresses Matrix H_{imk} that defines for every office *i* the IEQ factors *j* affected by Retrofit Option k. Matrix *H* is deduced from Matrices *M* and *N* by the expression$H_{imk} = M_{im} \times N_{km}$.

It is important to note that some renovation 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 6is used to ensure that the cost of the selected options for retrofit does not exceed the available budget *B*.

$$\sum_{k=1}^{K}(X_k \times C_k) \leq B \qquad (6)$$

Table 8 Retrofit influence binary variable (for illustration)

H_{ijk}																
Office 1	IEQ Factor *j*															
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 *j*															
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 *j*															
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 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 of 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 *j* 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 $H_{ijk}$by X_k, 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$H_{ij}^{'}$. The mathematical expression for calculating $H_{ij}^{'}$is described by Equation 7.

$$H_{ij}^{'} \leq \sum_{k=1}^{K} X_k \times H_{ijk} \leq 1 \qquad (7)$$

Working with the previous hypothetical example of three retrofit options, and if 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 9, since its related decision variable by which it will be multiplied is zero. Also, in the third office, both retrofit options 1 and 3 were selected, but the final $H_{3\text{k}}^{'}$ eliminated the redundancy of effect in IEQ factors 1 and 5. The resulting values of$H_{\text{ik}}^{'}$ are described in Table 10.

Table 9Retrofit influence binary variable for a feasible solution build-up (for illustration)

H_{ikm}																
Office 1	IEQ Factor *j*															
Retrofit Option k		**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**
	1	1	1			1										
	~~**2**~~	~~1~~			~~1~~								~~1~~			
	3															
$H_{1k}^{'}$		1	1			1										
Office 2	IEQ Factor *j*															

		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**
Retrofit Option k	**1**	1	1			1										
	~~**2**~~	~~1~~			~~1~~								~~1~~			
	3															
H'_{2k}		1	1			1										
Office 3	IEQ Factor j															
		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**
Retrofit Option k	**1**	1	1			1										
	~~**2**~~	~~1~~			~~1~~								~~1~~			
	3	1				1	1		1							
H'_{3k}		1				1	1		1							

Table 10Retrofit influence binary variable for a feasible solution (for illustration)

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

2. *Data Input Tool*

As mentioned before, this tool is made to be user friendly. Therefore, another “Window Form Application” was coded using Visual Basic to collect data regarding the renovation suggestions and their effects on offices and IEQ. The Application will ask the user to enter the name and the corresponding cost of a retrofit option, along with the expected IEQ factors and offices to be affected if this option was implemented. In addition, this Application proposes 12 renovation processes that were found through the literature, along with the affected IEQ factors by each retrofit option.

The figure below shows the design of the “Window Form Application” used for entering IEQ rating.

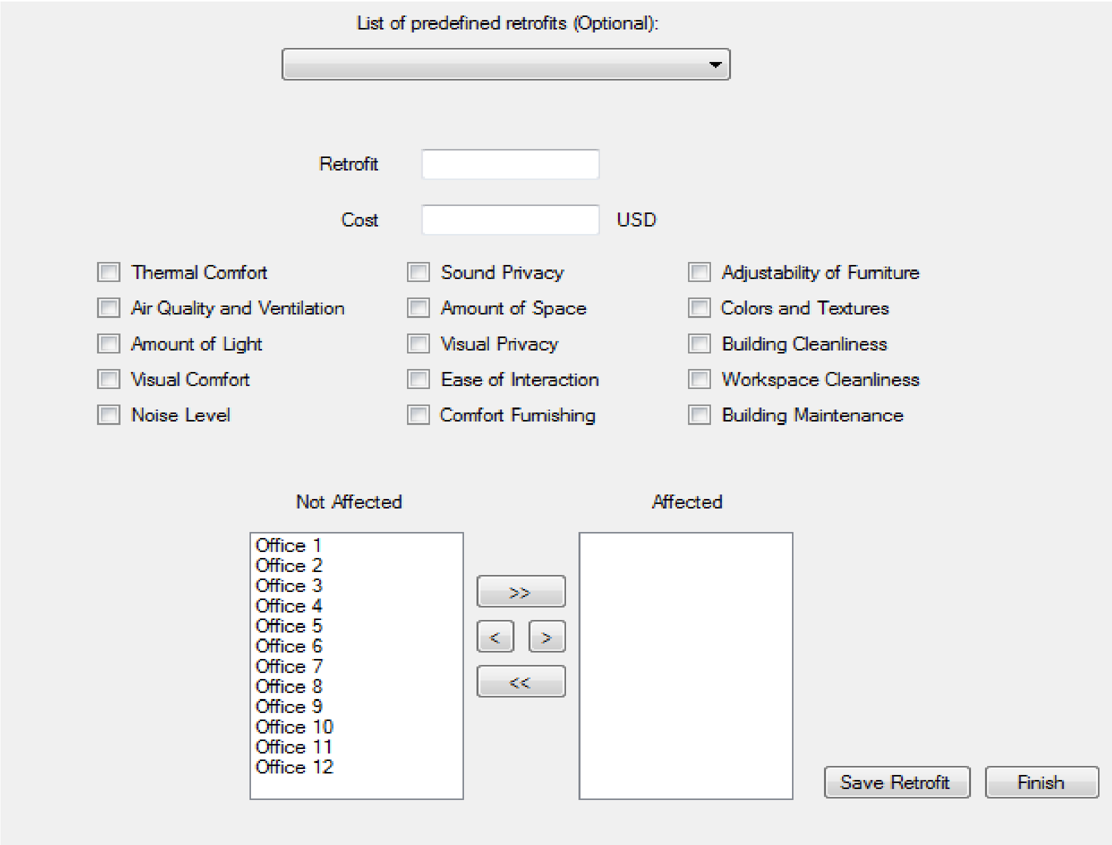


Table 11 represents the list of predefined retrofit options along with the affected IEQ factors that were introduced into the application.

Paper	Renovation Process	IEQ Factors Affected	Notes
Zagreus et al. (2004) [94]	Installing Operable Windows	Thermal Comfort, Air Quality and Ventilation, Adjustability of Furniture	This option is considered a replacement for HVAC systems
Atzeri et al. (2016) [95]	Increasing window to wall ratio+ roller shades + glazing	Thermal Comfort, Visual Comfort, Amount of Light	
Du et al. (2015) [96]	Insulating the Building (including previous windows/balcony doors replacement and maintenance)	Thermal Comfort, Noise Level, Air Quality and Ventilation	
Du et al. (2015) [96]	Installing CO_2 sensors or CO_2 monitors in all densely occupied spaces	Air Quality and Ventilation	
USGB Council [97]	Establishing lighting Control with 3 levels (30 – 70 – 100%)	Amount of Light	
USGB Council [97]	Installing LED lights	Visual Comfort	
Kim et al. [98]	Installing Air humidifier	Air Quality and Ventilation, Thermal Comfort	
Freihoefer et al. [99]	Using ceiling tiles and wall panels with high NRC (Noise Reduction Coefficient)	Sound Privacy, Noise Level	
West et al. [100]	Installing thermostats and humidistats to control temperature and humidity	Thermal Comfort, Air Quality and Ventilation	

Godish (2016) [101]	Sealing cracks in walls, adding physical barriers to pest entry and movement (e.g., Using screens)	Building cleanliness, Workspace cleanliness	
Lee et al. (2009) [102]	Repair surface finishes	Comfort furnishing, Colors and textures	

C. The Involved Randomness

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. For every employee *m* 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.

The program as such falls under two scenarios:

- The first is that the retrofit binary variable for a feasible solution H'_{ij} turned out to be 0. Indicating that IEQ *j* was not enhanced in office *i*.
- The second would be the opposite, where the binary variable will be 1, indicating that IEQ factor *j* was enhanced in office *i*.

If the first scenario turns out to be the case, then it is normal to expect that no improvement in IEQ satisfaction with IEQ factor *j* would occur in office *i*. On the other hand, if the second scenario applies, the program then interpolates the results to estimate the total increase in IEQ satisfaction for employees working in office *i*, taking into consideration the difference in IEQ perception between gender, and due to the type of office and the distance of the employee to a window. The program automatically generates unique random function for each subgroup of occupants, with different mean values based on the hierarchy in satisfaction with the indoor environment among these subgroups. In addition, these functions assume that no two employees falling within the same subgroup will have the same IEQ satisfaction; this is because many personal and psychological factors (random variables) interfere in the idea of satisfaction with the workplace indoor environment.

Equations 8 and 9 compute the expected improved level of satisfaction of a certain employee *m* within an office *i*.

$$\left\{\begin{array}{c} if\ \mathrm{H}_{\mathrm{ij}}^{'} = 0,\ MOS_{im} = IS_{im} (8) \\ if\ \mathrm{H}_{\mathrm{ij}}^{'} = 1,\ MOS_{im} = IS_{im} + \sum_{w=1}^{2}\sum_{o=1}^{2}\sum_{g=1}^{2}\sum_{j=1}^{J=15}\left[F_{gow}^{'} \times \left(\alpha_j^1 - \alpha_{imj}\right)\right] \quad (9) \end{array}\right\}$$

Where:

- α_j^1: The impact parameter from the satisfied group of IEQ factor *j* on the overall satisfaction of employees at their workplace (Table 5)
- α_{imj}: The initial level of satisfaction of employee *m* with IEQ factor *j* in office *i* before implementing any renovation process
- $(\alpha_j^1 - \alpha_{imj})$: The difference represents the maximum allowable improvement in IEQ satisfaction after the implementation of a certain renovation process
- $F_{gow}^{'}$: Proportion of net improvement in the satisfaction of employees. The degree of improvement depends on the gender *g* of the employee, the type of office he/she is working in and his/her distance to window *w*. these three factors. The net improvement is assumed to follow a beta distribution over the interval [0,1]

In probability theory and statistics, the beta distribution is a family of continuous probability distributions defined on the interval [0,1] parameterized by two positive shape parameters, denoted by α and β, that appear as exponents of the random variable and control the shape of the distribution. The beta distribution has been applied to model the behavior of random variables limited to intervals of finite length in a wide variety of disciplines. In addition, the beta distribution is always a suitable model for the random behavior of percentages and it is particularly suitable to the statistical modeling of proportions [103]. In this case, the tool will be modeling the proportion of improvement in IEQ satisfaction from the overall allowable enhancement.

- IS_{im}: The initial satisfaction of employee *m* with the workplace at office i
- MOS_{im}: The maximized overall satisfaction of employee *m* with the workplace at office i

The two positive shape parameters, α and β of the beta distribution can be calculated using the mean and variance of the function at hand. As mentioned earlier, the mean depends on the profile to which the employee belongs (gender, office type and distance to a window). A literature review was conducted to collect the mean level of satisfaction based on these three factors. Table 11 summarizes the mean values of satisfaction based on these factors.

Table 11Mean values of satisfaction with indoor environmental parameters and building features assessed in the CBE occupant satisfaction survey in different office types and different distances from a window and based on gender [81,59]

IEQ Factor	Close to a window	Far away from a window	Female	Male	Single Offices	Shared Offices
Temperature	-0.07	-0.34	-0.37	0.18	0.18	0.04
Air Quality	0.43	0.11	0.10	0.53	0.55	0.32
Amount of Light	1.43	0.90	1.28	1.43	1.66	1.41
Visual Comfort	1.01	0.64	0.86	1.06	1.21	1.02
Noise Level	0.27	-0.13	0.14	0.29	0.95	0.63
Sound Privacy	-0.69	-1.10	-0.89	-0.53	0.63	-0.49
Amount of Space	1.06	0.62	0.93	1.04	1.62	0.81
Visual privacy	0.67	0.10	0.50	0.68	1.97	0.32
Ease of Interaction	1.40	1.09	1.30	1.43	1.67	1.37
Comfort of Furnishing	1.14	0.88	1.02	1.13	1.34	0.99
Furniture Adjustability	0.89	0.65	0.76	0.91	1.00	0.79
Colors and textures	0.90	0.66	0.73	0.86	0.94	0.70
Building Cleanliness	1.03	0.97	0.97	1.17	1.21	1.05
Workspace Cleanliness	0.88	0.79	0.76	1.09	1.02	0.94
Building Maintenance	0.96	0.90	0.93	1.03	1.02	1.02
Sample Size	27175	14638	21452	16805	11381	2759

As mentioned before, each group of occupants will be associated with a unique level of satisfaction describing the profile to which they belong (Gender, Office type, Distance to a window). The rule of combined arithmetic mean allows merging the means of different samples into a single combined mean. Given that all the available data in table 11, were collected using the same CBE survey, the only statistical assumption needed to use the combined mean theory is fulfilled; If all the groups are merely sub-samples of a single group or data set (CBE survey) and combining them merely restores them back into the original single group the combined arithmetic mean equation is applicable [105].

The combined mean formula is given by equation 10:

$$\mu = \frac{\sum_{i=1}^{k} x_i \times n_i}{\sum_{i=1}^{k} n_i} \quad (10)$$

Where:

μ: Combined arithmetic mean

x_i: Sample mean of group *i*

n_i: Sample size of group *i*

Table 12 below represents the combined mean level of satisfaction for 6 different profiles of occupants.

Table 12 Combined arithmetic means describing the different occupants' profiles

IEQ Factor	Close, Female, Single.	Close, Male, Single.	Close, Female, Shared.	Close, Male, Shared.	Far, Female, Single.	Far, Female, Shared.	Far, Male, Single.	Far, Male, Shared.
Temperature	-0.13	0.06	-0.19	0.03	-0.23	-0.33	0.00	-0.05
Air Quality	0.33	0.49	0.29	0.46	0.21	0.12	0.39	0.33
Amount of Light	1.42	1.48	1.37	1.43	1.25	1.15	1.31	1.20
Visual Comfort	0.99	1.07	0.95	1.03	0.88	0.79	0.96	0.88
Noise Level	0.35	0.42	0.24	0.30	0.25	0.07	0.32	0.14
Sound Privacy	-0.51	-0.37	-0.76	-0.62	-0.59	-0.94	-0.42	-0.77
Amount of Space	1.12	1.17	0.99	1.04	1.00	0.80	1.05	0.84
Visual privacy	0.86	0.94	0.58	0.65	0.73	0.34	0.82	0.40
Ease of Interaction	1.42	1.46	1.36	1.41	1.32	1.23	1.38	1.28

Comfort of Furnishing	1.14	1.18	1.08	1.13	1.05	0.97	1.10	1.01
Furniture Adjustability	0.86	0.92	0.83	0.89	0.78	0.72	0.85	0.79
Colors and textures	0.85	0.90	0.82	0.87	0.76	0.70	0.81	0.76
Building Cleanliness	1.04	1.11	1.01	1.08	1.03	0.98	1.11	1.07
Workspace Cleanliness	0.86	0.97	0.83	0.96	0.83	0.78	0.97	0.95
Building Maintenance	0.96	0.99	0.95	0.99	0.94	0.93	0.98	0.97

The CBE survey uses a scale of -3 (very dissatisfied) to +3 (very satisfied) to report the level of satisfaction of an occupant with the IEQ conditions. Thus, the combined means level of satisfaction calculated in table 12 will be adjusted from the CBE scale [-3, +3] to the [0, 1]; the same scale that would fit the aforementioned beta distributions.

Table 13 shows the rescaled combined arithmetic means.

Table 13 Rescaled combined arithmetic means

IEQ Factor	Close, Female, Single.	Close, Male, Single.	Close, Female, Shared.	Close, Male, Shared.	Far, Female, Single.	Far, Female, Shared.	Far, Male, Single.	Far, Male, Shared.
Temperature	0.48	0.51	0.47	0.50	0.46	0.45	0.50	0.49
Air Quality	0.56	0.58	0.55	0.58	0.54	0.52	0.57	0.56
Amount of Light	0.74	0.75	0.73	0.74	0.71	0.69	0.72	0.70
Visual Comfort	0.67	0.68	0.66	0.67	0.65	0.63	0.66	0.65
Noise Level	0.56	0.57	0.54	0.55	0.54	0.51	0.55	0.52
Sound Privacy	0.41	0.44	0.37	0.40	0.40	0.34	0.43	0.37
Amount of Space	0.69	0.69	0.67	0.67	0.67	0.63	0.68	0.64
Visual privacy	0.64	0.66	0.60	0.61	0.62	0.56	0.64	0.57
Ease of Interaction	0.74	0.74	0.73	0.73	0.72	0.70	0.73	0.71
Comfort of Furnishing	0.69	0.70	0.68	0.69	0.68	0.66	0.68	0.67
Furniture Adjustability	0.64	0.65	0.64	0.65	0.63	0.62	0.64	0.63
Colors and textures	0.64	0.65	0.64	0.65	0.63	0.62	0.64	0.63
Building Cleanliness	0.67	0.68	0.67	0.68	0.67	0.66	0.69	0.68
Workspace Cleanliness	0.64	0.66	0.64	0.66	0.64	0.63	0.66	0.66
Building Maintenance	0.66	0.67	0.66	0.66	0.66	0.65	0.66	0.66

On the other hand, the standard deviation will be assumed to be 0.05 for all of the 6 profiles, so that no over randomness would be involved in one group's response over the other. The small value of standard deviation would be attributed to the fact that the sample sizes of the diverse groups are considered large which would reduce the variability among the data. The size (n) of a statistical sample affects the standard error for that sample. Because n is in the denominator of the standard error formula, the standard error decreases as n increases. It makes sense that having more data gives less variation and more precision in the results.

Now, the shape parameters α and β of the beta distributions can be calculated using the following two equations 11 and 12:

$$\alpha = \left(\frac{1-\mu}{\sigma^2} - \frac{1}{\mu}\right) \times \mu^2 \quad (11)$$

$$\beta = \alpha \times \left(\frac{1}{\mu} - 1\right) \quad (12)$$

Where,

α, β: The two shape parameters of a beta distribution

μ: The arithmetic mean

σ: The standard deviation

D. Searching for the Optimal Solution

Now that the maximized overall satisfaction per employee MOS_{im} is calculated, the program will continue in an equivalent way to what was explained in section 4.2.

The expected percent overall satisfaction per employee and the average level of expected overall satisfaction per office are computed using equations 13 and 14, respectively.

$$MPOS_{im} = \left(\frac{MOS_{im} - (-3.37)}{2.85 - (-3.37)}\right) \times 100\% \quad (13)$$

$$MOS_i = \frac{\sum_{m=1}^{M_i} MPOS_{im}}{M} \quad (14)$$

The expected percent productive time for employee *m* of office *i* is computed for every feasible solution using Equation 15.

$$MPPT_{im} = (0.39 \times MPOS_{im} + 0.01 \times l_{im} + 0.49) \times 100\% \quad (15)$$

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 16.

$$MPPT_i = \frac{\sum_{m=1}^{M_i} S_{im} \times MPPT_{im}}{\sum_{m=1}^{M} S_{im}} \quad (16)$$

E. 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.

- As stated previously, those who perform more are rewarded more, and vice 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 17.

$$CF_i = \frac{\sum_{m=1}^{M_i} S_{im}}{S} \quad (17)$$

- 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 82 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.

- 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 18.

$$Maximize \quad OPPT = \sum_{i=1}^{I} CF_i \times (MPPT_i - \ PPT_i) \quad (18)$$

CHAPTER V

GENETIC ALGORITHM TESTING AND VALIDATION

Testing, validation and verification of optimization models is considered a challenging task. The challenge resides in the idea that the true optimal solution remains unknown. Sometimes the goal of an optimization is to find the global minimum or maximum of a function—a point where the function value is smaller or larger at any other point in the search space. However, optimization algorithms sometimes return a local minimum—a point where the function value is smaller than values at nearby points, but possibly greater than values at a distant point in the search space. The genetic algorithm can sometimes overcome this deficiency with the right settings. However, this is suitable for cases with a small amount of decision variables; when the scale of the problem increases spotting the optimal solution becomes even harder.

Nevertheless, it is recommended to test the validity of the genetic algorithm and its generated solutions using a small-scale problem. These problems will allow the tester to enumerate all the solutions and identify whether the GA is working properly, before testing the algorithm on large scale problems. For this purpose, a small case problem was suggested. This case will be used to assess:

- The “Renovation” function in the program.
- The point at which GA fails to reach the global optimum under the default settings in MATLAB.
- The cost constraint.

Problem Formulation:

- Number of offices = 5
- Number of employees in each office = 4

- Number of renovation options = 6
- Available budget for renovation = 16000$
- The costs of the assumed retrofit options were as follow:

Retrofit Option	1	2	3	4	5	6
Costs	6000$	8000$	7000$	4000$	5000$	4000$

- The effects of each retrofit on each of the 15 IEQ factors and 5 offices were clearly identified, for example: Retrofit option 1 (replacing old HVAC systems) will be affecting thermal comfort, indoor air quality and building maintenance, in all offices.

- The IEQ perception was assumed to be similar with no variation within and between the different occupants group. This was done to be able to identify a unique optimal solution without any randomness involved in the optimization process. Since variability and randomness was eliminated, the "Monte Carlo" simulation part was disregarded, and the fitness function becomes the "Renovation" function. However, it is worth noting that in a real case scenario randomness is essential to capture the difference in IEQ perception among different group of occupants.

Having 6 renovation options establishes 6 binary decision variables (whether to accept or reject the option). The overall number of binary combinations available for investigation is $2^6 = 64$ options. A simple code was implemented to enumerate all the solutions, their corresponding increase in productivity and costs. The results showed that the GA was able to spot the global optimum and its corresponding decision variables under the default options of the GA in MATLAB. As the number of renovation options increases (i.e. the combination of available retrofit options), the GA kept on identifying the global optimum until it reached 12 decision variables (a total of 4096 combinations). At that point, the GA optimal solution reached a score that is

1.15% less than the global optimum. To check whether the GA is abiding by the cost constraint, the costs of all the retrofit options were set to be higher than the available budget for renovation. GA’s optimal solution in that case was not to go with any of the options.

CHAPTER VI

CASE STUDY

Learning about the recently completed renovation project that took place at one of the old buildings 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 building is medium sized consisting of five stories; the first two floors are used for miscellaneous tasks and jobs with no offices, while the three remaining upper floors consist of 48 offices. These occupants in accordance with their offices form the necessary population to assess the effectiveness of the tool under study and draw a conclusion on the improvement of IEQ satisfaction among different profiles of occupants (gender, type of office and distance to a window) considering a renovation project. The questionnaire survey presented in Appendix-I was distributed over the different occupants of the 48 offices. The response rate was 66.67%, with 34 occupants' responses from a pool of 51 employees. The distribution of the offices over the three floors, their characteristics and the description of the 34 occupants sample are presented in Table 7.

The main reasons behind the renovation project were the fact that the building was built more than 60 years ago, and with the degrading conditions of the indoor environment, occupants' complaints are increasing notably: humidity, dust, poor lighting, poor HVAC systems, no temperature control, and water leaks, etc. Occupants' complaints and spotted problems prior to renovation are listed in Table 8.

In Table 9 presents 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 selected and implemented in the renovation project, and the options that should have been selected as optimized by the proposed optimization program. Painting is considered a doubtless retrofit option, thus the cost associated with painting was subtracted from the total budget available for renovation. In addition, the effect of painting on IEQ was taken into consideration while searching for the optimal solution. All offices were affected by this retrofit option, given that the whole building was repainted internally. The total budget allocated to the renovation project was 1,100,000 USD.

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 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 then optimizes 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 10.

Table 14 Employees characteristcis and their distibution over the offices

Floor	Office Ref. #	Number of employees	Employee's Gender	Shared/ Single	Distance to a Window
Third Floor	1	1	Female	Shared	$> 4.6\,m$
	2	4	Male	Shared	$> 4.6\,m$
			Female		$< 4.6\,m$
			Female		$> 4.6\,m$
			Female		$< 4.6\,m$
	3	1	Female	Shared	$< 4.6\,m$
	4	1	Female	Shared	$> 4.6\,m$
	5	1	Male	Single	$< 4.6\,m$
	6	1	Male	Single	$< 4.6\,m$
	7	1	Female	Shared	$> 4.6\,m$
	8	1	Male	Single	$< 4.6\,m$
	9	1	Female	Single	$< 4.6\,m$
	10	1	Male	Shared	$> 4.6\,m$
	11	1	Male	Single	$< 4.6\,m$
	12	1	Female	Shared	$> 4.6\,m$
	13	1	Male	Single	$< 4.6\,m$
	14	1	Male	Single	$< 4.6\,m$
	15	1	Female	Single	$< 4.6\,m$
Fourth Floor	16	1	Male	Single	$< 4.6\,m$
	17	1	Male	Single	$< 4.6\,m$
	18	1	Male	Single	$< 4.6\,m$
	19	1	Female	Single	$< 4.6\,m$
	20	1	Male	Single	$< 4.6\,m$
Fifth Floor	21	1	Male	Single	$< 4.6\,m$
	22	1	Male	Single	$< 4.6\,m$
	23	1	Male	Single	$< 4.6\,m$
	24	1	Male	Single	$< 4.6\,m$
	25	1	Male	Single	$< 4.6\,m$
	26	1	Male	Single	$< 4.6\,m$
	27	1	Male	Single	$< 4.6\,m$
	28	1	Male	Single	$< 4.6\,m$
	29	1	Male	Single	$< 4.6\,m$
	30	1	Male	Single	$< 4.6\,m$
	31	1	Male	Single	$< 4.6\,m$

Note: Some offices are considered shared although there is only one employee in that office. These offices should not be locked, and anyone is allowed to enter whenever they want, thus they were assumed to be shared rather than single units.

Table 15 Spotted problems in need for retrofit

Problem Ref. #	Spotted Problem	Description of problem	Location
1	Lack of temperature control	All occupants did not have control over the temperature in their offices	All offices of allthree floors
2	Central heating system	Noisy central heating system to most occupants. Considered very old. High occupants complaints	Offices of the 4th and 5th floors
3	Lighting	Poor Luminance	Shared offices of the 3rd floor
4	Lighting	Mostly incandescent lights; high electricity costs	All offices of all three floors
5	Day lighting	Poor day lighting; occupants complaining about feeling nausea and dizzy all day long	Shared offices of the 3rd floor and offices of the 4th and 5th floors
6	Furnishings	Old furnishing that need replacement	All offices of all three floors
7	Furnishings	Wall paint in very poor conditions due to humidity and water leaks	All offices of all three floors
8	Space	Limited Workspace in some offices	West side of the 3rd floor, 4th and 5th floors
9	Maintenance	Water leaks	Bathrooms and kitchens of all three floors
10	Air quality	High occupants complaints	Offices of the 3rd floor
11	Lack of Conference rooms	No conference rooms for employees to set up weekly and monthly meetings	Offices of the 4th and 5th floors
12	Thin walls	Occupants feel that their conversations on the phone and within their offices can be heard by their co-workers in nearby offices	All offices of all three floors

Table 16 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	Repair the central heating HVAC system	80,000		✘
2	Include humidifiers in offices with high humidity levels	10,000		✘
3	Install fan coil thermostats in all offices to allow for temperature control	11,000	✓	✘
4	Increase the area of all offices	50,000	✓	✘
5	Installing VRV HVAC system with slot diffusers for offices of the 3rd floor	50,000	✓	
6	Installing VRV HVAC system with slot diffusers for offices of the 4th floor	35,000	✓	
7	Installing VRV HVAC system with slot diffusers for offices of the 5th floor	35,000	✓	
8	Replace existing lighting with LED equivalents for all offices in all floors	47,000	✓	✘
9	Use ceiling tiles and wall panels with high NRC (Noise Reduction Coefficient)	80,000		✘
10	Insulate the building by installing fiberglass insulation in the walls and the ceiling	90,000		
11	Renew all personal computers in all offices	32,000		✘
12	Replace old furnishing in all offices	150,000	✓	
13	Transform open-space offices on the third floor into single offices for more privacy and sound control	30,000		✘
14	Fix water leaks (Repair bathrooms and kitchens)	20,000	✓	✘
15	Separate all single offices with gypsum boards filled with high density rock wool to reduce sound dissipation	100,000	✓	
16	Build two conference rooms on the fourth floor	16,000	✓	✘
17	Build two conference rooms on the fifth floor	16,000	✓	
18	Install sunscreen glass for windows of all offices	20,000	✓	
19	Install new tiling for all floors	390,000	✓	✘
20	Apply privacy films on glass doors of single offices	12,000	✓	✘
21	Replace wooden doors with glass doors to allow for maximum daylight sharing	55,000	✓	✘
22	Establish lighting control with 3 levels (30% – 70% – 100%)	35,000		✘
23	Increase windows' area by 1.5 m^2	50,000		✘
24	Installing green roof on top of the building to reduce heating	45,000		

Table 17 Implemented vs. optimized renovation outcomes (IEQ satisfaction and productive time)

Offices and employees affected by renovation			**Expected IEQ Satisfaction**		**Expected Increase in Productive Time**	
Floor	Office Ref. #	Employee Ref. #	Implemented Renovation	Proposed Opt. Renovation	Implemented Renovation	Proposed Opt. Renovation
Third Floor	1	1	80%	82%	4.6%	5.3%
	2	2	63%	64%	7.1%	6.6%
		3	68%	74%	6.1%	8.3%
		4	45%	52%	6.6%	10.0%
		5	45%	51%	6.4%	8.8%
	3	6	79%	81%	7.1%	7.8%
	4	7	75%	77%	3.5%	4.6%
	5	8	89%	92%	3.9%	5.4%
	6	9	83%	86%	3.3%	4.7%
	7	10	64%	69%	3.8%	5.8%
	8	11	83%	85%	10.4%	10.9%
	9	12	61%	66%	5.8%	7.5%
	10	13	81%	82%	3.3%	3.9%
	11	14	79%	82%	6.0%	7.2%
	12	15	55%	62%	3.9%	6.3%
	13	16	89%	91%	5.1%	6.1%
	14	17	83%	83%	6.8%	7.3%
	15	18	78%	81%	7.1%	8.2%
Fourth Floor	16	19	82%	84%	9.4%	10.3%
	17	20	74%	79%	11.2%	13.5%
	18	21	75%	77%	14.9%	16.5%
	19	22	82%	84%	10.2%	10.6%
	20	23	81%	86%	5.2%	7.3%
Fifth Floor	21	24	82%	88%	3.9%	6.2%
	22	25	81%	87%	7.2%	8.9%
	23	26	91%	93%	4.3%	4.7%
	24	27	73%	74%	18.6%	19.0%
	25	28	91%	91%	7.3%	6.9%
	26	29	77%	83%	8.7%	10.3%
	27	30	90%	90%	9.4%	8.9%
	28	31`	69%	75%	14.4%	17.1%
	29	32	95%	97%	1.1%	2.0%
	30	33	79%	84%	9.2%	11.8%
	31	34	84%	86%	9.5%	10.5%
			Total increase in productive time for the organization as whole		7.2 %	8.5%
			Cost of renovation (selected retrofit options)		$1087000	$938000

A. Comparison Between Actual and Expected Level of Satisfaction

To assess the level of success of the proposed tool, this section will present a comparison between the level of employees' satisfaction with the IEQ conditions after renovation (collected through the survey, "After Renovation") and the anticipated level of satisfaction calculated by the tool based on the actual renovation. A paired t-test was conducting to assess the percentage level of satisfaction of the 34 employees using R.

The process of this t-test is as follow:

- The null and the alternative hypotheses are defined:

$$H_0\text{: }The\ data\ of\ the\ two\ samples\ are\ identical$$

$$H_a\text{: }The\ data\ of\ the\ two\ samples\ are\ not\ identical$$

- The acceptable type I error (α) is assumed to be 0.1. The alpha level is the probability of rejecting the null hypothesis when the null hypothesis is true.

- The rejection region of the test statistic under the null hypothesis is identified.

- The test statistic using the observed data is calculated using R.

- Reject the null if the observed statistic is inside the rejection region.
- Fail to reject the null hypothesis if the observed statistic is outside the rejection region.

In this type of t-test comparing the means of two independent samples, the following assumptions should be met:

- Each of the two populations being compared should follow a normal distribution. This can be tested using a normality test, such as the Shapiro–Wilk test in R.
- The two samples being compared should have the same variance. This can be tested using a simple F-test or a Bartlett's test in R. [106]

The degree of satisfaction before renovation was collected through the survey, fed to the program and the expected percentage level of satisfaction per employee after the actual renovation is calculated. On the other hand, the true degree of satisfaction after renovation of each occupant is reported through the survey. The actual percentage of satisfaction is calculated using equations (1) and (2) as discussed in section 4. These percentages (actual and expected) are compared to assess the mathematical model presented before. The assumptions of the t-test were verified, and the test statistic value was -1.1348with a *p* value of 0.2647. The results suggest that the data do not provide enough evidence to reject the null hypothesis at the 0.1confidence level and as such it can be concluded that the program was able to predict the level of satisfaction of the employees after renovation

Table 18 Comparison between tool and survey's results

Floor	Office Ref. #	Employee Ref. #	Actual Level of Satisfaction (Survey)	Expected Level of Satisfaction (Tool)	Difference (Actual - Expected)
Third Floor	1	1	82	80	2
	2	2	61	63	-2
		3	74	68	6
		4	49	45	4
		5	50	45	5
	3	6	74	79	-5
	4	7	79	75	4
	5	8	86	89	-3
	6	9	83	83	0
	7	10	73	64	9
	8	11	80	83	-3
	9	12	66	61	5
	10	13	85	81	4
	11	14	80	79	1
	12	15	60	55	5
	13	16	87	89	-2
	14	17	85	83	2
	15	18	76	78	-2
Fourth Floor	16	19	79	82	-3
	17	20	75	74	1
	18	21	74	75	-1
	19	22	83	82	1
	20	23	80	81	-1
Fifth Floor	21	24	85	82	3
	22	25	90	81	9
	23	26	92	91	1
	24	27	61	70	-9
	25	28	88	91	-3
	26	29	75	77	-2
	27	30	84	89	-5
	28	31`	67	69	-2
	29	32	94	95	-1
	30	33	80	79	1
	31	34	93	84	9

B. Discussion

Referring to Table 9, the optimum solution generated by the tool entailed repairing the existing HVAC system instead of installing a VRV HVAC system with diffuser on the said three floors. The option of repairing the HVAC system generated by the tool, affects the indoor air quality on the three floors, whereas the option of installing a VRV

HVAC system would require the user to install it on each floor separately. This implies that it costs the user only $80,000 instead of $120,000. A similar comparison would be the option of separating all offices with gypsum board filled with rocks to reduce sound dissipation, this option was implemented, and it costs $100,000, but it was not included in the optimum solution generated by the tool. On the other hand, the tool proposed to use ceiling tiles and wall panels with high NRC, this option costs only $80,000 and serves the same purpose with regards to sound privacy and noise level IEQ factors. Another option that was proposed by the tool and not actually implemented is transforming open-space offices on the third floor into single offices. It is evident from the literature that open-space offices have negative impacts on the visual and sound privacy and on the noise level. Consequently, if the user chose the option of transforming the open-space offices (as was proposed by the tool) then the IEQ satisfaction with regards to the IEQ factors, within these offices, will increase leading to a boost in their productivity.

Moving on to the option of building the conference rooms on the fourth and fifth floors, the tool recommended to build the conference rooms on the fourth only whereas two conference rooms where built on both floors. Building the two conference rooms would cost $16,000 for each floor, and their influence on IEQ satisfaction is only counted once given that the same people would be affected, thus the tool suggested building the conference rooms on the fourth floor only allowing for the other $16,000 to be invested in other renovation options.

It is critical to note that some IEQ factors are affected by a specific renovation option and thus the tool would be obliged to choose this option to tackle as much IEQ factors as possible which leads to an increase in IEQ satisfaction and thus maximizing productivity improvement. For instance, the amount of space factor can only be enhanced when the option of increasing the area of all offices is implemented; no other renovation options can improve this IEQ factor. Another example would be the building cleanliness factor where the only option that influences it is fixing the water leaks in bathrooms and kitchens. Also, the visual privacy factor is only affected by applying privacy films on glass doors of single offices. As shown in Table 9 all these options were selected by the tool.

Table 10 provides a comparison between the expected proposed and the implemented IEQ satisfaction and increase in productive time. The proposed solution by the program leads to a higher expected IEQ satisfaction and to a greater productive time for every single employee in comparison with the implemented renovation. Nevertheless, the total increase in productive time for the organization is higher by approximately 1.5%, with $150,000 as savings, when the renovation options selected by the tool are implemented.

C. Sensitivity Analysis on Budget

In addition to optimizing the selection of retrofit options to maximize the 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, the lack of performing 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, to avoid spending the entire available budget when the 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.

To perform the mentioned sensitivity analysis on the influence of the budget size on the level of increase in productive time, the user can divide the maximum budget into multiple 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 9, the lowest cost of retrofit option is 10,000USD and the maximum budget is 390,000 USD. The sensitivity analysis problem is incremented by 100,000 USD. Figure 2 plots the outcome, indicating for each budget increment the optimal selection of retrofit options and the expected increase in productive time.

As observed in Figure 2, two plateaus exist; the first at a productivity level of 7.83% approximately and the other one is at a productivity level around 8.5%. The first plateau corresponds to a budget that ranges between 600,000- 800,000 USD. When the budget increased to 900,000 the productivity improvement amplified to 8.5%. This is because a renovation option (installing new tiling) costs around 320,000 USD. The tool preferred not to consider it in favor of other cheap renovation options that would improve the IEQ satisfaction more in comparison to that alternative.

When the budget increased to 900,000 USD the tool was able to afford the cost of installing new tiling which boosted the productivity improvement to 8.5% and initiated the second plateau. This plateau was quite expected; the problem itself will drive the sensitivity towards a plateau. The tool won't be able to find any renovation option that can enhance the productivity any further, given that all offices and all IEQ factors already got improved based on the predefined renovation options and their effects on offices and IEQ.

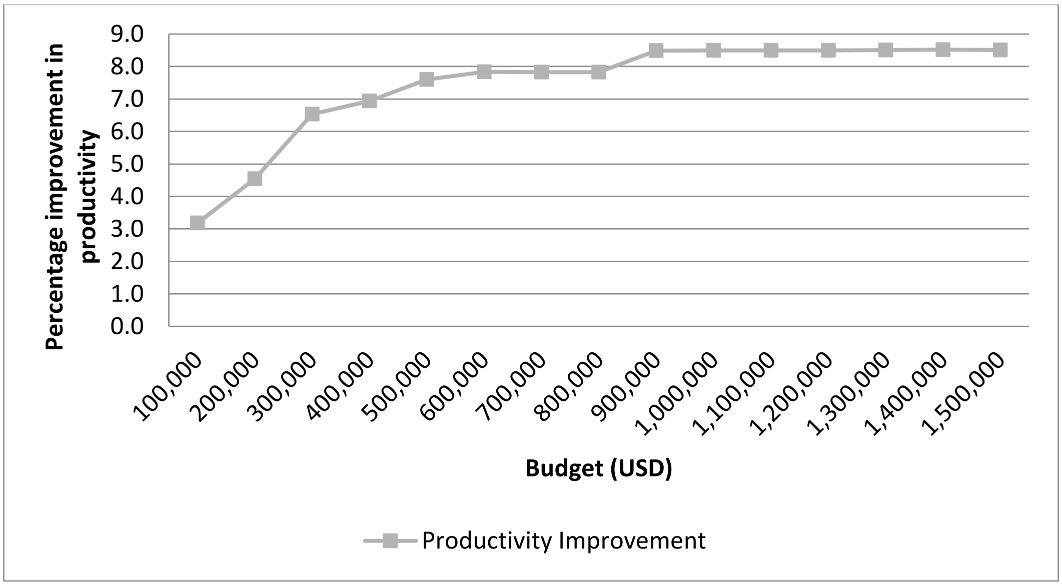


Figure 3 Budget vs. Productive Time sensitivity analysis

D. Sensitivity Analysis on Gender, Type of Office and Distance to a Window

Since the modeling process involves stochastic behavior, it can have a significant impact on the final output. To assess the impact of the three main factors that are contributing to the uncertainty of the model, a sensitivity analysis was performed on the effect of gender, type of the office and the distance to a window resulting in the overall percentage improvement in productivity. Using the optimal solution, the gender composition within the building under study was modified under four different combinations of type of office and distance to the window and the percentage improvement in productivity was reported. Figure 3 graphically represents the outcome of this analysis.

The results suggest the following:

- When fixing the type of office and the distance to a window, the effect of the gender composition is found to be minimal. For instance, in the case where all offices are assumed to be single and all the employees are close to a window, the difference between having a 100% male composition and a 100% female composition is only 0.2% of productivity improvement.
- The negative effect of being in a shared office is equalized by positive effect of being close to a window. This is shown in Figure 3, where the curves B and C are found to be overlapping. Also, the literature shows that satisfaction with the workplace with almost all indoor environmental parameters and as such productivity level was higher in private offices/workstations that are close to a window compared with shared offices/workstations that are far from a window [25], [40]. This explains why curve A; representing a single office and close to a

window is higher than all other curves representing different combinations of type of office and distance to a window.

- The curves display a non-linear trend. Because of the randomness associated with the three factors under study, the percentage improvement in productivity cannot be associated with a specific variation whenever the gender composition changes.
- The productivity improvement is not very sensitive to the three factors (gender, type of office and distance to a window) when compared to the sensitivity reported on budget. The highest variation found based on the sensitivity of these three factors is approximately equal to 0.7%, whereas the variability in the sensitivity of budget is approximately equal to 5.5%.

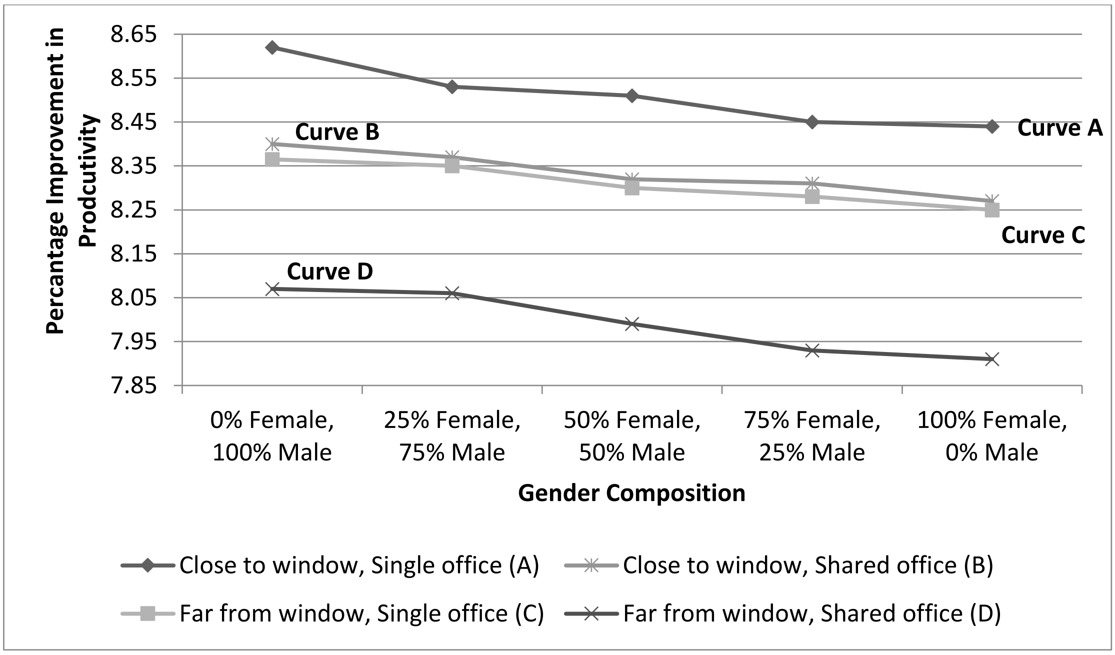


Figure 4 Sensitivity analysis based on gender composition, type of office and distance to a window

CHAPTER VII

CONCLUSIONS

Renovation projects are inevitably the fate of every office building as its occupants' complaints start going high, and their productivity and competitiveness begin to decline. 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 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 sufficing, several other important factors are left out of the decision-making process, rendering such renovation projects as suboptimal. 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 crucial factor behind successful organizations. Only after properly 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 using genetic algorithm, by assessing the expected increase in satisfaction levels and productive time per office, aiming to maximize that increase for the organization while taking into consideration the difference in IEQ satisfaction among the employees. Three numerous factors were taken into consideration (gender, type of office and the distance to a window). A stochastic simulation of the effect of these factors on IEQ satisfaction was introduced into the program to capture their effect on the optimal solution.

When implementing the proposed model on a case study, the results showed that the proposed optimal solution guaranteed a 1.5% higher improvement in productive time with 150,000$ as savings in comparison with the actual implemented solution. Sensitivity analyses were also conducted on four numerous factors: budget, gender, type of office and the distance to a window. The percentage improvement in productivity was found to be very sensitive to budget but was not much affected by the three other factors.

The proposed tool is only a first step towards better optimizing renovation projects based on improved productive time for the organization as a whole. It can be very useful for projects seeking a LEED certification under the category of existing buildings, since it gives the users an idea about the expected level of satisfaction after renovation and the enhanced indoor environmental conditions within the building. However, the study can be further expanded to include the degree of expected enhancement for each suggested renovation option. The paper suggests that one renovation option tackling a certain IEQ component can guarantee the improvement of that factor. Another point to shed light on, is that 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.

CHAPTER VIII

APPENDIX

Table 19 In-house conducted survey questionnaire

Questioned Theme	Question	Before Renovation	After Renovation
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/office?		
	How satisfied are you with general maintenance of the building?		
Longevity	How long have you been working at your currently occupied workplace/office?		

Note: The survey respondents express their satisfaction level with each questionnaire item on the seven point bipolar scale ranging from ‘very dissatisfied’(coded as -3) through ‘neutral’ (coded as 0) to ‘very satisfied’ (coded as +3).

CHAPTER IX

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