SIMULATION-BASED PERFORMANCE AND LIFE-CYCLE COST EVALUATION OF IN-DUCT ULTRAVIOLET GERMICIDAL IRRADIATION SYSTEMS

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by
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ABSTRACT

In-duct ultraviolet germicidal irradiation (UVGI) systems treat moving air streams in heating, ventilation, and air-conditioning (HVAC) systems to inactivate airborne microorganisms. UVGI system performance depends on air temperature, airflow velocity, variations in exposure time and other parameters. These parameters are generally functions of time. There is a lack of investigation in the current literature on the operation of UVGI systems over extended periods to capture the effects of these time-varying parameters. This research investigates a simulation-based evaluation procedure that considers the effect of time-varying parameters on the performance and life-cycle cost of in-duct UVGI systems. The evaluation procedure is applied to a hypothetical commercial building in a parametric study that investigates UVGI systems designed for different design strategies, installation locations, and geographical locations. The results are also compared to those provided by ventilation and filtration.

For the reference case of inactivating S. aureus, UVGI air treatment results in lower predicted space concentrations than those provided by elevated ventilation with respect to ASHRAE Standard 62.1, and similar levels to those achieved by high-efficiency filtration at a lower cost. Cost increases proportionally with performance; therefore, it is very important to ensure the performance target is marginally met for the desired percentage of time to avoid over or under sizing the UVGI system in order to control cost. This design methodology can possibly only be done with a simulation-based evaluation procedure. Uncertainties in modeling assumptions result in uncertainties in the simulated performance and life-cycle cost. Sensitivity analysis provides an insight into the amount of possible variation around the predicted values.

The results of the parametric study suggest that a simulation-based evaluation procedure is an indispensable tool in the design process of UVGI systems. The procedure presented in this research can be further refined and incorporated into design practice in the future.
### TABLE OF CONTENTS

LIST OF FIGURES .................................................................................................................. vii

LIST OF TABLES .................................................................................................................... ix

ACKNOWLEDGEMENTS .......................................................................................................... xi

Chapter 1 Introduction ............................................................................................................. 1

1.1 Distribution and control of airborne pathogens ............................................................... 1
1.2 Background on in-duct UVGI systems .......................................................................... 2
1.3 Incentive for conducting simulation-based evaluation .................................................. 3
1.4 Objectives, approaches and scope ................................................................................. 4

Chapter 2 Literature Review .................................................................................................. 5

2.1 Efficiency of UVGI devices ........................................................................................... 5
   2.1.1 Single-stage inactivation model for UVGI devices .................................................. 5
   2.1.2 UVGI device design and operational parameters .................................................. 7
      2.1.2.1 Lamp level parameters .................................................................................. 8
      2.1.2.2 Device level parameters ............................................................................. 11
2.2 Performance of UVGI systems ...................................................................................... 12
   2.2.1 Absolute performance criteria ............................................................................. 12
      2.2.1.1 Indoor bacteria level .................................................................................. 12
      2.2.1.2 Indoor bacteria generation rate .................................................................. 14
      2.2.1.3 Required reduction in microorganism concentration ................................. 15
   2.2.2 Ventilation and air filtration ................................................................................ 15
      2.2.2.1 Minimum requirement for ventilation and air filtration ......................... 15
      2.2.2.2 Filtration and MERV rating .................................................................... 16
2.3 Life-cycle cost analysis ................................................................................................ 16
   2.3.1 Economic analysis of UVGI .......................................................................... 17
   2.3.2 Potential IAQ benefits ..................................................................................... 18
      2.3.2.1 Relative risk of sickness and ventilation rate ......................................... 19
2.4 Gaps in the existing literature ....................................................................................... 20

Chapter 3 Methodology ......................................................................................................... 22

3.1 Establishing the efficiency of UVGI devices ................................................................. 22
   3.1.1 Whole-building energy simulation ...................................................................... 23
   3.2 Design and off-design dose ..................................................................................... 23
   3.1.3 Design dose and single-pass inactivation efficiency ........................................... 24
   3.1.4 Design strategies ............................................................................................. 25
   3.1.5 Sizing of UVGI device .................................................................................... 26
3.2 Predicting the relative performance of UVGI systems .................................................. 27
   3.2.1 Modeling of space microorganism concentration .............................................. 27
   3.2.2 Relative performance evaluation for UVGI systems ........................................... 28
      3.2.2.1 Comparison of the UVGI system and particulate matter filtration .... 29
REFERENCES

Chapter 7 Results of the Parametric Study of Geographical Locations .................................................. 73

7.1 Characteristics of the UVGI system ............................................................................................................. 73
  7.1.1 Time-varying ambient conditions ............................................................................................................. 74
  7.1.2 Lamp output ........................................................................................................................................... 79
  7.1.3 Design parameters of the UVGI system ................................................................................................. 80

7.2 Performance evaluation ................................................................................................................................. 82
  7.2.1 Inactivation efficiency ............................................................................................................................. 83
  7.2.2 Space microorganism concentration ....................................................................................................... 84

7.3 Life-cycle cost analysis ................................................................................................................................. 88
  7.3.1 Energy consumption and cost ................................................................................................................ 88
  7.3.2 Annualized life-cycle cost ....................................................................................................................... 90
  7.3.3 Potential IAQ benefit ............................................................................................................................. 92

Chapter 8 Discussion .......................................................................................................................................... 95

8.1 Variation in inactivation efficiency ............................................................................................................... 95
  8.1.1 Annual profile of inactivation efficiency ................................................................................................. 96
  8.1.2 Effect on space microorganism concentration ....................................................................................... 97
  8.1.3 Impact on energy consumption and cost ............................................................................................... 97
  8.1.4 Annualized life-cycle cost ..................................................................................................................... 98

8.2 Variation in target microorganism .............................................................................................................. 100
  8.2.1 Inactivation efficiency and space concentration for non-target microorganisms .................................. 100
  8.2.2 UVGI systems designed for other target microorganisms ...................................................................... 102
    8.2.2.1 Impact on energy consumption and cost ......................................................................................... 102
    8.2.2.2 Annualized life-cycle cost ............................................................................................................. 103

8.3 Sensitivity of life-cycle cost to economic assumptions .............................................................................. 104
  8.3.1 Economic parameters of interest ......................................................................................................... 105
  8.3.2 Deterministic analysis ........................................................................................................................... 105
  8.3.3 Probabilistic analysis ............................................................................................................................. 107

Chapter 9 Conclusions and Recommendations ............................................................................................. 110

9.1 Assessment issues with current design practice .......................................................................................... 110
  9.1.1 Time-varying ambient conditions ......................................................................................................... 111
  9.1.2 Performance standard .......................................................................................................................... 111
  9.1.3 Impact on HVAC system ...................................................................................................................... 112

9.2 Conclusions of the parametric studies ...................................................................................................... 113
  9.2.1 Design strategy ....................................................................................................................................... 113
  9.2.2 Installation locations ............................................................................................................................. 114
  9.2.3 Geographical locations ........................................................................................................................ 115

9.3 Recommendations for future research ...................................................................................................... 116
  9.3.1 Integrated software design tool ........................................................................................................... 116

REFERENCES ....................................................................................................................................................... 118
LIST OF FIGURES

Figure 2-1: Lamp output as a function of cold-spot temperature (Philips, 2006).........................8
Figure 2-2: Air velocity dependence of standard and high output lamps (Philips, 2006). ............9
Figure 2-3: Lamp output vs air temperature and velocity for a particular setup (Lau et al. 2009). .................................................................10
Figure 2-4: Typical mercury vapor lamp depreciation (Philips, 2006).................................10
Figure 2-5: Removal efficiency for MERV 6–16 filters (Kowalski and Bahnfleth, 2002). .........16
Figure 3-1: Schematic of HVAC system with dilution ventilation, filtration, and UVGI........28
Figure 3-2: Analogy between UVGI air treatment (a) and equivalent ventilation (b)...........34
Figure 4-1: Typical arrangement of UVGI devices installed at the supply air or mixed air. ......41
Figure 5-1: Air temperature at the studied UVGI device location.........................................48
Figure 5-2: Air velocity at the studied UVGI device location.............................................48
Figure 5-3: Seasonal variation in lamp output .................................................................49
Figure 5-4: Inactivation efficiency, devices designed for average and worst cases. ...............51
Figure 5-5: Duration curves of inactivation efficiency for different design strategies..........52
Figure 5-6: Space concentration for various air treatment scenarios on July 16......................54
Figure 5-7: Space concentration for various air treatment scenarios on January 23. ..............54
Figure 5-8: Space concentration, different design strategies, summer (a), winter (b)..........55
Figure 5-9: Duration curves of space concentration among various air treatment cases........56
Figure 5-10: Duration curves of space concentration among different design strategies........56
Figure 5-11: Duration curves of normalized CADR among different design strategies. .........57
Figure 5-12: Duration curves of relative risk for different design strategies........................61
Figure 6-1: Air temperature at mixed and supply air installation locations..........................64
Figure 6-2: Air velocity at mixed and supply air installation locations.................................64
Figure 6-3: Seasonal variation in lamp output at mixed and supply air installation locations. .....65
Figure 6-4: Inactivation efficiency for devices installed at mixed and supply air locations. ......67
Figure 6-5: Duration curves of $\eta_{\text{UVGI}}$ for devices installed at mixed and supply air locations. .....68
Figure 6-6: Duration curves of space concentration for systems installed at mixed and supply air locations. ................................................................. 68

Figure 6-7: Duration curves of normalized CADR for systems installed at mixed and supply air locations. ................................................................. 69

Figure 6-8: Duration curves of relative risk for systems installed at mixed and supply air locations. ................................................................. 72

Figure 7-1: Supply air temperature for buildings in three geographical locations. ...................... 75

Figure 7-2: Mixed air temperature for buildings in three geographical locations. ...................... 75

Figure 7-3: Air velocity at the supply air for buildings in three geographical locations. ............ 77

Figure 7-4: Duration curves of lamp output at supply air for three geographical locations. ...... 79

Figure 7-5: Duration curves of lamp output at mixed air for three geographical locations....... 80

Figure 7-6: Duration curves of supply air $\eta_{UVGI}$ for three geographical locations ...................... 83

Figure 7-7: Duration curves of mixed $\eta_{UVGI}$ for three geographical locations ...................... 84

Figure 7-8: Duration curves of space concentration for supply air UVGI in three geographical locations ........................................................................ 85

Figure 7-9: Duration curves of space concentration for mixed air UVGI in three geographical locations ........................................................................ 85

Figure 7-10: Duration curves of normalized CADR at supply air for three geographical locations .................................................................................. 86

Figure 7-11: Duration curves of normalized CADR at mixed air for three geographical locations .................................................................................. 86

Figure 7-12: Duration curves of effectiveness at supply air for three geographical locations ...... 87

Figure 7-13: Duration curves of effectiveness at mixed air for three geographical locations ...... 87

Figure 7-14: Duration curves of relative risk at supply air for three geographical locations ....... 93

Figure 7-15: Duration curves of relative risk at mixed air for three geographical locations ...... 94

Figure 8-1: Duration curves of $\eta_{UVGI}$ for systems designed at different $\eta_{UVGI}$ ...................... 96

Figure 8-2: Duration curves of space concentration for systems designed at different $\eta_{UVGI}$ ....... 97

Figure 8-3: Duration curves of $\eta_{UVGI}$ for different target microorganisms .......................... 101

Figure 8-4: Duration curves of space concentration for different target microorganisms ......... 101

Figure 8-5: Cumulative frequency curves of deviation of predicted life-cycle cost .................. 108
**LIST OF TABLES**

Table 2-1: Summary of documented indoor airborne total bacteria count. ........................................... 13

Table 2-2: Documented cost analyses of in-duct UVGI systems. ............................................................ 17

Table 4-1: Parametric studies.................................................................................................................. 42

Table 4-2: Analyses for variation in inactivation efficiency and rate constant. ................................. 44

Table 4-3: Assumed values and sensitivity ranges of economic inputs.................................................. 45

Table 5-1: Design parameters of different design strategies................................................................. 50

Table 5-2: Annual energy consumption and cost for different design strategies................................. 59

Table 5-3: Annualized life-cycle cost for different design strategies....................................................... 60

Table 5-4: Annualized life-cycle cost per unit area for different design strategies............................... 60

Table 5-5: Annual IAQ benefit as a result of lower relative risk for different design strategies............. 62

Table 6-1: Design parameters of devices installed at mixed and supply air locations. .................. 66

Table 6-2: Annual energy consumption and cost of devices installed at mixed and supply air locations. ........................................................................................................................................... 70

Table 6-3: Annualized life-cycle cost of devices installed at mixed and supply air locations.......... 71

Table 6-4: Annualized life-cycle cost per unit area of devices installed at mixed and supply air locations. ........................................................................................................................................... 71

Table 6-5: Annual IAQ benefit as a result of lower relative risk of devices installed at mixed and supply air locations ........................................................................................................................................... 72

Table 7-1: Summary statistics of the supply and mixed air temperature at three geographical locations. ........................................................................................................................................... 74

Table 7-2: Summary statistics of the air velocity at three geographical locations............................ 77

Table 7-3: Design parameters for installations at supply air for three geographical locations...... 81

Table 7-4: Design parameters for installations at mixed air for three geographical locations........ 82

Table 7-5: Annual energy consumption and cost at supply air for three geographical locations.... 88

Table 7-6: Annual energy consumption and cost at mixed air for three geographical locations. .... 89
Table 7-7: Annualized life-cycle cost at supply air for three geographical locations .................. 90
Table 7-8: Annualized life-cycle cost per unit area at supply air for three geographical
locations. ........................................................................................................................................ 91
Table 7-9: Annualized life-cycle cost at mixed air for three geographical locations. .......... 91
Table 7-10: Annualized life-cycle cost per unit area at mixed air for three geographical
locations. ........................................................................................................................................ 92
Table 7-11: Annual IAQ benefit as a result of lower relative risk at supply air for three
geographical locations..................................................................................................................... 93
Table 7-12: Annual IAQ benefit as a result of lower relative risk at mixed air for three
geographical locations..................................................................................................................... 94
Table 8-1: Annual energy consumption and cost for systems designed for different $\eta_{\text{UVGI}}$ ...... 98
Table 8-2: Annualized life-cycle cost for systems designed for different $\eta_{\text{UVGI}}$...................... 99
Table 8-3: Annualized life-cycle cost per unit area for systems designed for different $\eta_{\text{UVGI}}$.... 99
Table 8-4: Annual energy consumption and cost for systems designed for microorganisms
of different rate constants............................................................................................................... 103
Table 8-5: Annualized life-cycle cost for systems designed for microorganisms of different
rate constants. ................................................................................................................................. 104
Table 8-6: Annualized life-cycle cost per unit area for systems designed for microorganisms
of different rate constants............................................................................................................... 104
Table 8-7: Percentage deviation of predicted life-cycle cost....................................................... 106
Table 8-8: Confidence interval of percentage deviation of predicted life-cycle cost. .............. 109
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Chapter 1

Introduction

Most commercial buildings are served by mechanical heating, ventilation and air-conditioning (HVAC) systems (EIA, 2006). HVAC ductwork may play a significant role in the distribution and control of airborne diseases. An in-duct ultraviolet germicidal irradiation (UVGI) system may well serve as a supplement to other air-cleaning mechanisms such as air filtration and dilution ventilation to reduce microorganism concentration in a space.

1.1 Distribution and control of airborne pathogens

The transmission of respiratory diseases by airborne pathogens is one of the major problems of indoor air quality (IAQ). Tremendous costs are associated with respiratory infections, either directly as a result of medical treatment, or indirectly due to productivity loss. Droplet residues of airborne pathogens generated by talking, coughing and sneezing can be suspended in the air for several hours, entrained into HVAC ductwork, and distributed throughout a building (Sehulster et al., 2004). Furthermore, some airborne pathogens will further proliferate in spore form within the ductwork especially in the presence of moisture and nutrients, which are common in the cases of problem buildings (Kowalski and Bahnfleth, 1998).

There are currently limited guidelines to control the airborne pathogen concentration level in commercial buildings. It is a common practice simply to introduce a higher ventilation rate (than that required by building code) to dilute the polluted indoor air with outdoor air as a
solution for buildings with IAQ complaints. Air filtration or other air-cleaning mechanisms capable of removing or inactivating airborne microorganisms may also reduce disease transmission through HVAC ductwork. Depending on the air filtration system in place, small microorganisms of size \( \sim 0.1 \) to \( 1 \) µm are not readily removable by ordinary filters. An increased ventilation rate will unavoidably incur additional HVAC loads and high efficiency filters will induce an undesirable pressure drop; inevitably, both will translate into higher energy costs for the buildings.

### 1.2 Background on in-duct UVGI systems

UVGI systems have potential for reducing viable microorganism concentration in buildings and thus for reducing health risks and productivity loss that result from airborne illness. UVGI systems treat moving airstreams as they pass through a building’s ductwork by applying UVC radiation to inactivate microorganisms in the air, and are particularly effective in inactivating microorganisms in the aforementioned size range (Kowalski and Bahnfleth, 2002).

UVGI systems generate electromagnetic energy in the UVC spectrum from 100 to 280 nm wavelength. Commercially available low-pressure mercury vapor lamps produce most of their output at 254 nm, which attains \( \sim 85\% \) of the maximum germicidal effect produced by the optimal 265 nm wavelength (Philips, 2006). UVC light at 254 nm is readily absorbed by the microorganisms’ DNA to create lethal photoproducts that prevent the DNA from replication, and thus retard the growth of the microorganisms (Noakes et al., 2004).

The use of UVC light in air disinfection has a long history. Research on applying UVC for air disinfection in the upper air can be traced back to the 1930s. In the 1990s, as the UVGI industry expanded, application of in-duct UVGI systems to disinfect airstreams was introduced to the market, gradually generating interest. A recent increase in tuberculosis cases and concerns
about bioterrorism that uses deadly pathogens have fueled more interest in this technology (Brickner et al., 2003). Specifically, air handler surfaces such as those downstream of the cooling coils and drain pans have had to be disinfected with UVGI systems for all General Services Administration (GSA)-funded new construction projects since 2000 (GSA, 2005).

1.3 Incentive for conducting simulation-based evaluation

A simulation-based evaluation is important for optimizing the performance capabilities of UVGI systems. UVGI devices are designed to operate at a certain air temperature and velocity. However, the ambient conductions inside HVAC systems, to which the UVGI devices are exposed, may vary greatly from hour to hour. For example, air temperature may vary greatly for both constant air volume (CAV) systems and variable air volume (VAV) systems, depending on the location in the systems and how they are setup. Air velocities also change significantly for VAV systems in particular, and, at times, for CAV systems if economizers are present. The UVC output of UV lamps also depreciates over the cumulative operating time. The average amount of exposure time available for the air to be treated is governed by the airflow rate. These time-varying parameters imply that the performance of UVGI devices evaluated at any particular set of conditions at best illustrates the operation at one point in time, and at worst misrepresents the performance that leads to over or under sizing of the UVGI devices, which either incurs extra cost to operate or fails the expectation in a critical mission. In contrast, a simulation-based evaluation takes time into consideration. Performance of UVGI characterized in the time domain allows critical mission appraisal or health benefit analysis of these systems to be conducted, and thus enables proper design decisions to be made for a particular requirement.
1.4 Objectives, approaches and scope

The objective of this research is to analyze the effect of time-varying parameters on the performance and life-cycle cost of in-duct UVGI systems. The research develops a simulation-based evaluation procedure and concludes with a parametric study that demonstrates the importance and the application of such procedure, and contrasts the simulation-based data with evaluations that ignore the time-varying factors.

The evaluation procedure in this research includes predicting the efficiency of UVGI devices, determining the performance of UVGI systems, and appraising the cost and health benefit. Predicting the efficiency of UVGI devices involves establishing the time-varying parameters and investigating their effect on the efficiency of UVGI devices in inactivating microorganisms. An in-duct UVGI device is usually installed within the air-handling unit (AHU) of the HVAC system. The efficiency of the device, together with the ventilation / air circulation effect of the HVAC system, forms the basis to determine the performance of the UVGI system, which can be measured in terms of microorganism concentration in the space served. The cost and health benefit of the systems are attributed to the prescribed performance level.

The scope of this research is limited to the in-duct application of UVGI systems for commercial buildings. The parameters of interest are limited to those that affect UVGI system operation in the time domain, and will be studied extensively.
Chapter 2

Literature Review

The existing literature discusses UVGI operation and provides microorganism data in general, but furnishes no information on simulation-based evaluation in particular. This chapter reviews parameters that affect the efficiency of UVGI devices, evaluation approaches that quantify the performance of UVGI systems, and procedures that estimate the cost and benefit.

2.1 Efficiency of UVGI devices

The performance of in-duct UVGI devices is generally expressed in terms of single-pass efficiency, that is, how much microorganism concentration has been reduced as a result of inactivation when air passes from the input end to the output end of a device. Microorganisms exposed to the UVGI irradiance field are subject to exponential decay (Chick as cited in Kowalski et al., 2000). A two-stage model describes the scenario in which the microorganism population might not respond to UVGI irradiance at the same rate; some might be more susceptible, while others might be more resistant. In some other cases, the population might not respond to UVGI irradiance until a certain threshold dose has been received, which can be expressed as a shoulder model (Kowalski et al., 2000). As a first approximation and for the purpose of this research, a single-stage inactivation model is deployed.

2.1.1 Single-stage inactivation model for UVGI devices

The survival fraction is commonly used to quantify the amount of microorganisms not being inactivated by UVGI, and is defined as the ratio of the active microorganism population to
the total initial microorganism population after receiving a certain UV dose. The survival fraction can be approximated by the single-stage inactivation model (Philips, 2006):

\[ S = \frac{N_t}{N_0} = e^{-k(Dose)} = e^{-k(I \cdot t)} \quad (2-1) \]

\( N_0 \) = the initial population of active microorganisms,

\( N_t \) = the population of active microorganism after time \( t \) under UV exposure,

\( S = \frac{N_t}{N_0} \), the survival fraction of the microorganisms,

\( k \) = microorganism-specific rate constant, cm\(^2\)/µJ,

\( I \) = the effective (germicidal) irradiance received by the microorganisms, µW/cm\(^2\),

\( t \) = exposure time, s,

\( \text{Dose} = \text{the product of } I \cdot t = \mu J/cm^2 \).

The microorganism-specific rate constant \( k \) [cm\(^2\)/µJ] represents the susceptibility of a microorganism. The lower the value, the more resistance the microorganism has to UV irradiation.

For a UVGI device, single-pass efficiency is defined as the complement of the survival fraction (Lau et al., 2009), and can be derived from Equation 2-1:

\[ \eta_{UVGI} = 1 - S = 1 - e^{-k(I \cdot t)} \quad (2-2) \]

The survival fraction of a particular microorganism is dependent on both the unique rate constant and the UVC dose the microorganism received, as expressed by Equation 2-1. The UVC
dose is the product of the exposure time and the effective irradiance that the microorganism received during that time. UV lamps of different types and from different manufacturers have different rated irradiance output values. However, all lamps exhibit the similar characteristic that the irradiance changes as a function of the saturated pressure of mercury inside the lamps, which in turn depends on the cold-spot temperature of the lamps (Philips, 2006). The operational characteristics of UVGI devices will be discussed in the following sections.

2.1.2 UVGI device design and operational parameters

The ASHRAE Handbook — HVAC Systems and Equipment (ASHRAE, 2008) lists the following parameters that have an influence on the sizing and operation of in-duct UVGI systems for airstream disinfection:

- Duct height and width
- Duct length where airstream is exposed to UV
- Air velocity
- Air temperature
- Target microorganisms and their rate constant, $k$ (susceptibility to UV)
- Disinfection performance required
- Lamp age (cumulative burning time, also known as depreciation)
- Lamp fouling (decreases the UV delivered)
- Type of power supply / ballast driving the UV lamps
- Reflectivity of duct material or duct lining
- Location of lamps with respect to duct
- Humidity
Among these parameters, only time-varying ones are of interest in this research, of which only air temperature and velocity will be under detailed investigation, since both fluctuate with time and are dependent on the installation situation. On the other hand, depreciation and fouling increase with time in one direction; thus their impacts need not be modeled through simulation.

2.1.2.1 Lamp level parameters

The technology of low-pressure mercury vapor germicidal lamps used in UVGI systems is essentially identical to that of fluorescent lamps used for illumination. The UVC output of these lamps, and thus the irradiance, is a function of the mercury vapor pressure inside the lamps, which varies with the temperature of the coolest location on the lamp surface, commonly referred to as the “cold-spot temperature”. Depending upon the lamp type, maximum output occurs when the cold-spot temperature is between 39°C and 50°C (103°F – 122°F) (ASHRAE, 2008). Figure 2-1 shows a typical performance curve (Philips, 2006) that relates the relative UVC output of the lamp with its cold-spot temperature with a peak at 40°C (104°F).

![Figure 2-1: Lamp output as a function of cold-spot temperature (Philips, 2006).](image-url)
Cold-spot temperature is a function of the energy balance relating input power, useful UVC emission, thermal radiation, and convection. Because the main determinants of cold-spot temperature are ambient air temperature and velocity (Philips, 2006), the variation of the capacity with environmental conditions is commonly called the “windchill effect”. Figure 2-2 illustrates the windchill effect for two geometrically similar lamps operating in a 21°C (70°F) airstream. One lamp is a “standard output” model with 36W of input power while the other is a “high output” (or “windchill-corrected”) lamp with an input power of 60W. The high output lamp dissipates more heat than the standard output one while having the same surface area; as such it operates at a higher temperature. As a result, the maximum output condition for the high output lamp is shifted to a higher velocity relative to the standard output lamp. The output of the high output lamp decreases at a low velocity due to overheating.

![Figure 2-2: Air velocity dependence of standard and high output lamps (Philips, 2006).](image)

The curves shown in Figure 2-1 and 2-2 represent the output of the UVC lamps of one manufacturer. Other manufacturers produce lamps that exhibit similar performance characteristics and yield curves with similar shapes. A previous investigation (Lau et al. 2009) at Penn State experimentally validated a calibrated heat transfer model for a number of commonly deployed
lamps. The polynomial heat transfer model can be used to predict the lamp output under varying ambient air temperature and air velocity conditions. Figure 2-3 shows contours of a lamp’s relative output as a function of air temperature and velocity for a single-ended, twin-tube, high-output hot cathode lamp (Philips TUV PL-L 60W HO) in a cross-flow arrangement.

UVC output also diminishes (depreciates) over the life of a lamp. Figure 2-4 presents a typical example of depreciation in which output falls by 15% (for the Philips lamps) during the first 1650 hours of operation, then levels off for the remaining life of the lamp.

Figure 2-3: Lamp output vs air temperature and velocity for a particular setup (Lau et al. 2009).

Figure 2-4: Typical mercury vapor lamp depreciation (Philips, 2006).
2.1.2.2 Device level parameters

Design air velocity may vary from 5 m/s (1000 fpm) or more in air-distribution ducts to less than 2 m/s (400 fpm) in AHU with substantial variation below these figures for variable air volume (VAV) systems. Lamps inside ductwork can be thought of as lamps installed in an enclosure with open ends. The device enclosure is defined by the irradiance field (Kowalski et al., 2000), where microorganisms have been exposed to UV irradiation and been inactivated. The direct irradiance decreases roughly with the inverse of the distance from a lamp (ASHRAE, 2008). For an installation inside the AHU, the limitation is not on how far the irradiance can reach, but on how much clearance in practice the AHU allows. Confidential surveys conducted with several UVGI device vendors suggest a typical clearance of 22 – 38 cm (8.5 – 15 inches) on either side of the lamps, limited by space commonly available inside the AHU. Therefore, the typical total length of the flow path in which air is under UV irradiation is 44 – 76 cm (17 – 30 inches).

The average exposure time can be calculated by dividing the length of the flow path by the air velocity. The calculation is based on the assumption that airborne microorganisms are carrying the same velocity profile as the airstream and are considered uniform. Even though the velocity profile in reality is not uniform, Kowalski and Bahnfleth (2000) suggested that the mixing effect is great enough to compensate for the effect of a non-uniform velocity profile at an air velocity of 2 m/s (400 fpm). At such a velocity and at the suggested flow path length, the exposure time commonly available inside the AHU to deliver a UVC dose is as little as 0.2 – 0.375 s.
2.2 Performance of UVGI systems

The performance of UVGI systems can be quantified through the measurement of microorganism concentration in treated spaces. Ideally, health authorities should provide concentration level guidelines for a space that is considered healthy. If definitive guidelines are available and the space concentration is known, then the UVGI system performance can be relevantly expressed in terms of the absolute reduction of microorganism concentration in a space to a certain healthy level. UVGI systems performance can also be evaluated with respect to other air-cleaning mechanisms in terms of the relative microorganism concentration reduction.

2.2.1 Absolute performance criteria

The UVC dose delivered by UVGI systems is meant to inactivate viable airborne pathogens as they are carried through the systems by the airstream. Therefore, it is important to examine documented reports of microorganism concentration on current building stocks, the microorganism generation rate in the building, and microorganism concentration level guidelines for the buildings that are considered healthy by health authorities.

2.2.1.1 Indoor bacteria level

Contagious respiratory pathogens, in most cases, are airborne viruses and bacteria; but only twenty of those cause a great number of contagious respiratory diseases (Kowalski and Bahnfleth, 1998). Numerous researchers have measured the indoor bacteria level in a variety of buildings. The reported values vary greatly depending on geographical location, building end use, occupancy level, etc. Total bacteria count is a common indicator to reflect the indoor bacteria level in general without referring to any particular bacterium. Eleven papers (Table 2-1) were
found in scientific journals and conference proceedings reporting a measured indoor airborne total bacteria count for buildings served by mechanical ventilation systems.

Due to differences in sampling methods and the interpretation of the measured results (Straja and Leonard, 1996; Tsai and Macher, 2005), the summarized values cannot be cross-compared but rather serve as an indication of how diverse the values are. All the referenced studies show a much higher concentration of bacteria indoors than outdoors, and a strong correlation between indoor bacteria level and occupancy level.

Table 2-1: Summary of documented indoor airborne total bacteria count.

<table>
<thead>
<tr>
<th>Geographical Location</th>
<th>Building End Uses</th>
<th>Total Bacteria Count (cfu/m$^3$)</th>
<th>Notes</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Canada</td>
<td>Classroom</td>
<td>166</td>
<td>mean of 62 samples</td>
<td>Bartlett et al., 2004a</td>
</tr>
<tr>
<td>Singapore</td>
<td>Library</td>
<td>1729 – 3651</td>
<td>occupied</td>
<td>Goh et al., 2000</td>
</tr>
<tr>
<td></td>
<td></td>
<td>892</td>
<td>unoccupied</td>
<td></td>
</tr>
<tr>
<td>Greek</td>
<td>Office</td>
<td>~ 140 – 450</td>
<td>varies with occupancy</td>
<td>Kalogerakis et al., 2005</td>
</tr>
<tr>
<td>Hong Kong</td>
<td>Office</td>
<td>~ 550 – 1440</td>
<td>small office of 6</td>
<td>Law et al., 2001</td>
</tr>
<tr>
<td>Hong Kong</td>
<td>Office</td>
<td>~ 500</td>
<td>shopping mall = 950</td>
<td>Lee et al., 2002</td>
</tr>
<tr>
<td>Hong Kong</td>
<td>Shopping Mall</td>
<td>~ 500 – 1450</td>
<td>9 malls, weekdays</td>
<td>Li et al., 2001</td>
</tr>
<tr>
<td></td>
<td></td>
<td>~ 800 – 1500</td>
<td>9 malls, weekends</td>
<td></td>
</tr>
<tr>
<td>Denmark</td>
<td>Office</td>
<td>120 – 2100</td>
<td>mean = 574</td>
<td>Menzies and Bourbeau, 1997</td>
</tr>
<tr>
<td>Singapore</td>
<td>Office</td>
<td>19 – 1360</td>
<td>mean = 204</td>
<td>Ooi et al., 1998</td>
</tr>
<tr>
<td>US</td>
<td>Office</td>
<td>252 – 306</td>
<td>winter - summer</td>
<td>Tsai et al., 2002</td>
</tr>
<tr>
<td>US</td>
<td>Office</td>
<td>102</td>
<td>mean of 100 buildings</td>
<td>Tsai and Macher, 2005</td>
</tr>
<tr>
<td>US</td>
<td>Office</td>
<td>~ 500</td>
<td></td>
<td>Zhu et al., 2003</td>
</tr>
</tbody>
</table>
Goh et al. (2000) proposed a linear relationship between bacteria level and the average number of people within a 10 m radius of the sampler; the background level was measured at approximately 350 cfu/m$^3$, and the bacteria level increased at a rate of roughly 150 cfu/m$^3$ per person. These numbers were deduced through regression with a coefficient of 0.96, with which the sampling was done in a continuous manner (the sampling time for each observation was not provided). Kalogerakis et al. (2005) observed a similar increase in bacteria level as the number of persons in an office increases. These findings suggested that human occupants are a principal source of indoor bacteria.

2.2.1.2 Indoor bacteria generation rate

Indoor bacteria are in general generated by different expiratory activities. Duguid (1946) found that 97% of droplet nuclei expelled due to sneezing, coughing, and talking were in the range of 0.5 to 12 µm, and the majority were between 1 and 2 µm, remained in the air for 30 minutes to an hour. Skin surface can be another source of bioaerosol. May and Pomeroy (as cited in Spendlove and Fannin, 1983) conducted measurements on 17 male and 11 female subjects and found that the bioaerosol dissemination rate was higher for males than for females; clothed males yielded 1008 cfu per minute, unclothed males yielded 4247 cfu/min, whereas females yielded approximately 800 cfu/min, regardless of clothing level. The suggestion that males disperse a higher rate of bioaerosol than females coincides with the results of a test performed by Hill et al. (1974) on staphylococcus aureus (S. aureus) dispersal rate differences between genders. The test results indicated that 13% of the males produced S. aureus while only 1% the females produced S. aureus and at a lesser quantity. These findings provide support for the notion that indoor bacteria level is strongly related to occupancy level, gender, and seasonal variations (that may come as a result of differences in clothing level). The generation rate values are relevant to S. aureus only, and cannot be applied to other bacteria.
2.2.1.3 Required reduction in microorganism concentration

The World Health Organization (WHO) recommends a ceiling of 100 cfu/m$^3$ total bacteria count, and 50 cfu/m$^3$ total fungi count for hospitals and health care facilities (WHO as cited in Kowalski, 2007). However, no specific ceiling is prescribed for commercial buildings. Moreover, the recommendation for health care facilities proposes only a total count while ignoring the variation in microorganism species, in which some are more contagious than others, which are more relevant for this research. Infectious persons may carry one or more species of pathogen and transmit them at different rates. Precise modeling requires detailed epidemiological data that are case dependent and cannot be generalized. A few species of bacteria and viruses have been studied in great depth and supported by enough data to have infectious doses (ID$_{50}$) established. Kowalski (2006a) compiled a list of microorganisms with their respective ID$_{50}$. For example, the Influenza A virus was identified with an ID$_{50}$ of 20–790, a rather broad range whereby the values are informative rather than conclusive. To date, ID$_{50}$ for most species of interest have not been established.

2.2.2 Ventilation and air filtration

Space concentration reduction of microorganisms can be achieved through other commonly applied air-cleaning mechanisms such as ventilation or air filtration. The reduction provided by these mechanisms can be compared with that of UVGI systems.

2.2.2.1 Minimum requirement for ventilation and air filtration

ASHRAE Standard 62.1 (ASHRAE, 2007) prescribes a minimum ventilation rate of 8.5 L/s-person (17 cfm/person) for office spaces at a default occupant density. The lowest level of air
filtration allowed must be rated at a minimum efficiency report value (MERV) 6. The concentration reduction that is realized with these minimum air-cleaning mechanisms in place serves as a good reference point for evaluating the performance of the UVGI system in relative terms.

2.2.2.2 Filtration and MERV rating

Particle removal efficiency for a range of MERV ratings as a function of particle size is shown in Figure 2-5. The figure indicates the removal rate of microorganism of a particular size by a certain MERV rated filter.

![Figure 2-5: Removal efficiency for MERV 6–16 filters (Kowalski and Bahnfleth, 2002).](image)

2.3 Life-cycle cost analysis

The life-cycle cost of a UVGI system includes both installation and operation costs. Costs of future years have to be converted into their present worth.
2.3.1 Economic analysis of UVGI

Kowalski and Bahnfleth (2000) and the U.S. Environmental Protection Agency (EPA, 2008) provided cost analyses for UVGI systems. Both assumed in their analyses that the systems were operated at a fixed air velocity of 2 m/s (400 fpm), so varying HVAC conditions were not accounted for. These analyses present a good first approximation of the possible cost and benefit of UVGI systems, but may not accurately represent the actual operation of an in-duct system in some applications, for example, VAV systems in which air velocity varies with load or in the mixing section of an air handler where temperature varies widely. Table 2-2 summarizes these documented cost analyses (together with various degrees of air filtration).

Table 2-2: Documented cost analyses of in-duct UVGI systems.

<table>
<thead>
<tr>
<th>Design airflow (cfm)</th>
<th>Energy cost + Maintenance cost = Annual operating cost ($)</th>
<th>Cost per cfm-year</th>
<th>Predicted single-pass efficiency</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>10,000</td>
<td>306 + 800 = 1,106</td>
<td>$0.11</td>
<td>90%</td>
<td>Kowalski and Bahnfleth, 2000</td>
</tr>
<tr>
<td>100,000</td>
<td>53,652 + 27,700 = 81,352</td>
<td>$0.81</td>
<td>not given</td>
<td>EPA, 2008</td>
</tr>
</tbody>
</table>

The difference in unit electricity price (charged at $0.08 / kW-hr for the first study and $0.13 / kW-hr for the second study) does not account for the huge difference in cost / cfm-year between the two studies. In fact, the annual energy consumption of the UVGI systems was 0.027 kWh/cfm and 3.044 kWh/cfm for the first and the second study, respectively; as a result, the system of the second study consumed more than 100 times the electricity of the first one. The annual energy consumption as predicted by the first study is more in line with the findings of this research. According to the second study, the UVGI system under investigation was based on a confidential discussion with a vendor, and therefore no system specifications were disclosed in...
the report. The first study, on the other hand, specified the performance requirement of inactivating 90% of the bacteria *E. coli* in a single-pass. Cost is a function of performance and can only be properly determined with well-defined performance requirements.

### 2.3.2 Potential IAQ benefits

A number of studies have expressed the cost of respiratory disease in economic terms, such as loss of productivity and incurred number of sick leaves (and the resulting cost with respect to wages). Fisk (2000) estimated a potential productivity gain in the range of US$6 to 14 billion each year in the US due to the possibility of a reduction of acute respiratory illness (ARI) alone. This estimate was based on eight other studies that predicted a range of 9% to 20% for possible reduction in respiratory illness, which were translated into 16 to 37 million cases of the common cold or influenza to be avoided each year, by introducing a higher ventilation rate, installing UVGI systems, and using other means.

The following two papers discuss IAQ benefits as related to the operation of UVGI. Menzies et al. (2003) compared the reduction in pathogens with the reported symptoms, and indicated that UVGI may be able to ease HVAC-related sick symptoms with negligible reduction in airborne pathogen concentration level. Fisk (2000), using data from other studies, estimated approximately a 16% reduction in respiratory illness with the UVGI installed in barracks. However, these studies only provided the possibility of benefits without quantifying either the degree of the benefits in economic terms or the size of the installed UVGI systems. In essence, there is no established method to quantify how much benefit UVGI systems produce for each dollar spent on them. It will be complicated if the objective is to investigate the incremental benefit of the UVGI systems in addition to other air-cleaning mechanisms, such as filtration or dilution ventilation.
2.3.2.1 Relative risk of sickness and ventilation rate

The outdoor air (OA) economizer has long been deployed to conserve energy and thus lower energy cost when weather conditions are mild. The elevated ventilation rate also has the potential side benefit of reducing airborne transmission of respiratory illness. Fisk et al. (2005) investigated the relationship between an increase in the ventilation rate and the reduction in new disease cases. Numerous prior studies provide data that relate the number of infectious people and the ventilation rate, and form the basis for Fisk et al.’s study. Fisk et al. utilized a slightly modified form of the Wells-Riley equation (Nardell as cited in Fisk et al., 2005), and presented the prevalence (new disease cases per susceptible persons) as:

\[
P = \frac{D}{s} = 1 - \exp \left[ \frac{-ipqt / \mathcal{V}}{\alpha_v + \alpha_f + \alpha_d} \right]
\] (2-3)

\( P \) = prevalence

\( D \) = new diseases cases

\( s \) = susceptible persons

\( i \) = infectors (\( i/\mathcal{V} \) can be thought of as infectors per space volume)

\( p \) = breathing rate

\( q \) = infectious particle dissemination rate per infector

\( t \) = time that infectors and susceptible individuals share the same room

\( \mathcal{V} \) = space volume

\( \alpha_v = Q_{OA} / \mathcal{V} \), ventilation rate per unit volume, where \( Q_{OA} \) is the OA supply rate

\( \alpha_f \) = filter removal rate

\( \alpha_d \) = particle deposition rate
Fisk et al. also suggested a simplified model, in which prevalence is inversely proportional to the total contaminant removal rate as in Equation 2-4. With an increased ventilation rate (as compared to the reference ventilation rate), the relative risk (RR) of infection is defined as:

\[
P \propto \frac{1}{\alpha_v + \alpha_f + \alpha_d}
\]

\[
P_{\text{ref}} \propto \frac{1}{\alpha_{v,\text{ref}} + \alpha_f + \alpha_d}
\]

\[
RR = \frac{P}{P_{\text{ref}}} = \frac{1/(\alpha_v + \alpha_f + \alpha_d)}{1/(\alpha_{v,\text{ref}} + \alpha_f + \alpha_d)}
\]

Fisk et al. (2005) further translated the reduction in relative risk (due to a higher ventilation rate) into economic terms according to statistical wages ($200 per day per person) and sick leave data (7 days of sick leave per person-year).

2.4 Gaps in the existing literature

The existing literature extensively covers the modeling of UVGI devices with a fixed set of conditions. There is a lack of information, however, on how to design the devices to work with time-varying conditions, or how to quantify the performance under such conditions. UVGI device vendors base their designs on rule-of-thumb conditions. Therefore, the lack of standardized design and sizing practice creates devices of different levels of performance that cannot be cross-compared. On the other hand, there is no standardized performance guideline for the vendors to follow either.
There is no simple epidemiological model to suggest how two or more species of pathogens interact or act independently to cause infections, not to mention the ID$_{50}$ of many common pathogen species that have not yet been established. While the generation rate of the microorganism *S. aureus* has been established in a few studies, the rates for most other microorganisms are not known. There is no health guideline for the ceiling of microorganism concentration in spaces for commercial buildings. Epidemiological and microbiological data are so few and fragmented that the results of evaluation of space concentration in absolute terms cannot be substantiated.
Chapter 3

Methodology

Based on the knowledge and known deficiencies on the topic of UVGI system evaluation procedures gathered from the literature review, this chapter develops a simulation-based evaluation procedure for these systems in three stages: 1) establishing the efficiency of UVGI devices based on time-varying conditions, 2) developing a relative performance evaluation procedure and predicting the performance of UVGI systems, and 3) analyzing the life-cycle cost of UVGI systems.

3.1 Establishing the efficiency of UVGI devices

The fundamental components of UVGI devices, UV lamps, are subjected to time-varying conditions (particularly, air temperature and air velocity). In order to determine the efficiency of UVGI devices, the first step is to investigate the varying ambient conditions of the airstream to which the UV lamps are exposed. Proper lamp modeling is required to simulate the lamp output based on the time-varying conditions. As conditions vary with time, a sizing procedure based on a fixed design point will result in either over-sizing or under-sizing for the hours when the conditions deviate from the design point. The task then is to examine the annual distribution of the ambient conditions, to investigate the effect of sizing strategies on performance, and to study the corresponding device efficiency. The purpose is to ensure the UVGI systems work as intended under the time-varying conditions.
3.1.1 Whole-building energy simulation

Building energy simulation software — the eQUEST implementation of DOE-2 (Hirsch, 2009) — is used to perform an 8760-hour whole building energy analysis for a hypothetical building. Hourly data such as air temperatures and airflow rates at the installation location, where the UVGI device is situated, are gathered for post-processing with a custom simulation program developed in MATLAB (Mathworks, 2009). HVAC energy consumption is also recorded for cost analysis purposes.

Hourly data from eQUEST are used to determine the cold-spot temperature according to the heat transfer model of the lamp; the corresponding lamp output can be obtained with the cold-spot temperature—lamp output relationship as depicted in Figure 2-1.

3.1.2 Design and off-design dose

A design UV dose for a particular target (design basis) microorganism can be obtained by rearranging Equation 2-1 as follows:

\[
\left( It \right)_{\text{design}} = \frac{\ln(S_{\text{design}})}{-k}
\]  

(3-1)

The design dose is specific to a target microorganism (with a unique rate constant, \(k\)) that is intended to be inactivated to a desired survival fraction \(S_{\text{design}}\). By combining Equation 2-2 and 3-1, an expression for device inactivation efficiency can be derived as shown in Equation 3-2.

Taking into account both the effects of air temperature and velocity on lamp output, and the effects of geometry and flow rate on exposure time, the off-design dose \((I\tau)\) is a variable that reflects the effect of time-varying conditions.
The UV irradiance is directly proportional to the lamp output, while the exposure time is inversely proportional to the air velocity. Therefore, the ratio of the off-design dose to the design dose can be expressed as follows:

$$\eta_{UVGI} = 1 - e^{-\ln(S_{design}) \frac{It}{(It)_{design}}}$$

(3-2)

$$\frac{It}{(It)_{design}} = \left( \frac{\text{LampOutput}}{\text{LampOutput}_{design}} \right) \left( \frac{V_{design}}{V} \right)$$

(3-3)

3.1.3 Design dose and single-pass inactivation efficiency

From Equation 3-2, it can be observed that the only independent variable needed to determine the required single-pass inactivation efficiency for a given design survival fraction is the off-design dose (It), which can be calculated with Equation 3-3 with the known off-design lamp output (LampOutput) and air velocity (V) values obtained through the simulation procedure as explained in Section 3.1.1.

If the off-design lamp output is less than the design lamp output and the off-design velocity is higher than the design velocity, then the off-design dose will be less than the design dose. Likewise, if the off-design conditions are more favorable, then the off-design dose will be more than the design dose. In other words, the UVGI systems will generally be either under or over sized whenever ambient conditions (temperature and velocity) deviate from that of the design conditions.
The previous discussion is based on the premise of delivering the design dose in order to achieve the design single-pass inactivation efficiency. However, the design value of $\eta_{UVGI}$ itself is arbitrary in the sense that there is no authoritative recommendation that specifies a design value for any particular situation. The effect of selecting a high and low value of $\eta_{UVGI}$ on performance and cost will be discussed in Section 4.3 Sensitivity analyses. Furthermore, as discussed in Section 2.2, a design based on a certain $\eta_{UVGI}$ does not necessarily guarantee a particular space concentration. However, the fact that there is no health guideline on space concentration, the single-pass $\eta_{UVGI}$ is customarily chosen as the design parameter. Its effect on space concentration will be further discussed in Section 3.2.

3.1.4 Design strategies

The problem of off-design conditions leads to a design strategy issue if the UVGI system is designed to deliver a dose higher than the design dose all of the time, or part of the time. The “average condition” sizing strategy is referred to as a system that yields the design $\eta_{UVGI}$ at the annual mean air temperature and air velocity at the installation location. It is expected that the design dose cannot be delivered for some time.

The “worst case” sizing strategy is based on the most extreme conditions for which the combination of air temperature and velocity yields the lowest $\eta_{UVGI}$. This strategy will ensure delivery of a design dose all the time at the expense of higher energy consumption.

An alternative approach to sizing that is not currently in use, but is analogous to the way in which building loads are determined to size HVAC equipment, is to size the system based on simulated hourly operating conditions, such that $\eta_{UVGI}$ is maintained 99% of the time (or an arbitrary percentage depending on performance requirements). This novel strategy could strike a suitable balance between economy and performance.
In practice, air temperature and velocity data from simulation are not readily available for the purpose of UVGI system design. UVGI device vendors base their designs on rule-of-thumb conditions — conditions that are representative of the worst conditions based on experience. Therefore, the design strategy based on “vendor selection conditions” does not require simulation to obtain the design conditions.

A custom simulation program developed in MATLAB processes the hourly data from eQUEST based on the design survival fraction, design dose and design strategy according to the methodology just outlined. The annual profile of device inactivation efficiency is simulated for different deployed design strategies. With the “worst case” sizing strategy, it is expected that the device could maintain the design inactivation efficiency for the whole year.

3.1.5 Sizing of UVGI device

Design conditions are determined by the design strategies as described in the previous section. The UVGI device has to deliver the design dose at the design conditions, at which lamps are operating at a reduced lamp output. Lamps are selected based on the required dose delivery at the rated condition (that is, when the lamp output is 100%). In other words, the required dose to be delivered at the 100% rated lamp output is equal to the design dose divided by the relative lamp output at the design conditions. The nominal irradiance (the fluence rate) can be calculated by dividing the dose (at rated output) with the exposure time at the design conditions. The input power required to deliver the fluence rate is to be provided by the vendor.
3.2 Predicting the relative performance of UVGI systems

The survival fraction and the corresponding single-pass inactivation efficiency of UVGI devices do not fully reflect the performance of the UVGI systems, nor suggest the cleanliness level of air in the space concerned. Rather, a good indicator for air quality is the microorganism concentration in space. The amount of reduction in space microorganism concentration represents the performance of air-cleaning mechanisms such as UVGI systems.

3.2.1 Modeling of space microorganism concentration

Although, in reality, a HVAC system serves a space with multiple volumes separated by partitions; the space under investigation is considered a simple, well-mixed volume with no partitions. The governing equation for the concentration of a contaminant in a single well-mixed space of volume ($V$) with dilution ventilation, air filtration, and UVGI in place is:

$$\frac{dC}{dt} = \frac{G}{V} - \left\{1 - (1 - \eta_{UVGI})(1 - \eta_f)(1 - F_{OA})\right\} \cdot \left(\frac{Q}{V}\right) \cdot C$$  \hspace{0.5cm} (3-4)

$G$ is the source strength of the contaminant generated in the space. The contaminant source is assumed to be of constant strength during occupied hours (from 9 AM to 5 PM, workdays only, a total of 2008 hours per year), and is well distributed throughout the space. $F_{OA}$ is the fraction of outside air in the supply air. Outside air is assumed to be free of contaminant. Therefore, the introduction of outside air through ventilation is thought to have diluted the concentration of the contaminant in space. The filtration efficiency, $\eta_f$ is considered a constant, and is the average of the initial and final efficiency of the installed filter. The inactivation efficiency of the UVGI device, $\eta_{UVGI}$ is a time-varying variable established in Section 3.1.3.
Equation 3-4 states that the rate of accumulation of the contaminant in a space is equal to the rate of generation less the rate of removal by all three air-cleaning mechanisms (dilution ventilation, air filtration, and UVGI). Figure 3-1 depicts a possible configuration of these three air-cleaning mechanisms. Contaminant source strength and contaminant concentration are also indicated in the figure. The UVGI device is installed at the supply air location.

![Schematic of HVAC system with dilution ventilation, filtration, and UVGI.](image)

Figure 3-1: Schematic of HVAC system with dilution ventilation, filtration, and UVGI.

It can be observed from Equation 3-4 that the air-change rate \( \frac{Q}{V} \) has a profound direct effect on the rate of change in concentration. Annual and daily profiles of space concentration are determined with a custom program developed with the ordinary differential equations solving tools of MATLAB.

3.2.2 Relative performance evaluation for UVGI systems

It has been noted that reduction in space contaminant concentration cannot be systematically studied in absolute terms due to the lack of epidemiological data. However, space contaminant concentration data of the studied cases can be normalized with that of a defined reference case, such that reduction in concentration can be illustrated in relative terms.
ASHRAE Standard 62.1 (ASHRAE, 2007) specifies the minimum amount of outdoor air and the minimum level of particulate matter filtration to be provided. This setting of a minimum requirement can well serve as the reference case when evaluating UVGI systems. Normalized concentration data reflect the amount of additional reduction brought forth by the studied cases.

3.2.2.1 Comparison of the UVGI system and particulate matter filtration

The UVGI system inactivates microorganisms of different susceptibilities at different rates, while particulate matter filtration removes particles of different sizes at different efficiencies. The performance of UVGI systems is a function of both air temperature and velocity, while filtration efficiency for a given particle size is a function mainly of airflow. Both air-cleaning mechanisms have their own applications, so cannot be compared using a generalized equivalence of efficiency. However, the reduction in concentration for a particular target microorganism brought forth by a UVGI system of a certain inactivation efficiency is in essence the same as that maintained by a filtration system of the same single pass efficiency at the size of the target microorganism. For the limited case of that target microorganism, the relative performance in contaminant concentration reduction between UVGI and the equivalent filtration can then be compared.

3.2.3 Metric that reflects single pass reduction in space microorganism concentration

Equation 3-4 is applied to evaluate the space microorganism concentration by considering the cumulative removal effect of each air-cleaning mechanism. However, the use of a custom program to solve the ordinary differential equation has never been adopted as a common design practice. In terms of the single pass performance of the UVGI systems, the only two variables of interest in Equation 3-4 are the inactivation efficiency \( \eta_{UVGI} \) and the airflow rate \( Q \), which both
act together to reduce the space concentration. In fact, the product of the two serves as a metric to indicate how well the UVGI systems perform in terms of space concentration reduction in a single pass at any point in time. The Association of Home Appliance Manufacturers (AHAM, 2006) refers to this product as clean-air delivery rate (CADR). The original intent of CADR was to measure the performance of portable air cleaners, so therefore the airflow rate was part of a design parameter for such a device. For the in-duct UVGI system, the airflow rate is instead an intrinsic property of the HVAC system. Therefore, in order to facilitate a comparison of UVGI systems installed in a variety of HVAC systems, a dimensionless value is preferred. The airflow rate can be normalized with the design supply airflow rate. The product of the inactivation efficiency and the normalized airflow rate is referred to as a normalized CADR throughout this paper. Even for a system designed for the worst case, a low value of a normalized CADR is possible if the system is experiencing low airflow. Normalized CADR is a useful metric particularly for VAV systems, which are subjected to a wide range of airflow.

Normalized CADR inherits the same limitations as its two components, and has to be applied within their original contexts. The inactivation efficiency being developed in Section 3.1.2 is specific to a target microorganism of a unique rate constant. The space concentration model developed in Section 3.2.1 assumes a single, well-mixed volume of space. Therefore, the normalized CADR could be applied only for that particular target microorganism in a single volume of space with an evenly distributed airflow. The higher the normalized CADR, the better the reduction of the target microorganism in space, and thus the lower the concentration. This metric will be provided in each of the parametric studies together with the sections on space concentration, and is to be calculated hourly for occupied-hours, along with other time-varying parameters of interest.
3.2.4 Effectiveness of UVGI systems relative to the reference system

Recently, Nazaroff and Weschler (2009) proposed that the performance of an air cleaner at the system level should be described in terms of a steady-state effectiveness, $\varepsilon$, which is defined as:

$$
\varepsilon = \frac{C_{\text{controlled}} - C_{\text{uncontrolled}}}{C_{\text{uncontrolled}}}
$$

(3-5)

This effectiveness is a dimensionless entity that compares the space concentration as maintained by an air-cleaner (the controlled condition) with that of the uncontrolled condition. The uncontrolled condition is when the air-cleaner is not active; for this research, it is the condition of the reference system maintained by minimum outdoor air and MERV 6 filtration. Effectiveness can be calculated with simulated space concentration data (as discussed in Section 3.2.1) for each time step. In practice, it is not common to simulate an hourly space concentration with differential equation. Instead, effectiveness can be evaluated at the steady-state conditions, in which the concentration of the reference system (uncontrolled condition) can be formulated as:

$$
C_{\text{uncontrolled}} = \frac{G/Q}{1 - (1 - \eta_f)(1 - F_{OA})}
$$

(3-6)

For the application of UVGI, the controlled condition is maintained by a UVGI device together with the reference system. The steady-state concentration can be expressed as:

$$
C_{\text{controlled}} = \frac{G/Q}{1 - (1 - \eta_{UVGI})(1 - \eta_f)(1 - F_{OA})}
$$

(3-7)
An effectiveness of 0 implies no incremental reduction in concentration due to the deployment of the UVGI system; whereas an effectiveness of 1 implies that the complete removal of contaminants is fully contributed by the UVGI system. Unlike normalized CADR, the effect of the air-change rate is not considered in effectiveness (since it is a relative term). On the other hand, the effectiveness provides a means to compare the transient concentration reduction capability of different UVGI systems with respect to the reference system. The effectiveness will be studied on an hourly basis for the occupied-hour and will be presented in the parametric study of geographical locations with an example to demonstrate its application.

### 3.3 Analyzing the life-cycle cost

One of the main goals of this research is to investigate the effect of time-varying ambient conditions, design strategies, and performance expectation on the life-cycle cost of UVGI systems. Unit energy consumption and installation cost data of the UVGI device are to be provided by the vendor. Energy and cost data facilitate comparison among different studied cases, and illustrate the cost effectiveness among different implementations of UVGI systems. However, exact installation and operation costs are job- and vendor-specific; therefore, they should be investigated on a case-by-case basis.

#### 3.3.1 Energy consumption analysis

UVGI systems affect the energy consumption of a building in at least two ways: the direct consumption incurred due to UVGI system operation, and the indirect consumption due to the generated heat relayed to the HVAC system.
3.3.1.1 Energy consumption of the UVGI systems

Direct energy consumption is simply the energy consumed by the UVGI systems, and is therefore the input power to the UV lamps multiplied by the amount of operating hours. Indirect energy consumption is one that is incurred due to the operation of the UVGI systems.

During the summer, input power will eventually be translated into cooling load directly or indirectly, which increases the workload of the cooling system. During winter, such power input may lower the heating requirement. The input power of the UVGI device is treated as an additional internal load to the building energy analysis model. A parametric run of eQUEST reveals the resulting cooling load penalty or heating load credit.

Foarde et al. (2006) conducted a series of tests on UVGI devices; it was found that the pressure drop across devices (arranged in crossflow) was less than 8 Pa (0.032” w.g.). Such a pressure drop accounts for about 1% of the total system pressure drop for the hypothetical building, which is going to be discussed in Section 4.1.2. Therefore, its effect on fan energy consumption is treated as negligible.

3.3.1.2 Energy consumption of particulate filtration

As discussed in Section 3.2.2.1, the effect on IAQ (the effect on concentration reduction) provided by a filter of a certain MERV rating is comparable to that provided by a UVGI system of a certain inactivation efficiency for a microorganism of a certain size. Therefore, the energy consumption of such an equivalent filtration (same single pass efficiency of the studied UVGI system at the size of the target microorganism as depicted in Figure 2-5) is taken for comparison in this research. Enhanced filtration induces a significant pressure drop. An average pressure drop of 250 Pa (1” w.g.) and 300 Pa (1.2” w.g.) was expected for a filter rated at MERV 9 – 12 and MERV 13 – 16, respectively (Schloss, 2007). Depending on the equivalent filtration, the
corresponding additional pressure drop is added to the supply air path of the building energy analysis model. A parametric run of eQUEST estimates the extra fan energy consumption and its effect on cooling/heating for the whole year due to the installation of the enhanced filter.

### 3.3.2 Economic analysis

In order to present a comprehensive picture of the total cost of ownership throughout the economic life of the UVGI system, a life-cycle cost (LCC) analysis is performed. The total life-cycle cost, that is, the present worth (P) of the total cost of ownership over the life of the system in operation, includes the initial investment and the operation cost incurred over the years. The life-cycle cost is calculated based on an economic life of \( n \) years. No residual value is assumed in this research. The life-cycle cost is calculated based on the procedures outlined in the Life-Cycle Costing Manual (NIST, 1995).

Energy consumption is of particular interest since it is closely tied with the design. The Energy Information Administration (EIA, 2008) provided the baseline electricity rate for the year 2008 as $0.0977 per kWh of energy consumption (input power times the operating hours). A fuel price index for a future year is a ratio of the projected fuel price of that year to the fuel price of the base year. The energy cost for each year is adjusted by the published fuel price indices (NIST, 2008), \( E_i \), and translated into the present worth with Equation 3-8 at a discount rate, \( r \). \( W \) is the energy cost of the base year.

\[
P_w^p = \sum_{i}^n \left(W \cdot E_i \cdot \frac{1}{(1 + r)^i}\right)
\]  

(3-8)

Annual replacement cost is taken as a uniform yearly expenditure and translated into the present worth with Equation 3-9.
The installation cost \( (P_I) \) is assumed to be paid up front. The total life-cycle cost is the sum of the present worth of installation \( (P_I) \), replacement \( (P_R) \) and energy cost \( (P_W) \). The annualized LCC can be calculated as an amortized uniform amount \( (LCC_A) \).

\[
P_R = \sum_{i=1}^{n} \left( R \cdot \frac{1}{(1+r)^i} \right)
\]

(3-9)

\[
LCC_A = \frac{P_W + P_R + P_I}{(1+r)^n - 1} \left( r(1+r)^n \right)
\]

(3-10)

3.3.3 Potential IAQ benefits

One way to demonstrate the cost effectiveness of different implementations of UVGI systems is to see whether the benefits outweigh the costs. The potential health benefits produced by improved IAQ are expressed in economic terms.

3.3.3.1 Equivalent ventilation rate and relative risk model

The calculation of IAQ benefits (as a result of an elevated ventilation rate) generally follows the method employed by Fisk, et al. (2005) in their analysis of economizer operation. In this research, the inactivation efficiency of microorganisms by UVGI systems is to be expressed as an equivalent ventilation rate, such that the installation of UVGI systems can be modeled as an analogy to the economizer operation.
Referring to Figure 3-2 (a), the effect of a UVGI system on an airstream containing a microbial contaminant can be described by the single-pass inactivation efficiency:

\[
\frac{C_{\text{out}}}{C_{\text{in}}} = 1 - \eta_{\text{UVGI}}
\]  

(3-11)

If, instead, the incoming airstream of contaminated air is diluted to the same leaving concentration by contaminant-free outdoor air at a rate of \(Q_{\text{EQV}}\), as in Figure 3-2 (b), the reduction in concentration is given by:

\[
\frac{C_{\text{out}}}{C_{\text{in}}} = (1 - \frac{Q_{\text{EQV}}}{Q})
\]  

(3-12)

It is clear that there is a direct analogy between ventilation and UVGI such that the use of UVGI with a single-pass inactivation efficiency on an airstream with a flow rate of \(Q\) is equivalent to dilution with an uncontaminated air flow of \(Q_{\text{EQV}}\). By analogy to Equation 2-2, inactivation efficiency of UVGI can be expressed in terms of an equivalent ventilation rate per unit volume with Equation 3-13.
\[ \alpha_{\text{UVGI}} = \frac{Q_{\text{UVGI}}}{\nu} \]  

(3-13)

\( \alpha_{\text{UVGI}} \) as obtained from Equation 3-13 can be applied to the relative risk model as described in Section 2.3.3.1. Equation 2-6 can be modified as:

\[ \frac{RR}{P_{\text{ref}}} = \frac{1}{(\alpha_{\text{UVGI}} + \alpha_v + \alpha_f + \alpha_d)} \times \frac{1}{1/((\alpha_{\text{v,ref}} + \alpha_f + \alpha_d))} \]  

(3-14)

A relative risk (RR) smaller than 1 suggests that UVGI systems do provide incremental benefits (shown by the reduction in sick leave, or other means of illness measurement) in addition to the reference case. A RR of 1 or larger simply implies that there is no incremental benefit (that is, the effectiveness of UVGI systems is either equal to or less than that of the reference system).

3.3.3.2 Reduction of sick leave

A quantifiable measurement of health benefit from a UVGI system is the reduction of sick leave with respect to the reference case. This research follows Fisk et al.’s (2005) procedure and assumes a reference case of 7 days of sick leave per person per year at a cost of US$200 per day. Sick leave is customarily taken in units of a full day or a half day. However, it is treated as divisible into smaller units to provide finer details in this research.

Hourly relative risk data are simulated by a custom program developed in MATLAB, and the maximum risk for each workday is used to evaluate the proportionate amount of reduction of sick leave for that day (the maximum reduction is 7 days per annum if RR = 0 for all hours).

Contrary to cost, which does not change once the system is designed and in operation, health benefits produced by the UVGI system depend on the time-varying performance of the system.
Chapter 4

Description of Parametric Studies

The performance and life-cycle cost evaluation procedures for UVGI system are applied
to a hypothetical case of UVGI implementation for a commercial building. The studied parameters
include design strategies, installation locations, and geographical locations. Assumed values of
other parameters are investigated with sensitivity analyses.

4.1 Hypothetical case

The hypothetical case represents a typical UVGI implementation for a representative
commercial building environment in the US that is suitable as a point of reference. The
procedures applied to this hypothetical case can readily be applied to other UVGI
implementations and buildings.

4.1.1 Studied building

The hypothetical building under investigation in this parametric study is a four-storey
commercial building of light-weight construction. The building is served by simple VAV
system with no temperature setback. Each floor measuring 2,380 m² (25,600 ft²) is served by
an independent AHU capable of delivering a supply airflow rate of 8 m³/s (17,000 cfm). The
amount of outside airflow is fixed at 1.8 m³/s (3,837 cfm) according to the minimum outdoor air
requirement of the ASHRAE Standard 62.1 (ASHRAE, 2007). The duct dimension of 1.8 m x 1.8
m (70 inch x 70 inch) translates the design airflow rate to a face velocity of 2.5 m/s (500 fpm) across the cooling coils.

Each AHU is fitted with a MERV 6 filter as required by the ASHRAE Standard 62.1 (2007). For the purpose of simulating the removal rate by filtration, the diameter of the target microorganism (S. aureus) is assumed to be 1 µm. The filtration efficiency, \( \eta_f \), is approximately 15% and 85%, respectively, for a typical MERV 6 filter and a MERV 12-13 filter to filter a contaminant of 1 µm, as illustrated in Figure 2-5.

For the purposes of this case study, only one system from a middle floor of the studied building is investigated in detail. The HVAC systems and UVGI devices are assumed to be operating continuously (8760 hours per year).

4.1.2 Studied UVGI device

The UVGI device for the parametric study is fitted with commonly deployed, single-ended, twin-tube, high-output hot cathode lamps — Philips TUV PL-L 60W HO in a cross-flow arrangement. High-output lamps are also called “windchill-corrected” lamps since their output is less prone to the cooling effect of the airstream under a high velocity, and therefore, are more suitable for in-duct application. The device is investigated with a design inactivation efficiency of 85% — a value suggested by the vendor as commonly applied for systems in commercial buildings. Dispersion mechanisms and concentration levels of Staphylococcus aureus (S. aureus) in an indoor environment have been studied extensively in the existing literature; hence S. aureus is chosen as the target microorganism in this parametric study. The rate constant \( k \) for S. aureus is taken as 0.0035 cm\(^2\)/µJ (Sharp, 1940). A UVGI device is installed for each AHU.
4.1.3 Economic assumptions

The life-cycle cost of UVGI systems, which includes installation, replacement and energy costs, is calculated for an economic life \( n \) of 15 years. For this studied UVGI device, the vendor provided an estimate of $10 / W of input power for the initial investment cost of fixtures and installation. Lamps of the kind used for this parametric study are rated for a life in excess of 9000 hours. They are assumed to be replaced once every year if the UVGI systems are operated full time. The replacement cost of lamps was estimated at $1 / W by the vendor.

Based on the costs published by a number of on-line sources, the initial cost of a MERV 12 filter system is assumed to be $1650 per m\(^2\) ($150/sq.ft.) of the cross-sectional area of the AHU, and a replacement cost of $220/m\(^2\) ($20/sq.ft.). Filters are assumed to be replaced every half year.

The energy cost is the electricity cost associated with the energy consumption due to both direct and indirect means as a result of UVGI operation. The cost of purchasing electricity in the base year (year 2008) is assumed to be $0.0977/kWh (EIA, 2008). According to projected fuel price indices compiled by National Institute of Standards and Technology (NIST, 2008), the annual average real electricity cost is expected to vary from 89% to 98% of the baseline year (2008) cost for the study period. The adjusted value is taken as the energy cost for each of the years.

For the life-cycle period that started from year 2008, a real discount rate \( r \) of 3% is adopted (NIST, 2008). The annualized LCC can be summarized as Equation 4-1 based on Equation 3-8 to 3-10.

\[
LCC_A = \left[ \sum_i \left( W \cdot E_i \cdot \frac{1}{(1+r)^i} \right) + \sum_i \left( R \cdot \frac{1}{(1+r)^i} \right) + I \right] \bigg/ \left[ \frac{(1+r)^n - 1}{r \cdot (1+r)^n} \right] \quad (4-1)
\]
4.2 Studied parameters

The objective of this research is to study UVGI systems under time-varying conditions. The parametric cases of interests are those that have a profound influence on the performance and cost with respect to time. Other parameters that have a significant impact on performance and cost but are independent of time are studied through sensitivity analyses.

The design strategies discussed in Section 3.1.4 have a profound effect on system performance and life-cycle cost of UVGI systems. The device is studied for all four design strategies discussed, that is, the average case, worst case, 99th percentile, and vendor selection design strategy.

UVGI devices can be installed at different locations within the HVAC systems. However, due to installation space constraints and the additional benefit of irradiating the cooling coil to control microbial growth, UVGI devices are usually installed either downstream of the cooling coils (supply air, or SA) or upstream of the cooling coils (mixed air, or MA) inside the AHU as shown in Figure 4-1.

![Diagram of UVGI devices installed at supply air or mixed air](image)

Figure 4-1: Typical arrangement of UVGI devices installed at the supply air or mixed air.
Since the ambient conditions inside the AHU are considerably affected by a building’s geographic location, UVGI system installed in the same hypothetical building is investigated in the diverse climatic zones of New York, Houston, and Los Angeles for this parametric study.

The parametric studies presented in Table 4-1 intend to demonstrate the effect of different parameters on the performance and cost of UVGI systems with respect to time. The studied parameters included design strategies, installation locations, and geographical locations. For each parametric study, the parameter of interest is investigated with the listed variables (highlighted boxes) and run for a representative case of the other parameters (fixed at one or two variables with a ✓ mark). The simulation-based procedures outlined in the previous chapter are applied to each of the parametric studies for the hypothetical building and device.

Table 4-1: Parametric studies.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Variables</th>
<th>Design strategy</th>
<th>Installation locations</th>
<th>Geographical locations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Geographical locations</td>
<td>New York, NY</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td></td>
<td>Houston, TX</td>
<td></td>
<td></td>
<td>✓</td>
</tr>
<tr>
<td></td>
<td>Los Angeles, CA</td>
<td></td>
<td></td>
<td>✓</td>
</tr>
<tr>
<td>Installation locations</td>
<td>Supply Air</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td></td>
<td>Mixed Air</td>
<td></td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Design strategies</td>
<td>Average case</td>
<td>✓</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Worst case</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td></td>
<td>99th percentile</td>
<td>✓</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Vendor Selection</td>
<td>✓</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
The parameters of interest are not totally independent of each other. For example, the ambient conditions at the supply air location are different than those at the mixed air location for a building in New York; however, the difference could be greater or less if the building were at a different geographical location. The parametric studies are therefore structured in a progressive manner to present this interdependency. The effect of the design strategy will be studied first. The design strategy of a worst case will then be applied to the two installation locations for an implementation in New York to contrast the effect that is due to installation locations. The implementations at those two installation locations will then be applied to the three geographical locations to demonstrate the effect of climate on UVGI systems.

4.3 Variations in value of design parameters

The parametric studies discussed in the previous section depend on a number of key assumed values, notably the rate constant of the target microorganism, the design inactivation efficiency, and a number of economic assumptions. A variation in these values will have an impact on performance and cost, issues that are briefly discussed in the following sections will be further addressed in Chapter 8.

4.3.1 Variation in inactivation efficiency and rate constant

Based on the case with the UVGI system designed for the worst case design strategy and installed at the supply air in the hypothetical building in New York, an analysis to study the impact of the aforementioned variations was performed. The intent is to answer questions such as how much more energy is required if a more resistant microorganism is the target, or what would be the potential cost if a higher inactivation efficiency is desired.
The reference UVGI system (a typical system suggested by the vendor) is designed to inactivate a target microorganism with a rate constant of 0.0035 cm$^2$/µJ at an efficiency of 85%. The performance and life-cycle cost of the systems designed for a higher or lower inactivation efficiency is investigated. The higher and lower bound of the inactivation efficiency are set arbitrarily at 98% (suggested by the vendor) and 70% respectively.

The performance of the reference system, which is challenged by an arbitrary resistive microorganism with a rate constant of 0.0005 cm$^2$/µJ and an arbitrary susceptible microorganism with a rate constant of 0.05 cm$^2$/µJ, is investigated. On the other hand, the life-cycle costs of the systems that are able to handle the resistive microorganism and the susceptible microorganism at a design efficiency of 85% are also estimated. Microorganisms that are more susceptible than \textit{N. meningitidis}, a widespread pathogen (Kowalski and Bahnfleth, 1998) that has a rate constant of 0.000523 cm$^2$/µJ (Nagy as cited in Kowalski, 2006b), will get inactivated with a higher efficiency for a UVGI system designed for a target microorganism with a rate constant of 0.0005 cm$^2$/µJ. In contrast, most commonly found microorganisms will not be inactivated at the designed efficiency for a device designed for a target microorganism of rate constant of 0.05 cm$^2$/µJ. Table \textbf{4-2} summarizes the studied cases for variations in inactivation efficiency and rate constant.

\begin{table}[h]
\centering
\begin{tabular}{|c|c|c|c|}
\hline
\textbf{Systems designed for} & \textbf{Sensitivity range} & \textbf{performance} & \textbf{life-cycle cost} \\
\hline
k = 0.0035 cm$^2$/µJ & $\eta_{UVGI} = 70\% – 98\%$ & ✓ & ✓ \\
\hline
$\eta_{UVGI} = 85\%$, k = 0.0035 cm$^2$/µJ & challenged by k = 0.05 — 0.0005 cm$^2$/µJ & ✓ & \\
\hline
$\eta_{UVGI} = 85\%$ & designed for k = 0.05 — 0.0005 cm$^2$/µJ & ✓ & \\
\hline
\end{tabular}
\caption{Analyses for variation in inactivation efficiency and rate constant.}
\end{table}
4.3.2 Sensitivity of economic assumptions

The annualized life-cycle cost can be estimated with Equation 4-1. The installation and replacement costs are provided by the vendor based on the performance requirement. The power input to the UVGI system is also provided by the vendor, and is used to calculate the total energy consumption (including heating / cooling / fan impacts), and the corresponding energy cost. All inputs to the life-cycle cost have associated uncertainties. UVGI systems designed by different vendors or with different lamps, or marketed through different channels can have an impact on installation (I), replacement (R), and base energy (W) costs. Energy cost projections based on fuel price indices (Ei) are dependent on the accuracy of the indices themselves. The discount rate used to calculate the present worth and annualized cost is yet another factor of uncertainty. Table 4-3 summarizes the assumed values of inputs and the corresponding sensitivity ranges that are applied for the economic analysis.

Table 4-3: Assumed values and sensitivity ranges of economic inputs.

<table>
<thead>
<tr>
<th>Life-cycle cost inputs</th>
<th>Assumed Value</th>
<th>Sensitivity Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Installation cost (I)</td>
<td>$10/W</td>
<td>± 20 %</td>
</tr>
<tr>
<td>Replacement cost (R)</td>
<td>$1/W</td>
<td>± 20 %</td>
</tr>
<tr>
<td>Base energy cost (W)</td>
<td>$0.0977/kWh</td>
<td>± 20 %</td>
</tr>
<tr>
<td>Fuel price indices (Ei)</td>
<td>Table Ca (NIST, 2008)</td>
<td>± 10 %</td>
</tr>
<tr>
<td>Discount rate (r)</td>
<td>3%</td>
<td>± 200 bp (basis point)</td>
</tr>
</tbody>
</table>

The sensitivity ranges are, first of all, arbitrary; they are summarized from the vendors’ suggestions and past experience. The purpose is to illustrate the range of deviation from the predicted life-cycle cost if the input values differ within the sensitivity range from the assumed values. The most extreme cases of deviation from the predicted life-cycle cost will be those when
all of the input values are at either ends of the sensitivity range. There will be countless combinations of cases, with some inputs being more than the assumed values, while others are less. The probability of having inputs deviating from the assumed values is not known, nor is the probability distribution of such deviation. Since the assumed input values are suggested by the vendor, they might not represent typical values for the whole industry. If that is the case, deviation from the assumed values should be treated as uniformly distributed. On the other hand, if the assumed values are indeed typical, deviations can be treated as normally distributed. The commercial quantitative risk analysis package @RISK (Palisade, 2009) is deployed to perform a Monte Carlo simulation. Ranges of values, which are described by the probability distribution, are processed through random sampling into a distribution of possible outcomes.
Chapter 5

Results of the Parametric Study of Design Strategy

The simulation based evaluation procedure for UVGI systems is described in Chapter 3. The parametric study described in Chapter 4 introduces the different parameters that affect the performance and cost of UVGI systems. The first parametric study of design strategy is presented in this chapter.

5.1 Characteristics of the UVGI system

The studied UVGI device (described in Section 4.1.2) is installed at the supply air location of the VAV system of a hypothetical commercial building in New York, and is investigated for different design strategies. Since there is no change in the location of the installation, the ambient conditions do not change for each of the studied design strategies. The choice of design strategy does affect the performance and the cost of the system, however.

5.1.1 Time-varying ambient conditions

Figure 5-1 shows the annual air temperature distribution at the supply air location (downstream of the cooling coils) where the UVGI device is located. Figure 5-2 is a similar plot of air velocity data. The hourly data are presented in a monthly box and whisker format. For each month of data, the line inside the box denotes the median of all the data. The ends of the box identify the 25th and 75th percentile of the data. The lines of the whiskers attached to each end of
the box show the high and low values. Asterisks indicate data outliers, i.e., unique conditions outside the range in which large numbers of data points are distributed.

Figure 5-1: Air temperature at the studied UVGI device location.

Figure 5-2: Air velocity at the studied UVGI device location.
5.1.2 Lamp output

Figure 5-3 shows the impact of air temperature and velocity on lamp output. These data reflect only the lamp ambient condition response and not depreciation. The monthly median hovers around 32%. The extreme values approach a low of 23%. The lowest value occurs in January, when the air temperature can drop to 6.3°C (43°F).

![Seasonal variation in lamp output](image)

Figure 5-3: Seasonal variation in lamp output.

5.1.3 Design parameters of the UVGI system

The UVGI device has to deliver the design dose at the design conditions. Section 3.1.4 presents four possible design strategies that could be deployed depending on performance and cost considerations. Table 5-1 summarizes the design conditions for the four design strategies.

The lamp output varies with the ambient conditions, therefore, UVGI devices that are going to deliver the same dose at different design conditions require different power input.

According to the “average condition” sizing strategy, the design condition for the hypothetical
example is 10.1°C (50.2°F) at 1.7 m/s (340 fpm), at which the lamp output is 31.7%. At the design velocity, the exposure time calculated is 0.44 s.

According to Equation 3-1, a design dose of 542 µJ/cm² is required to inactivate 85% ($S=0.15$) of *S. aureus* in a single-pass through the UVGI device. If the device is designed to deliver a dose of 542 µJ/cm² at the design conditions with an exposure time of 0.44 s and a lamp output of 31.7%, then the device has to deliver a nominal spherical irradiance (fluence rate) of 3,869 µW/cm² at the rated output (at a lamp output of 100%). The input power required to operate such a UVGI device is estimated based on information provided by the vendor for similar devices. The input power required to implement UVGI systems based on the four design strategies is summarized in Table 5-1.

Table 5-1: Design parameters for different design strategies.

<table>
<thead>
<tr>
<th>Design parameters</th>
<th>Average condition</th>
<th>Worst case</th>
<th>99th percentile</th>
<th>Vendor selection conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature, °C (°F)</td>
<td>10.1 (50.2)</td>
<td>10.8 (51.4)</td>
<td>10.7 (51.3)</td>
<td>10.0 (50.0)</td>
</tr>
<tr>
<td>Velocity, m/s (fpm)</td>
<td>1.7 (340)</td>
<td>2.7 (540)</td>
<td>2.5 (500)</td>
<td>2.5 (500)</td>
</tr>
<tr>
<td>Exposure time (s)</td>
<td>0.44</td>
<td>0.28</td>
<td>0.3</td>
<td>0.3</td>
</tr>
<tr>
<td>Lamp Output (%)</td>
<td>31.7</td>
<td>29.5</td>
<td>29.9</td>
<td>27.8</td>
</tr>
<tr>
<td>Fluence rate (µW/cm²)</td>
<td>3,869</td>
<td>6,455</td>
<td>5,859</td>
<td>6,401</td>
</tr>
<tr>
<td>Input Power (W)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>W/m²</td>
<td>428</td>
<td>713</td>
<td>647</td>
<td>707</td>
</tr>
<tr>
<td>W/ft²</td>
<td>0.18</td>
<td>0.30</td>
<td>0.27</td>
<td>0.30</td>
</tr>
<tr>
<td></td>
<td>0.017</td>
<td>0.028</td>
<td>0.025</td>
<td>0.028</td>
</tr>
</tbody>
</table>
5.2 Performance evaluation

The design inactivation efficiency, $\eta_{UVGI}$ is set to be 85%. In reality, for a VAV system, a constant inactivation efficiency cannot be maintained because both lamp output and exposure time vary with airflow rate. The lamp output is in direct correspondence with the ambient conditions; that is, any combination of ambient conditions can be translated into a corresponding lamp output. However, the single-pass inactivation efficiency of the device depends on how it was originally designed.

5.2.1 Inactivation efficiency

Figure 5-4 depicts the annual profile of the inactivation efficiency of the studied UVGI device sized for both the average condition design strategy and the worst case design strategy.

Figure 5-4: Inactivation efficiency, devices designed for average and worst cases.
Recalling that the design target is 85%, it is clear that the system designed for average conditions generally meets the requirements during the winter but falls short during the summer — yet the low median is still above 75%. However, the system designed for the worst case meets the requirement year round.

Depreciation progressively reduces lamp output over time. When the depreciation effects shown in Figure 2-4 are included in the simulation, the outcome in terms of inactivation efficiency is worse. Some vendors size their systems based on the fully depreciated value.

Figure 5-5 shows the duration curves of inactivation efficiency for several UVGI design strategies without considering the depreciation effect. A duration curve shows the distribution of a quantity of interest plotted against the fraction of time that a given value is exceeded. The value at 0% is never exceeded but the value at 100% is always exceeded.

![Duration curves of inactivation efficiency for different design strategies.](image)

Figure 5-5: Duration curves of inactivation efficiency for different design strategies.

From Figure 5-5 it is clear that the average condition design strategy fails to deliver the design inactivation efficiency for roughly 30% of operating hours, while the worst case design strategy fulfills and exceeds the inactivation efficiency requirement year round. The 99th percentile design strategy meets the target as intended. Its adoption depends on how critical
the mission is and how much the cost element is factored in. Vendor selection conditions come very close to the worst case in this example, but may be under or over sized in other cases.

5.2.2 Space microorganism concentration

The performance of UVGI systems can be expressed in terms of the reduction of the microorganism concentration in space relative to other air-cleaning mechanisms. The minimum requirement of ASHRAE Standard 62.1 (2007) for outdoor air ventilation and particulate filtration can be taken as the reference case that defines the scale factor for the normalized concentration. Common air treatment practices include the deployment of elevated ventilation and higher-level filtration. For demonstration purposes, the space concentrations of the following air treatment scenarios are compared:

2. The addition of the UVGI system at an inactivation efficiency of 85% designed with the worst case design strategy.
3. The elevated ventilation rate with 30% more outdoor air than the requirement of ASHRAE Standard 62.1 (2007).
4. The addition of a higher-level MERV 12 filter.

Figure 5-6 depicts a typical day of normalized space microorganism concentration resulting from the distributed, occupied-hour release of S. aureus under different air treatment scenarios for the summer (July 16). The elevated ventilation, as shown in the figure, does not reduce the space concentration as much as the UVGI system or the enhanced filtration. The UVGI system rated at 85% inactivation efficiency provides a similar reduction to that of MERV 12 filtration.
Figure 5-6: Space concentration for various air treatment scenarios on July 16.

Figure 5-7 is a similar plot for a typical day in the winter (January 23). The seasonal concentration results suggest that microorganisms are not being removed as quickly in the winter as in the summer regardless of air treatment mechanisms. Although the inactivation efficiency is higher in the winter than in the summer as indicated by Figure 5-4, the airflow rate is in fact much lower in the winter (Figure 5-2). As observed from Equation 3-4, the OA air-change rate \( \frac{Q}{V} \) indeed has a profound direct impact on microorganism concentration in a space.

Figure 5-7: Space concentration for various air treatment scenarios on January 23.
Figure 5-8 (a) and (b) depict a typical day of normalized space microorganism concentration under the four studied design strategies for summer (July 16) and winter (January 23) respectively. The space concentration difference among different design strategies is small. Due to the higher air-change rate, the space concentration is lower in the summer than in the winter for all four design strategies.

Figure 5-8: Space concentration, different design strategies, summer (a), winter (b).

Figure 5-9 shows the duration curves of normalized space concentration during occupied hours for the reference case and other air treatment cases. Elevated ventilation provides marginal concentration reduction over the reference case. Both the enhanced filtration and the UVGI system perform similarly and reduce space concentration to about half of the reference case value year round.
As observed from Figure 5-5, the difference in inactivation efficiency among different design strategies is small, with the only exception being the average condition design strategy. It is expected that the concentration reduction performance follows a similar pattern as presented in Figure 5-10, since the airflow conditions are the same across different design strategies.

Figure 5-9: Duration curves of space concentration among various air treatment cases.

Figure 5-10: Duration curves of space concentration among different design strategies.
Figure 5-11 demonstrates how a normalized CADR can be used as an alternative metric to reflect the reduction of microorganism concentration in a space. The normalized CADR of the system designed for the average condition is consistently lower than that of the systems designed for other design strategies by a large margin. Space concentration as depicted in Figure 5-10 follows a similar pattern of the reciprocal of CADR, since the higher the CADR, the lower the concentration. Caution has to be taken to interpret the similarity, since normalized CADR do not consider the cumulative effect as space concentration does. Normalized CADR only reflects the single pass reduction capability.

![Normalized CADR Duration Curves](image)

Figure 5-11: Duration curves of normalized CADR among different design strategies.

### 5.3 Life-cycle cost analysis

The previous section demonstrates that UVGI systems implemented for different design strategies will provide different levels of performance. A higher level of performance will inevitably require a higher cost to install and operate. Life-cycle cost is an important factor in deciding whether the selection of a certain performance level is cost justified.
5.3.1 Energy consumption and cost

The input power (as presented in Table 5-1) to operate the lamps cause direct energy consumption (input power multiplied by the hours of operation). Heat is dissipated from the lamps and is treated as an additional internal load to the building energy analysis model to simulate the indirect energy consumption due to increased cooling and fan load (or reduced heating load).

A UVGI device with a target inactivation rate of 85% for \textit{S. aureus} of 1 µm in diameter is interpreted as equivalent to a filter rated at MERV 12 as shown in Figure 2-5. An additional pressure drop of 250 Pa (1” w.g.) is added to the supply air path of the building energy analysis model. The additional fan energy consumption and its effect on cooling/heating for the whole year is estimated.

Table 5-2 summarizes the simulated results of the effect of the input power on HVAC system energy consumption by both direct and indirect means. The associated cost is calculated based on the electricity rate of the base year.

The annual energy cost for the UVGI operation varies from $0.12 to $0.19/m² ($0.011–$0.017/ft²). Enhanced filtration that provides a similar concentration reduction capability for \textit{S. aureus} to 85% efficiency of the UVGI system (as shown in Figure 5-6) costs more to operate at over $1/m² ($0.1/ft²). The total energy consumption of the studied building for the reference case was 1.8 GWh, as the addition of the UVGI system increased the total energy consumption by no more than 0.3%.
Table 5-2: Annual energy consumption and cost for different design strategies.

<table>
<thead>
<tr>
<th>Annual Energy Consumption</th>
<th>Design strategies</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Average condition</td>
<td>Worst case</td>
</tr>
<tr>
<td>Power to lamps (kWh)</td>
<td>3,745</td>
<td>6,249</td>
</tr>
<tr>
<td>Cooling (kWh)</td>
<td>775</td>
<td>1,300</td>
</tr>
<tr>
<td>Fan (kWh)</td>
<td>275</td>
<td>450</td>
</tr>
<tr>
<td>Heating-electric (kWh)</td>
<td>–1,971</td>
<td>–3,378</td>
</tr>
<tr>
<td>Net (kWh)</td>
<td>2,824</td>
<td>4,621</td>
</tr>
<tr>
<td>kWh/m²</td>
<td>1.19</td>
<td>1.94</td>
</tr>
<tr>
<td>kWh/ft²</td>
<td>0.11</td>
<td>0.18</td>
</tr>
<tr>
<td>Cost ($)</td>
<td>276</td>
<td>452</td>
</tr>
<tr>
<td>$/m²</td>
<td>0.12</td>
<td>0.19</td>
</tr>
<tr>
<td>$/ft²</td>
<td>0.011</td>
<td>0.018</td>
</tr>
</tbody>
</table>

5.3.2 Annualized life-cycle cost

Table 5-3 presents the annualized LCC results for the UVGI system or equivalent filtration as the total costs for the building. The costs per unit area are presented in Table 5-4. The cost data and the methodology used to calculate the annualized life-cycle cost are outlined in Section 4.1.3.
The lifetime energy cost accounts for only 25% of the total cost of the UVGI operation irrespective of design strategies, whereas the lifetime energy cost for the MERV 12 filtration is more than half the total life-cycle cost.

Table 5-3: Annualized life-cycle cost for different design strategies.

<table>
<thead>
<tr>
<th>Annualized Life-cycle Cost [$]</th>
<th>Design strategies</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Average condition</td>
<td>Worst case</td>
<td>99th percentile</td>
<td>Vendor selection conditions</td>
</tr>
<tr>
<td>Installation</td>
<td>358</td>
<td>598</td>
<td>542</td>
<td>593</td>
</tr>
<tr>
<td>Replacement</td>
<td>428</td>
<td>713</td>
<td>647</td>
<td>707</td>
</tr>
<tr>
<td>Energy</td>
<td>255</td>
<td>417</td>
<td>377</td>
<td>412</td>
</tr>
<tr>
<td>Total</td>
<td>1,041</td>
<td>1,728</td>
<td>1,566</td>
<td>1,712</td>
</tr>
</tbody>
</table>

Table 5-4: Annualized life-cycle cost per unit area for different design strategies.

<table>
<thead>
<tr>
<th>Annualized Life-cycle Cost per unit area [$/m² ($/ft²)]</th>
<th>Design strategies</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Average condition</td>
<td>Worst case</td>
<td>99th percentile</td>
<td>Vendor selection conditions</td>
</tr>
<tr>
<td>Installation</td>
<td>0.15 (0.014)</td>
<td>0.25 (0.023)</td>
<td>0.23 (0.021)</td>
<td>0.25 (0.023)</td>
</tr>
<tr>
<td>Replacement</td>
<td>0.18 (0.017)</td>
<td>0.30 (0.028)</td>
<td>0.27 (0.025)</td>
<td>0.30 (0.028)</td>
</tr>
<tr>
<td>Energy</td>
<td>0.11 (0.010)</td>
<td>0.18 (0.016)</td>
<td>0.16 (0.015)</td>
<td>0.17 (0.016)</td>
</tr>
<tr>
<td>Total</td>
<td>0.44 (0.041)</td>
<td>0.73 (0.067)</td>
<td>0.66 (0.061)</td>
<td>0.72 (0.067)</td>
</tr>
</tbody>
</table>
5.3.3 Potential IAQ benefit

Both the UVGI systems and the MERV 12 filtration reduce the relative risk of infection, according to the method of Fisk et al. (2005), to less than half that of the reference case (Figure 5-12). Similar reduction is provided by systems of different design strategies with system sized for the average condition being the only exception.

Figure 5-12: Duration curves of relative risk for different design strategies.

The reference case assumes 7 days of sick leave per person at a wage of $200 per day. If a relative risk of 43% is observed throughout the year, then the number of days of sick leave is reduced to 3 days. In other words, the 4 day reduction in sick leave can be translated into a health benefit of $800 per person.

Table 5-5 summarizes the potential health benefit per unit area and per person. However, it is difficult to make an investment decision based on a cost-benefit analysis since the claimed benefits are of an order of magnitude greater than the costs, regardless of the choice of air treatment mechanisms.
Table 5-5: Annual IAQ benefit as a result of lower relative risk for different design strategies.

<table>
<thead>
<tr>
<th>Air treatment mechanisms</th>
<th>Health benefit, $/m² ($/ft²)</th>
<th>Health benefit, $/person</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average condition</td>
<td>51.7 (4.8)</td>
<td>962</td>
</tr>
<tr>
<td>Worst case</td>
<td>53.4 (5.0)</td>
<td>994</td>
</tr>
<tr>
<td>99th percentile</td>
<td>53.2 (4.9)</td>
<td>990</td>
</tr>
<tr>
<td>Vendor selection</td>
<td>53.4 (5.0)</td>
<td>993</td>
</tr>
<tr>
<td>MERV 12 filtration</td>
<td>51.6 (4.8)</td>
<td>960</td>
</tr>
</tbody>
</table>
Chapter 6

Results of the Parametric Study of Installation Locations

The parametric study presented in the preceding chapter studied the impact of different design strategies for a device installed at the supply air location. The parametric study of installation locations at the supply air and mixed air is presented in this chapter.

6.1 Characteristics of the UVGI system

The studied UVGI device (as described in Section 4.1.2) is investigated at both the supply air and mixed air locations of the VAV system of a hypothetical commercial building in New York. The ambient conditions are quite different between the two studied installation locations. The choice of installation location affects the performance and cost of the system. The worst case design strategy will be deployed for this parametric case.

6.1.1 Time-varying ambient conditions

Figure 6-1 shows the annual air temperature distribution at both the supply air location (downstream of the cooling coils) and the mixed air location (upstream of the cooling coils). It can be observed that the air temperature varies greatly at the mixed air location since a portion of the mixed air (amount of minimum outdoor air quantity prescribed by ASHRAE Standard 62.1) is unconditioned; the temperature approaches 6°C (43°F) in the winter and reaches 27°C (81°F) in the summer and fluctuates widely within the day and during the month. In comparison, the temperature at the supply air hovers within a much narrower range.
Figure 6-1: Air temperature at mixed and supply air locations.

Figure 6-2 presents the air velocity data. The same airstream draws through both the supply air and the mixed air locations; therefore, the same air velocity is expected since the cross-sectional area at both locations of the AHU remains the same.

Figure 6-2: Air velocity at mixed and supply air locations.
6.1.2 Lamp output

Figure 6-3 depicts the lamp output responses corresponding to the different ambient conditions as experienced at the two installation locations. The narrower range of temperature at the supply air location allows a relatively stable lamp output. On the other hand, the huge fluctuation in temperature at the mixed air location causes a much wider range of lamp output. However, it can be observed that the higher temperature experienced at the mixed air location, especially during the summer months, allows the lamps to operate at much higher output.

![Figure 6-3: Seasonal variation in lamp output at mixed and supply air locations.](image)

6.1.3 Design parameters of the UVGI system

The lamp output varies with the design conditions; therefore, UVGI devices that are going to deliver the same dose at different design conditions require different input power. Table 6-1 summarizes the design parameters and input power for UVGI devices sized by the worst case design strategy at the two installation locations. The design conditions for each implementation are also provided.
6.2 Performance evaluation

The inactivation efficiency is a function of both lamp output and exposure time. The lamp output is in direct correspondence to the ambient conditions, which are quite different between the two installation locations.

6.2.1 Inactivation efficiency

The UVGI devices are sized for the worst case conditions. They are 10.8°C (51.4°F) at 2.7 m/s (540 fpm) and 6.3°C (43.3°F) at 1.5 m/s (300 fpm) for the supply air and mixed air locations, respectively. As shown by Figures 6-1 and 6-2, the device at the supply air location is sized for the design conditions in the summer, while the device at the mixed air location is sized for the conditions in the winter.

<table>
<thead>
<tr>
<th>Design parameters</th>
<th>Installation locations</th>
<th>Supply air</th>
<th>Mixed air</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature, °C (°F)</td>
<td>10.8 (51.4)</td>
<td>6.3 (43.3)</td>
<td></td>
</tr>
<tr>
<td>Velocity, m/s (fpm)</td>
<td>2.7 (540)</td>
<td>1.5 (300)</td>
<td></td>
</tr>
<tr>
<td>Exposure time (s)</td>
<td>0.28</td>
<td>0.52</td>
<td></td>
</tr>
<tr>
<td>Lamp Output (%)</td>
<td>29.5</td>
<td>23.3</td>
<td></td>
</tr>
<tr>
<td>Fluence rate (µW/cm²)</td>
<td>6,455</td>
<td>4,480</td>
<td></td>
</tr>
<tr>
<td>Input Power (W)</td>
<td>713</td>
<td>495</td>
<td></td>
</tr>
<tr>
<td>W/m²</td>
<td>0.30</td>
<td>0.21</td>
<td></td>
</tr>
<tr>
<td>W/ft²</td>
<td>0.028</td>
<td>0.019</td>
<td></td>
</tr>
</tbody>
</table>

Table 6-1: Design parameters of devices installed at mixed and supply air locations.
Figure 6-4 depicts the annual profile of the inactivation efficiency of the hypothetical UVGI device installed at the supply air and the mixed air locations. The inactivation efficiency is the lowest at the design conditions (for the worst case design strategy), and is higher for other times. Therefore, UVGI devices perform better at the mixed air location, especially during the summer, at least for this hypothetical case. Since the worst case design strategy is deployed, the design inactivation efficiency target of 85% is achieved all the time.

Figure 6-4: Inactivation efficiency for devices installed at mixed and supply air locations.

Figure 6-5 shows the duration curves of the inactivation efficiency for the devices installed at the supply air and the mixed air locations. The inactivation efficiency for the device at the mixed air is higher than that of the supply air, since the temperature at the mixed air is in general much warmer than that of the supply air, and thus provides a more favorable operation environment for the UV lamps. Since mixed air conditions are significantly affected by variation in outdoor air conditions, a UVGI device installed in a building at another geographical location might not pose the same advantage as depicted in this example, and has to be studied accordingly.
6.2.2 Space microorganism concentration

The device installed at the mixed air operates at a higher inactivation efficiency, thus maintaining a lower space concentration than that of the device installed at the supply air year round as shown in Figure 6-6. Since the space concentration reduction effect is cumulative, the air-change rate ($Q/V$) plays an important role in assisting the reduction process. The air-change rate is the same among the two installation locations; therefore, the difference between the two space concentration curves is more subtle than that between the two $\eta_{UVGI}$ curves.

Figure 6-5: Duration curves of $\eta_{UVGI}$ for devices installed at mixed and supply air locations.

Figure 6-6: Duration curves of space concentration for systems installed at mixed and supply air locations.
Presented in Figure 6-7, normalized CADR reflects the single pass air-cleaning capability of the UVGI device. If one UVGI device has a higher normalized CADR than the other for most of the hours, as in the case of the device installed at the mixed air location compared to that at the supply air location, the space concentration maintained by that device should be lower (as shown in Figure 6-6). The device is designed to inactivate the target microorganism with a rate constant of $0.0035 \text{ cm}^2/\mu\text{J}$ at 85%. Therefore, the normalized CADR curve as depicted in the figure is only valid in this particular implementation.

![Duration curves of normalized CADR for systems installed at mixed and supply air locations.](image)

**Figure 6-7**: Duration curves of normalized CADR for systems installed at mixed and supply air locations.

### 6.3 Life-cycle cost analysis

Since the ambient conditions are different at the two installation locations, the design parameters are also different; and accordingly, the cost to implement systems with a similar performance level at the two installation locations will be quite different.
6.3.1 Energy consumption and cost

Table 6-2 summarizes the simulated results of the different contributing factors on energy consumption by both direct and indirect means.

Table 6-2: Annual energy consumption and cost of devices installed at mixed and supply air locations.

<table>
<thead>
<tr>
<th>Annual Energy Consumption</th>
<th>Installation locations</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Supply air</td>
</tr>
<tr>
<td>Power to lamps (kWh)</td>
<td>6,249</td>
</tr>
<tr>
<td>Cooling (kWh)</td>
<td>1,300</td>
</tr>
<tr>
<td>Fan (kWh)</td>
<td>450</td>
</tr>
<tr>
<td>Heating-electric (kWh)</td>
<td>–3,378</td>
</tr>
<tr>
<td>Net (kWh)</td>
<td>4,621</td>
</tr>
<tr>
<td>kWh/m²</td>
<td>1.94</td>
</tr>
<tr>
<td>kWh/ft²</td>
<td>0.18</td>
</tr>
<tr>
<td>Cost ($)</td>
<td>452</td>
</tr>
<tr>
<td>$/m²</td>
<td>0.19</td>
</tr>
<tr>
<td>$/ft²</td>
<td>0.018</td>
</tr>
</tbody>
</table>

Due to the fact that the ambient conditions are more favorable at the mixed air location for this hypothetical case, the UVGI implementation at this location can be sized with fewer lamps and operated with less energy.
6.3.2 Annualized life-cycle cost

Tables 6-3 and 6-4 present the annualized LCC results for the UVGI systems at both installation locations as the total costs for the building and as the costs per unit area, respectively.

Table 6-3: Annualized life-cycle cost of devices installed at mixed and supply air locations.

<table>
<thead>
<tr>
<th>Annualized Life-cycle Cost [$]</th>
<th>Installation locations</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Supply air</td>
<td>Mixed air</td>
</tr>
<tr>
<td>Installation</td>
<td>598</td>
<td>415</td>
</tr>
<tr>
<td>Replacement</td>
<td>713</td>
<td>495</td>
</tr>
<tr>
<td>Energy</td>
<td>417</td>
<td>303</td>
</tr>
<tr>
<td>Total</td>
<td>1,728</td>
<td>1,213</td>
</tr>
</tbody>
</table>

Table 6-4: Annualized life-cycle cost per unit area of devices installed at mixed and supply air locations.

<table>
<thead>
<tr>
<th>Annualized Life-cycle Cost per unit area [$/m² (S/ft²)]</th>
<th>Installation locations</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Supply air</td>
</tr>
<tr>
<td>Installation</td>
<td>0.25 (0.023)</td>
</tr>
<tr>
<td>Replacement</td>
<td>0.30 (0.028)</td>
</tr>
<tr>
<td>Energy</td>
<td>0.18 (0.016)</td>
</tr>
<tr>
<td>Total</td>
<td>0.73 (0.067)</td>
</tr>
</tbody>
</table>
6.3.3 Potential IAQ benefit

As illustrated in Figure 6-8, the relative risk of infection does not differ much between UVGI systems installed at the two installation locations.

Due to the similarity in the relative risk, the potential benefits as presented in Table 6-5 are nearly the same for the systems installed at the two locations. For this particular case, it might be worthwhile to consider installation at the mixed air location for its lower life-cycle cost and slightly better performance.

Table 6-5: Annual IAQ benefit as a result of lower relative risk of devices installed at mixed and supply air locations.

<table>
<thead>
<tr>
<th>Installation locations</th>
<th>Health benefit, $/m² ($/ft²)</th>
<th>Health benefit, $/person</th>
</tr>
</thead>
<tbody>
<tr>
<td>Supply air</td>
<td>53.4 (5.0)</td>
<td>994</td>
</tr>
<tr>
<td>Mixed air</td>
<td>53.8 (5.0)</td>
<td>1,000</td>
</tr>
</tbody>
</table>
Chapter 7

Results of the Parametric Study of Geographical Locations

The performance and cost of operating UVGI systems in different geographical locations with distinct climates are discussed in this chapter. As demonstrated in the preceding chapter, ambient conditions at the supply air and mixed air locations differ greatly for the installation in New York. Since ambient conditions closely depend on the climatic conditions, geographical locations further complicate the effect of installation locations. For example, temperature at the mixed air location will differ greatly for buildings in different geographical locations, since a portion of the mixed air is unconditioned outdoor air; however, the temperature at the supply air location of a VAV system (for buildings in different climates) should differ by a smaller margin since the air is conditioned to a defined temperature range. On the other hand, the air velocity could differ significantly with geographical locations as the VAV system adjusts its conditioning capacity by throttling the airflow.

7.1 Characteristics of the UVGI system

The studied UVGI device (as described in Section 4.1.2) was investigated for both the supply air and mixed air locations of the VAV system of the hypothetical commercial building in three climatically distinct U.S. locations: New York, Houston, and Los Angeles. The ambient conditions vary greatly among the three locations.
7.1.1 Time-varying ambient conditions

Table 7-1 presents the summary statistics of the air temperature at both the supply air and mixed air locations at the three geographical locations. At the supply air location, the temperature hovers within a limited range centered around 10°C (50°F) with a small standard deviation for all three geographical locations. In contrast, the temperature at the mixed air location varies in a range as wide as 21°C (37°F) in New York, and approaches 6°C (43°F) during the winter.

Table 7-1: Summary statistics of the supply and mixed air temperature at three geographical locations.

<table>
<thead>
<tr>
<th>Temperature, °C (°F)</th>
<th>Supply Air</th>
<th></th>
<th>Mixed Air</th>
</tr>
</thead>
<tbody>
<tr>
<td>New York</td>
<td>Houston</td>
<td>Los Angeles</td>
<td>New York</td>
</tr>
<tr>
<td>Minimum</td>
<td>6.3 (43.3)</td>
<td>9.4 (49.0)</td>
<td>9.8 (49.7)</td>
</tr>
<tr>
<td>Maximum</td>
<td>10.9 (51.6)</td>
<td>10.9 (51.7)</td>
<td>10.9 (51.6)</td>
</tr>
<tr>
<td>Mean</td>
<td>10.1 (50.2)</td>
<td>10.4 (50.7)</td>
<td>10.4 (50.6)</td>
</tr>
<tr>
<td>Std. dev.</td>
<td>0.4 (0.7)</td>
<td>0.3 (0.5)</td>
<td>0.2 (0.4)</td>
</tr>
</tbody>
</table>

Figure 7-1 shows the annual air temperature distribution at the supply air location at the three geographical locations. The monthly box and whisker plots present the annual temperature profiles. There are little variation among months at all three geographical locations, with the only exception being the case of winter in New York, in which temperature could go as low as 6.2°C (43.2°F). These occasional outliers happen since the HVAC systems are designed to satisfy most conditions but have some unmet hours if the conditions are more extreme than the design.
Figure 7-1: Supply air temperature for buildings in three geographical locations.

Figure 7-2 (a), (b), and (c) show the annual air temperature distribution at the mixed air locations for the buildings in New York, Houston, and Los Angeles, respectively. The temperature distribution at the mixed air location differs greatly with geographical location. In a milder climate, Los Angeles varies within a narrower temperature range (~10°C, or 18°F) year round.

Figure 7-2: Mixed air temperature for buildings in three geographical locations.
Table 7-2 presents the summary statistics of the air velocity for the buildings in New York, Houston, and Los Angeles, respectively for both installation locations, since the cross-sectional area of the AHU at both locations is the same.

Figure 7-2 (continued): Mixed air temperature for buildings in three geographical locations.
Table 7-2: Summary statistics of the air velocity at three geographical locations.

<table>
<thead>
<tr>
<th>Velocity, m/s (fpm)</th>
<th>New York</th>
<th>Houston</th>
<th>Los Angeles</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum</td>
<td>1.5 (300)</td>
<td>1.4 (280)</td>
<td>1.6 (320)</td>
</tr>
<tr>
<td>Maximum</td>
<td>2.7 (540)</td>
<td>2.6 (520)</td>
<td>2.6 (520)</td>
</tr>
<tr>
<td>Mean</td>
<td>1.7 (340)</td>
<td>1.8 (360)</td>
<td>1.9 (380)</td>
</tr>
<tr>
<td>Std. dev.</td>
<td>0.3 (60)</td>
<td>0.3 (60)</td>
<td>0.2 (40)</td>
</tr>
</tbody>
</table>

Figures 7-3 (a), (b), and (c) show air velocity data presented in box and whisker format.

During the winter months, heating load is predominant in New York, and thus much less airflow is required than in the summer. The air velocity distribution profiles are very similar for Houston and Los Angeles, with that of Los Angeles being narrower in range for its milder weather (see temperature profile).

(a) New York

Figure 7-3: Supply air velocity for buildings in three geographical locations.
(b) Houston

(c) Los Angeles

Figure 7-3 (continued): Supply air velocity for buildings in three geographical locations.
7.1.2 Lamp output

For all geographical locations, supply air temperatures are close to 10°C (50°F) most of the time and air velocities range from 1.5 to 2.3 m/s (300 to 460 fpm); within this range, lamp outputs for the devices installed at all three geographical locations are similar and the monthly medians are around 32% as presented in Figure 7-4. As observed from Figure 7-1, there are occasional low temperatures in January and February for the device installed in New York; therefore, lamp output in New York can drop below 30% for a limited number of hours. Lamp outputs for the other two geographical locations are similarly distributed across all twelve months.

![Figure 7-4: Duration curves of lamp output at supply air for three geographical locations.](image)

At the mixed air location, lamps are subjected to the same air velocity profile as at the supply air location, but with a much wider range of temperature for all three geographical locations. New York experiences a wider range of temperature (21°C, or 37°F, as presented in Table 7-1) while Los Angeles encounters a narrower one (10°C, or 18°F), causing Los Angeles to have the least variation in lamp output. Figure 7-5 presents the duration curves of lamp output at the mixed air location. Regardless of geographical influences, the mixed air location is subjected to double-digit variation verse single-digit for the supply air location.
7.1.3 Design parameters of the UVGI system

The systems presented in this parametric study are all sized by the worst case design strategy. The design conditions and parameters at the supply air location for the three geographical locations are summarized in Table 7-3. The worst case conditions are those at which the combination of temperature and velocity yields the worst inactivation efficiency. Since both the temperature and lamp output ranges are similar among the three geographical locations at the supply air location, and the velocities reach similar maxima at around 2.6 m/s (520 fpm), the design conditions and parameters (for the worst case) are therefore very similar for the three locations. With short exposure time and low lamp output at the design conditions, devices at the supply air location have to be sized larger relative to the mixed air location.
Installation at the mixed air location is subjected to a greater variation in temperature. As a result, lamp output can range from 20% to 80%. Over such a great range, the worst case may not occur at the highest velocity, but at the velocity that the combination of lamp output and velocity yields the worst inactivation efficiency. Such is the case for New York and Houston, where the worst case happens at a rather low velocity of 1.5 m/s (300 fpm). The lower velocity permits a longer exposure time and thus allows the systems to be sized smaller yet provides the same design dose at the design airflow and temperature.

Table 7-3: Design parameters for installations at supply air for three geographical locations.

<table>
<thead>
<tr>
<th>Design parameters</th>
<th>Geographical locations</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>New York</td>
</tr>
<tr>
<td>Temperature, °C (°F)</td>
<td>10.8 (51.4)</td>
</tr>
<tr>
<td>Velocity, m/s (fpm)</td>
<td>2.7 (540)</td>
</tr>
<tr>
<td>Exposure time (s)</td>
<td>0.28</td>
</tr>
<tr>
<td>Lamp Output (%)</td>
<td>29.5</td>
</tr>
<tr>
<td>Fluence rate (µW/cm²)</td>
<td>6,455</td>
</tr>
<tr>
<td>Input Power (W)</td>
<td>713</td>
</tr>
<tr>
<td></td>
<td>W/m²</td>
</tr>
<tr>
<td></td>
<td>W/ft²</td>
</tr>
</tbody>
</table>
Table 7-4 summarizes the design conditions and parameters at the mixed air location for the three geographic locations. A warmer climate in Los Angeles allows lamps to be operated at a much higher output in the worst case; therefore, much less power is needed to provide the same dose. The input power designed for the device in Los Angeles is roughly half that of New York. The effect of the geographic locations is more pronounced at the mixed air location.

Table 7-4: Design parameters for installations at mixed air for three geographical locations.

<table>
<thead>
<tr>
<th>Design parameters</th>
<th>Geographical locations</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>New York</td>
</tr>
<tr>
<td>Temperature, °C (°F)</td>
<td>6.3 (43.3)</td>
</tr>
<tr>
<td>Velocity, m/s (fpm)</td>
<td>1.5 (300)</td>
</tr>
<tr>
<td>Exposure time (s)</td>
<td>0.52</td>
</tr>
<tr>
<td>Lamp Output (%)</td>
<td>23.3</td>
</tr>
<tr>
<td>Fluence rate (µW/cm²)</td>
<td>4,480</td>
</tr>
<tr>
<td>Input Power (W)</td>
<td>495</td>
</tr>
<tr>
<td>W/m²</td>
<td>0.21</td>
</tr>
<tr>
<td>W/ft²</td>
<td>0.019</td>
</tr>
</tbody>
</table>

7.2 Performance evaluation

Since the variation in the supply air lamp output among the three geographical locations is insignificant, as shown in Figure 7-4, it is expected that the performance will follow a similar suit. On the other hand, a variation in lamp output at the mixed air location will cause a variation in performance among geographical locations.
7.2.1 Inactivation efficiency

Figure 7-6 compares the annual distribution of supply air inactivation efficiency among installations in New York (a), Houston (b), and Los Angeles (c). The inactivation efficiency for the installations at the three geographical locations falls within a similar range. The distribution profile of the Los Angeles location, in general, resembles that of Houston with roughly 2% less efficiency. From the duration curves, it can be observed that the single pass inactivation efficiency differs by less than 5% at the supply air among the three geographical locations throughout the whole year. The relatively similar lamp output helps explain the results.

![Inactivation Efficiency Graph](image)

Figure 7-6: Duration curves of supply air $\eta_{UVGI}$ for three geographical locations.

Similar to the results of the lamp output at the mixed air location, the inactivation efficiency also differs greatly among the three geographical locations as presented in Figure 7-7. New York, in general, yields the worst lamp output among the three geographical locations; however, however, it offers the best single-pass inactivation efficiency year-round due to the lower air velocity. On the other hand, Los Angeles exhibits a higher velocity on average; therefore, its overall inactivation efficiency is the lowest among the three. The overall lower and yet flatter inactivation efficiency profile in Los Angeles is, in fact, closest to the design
inactivation efficiency; which implies the devices at other locations are oversized most of the time by providing efficiency much higher than the design value.

7.2.2 Space microorganism concentration

Despite the similarity in the inactivation efficiency among the three locations, the effect on space microorganism concentration does not follow the same pattern. The case of New York is a good example to illustrate the discrepancy. As Figure 7-6 shows, the UVGI device installed at the supply air location in New York outperforms those in the other two geographical locations by consistently having a higher inactivation efficiency. However, it can be observed in Figure 7-8 that the UVGI system at the supply air location in New York presents a higher space concentration than the systems in Houston and Los Angeles. In fact, for a significant period of time, the space concentration for the system in New York is nearly 10% more than that of the other two. In other words, the system in New York is not as efficient in reducing space concentration. A similar plot is provided for the space concentration at the mixed air location for the three geographical locations in Figure 7-9.

Figure 7-7: Duration curves of mixed air $\eta_{UVGI}$ for three geographical locations.
As illustrated in the previous two parametric studies, the air-change rate \( (Q/V) \) has a strong influence on the space concentration. As shown in Figure 7-3, the air velocity (and the airflow rate) for the installation in New York is lower than that of the other two locations; therefore, it hampers the concentration reduction capability. The impact of the air-change rate is further demonstrated by the comparisons in Figures 7-8 and 7-9; even though the inactivation
efficiency profiles are vastly different between the two installation locations, the space concentration profiles differ by less than 5%.

Figures 7-10 and 7-11 present the duration curves of normalized CADR. Albeit that normalized CADR serves well as an indicator of the reduction capability in space concentration for each single pass; it cannot directly predict space concentration since it does not include the cumulative effect.

Figure 7-10: Duration curves of normalized CADR at supply air for three geographical locations.

Figure 7-11: Duration curves of normalized CADR at mixed air for three geographical locations.
Figures 7-12 and 7-13 present the duration curves of effectiveness based on steady-state equations (the results are with ±10% of those based on simulated concentration data). Both effectiveness and normalized CADR reflect the single pass space concentration reduction capability. CADR demonstrates effect of the airflow rate, which is of particular importance if UVGI is to be deployed for a VAV system. On the other hand, effectiveness provides a means to actually quantify the transient concentration in relative terms. It provides a good metric to predict the space concentration reduction capability of the UVGI system with respect to the reference system.

![Figure 7-12: Duration curves of effectiveness at supply air for three geographical locations.](image1)

![Figure 7-13: Duration curves of effectiveness at mixed air for three geographical locations.](image2)
7.3 Life-cycle cost analysis

The design conditions at the supply air location for the three geographical locations do not differ by a significant amount; therefore, the three UVGI systems are sized with a similar number of lamps. On the other hand, the equipment selected at the mixed air location differ greatly among the three geographical locations, but in general require fewer lamps than their counterparts at the supply air location. The designs are presented in Tables 7-3 and 7-4.

7.3.1 Energy consumption and cost

The impact of the operation of UVGI system on the total HVAC system energy consumption at the supply air and mixed air are summarized in Table 7-5 and 7-6, respectively.

Table 7-5: Annual energy consumption and cost at supply air for three geographical locations.

<table>
<thead>
<tr>
<th>Annual Energy Consumption</th>
<th>Geographical locations</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>New York</td>
</tr>
<tr>
<td>Power to lamps (kWh)</td>
<td>6,249</td>
</tr>
<tr>
<td>Cooling (kWh)</td>
<td>1,300</td>
</tr>
<tr>
<td>Fan (kWh)</td>
<td>450</td>
</tr>
<tr>
<td>Heating-electric (kWh)</td>
<td>–3,378</td>
</tr>
<tr>
<td>Net (kWh)</td>
<td>4,621</td>
</tr>
<tr>
<td>kWh/m²</td>
<td>1.94</td>
</tr>
<tr>
<td>kWh/ft²</td>
<td>0.18</td>
</tr>
<tr>
<td>Cost ($)</td>
<td>452</td>
</tr>
<tr>
<td>$/m²</td>
<td>0.19</td>
</tr>
<tr>
<td>$/ft²</td>
<td>0.018</td>
</tr>
</tbody>
</table>
The design conditions for all three systems are nearly identical; as a result, the input power required to operate such systems are very much the same. That is, all the systems are sized for a similar number of lamps. However, the impact of operating such a system as part of the HVAC system is not the same among different systems. The same amount of heat dissipated by the UVGI systems installed at the three geographical locations has a different energy impact on each of the HVAC systems. As observed in Table 7-5, the UVGI system in Houston costs 33% more for energy than in the other two locations, due to the fact that Houston is in a warmer climate, and therefore less heating credit is realized.

The effect of cooling penalty and heating credit is further demonstrated in Table 7-6 for the systems at the mixed air location. The system in New York, though larger than the one in Houston with a higher input power, actually costs less energy to operate, since the system offers higher heating credit in New York than in Houston.

Table 7-6: Annual energy consumption and cost at mixed air for three geographical locations.

<table>
<thead>
<tr>
<th>Annual Energy Consumption</th>
<th>Geographical locations</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>New York</td>
</tr>
<tr>
<td>Power to lamps (kWh)</td>
<td>4,336</td>
</tr>
<tr>
<td>Cooling (kWh)</td>
<td>800</td>
</tr>
<tr>
<td>Fan (kWh)</td>
<td>275</td>
</tr>
<tr>
<td>Heating-electric (kWh)</td>
<td>-2,052</td>
</tr>
<tr>
<td>Net (kWh)</td>
<td>3,359</td>
</tr>
<tr>
<td>kWh/m²</td>
<td>1.41</td>
</tr>
<tr>
<td>kWh/ft²</td>
<td>0.13</td>
</tr>
<tr>
<td>Cost ($)</td>
<td>328</td>
</tr>
<tr>
<td>$/m²</td>
<td>0.14</td>
</tr>
<tr>
<td>$/ft²</td>
<td>0.013</td>
</tr>
</tbody>
</table>
The case of Los Angeles is of particular interest, as it has the lowest energy consumption, which is even less than half that of the other geographical locations. A rather homogeneous airflow and narrower range of lamp output allow the device at the mixed air location in Los Angeles to operate at an inactivation efficiency very close to its design value for the whole year as shown in Figure 7-7. Since the device is designed for the worst case, an inactivation efficiency profile that is not much higher than the design value implies that the device is not over sized, and therefore requires less energy to operate.

### 7.3.2 Annualized life-cycle cost

The annualized life-cycle costs at the supply air location are summarized in Table 7-7 and Table 7-8. For the studied systems, energy cost only constitutes about one third of the total life-cycle cost. The total cost to operate a UVGI system in Houston is still relatively more expensive than in the other two locations, but not by a significant margin since the three devices at the supply air location are sized similarly.

**Table 7-7:** Annualized life-cycle cost of supply air UVGI in three geographical locations.

<table>
<thead>
<tr>
<th>Annualized Life-cycle Cost [$]</th>
<th>Geographical locations</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>New York</td>
</tr>
<tr>
<td>Installation</td>
<td>598</td>
</tr>
<tr>
<td>Replacement</td>
<td>713</td>
</tr>
<tr>
<td>Energy</td>
<td>417</td>
</tr>
<tr>
<td>Total</td>
<td>1,728</td>
</tr>
</tbody>
</table>
Table 7-8: Annualized life-cycle cost per unit area of supply air UVGI in three geographical locations.

<table>
<thead>
<tr>
<th>Annualized Life-cycle Cost per unit area [$/m² ($/ft²)]</th>
<th>Geographical locations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Installation</td>
<td>New York</td>
</tr>
<tr>
<td>0.25 (0.023)</td>
<td>0.24 (0.023)</td>
</tr>
<tr>
<td>Replacement</td>
<td>0.30 (0.028)</td>
</tr>
<tr>
<td>Energy</td>
<td>0.18 (0.016)</td>
</tr>
<tr>
<td>Total</td>
<td>0.73 (0.067)</td>
</tr>
</tbody>
</table>

Tables 7-9 and 7-10 summarize the annualized life-cycle costs of the systems at the mixed air location. Despite the fact that overall energy consumption is the same in New York and in Houston due to the heating credit advantage of the New York system, it is nevertheless bigger by design, and therefore costs more to install and replace. In contrast, the UVGI system at the mixed air location in Los Angeles is the most economical among all six systems studied at different installation and geographical locations. The life-cycle cost is roughly one third of the most expensive system, which is at the supply air location in Houston.

Table 7-9: Annualized life-cycle cost of mixed air UVGI in three geographical locations.

<table>
<thead>
<tr>
<th>Annualized Life-cycle Cost [$]</th>
<th>Geographical locations</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>New York</td>
</tr>
<tr>
<td>Installation</td>
<td>357</td>
</tr>
<tr>
<td>Replacement</td>
<td>495</td>
</tr>
<tr>
<td>Energy</td>
<td>303</td>
</tr>
<tr>
<td>Total</td>
<td>1,155</td>
</tr>
</tbody>
</table>
Table 7-10: Annualized life-cycle cost per unit area of mixed air UVGI in three geographical locations.

<table>
<thead>
<tr>
<th>Annualized Life-cycle Cost per unit area [$/m² ($/ft²)]</th>
<th>Geographical locations</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>New York</td>
</tr>
<tr>
<td>Installation</td>
<td>0.15 (0.014)</td>
</tr>
<tr>
<td>Replacement</td>
<td>0.21 (0.019)</td>
</tr>
<tr>
<td>Energy</td>
<td>0.13 (0.012)</td>
</tr>
<tr>
<td>Total</td>
<td>0.49 (0.045)</td>
</tr>
</tbody>
</table>

The above cost evaluation suggests that regardless of the geographical locations, installation at the mixed air location is more economical. However, due to the fact that the ambient conditions at the mixed air location are more readily influenced by the outdoor climates, and cause greater variation in performance, systems to be installed at the mixed air location should be designed with a simulation-based evaluation procedure to ensure that the required performance is being delivered.

7.3.3 Potential IAQ benefit

Relative risk is a function of both the efficiency of the air treatment mechanism and the air-change rate; it responds similarly as space concentration does to these factors, but to a lesser extent since the relative risk is not a cumulative quantity. Figure 7-14 depicts the duration curves of relative risks for UVGI systems at the supply air location for the three geographical locations. Relative risks for the three locations differ by a small margin. Therefore, the corresponding potential health benefits, presented in Table 7-11, are nearly the same.
Figure 7-14: Duration curves of relative risk at supply air for three geographical locations.

Table 7-11: Annual IAQ benefit as a result of lower relative risk at supply air for three geographical locations.

<table>
<thead>
<tr>
<th>Air treatment mechanisms</th>
<th>Health benefit, $/m² ($/ft²)</th>
<th>Health benefit, $/person</th>
</tr>
</thead>
<tbody>
<tr>
<td>New York</td>
<td>53.4 (5.0)</td>
<td>994</td>
</tr>
<tr>
<td>Houston</td>
<td>54.4 (5.1)</td>
<td>1,012</td>
</tr>
<tr>
<td>Los Angeles</td>
<td>53.9 (5.0)</td>
<td>1,002</td>
</tr>
</tbody>
</table>

Figure 7-15 and Table 7-12, present the duration curve of relative risk and the corresponding health benefits for each of the UVGI systems installed at the mixed air location for the three geographical locations. The relative risk and the health benefits are directly related to microorganism concentration in space. As observed from Figure 7-8 and Figure 9, space concentration as maintained by UVGI systems installed at either the supply or the mixed air location are very similar; therefore the relative risk and the health benefits corresponding to the systems installed at the mixed air closely match those of the supply air.
Figure 7-15: Duration curves of relative risk at mixed air for three geographical locations.

Table 7-12: Annual IAQ benefit as a result of lower relative risk at mixed air for three geographical locations.

<table>
<thead>
<tr>
<th>Air treatment mechanisms</th>
<th>Health benefit, $/m^2 ($/ft^2)</th>
<th>Health benefit, $/person</th>
</tr>
</thead>
<tbody>
<tr>
<td>New York</td>
<td>53.8 (5.0)</td>
<td>1,000</td>
</tr>
<tr>
<td>Houston</td>
<td>54.7 (5.1)</td>
<td>1,017</td>
</tr>
<tr>
<td>Los Angeles</td>
<td>53.3 (5.0)</td>
<td>992</td>
</tr>
</tbody>
</table>
Chapter 8

Discussion

The parametric studies presented in Chapter 5 through 7 are based on simulation results that are valid only for the studied air treatment scenarios. The reference UVGI system presented in the parametric study is a system with 85% single pass inactivation efficiency for a target microorganism with a rate constant of 0.0035 cm$^2$/$\mu$J based on the sizing procedure of a particular manufacturer. The choice of different target microorganisms or inactivation efficiencies will have an impact on the performance or cost of the reference system. Moreover, the reference system is assumed to be designed for the worst case conditions, installed at the supply air location in a VAV system of a specific size in a commercial building located in New York, and operated at the published electricity rate and discount rate. Changing any one of the above specifications will have an impact on installation, replacement, and energy cost. In reality, UVGI systems are expected to operate under a wide range of conditions. Therefore, it is important to investigate the performance and cost of the systems if some of the assumptions are changed.

8.1 Variation in inactivation efficiency

The design inactivation efficiency for the parametric study is assumed to be 85%. A higher efficiency may be required for critical applications such as at hospitals where the disinfection requirement is stringent. Since the inactivation efficiency (complement of survival fraction) and dose relationship is exponential, a multifold increase in UV dose (and cost) only improves the efficiency by a slight margin. The vendor recommends a high limit of 98%
efficiency for most applications because of impact on cost. At the other end of the spectrum, a UVGI system with an inactivation efficiency of 70% is investigated.

8.1.1 Annual profile of inactivation efficiency

The UVGI systems considered were designed for the worst case conditions. Therefore, systems designed for inactivation efficiencies of 70%, 85%, and 98%, respectively, will achieve those values even at the worst conditions. Performance and cost of such systems installed at the supply air location in New York were studied. Figure 8-1 presents the duration curves for systems designed for the three efficiency values.

![Figure 8-1: Duration curves of $\eta_{UVGI}$ for systems designed at different $\eta_{UVGI}$.](image)

It can be observed that a system designed for 98% efficiency, in fact, operates at nearly 100% efficiency for most of the year. For this hypothetical example, a system designed for 70% efficiency operates at more than 85% efficiency nearly 80% of the time. For less stringent applications, systems could in fact be sized for a lower efficiency and investigated through simulation so that a desired efficiency is achieved for a certain amount of time.
8.1.2 Effect on space microorganism concentration

Despite the fact that the higher and lower limit of design inactivation efficiency is nearly 15% different than the reference case, the space microorganism concentrations as maintained by UVGI systems designed for the three cases of inactivation efficiency are within 4% of each other as shown from the duration curves in Figure 8-2.

![Figure 8-2](image_url)

Figure 8-2: Duration curves of space concentration for systems designed at different $\eta_{UVGI}$.

8.1.3 Impact on energy consumption and cost

The design conditions are exactly the same across the three systems. That is, they are all designed for a temperature of 10.8°C (51.4°F) and a velocity of 2.7 m/s (540 fpm). However, the number of UV lamps needed to deliver the UV dose required to achieve the design inactivation efficiency is different for each system. As compared to the 713 W input power for the system with a 85% design efficiency, 453 W and 1471 W of input power are required for the systems with a design efficiency of 70% and 98%, respectively. The impact on the total HVAC system energy consumption is summarized in Table 8-1.
The total energy consumption, and thus energy cost, for the system designed for 98% efficiency is more than double that of the system designed for 85% efficiency. In contrast, the additional reduction of space concentration provided by the system designed for higher efficiency is at most 2.5%, and the additional inactivation efficiency delivered is at most 5% for 80% of the time. On the other hand, the system designed for 70% efficiency costs approximately two thirds that of the reference system and lags behind with a wider performance gap.

### 8.1.4 Annualized life-cycle cost

The annualized life-cycle costs of the UVGI systems are summarized in Table 8-2, and the annualized costs per unit area are summarized in Table 8-3. Systems designed for higher inactivation efficiency require more UV lamps to be installed. Therefore, it is not just the energy cost portion that sees an increase for higher efficiency systems, but also costs in installation and replacement.
The previous illustration might help to explain why an inactivation efficiency of 85% is suggested by the vendor for commercial building application. As observed from Figure 8-2, the additional reduction in space concentration from a system designed for 70% efficiency to 85% efficiency is in the range of 2 to 4%; and from a system designed for 85% efficiency to 98% efficiency is in the range of 0.5 to 2%; the incremental increase in inactivation efficiency does not bring a corresponding amount in reduction in space concentration. In contrast, an 85% efficiency system costs around 50% more than that of a 70% efficiency system, while a 98% efficiency

### Table 8-2: Annualized life-cycle cost for systems designed for different $\eta_{UVGI}$.

<table>
<thead>
<tr>
<th>Annualized Life-cycle Cost [$]</th>
<th>Design inactivation efficiency</th>
<th>98%</th>
<th>85%</th>
<th>70%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Installation</td>
<td>1,232</td>
<td>598</td>
<td>379</td>
<td></td>
</tr>
<tr>
<td>Replacement</td>
<td>1,471</td>
<td>713</td>
<td>453</td>
<td></td>
</tr>
<tr>
<td>Energy</td>
<td>884</td>
<td>417</td>
<td>279</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>3,587</td>
<td>1,728</td>
<td>1,111</td>
<td></td>
</tr>
</tbody>
</table>

### Table 8-3: Annualized life-cycle cost per unit area for systems designed for different $\eta_{UVGI}$.

<table>
<thead>
<tr>
<th>Annualized Life-cycle Cost per unit area [$/m^2 ($/ft^2)]</th>
<th>Design inactivation efficiency</th>
<th>98%</th>
<th>85%</th>
<th>70%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Installation</td>
<td>0.52 (0.048)</td>
<td>0.25 (0.023)</td>
<td>0.16 (0.015)</td>
<td></td>
</tr>
<tr>
<td>Replacement</td>
<td>0.62 (0.057)</td>
<td>0.30 (0.028)</td>
<td>0.19 (0.018)</td>
<td></td>
</tr>
<tr>
<td>Energy</td>
<td>0.37 (0.035)</td>
<td>0.18 (0.016)</td>
<td>0.12 (0.011)</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>1.51 (0.140)</td>
<td>0.73 (0.067)</td>
<td>0.47 (0.044)</td>
<td></td>
</tr>
</tbody>
</table>
system costs more than double that of an 85% efficiency system. A UVGI system designed for 85% efficiency positions itself somewhere between an appreciably more expensive system with marginal performance improvement and a comparatively cheaper system with a notable performance penalty.

8.2 Variation in target microorganism

The reference UVGI system is designed to inactivate 85% of a target microorganism with a rate constant, \( k \), equal to 0.0035 \( \text{cm}^2/\mu \text{J} \) in a single pass. The performance will be affected if the reference system is challenged with either a more susceptible or a more resistive microorganism. On the other hand, if the system is designed for a target microorganism of a different rate constant, the cost will be affected.

8.2.1 Inactivation efficiency and space concentration for non-target microorganisms

The lower and upper bounds of the rate constants are chosen arbitrarily at 0.0005 \( \text{cm}^2/\mu \text{J} \) and 0.05 \( \text{cm}^2/\mu \text{J} \), respectively. Most common microorganisms are more susceptible than the lower bound and more resistive than the upper bound. Common infectious microorganisms such as \textit{S. aureus}, \textit{S. pneumoniae}, \textit{M. tuberculosis} and \textit{Influenza A} are all within this range (Kowalski, 2006b).

Figure 8-3 presents the duration curves of inactivation efficiency for the reference UVGI system that is challenged by microorganisms of the lower and upper bound \( k \). The curve for the reference microorganism is also included for comparison.

The susceptible microorganisms (upper bound \( k \)) are nearly completely inactivated in a single pass through the UVGI device. By contrast, the resistive microorganisms (lower bound \( k \))
can only be inactivated by 40% or less. As microorganisms are assumed to be generating at a constant rate inside the space during occupied hours, it is expected that the space concentration of the resistive microorganisms will stay at a relatively high level. The duration curves of space concentration are illustrated in Figure 8-4. On the contrary, the space concentrations for the susceptible microorganisms and the reference microorganisms do not differ by much.

Figure 8-3: Duration curves of $\eta_{UFGI}$ for different target microorganisms.

Figure 8-4: Duration curves of space concentration for different target microorganisms.
8.2.2 UVGI systems designed for other target microorganisms

From Figure 8-3 and 8-4, the performance of the reference UVGI system being challenged by the resistive microorganisms is less than satisfactory; at least, the predicted inactivation efficiency is far from the designed value for the whole year.

If the application does require the UVGI systems to be challenged by more resistive microorganisms, then the systems should be designed accordingly to handle the more stringent requirements. The cost to implement such systems is presented in the following sections. The performance, in terms of inactivation efficiency and space concentration, will be the same as the reference case if the systems are specifically designed for the new challenges.

8.2.2.1 Impact on energy consumption and cost

In order to handle the more resistive microorganisms, the systems have to be sized with more UV lamps, and thus incur more cost. Likewise, if the target microorganisms are more susceptible, smaller systems are possible. Table 8-4 summarizes the energy consumption involved with systems designed for microorganisms of different rate constants.

The choice of target microorganism is an epidemiological issue that includes the evaluation of risk, contagiousness, and lethality; and must be consulted with the experts accordingly. Table 8-4 illustrates that if the target microorganism is a very resistive one, the size of the system and thus the cost could be increased by nearly tenfold.
Table 8-4: Annual energy consumption and cost for systems designed for microorganisms of different rate constants.

<table>
<thead>
<tr>
<th>Annual Energy Consumption</th>
<th>Design rate constant</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.0005</td>
</tr>
<tr>
<td>Power to lamps (kWh)</td>
<td>43,741</td>
</tr>
<tr>
<td>Cooling (kWh)</td>
<td>8,500</td>
</tr>
<tr>
<td>Fan (kWh)</td>
<td>2,850</td>
</tr>
<tr>
<td>Heating-electric (kWh)</td>
<td>-19,783</td>
</tr>
<tr>
<td>Net (kWh)</td>
<td>35,308</td>
</tr>
<tr>
<td>kWh/m²</td>
<td>14.8</td>
</tr>
<tr>
<td>kWh/ft²</td>
<td>1.38</td>
</tr>
<tr>
<td>Cost ($)</td>
<td>3,450</td>
</tr>
<tr>
<td>$/m²</td>
<td>1.45</td>
</tr>
<tr>
<td>$/ft²</td>
<td>0.135</td>
</tr>
</tbody>
</table>

8.2.2.2 Annualized life-cycle cost

Annualized life-cycle costs for the whole system and per unit area are summarized in Table 8-5 and Table 8-6, respectively. As for the cases with systems designed for higher inactivation efficiency, the system designed for more resistive microorganisms requires more UV lamps to be installed. Therefore, all three cost components — installation, replacement, and energy — are increased.
Table 8-5: Annualized life-cycle cost for systems designed for microorganisms of different rate constants.

<table>
<thead>
<tr>
<th>Annualized Life-cycle Cost [$]</th>
<th>Design rate constant</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.0005</td>
</tr>
<tr>
<td>Installation</td>
<td>4,183</td>
</tr>
<tr>
<td>Replacement</td>
<td>4,993</td>
</tr>
<tr>
<td>Energy</td>
<td>3,187</td>
</tr>
<tr>
<td>Total</td>
<td>12,363</td>
</tr>
</tbody>
</table>

Table 8-6: Annualized life-cycle cost per unit area for systems designed for microorganisms of different rate constants.

<table>
<thead>
<tr>
<th>Annualized Life-cycle Cost per unit area [$/m² ($/ft²)]</th>
<th>Design rate constant</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.0005</td>
</tr>
<tr>
<td>Installation</td>
<td>1.76 (0.163)</td>
</tr>
<tr>
<td>Replacement</td>
<td>2.10 (0.195)</td>
</tr>
<tr>
<td>Energy</td>
<td>1.34 (0.124)</td>
</tr>
<tr>
<td>Total</td>
<td>5.19 (0.482)</td>
</tr>
</tbody>
</table>

8.3 Sensitivity of life-cycle cost to economic assumptions

Other than design issues (inactivation efficiency and target microorganism), variations in the assumed economic input values involved in the life-cycle cost model also cause deviation in the predicted life-cycle cost. The analysis presented in this section is based on the reference case.
8.3.1 Economic parameters of interest

The economic inputs of interest as presented in Equation 4-1 are; installation cost \((I)\), replacement cost \((R)\), base energy cost \((W)\), fuel price indices \((E_i)\), and discount rate \((r)\). The assumed values are based on published values or recommendations from the vendor. Changes in implementation will have an impact on one or more of these inputs. For example, a modification in design may increase the installation cost but decrease the base energy cost.

8.3.2 Deterministic analysis

To illustrate the extent of the impact of each of these inputs on the predicted life-cycle cost, a deterministic approach is deployed. Based on the end values of the arbitrary sensitivity range for each of the assumed input values (presented in Table 4-3), a combination of any two end values is used to evaluate the percentage of deviation from the predicted life-cycle cost. Variations in inputs are presented in Table 8-7 as both row and column categories.

Table 8-7 presents the possible percentage deviation in the predicted life-cycle cost if there are variations in any of the two input values (or just one input value). The presentation provides a convenient means to estimate the possible cost if there are changes in the assumptions. However, the cross-table format limits the dimension to two and neglects the situation when three or more inputs are subjected to change. Moreover, the deterministic approach provides a deviation in the predicted life-cycle cost of the extreme cases of inputs (at the end values of the range) only. But it fails to consider the random nature of the values within the sensitivity range.
Table 8–7: Percentage deviation of predicted life-cycle cost

<table>
<thead>
<tr>
<th></th>
<th>R –20%</th>
<th>I –20%</th>
<th>D –200 bp</th>
<th>W –20%</th>
<th>E –10%</th>
<th>0</th>
<th>E +10%</th>
<th>W +20%</th>
<th>D +200 bp</th>
<th>I +20%</th>
<th>R +20%</th>
</tr>
</thead>
<tbody>
<tr>
<td>R –20%</td>
<td>–</td>
<td>–15%</td>
<td>–13%</td>
<td>–13%</td>
<td>–11%</td>
<td>–8%</td>
<td>–6%</td>
<td>–3%</td>
<td>–3%</td>
<td>–1%</td>
<td>–</td>
</tr>
<tr>
<td>I –20%</td>
<td>–15%</td>
<td>–</td>
<td>–11%</td>
<td>–12%</td>
<td>–9%</td>
<td>–7%</td>
<td>–5%</td>
<td>–2%</td>
<td>0%</td>
<td>–</td>
<td>1%</td>
</tr>
<tr>
<td>D –200 bp</td>
<td>–13%</td>
<td>–11%</td>
<td>–</td>
<td>–10%</td>
<td>–7%</td>
<td>–5%</td>
<td>–2%</td>
<td>0%</td>
<td>0%</td>
<td>2%</td>
<td>3%</td>
</tr>
<tr>
<td>W –20%</td>
<td>–13%</td>
<td>–12%</td>
<td>–10%</td>
<td>–</td>
<td>–7%</td>
<td>–5%</td>
<td>–3%</td>
<td>–</td>
<td>0%</td>
<td>2%</td>
<td>3%</td>
</tr>
<tr>
<td>E –10%</td>
<td>–11%</td>
<td>–9%</td>
<td>–7%</td>
<td>–7%</td>
<td>–2%</td>
<td>–2%</td>
<td>–</td>
<td>2%</td>
<td>3%</td>
<td>5%</td>
<td>6%</td>
</tr>
<tr>
<td>0</td>
<td>–8%</td>
<td>–7%</td>
<td>–5%</td>
<td>–5%</td>
<td>–2%</td>
<td>0%</td>
<td>2%</td>
<td>5%</td>
<td>5%</td>
<td>7%</td>
<td>8%</td>
</tr>
<tr>
<td>E +10%</td>
<td>–6%</td>
<td>–5%</td>
<td>–2%</td>
<td>–3%</td>
<td>2%</td>
<td>–</td>
<td>2%</td>
<td>–</td>
<td>8%</td>
<td>8%</td>
<td>9%</td>
</tr>
<tr>
<td>W +20%</td>
<td>–3%</td>
<td>–2%</td>
<td>0%</td>
<td>–</td>
<td>2%</td>
<td>5%</td>
<td>8%</td>
<td>–</td>
<td>10%</td>
<td>12%</td>
<td>13%</td>
</tr>
<tr>
<td>D +200 bp</td>
<td>–3%</td>
<td>–3%</td>
<td>–</td>
<td>0%</td>
<td>3%</td>
<td>5%</td>
<td>8%</td>
<td>10%</td>
<td>–</td>
<td>13%</td>
<td>14%</td>
</tr>
<tr>
<td>I +20%</td>
<td>–1%</td>
<td>–</td>
<td>1%</td>
<td>2%</td>
<td>5%</td>
<td>7%</td>
<td>9%</td>
<td>12%</td>
<td>13%</td>
<td>–</td>
<td>15%</td>
</tr>
<tr>
<td>R +20%</td>
<td>–</td>
<td>1%</td>
<td>3%</td>
<td>3%</td>
<td>6%</td>
<td>8%</td>
<td>11%</td>
<td>13%</td>
<td>14%</td>
<td>15%</td>
<td>–</td>
</tr>
</tbody>
</table>

R = Replacement Cost (± 20%)
I = Installation Cost (± 20%)
D = Discount Rate (± 200 basis point)
W = Base Energy Cost (± 200)
E = Energy Cost (± 10%)
8.3.3 Probabilistic analysis

As described in the previous section, the deterministic analysis provides a means to determine the deviation in the predicted value if the variations in the assumptions are known. However, the variation is itself arbitrary in nature and is based on past experience or an educated guess. Moreover, it might be the case that the greater the variation, the lower the probability. Therefore, the variation should best be described by a probability distribution function. If that is the case, then a probabilistic analysis is necessary to predict not only how much the deviation is, but also how likely it is for such a deviation to occur.

As discussed in Section 4.3.2, the impact to the life-cycle cost (Equation 4-1) due to the variations in the inputs presented in Table 4-3 can be determined through a commercial analysis package — @RISK. @RISK deploys Monte Carlo simulation that predicts possible outcomes with randomly generated input values according to the selected probability distribution. @RISK can perform up to a maximum of 10,000 iterations and provide a distribution of predicted outcomes. It is impossible to select proper probability distribution of the suggested variations in inputs. In this analysis, two common probability distributions for variations in inputs, namely, normal distribution and uniform distribution, have been investigated. Figure 8-5 depicts the cumulative frequency for the deviation in the predicted life-cycle cost based on the variations in inputs in two types of probability distributions.
The results with uniformly distributed inputs agree with the results based on the deterministic approach. Most deviations are within ± 15%, since an increase in one input might not necessarily imply an increase in other inputs. Having all the inputs go to extremes in one direction is very unlikely. For this simulation, the deviation in the predicted life-cycle cost reaches the extreme of +26% / −22% for uniformly distributed inputs, and +13% / −13% for normally distributed inputs.

Table 8-8 summarizes the approximate deviation within confidence intervals of 90% and 95% for variations in inputs for both types of probability distribution. The three cost components, namely, installation, replacement, and energy, are all assumed to have a variation of ± 20%. Since they are assumed to be acting independently, the net effect of the three components may cancel one another out. Therefore, the predicted life-cycle costs do not even come close to ± 20% within a confidence interval of 95%.

![Cumulative frequency curves of deviation of predicted life-cycle cost.](image)

Figure 8-5: Cumulative frequency curves of deviation of predicted life-cycle cost.
In reality, there is an interdependency of the three cost components. An increase in the number of lamps would not only cost more to install, but also to replace and operate. On the other hand, the additional heat generated by the extra lamps may incur both cooling penalty and heating credit at the same time. However, the net effect is beyond the topic of economic analysis. Therefore, it is important to realize that the context of this sensitivity analysis of the life-cycle cost is applicable to economic factors only, not to design or performance factors. Possible economic factors include labor cost, lamp cost, energy rate, etc. These factors are unrelated to any particular design, and shall be studied with this economic analysis.

Table 8-8: Confidence interval of percentage deviation of predicted life-cycle cost.

<table>
<thead>
<tr>
<th>Variations in inputs</th>
<th>Confidence interval</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>90%</td>
</tr>
<tr>
<td>Normally distributed</td>
<td>± 5 %</td>
</tr>
<tr>
<td>Uniformly distributed</td>
<td>± 12 %</td>
</tr>
</tbody>
</table>
Chapter 9

Conclusions and Recommendations

UVGI can be deployed for surface disinfection at the coils, for air disinfection at the upper-room or inside ductwork. Coil surface disinfection is a continuous process and is not constrained by the exposure time. The ambient conditions at the upper-room are very stable and generally are not a function of time. By contrast, the application of UVGI for in-duct deployment faces time-varying parameters, which affect the performance so significantly that they should not be ignored. However, the current design practice fails to account for the effect of those parameters, whereas this research demonstrates how a simulation-based evaluation procedure could help in the design process. This chapter will first summarize the issues with the current design practice, then draw conclusions from the results of the parametric studies, and finally, make recommendations for future research.

9.1 Issues with current design practice

As mentioned, the current design practice neglects the effect of time-varying ambient conditions. In fact, there is no performance standard that governs the design practice. And the impact of heat generated by the UVGI device on the HVAC system has not been customarily considered. All of these issues have a profound impact on performance and cost, and will be discussed in the follow sections:
9.1.1 Time-varying ambient conditions

Current design practices size the UVGI system based on experience, but whether the selected design conditions really reflect the conditions in the actual HVAC system is more art than science. Under time-varying ambient conditions, UVGI systems could only be under sized or over sized. However, without simulation, the performance deficiency of the under sized system cannot be evaluated, nor can the unnecessary costs incurred with the over sized system be estimated. Without this information, it is difficult to optimize a design that strikes a good balance between performance and cost. The results presented in this research using the suggested simulation-based evaluation procedure, provide clear evidence that the current design practices cost clients more money to operate at best and fail to treat the air adequately at worst.

As demonstrated in Chapter 5, the design based on vendor selection conditions performs and costs very much the same as the worst case design. For that particular example, both the temperature and velocity are lower for the vendor selection conditions case than for the worst case; as a result, the vendor selection conditions case faces a longer exposure time and yet a lower relative lamp output, partly cancelling out the effect of one another. The issue is whether that is what the vendor is designing for, or if it is only taking place incidentally.

9.1.2 Performance standard

Instead of designing the UVGI system based on design temperature and velocity, another practice of the industry is to provide a ready-made or default solution based on rule-of-thumb values, such as a certain number of UV lamps per unit area. These values are not the same among vendors. As illustrated, a ready-made solution performs differently as the installation or design situation changes. Chapter 8 illustrates a case in which a UVGI system is challenged with
microorganisms of different rate constants; the system performs quite differently on each of the microorganisms. Therefore, a UVGI system should not be specified with just an arbitrary number of UV lamps per unit area, but must be designed specifically to handle certain target microorganisms with well-defined performance expectation.

Moreover, the number of UV lamps or the amount of UV power is only part of the equation, and cannot be directly translated into health benefit. Current practice fails to recognize that space microorganism concentration is the most direct metric for gauging the performance in relation to health benefit. As presented in the parametric study of three U.S. geographical locations in Chapter 7, the inactivation efficiency is the highest in New York throughout the year, but the space microorganism concentration there is the worst among the three locations. The discrepancy between inactivation efficiency and space concentration demonstrates that the former is a better metric to measure performance. Despite the known importance of evaluating space microorganism concentration, it is not customarily considered since the metric can only be evaluated through simulation with a differential equation, and cannot be easily interpreted without full epidemiological data. This research addresses both concerns by providing alternative performance metrics of normalized CADR and effectiveness, and a simulation-based procedure that compares the performance (space concentration) of the UVGI system to other well-established air treatment mechanisms such as ventilation and filtration.

### 9.1.3 Impact on HVAC system

Current practice generally considers the rated power of the UV lamps as the total energy consumption without recognizing the impact of the heat generated by the UV lamps on the HVAC system. The generated heat has to be investigated with its impact on cooling, heating, and fan — very much the same way the induced pressure drop of a filtration system must be studied.
with its effect on increased fan energy and cooling load. An integrative investigation can be performed by incorporating the UVGI system design with building energy simulation. Energy consumption analysis performed in the parametric study suggests that the impact on the HVAC system is too significant to be ignored. The UVGI system in Houston is a good example. As presented in Chapter 7, the devices at the supply air are all sized similarly across the three geographical locations, but the one at Houston consumes 33% more energy overall.

9.2 Conclusions of the parametric studies

Each of the parametric studies reveals certain aspects of the simulation-based evaluation procedure, and the results from these studies provide good support for the simulation-based approach. The following sections summarize the conclusions that can be drawn from the studies.

9.2.1 Design strategy

As demonstrated from the building simulation data, air temperature, air velocity, and the corresponding lamp output vary greatly with time. The design strategy plays an important role in defining the percentage of time that the target performance level, such as the inactivation efficiency, is fulfilled. A system designed for the average conditions will likely fall short in performance for a substantial amount of time, while a system designed for the worst conditions will exceed the target performance all the time.

A simulation-based design allows for fine-tuning of the design strategy such that an optimized level of performance and cost can be achieved. Moreover, the performance requirement should be based on the space concentration rather than on the single-pass inactivation efficiency, as long as an appropriate simulation tool is available for such evaluation.
It has been demonstrated that normalized CADR reflects the single pass microorganism reduction capability of the UVGI system.

The performance and cost of UVGI systems are also compared with systems operating with 30% elevated ventilation and high-level filtration. The 30% increase in ventilation (over the required minimum) simply cannot provide the same level of air treatment as the reference UVGI system nor the system with high-level filtration. High-level filtration provides comparable air treatment capability to the UVGI, but at a greater cost, especially in terms of energy.

Regardless of the design strategies, the installation of UVGI systems provides potential health benefits, which are in order of magnitude, more than costs, although the amount of benefits claimed is difficult to prove. On the other hand, the costs of deploying UVGI systems are comparatively small with respect to other HVAC-related costs, which may make a compelling case for UVGI deployment.

**9.2.2 Installation locations**

The temperature at the supply air location (downstream of the cooling coils) is stable, but is in general much colder than that of the mixed air location (upstream). Lamp output is therefore much higher at the mixed air location most of the time. Due to higher lamp output, inactive efficiency is also higher at the mixed air location. Therefore, a lower space concentration (for the presented hypothetical example) can be achieved at the mixed air location, since the airflow rate is exactly the same as that of the supply air location. As a result, a UVGI installation at the mixed air location costs less than one at the supply air location, and provides comparable if not better performance. This parametric study is based on the building in New York only; further study is needed to demonstrate whether the mixed air location is indeed more suitable for UVGI operation.
9.2.3 Geographical locations

Ambient conditions at the installation locations, particularly the mixed air location, are greatly influenced by outdoor air conditions. The conclusions drawn from the previous parametric study need to be reconfirmed with other geographical locations as well.

With the exception of a few outlier cases, supply air temperature across the three geographical locations is in fact very similar. Air velocity also falls within a similar range among the three geographical locations, but follows different distribution patterns. Due to the similarities in air temperature and velocity, the inactivation efficiency among the three geographical locations at the supply air does not differ by much. The cost to implement each of the systems at the supply air is nearly identical. Due to a lower air velocity for a significant portion of the year, New York poses a higher space concentration most of the time.

Despite the fact that the air temperature profiles of the mixed air are quite different among the three geographical locations, the costs to implement UVGI systems at the mixed air location is nearly half those at the supply air location for all three geographical locations, since the systems are nearly half the size. As observed from the space concentration, the performance of the UVGI systems installed at the mixed air is comparable to that at the supply air.

Out of the six cases investigated in this parametric study, the one at the mixed air location in Los Angeles is the least expensive to implement, and costs only one third of the most expensive case (at the supply air in Houston). Los Angeles is in a milder climate, and the ambient conditions there are comparatively more homogeneous than other locations. As a result, the performance (for example, the inactivation efficiency) throughout the year does not deviate too much from the design value. In other words, the UVGI system at the mixed air location in Los Angeles is sized just adequately. On the other hand, systems that are subjected to wider ranges of ambient conditions will see greater deviation in performance from the design value due to over sizing.
9.3 Recommendations for future research

There are basically two issues behind the lack of support or adoption of a simulation-based evaluation procedure in the industry. The first issue is that there is no existing guideline on performing simulation on the design of UVGI system; therefore, this research helps provide the procedure and the results that support its application. The second issue is that there is a gap between the design of the HVAC system and the design of the UVGI system. The UVGI system is either designed as a retrofit to an existing building where the HVAC system performance data are not available, or designed as an add-on to new construction where the UVGI system is considered an isolated component with no UV performance impact due to the HVAC ambient conditions nor HVAC cooling load penalty due to the added heat of the UVGI system. In order to solve this second issue, a tighter integration between the workflows of the HVAC system design and the UVGI system design has to be put into practice.

9.3.1 Integrated software design tool

To facilitate the integration, the UVGI system design procedure should in fact be incorporated into the HVAC system design process. The UVGI system shall be considered an integrated component of the HVAC system very much like the lighting system. The procedures suggested in this paper provide the basic framework for further development into a software design tool or plug-in to existing building simulation software.

On top of the existing features of the current UVGI system design tools, future tools should incorporate the time factor into the design process. Designers should be able to select a prescribed level of performance (e.g. inactivation efficiency) for a desirable percentage of time (occasional lapse in inactivation efficiency might not have an impact on space concentration). If
the building simulation software includes an airflow module, the prescribed level of performance can be expressed in terms of space concentration. The simulation of space concentration can be incorporated into or make use of the tools available from the building simulation software.

The ideal is to have a fully integrated UVGI system design tool that evaluates the time-varying performance with simulated ambient conditions on one hand, and feeds back the heat generation into the HVAC loop for a cost estimation on the other hand.
REFERENCES


