A DYNAMIC LIFE CYCLE ASSESSMENT FRAMEWORK FOR WHOLE BUILDINGS INCLUDING INDOOR ENVIRONMENTAL QUALITY IMPACTS

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Life cycle assessment (LCA) can aid in quantifying the environmental impacts of whole buildings by evaluating materials, construction, operation and end of life phases with the goal of identifying areas of potential improvement. Since buildings have long useful lifetimes, and the use phase can have large environmental impacts, variations within the use phase can sometimes be greater than the total impacts of other phases. Additionally, buildings are operated within changing industrial and environmental systems; the simultaneous evaluation of these dynamic systems is recognized as a need in LCA. At the whole building level, LCA of buildings has also failed to account for internal impacts due to indoor environmental quality (IEQ). The two key contributions of this work are 1) the development of an explicit framework for DLCA and 2) the inclusion of IEQ impacts related to both occupant health and productivity. DLCA was defined as "an approach to LCA which explicitly incorporates dynamic process modeling in the context of temporal and spatial variations in the surrounding industrial and environmental systems." IEQ impacts were separated into three types: 1) chemical impacts, 2) nonchemical health impacts, and 3) productivity impacts. Dynamic feedback loops were incorporated in a combined energy/IEQ model, which was applied to an illustrative case study of the Mascaro Center for Sustainable Innovation (MCSI) building at the University of Pittsburgh. Data were collected by a system of energy, temperature, airflow and air quality sensors, and supplemented with a post-occupancy building survey to elicit occupants' qualitative evaluation of IEQ and its impact on productivity. The IEQ+DLCA model was used to evaluate the tradeoffs or co-benefits of energy-savings scenarios. Accounting for dynamic variation changed the overall results in several LCIA categories - increasing nonrenewable energy use by 15% but reducing impacts due to criteria air pollutants by over 50%. Internal respiratory effects due to particulate matter were up to 10% of external impacts, and internal cancer impacts from VOC inhalation were several times to almost an order of magnitude greater than external cancer impacts. An analysis of potential energy saving scenarios highlighted tradeoffs between internal and external impacts, with some energy savings coming at a cost of negative impacts on either internal health, productivity or both. Findings support including both internal and external impacts in green building standards, and demonstrate an improved quantitative LCA method for the comparative evaluation of building designs.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

NOMENCLATURE

ACHD	Allegheny County Health Department
AEC	Architecture, Engineering and Construction
ASHRAE	American Society of Heating, Refrigeration and Air conditioning Engineers
BASE	Building Assessment and Survey Evaluation
BEES	Building for Environmental and Economic Sustainability
BRI	Building Related Illness
CAP	Criteria Air Pollutant
CF	Characterization Factor
DCV	Demand Controlled Ventilation
DLCA	Dynamic Life Cycle Assessment
EF	Effect Factor
EIA	Energy Information Administration
FF	Fate Factor
IAQ	Indoor Air Quality
IEQ	Indoor Environmental Quality
iF	intake Fraction
GHG	Greenhouse Gas
GWP	Global Warming Potential
HAP	Hazardous Air Pollutant
HVAC	Heating, Ventilating and Air Conditioning
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment

LEED	Leadership in Energy and Environmental Design
MCSI	Mascaro Center for Sustainable Innovation
NOx	Nitrogen Oxides
NREL	National Renewable Energy Laboratory
NREU	Non Renewable Energy Use
PAQS	Pittsburgh Air Quality Study
PID	Photo Ionization Detector
PM	Particulate Matter
PM2.5	Particulate Matter less than 2.5 µm in diameter
SETAC	Society for Environmental Toxicity and Chemistry
SBS	Sick Building Syndrome
TAWP	Time Adjusted Warming Potential
TRACI	The Tool for the Reduction and Assessment of Chemical and other environmental Impacts
TVOC	Total Volatile Organic Compounds
UNEP	United Nations Environmental Programme
USDOE	United States Department of Energy
USEPA	United States Environmental Protection Agency
USLCI	United States Life Cycle Inventory
VAV	Variable Air Volume
VOC	Volatile Organic Compounds
XF	Exposure Factor

PREFACE

I am profoundly grateful to my dissertation director, Dr. Melissa Bilec, for her sincere support and guidance throughout my graduate studies, as well as my dissertation committee and Dr. Amy Landis for their additional feedback and guidance.

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Thank you.

1.0 INTRODUCTION

1.1 ADVANCING LCA METHODS FOR THE BUILT ENVIRONMENT

The construction and operation of commercial and institutional buildings consumes a large amount of energy and materials, both of which contribute to known environmental problems in categories such as global climate change, human health, ecosystem services, and resource depletion. In the United States, the entire building sector consumed 41% of total primary energy in 2006, and the non-residential sector contributed approximately half of that total (19%) (USDOE 2011a). Globally, buildings have been estimated to consume 40% of raw materials annually (Young and Sachs 1994). However, buildings are perceived as a technological sector where large improvements in performance in sustainability-related categories are achievable (2030 2011; Griffith 2007; ILFI 2010; Levine 2007; USGBC 2012).

Life Cycle Assessment (LCA) provides a comprehensive and quantitative analysis of the environmental impacts of a product or process throughout its entire lifecycle. LCA is a powerful and widely used tool for measuring the environmental impact of an enterprise or concept and informing decisions with respect to sustainability and environmental considerations. LCA quantifies the environmental impacts of a product or process and can be a very helpful tool in identifying the most benign technologies among an array of options. Through the use of LCA, it is possible to observe which stage (i.e., creation, use, or end of life) causes the most impact and may offer suggestions to minimize impacts throughout a product's lifetime. Established guidelines for performing detailed LCAs are well documented by the Environmental Protection Agency (EPA), Society for Environmental Toxicologists and Chemists (SETAC), and the International Organization for Standardization (ISO) (Fava et al. 1991; ISO 2006; Vigon et al. 1992). As defined by the ISO 14040 series, LCA is an iterative four-stage process including: 1) ***Scoping*** – defines the extent of analysis and the system boundaries; 2) ***Inventory Analysis*** – documents material and energy flows which occur within the system boundaries (also called the life cycle inventory or LCI); 3) ***Impact Assessment*** – characterizes and assesses the environmental impacts using the data obtained from the inventory (also called the life cycle impact assessment or LCIA); and 4) ***Interpretation and Improvement***– identifies opportunities to reduce the environmental burden throughout the product's life.

Major reasons for conducting an LCA involve decision-making with respect to improvement and comparison of products, processes, or activities. Impact-minimizing LCAs provide information on which stage of production (creation, use, or disposal) causes the most environmental impact and may offer suggestions to minimize those burdens. Comparative LCAs can help to determine the environmentally preferable alternative when multiple alternatives exist. LCA has historically been used primarily for consumer goods, though there are examples of whole-building LCA studies in the literature. Whole-building LCAs have typically focused on total energy usage, including energy required to operate the building as well as energy embodied in the building materials (Junnila et al. 2006; Scheuer et al. 2003; Kofoworola and Gheewala 2008; Wu et al. 2011a). Some studies have examined waste generation and health-related air pollution (Scheuer et al. 2003), or expanded the scope to include construction impacts (Bilec et al. 2006; Bilec et al. 2010; Sharrard et al. 2008).

The goals typically outlined in high-performance or green building programs are broader than building-cycle energy usage or direct waste and pollutant generation, reflecting a perception among practitioners that, even from an environmental perspective, many other aspects are important. Green building rating systems such as the U.S. Green Building Council's (USGBC's) Leadership in Energy and Environmental Design (LEED) include categories not directly related to the external environment, such as minimum ventilation and daylighting requirements, which are believed to increase occupants' health and productivity, and credit for low-emitting materials (USGBC 2012). LEED and other systems also focus on sustainable building sites, recognizing that the total impact of buildings extends beyond their walls (e.g. orientation) and even beyond the site proper (e.g. connections to transport). Though commonly recognized as important, internal building impacts are not captured in most LCAs. For example, an increase in building ventilation, which improved indoor air quality but increased energy consumption, would appear in most LCAs as a negative impact only, instead of a tradeoff with both costs and benefits.

An additional drawback of LCA as commonly practiced with respect to buildings, is that it takes a static approach, essentially providing a "snapshot" of a building's footprint. Dynamic analysis is not often performed, yet buildings have the potential to undergo significant changes during their long (50-100 year) lifetimes. These changes can occur simultaneously with changes in the industrial or natural environment that also affect the ultimate environmental accounting. Typically, dynamic information has not been included in LCA because of its increased data and modeling requirements; however, as building automation becomes more common and environmental sensing becomes ubiquitous, information about building performance over time can be effectively incorporated into LCA.

1.2 RESEARCH GOALS AND OBJECTIVES

The goal of this research is to demonstrate an improved LCA method that includes dynamic scenario modeling and internal building metrics, and is of value to practitioners in the architecture, engineering, construction and management community. The specific research questions are as follows:

1. What are the effects of including dynamic data for both building operations and industrial/environmental systems on the results of LCA of buildings?
2. What are the effects of including whole-building internal human health impacts into LCA?
3. Can we include internal building impacts that do not align with traditional LCIA categories, such as health effects not related to specific chemicals, or impacts on occupants' productivity?
4. How do we apply this model to provide feedback on evaluating high performance, green buildings?

The specific objectives to be achieved in answering these questions are:

1. Develop a dynamic LCA modeling framework that is capable of handling dynamic variability in building operations and industrial/environmental systems, with results including traditional LCA categories.
2. Develop a framework for including internal health impacts analogous to traditional LCIA categories into LCA at the whole-building level.
3. Expand the framework to include non-chemical related health and productivity impacts alongside the traditional LCA categories and internal chemical categories.
4. Apply the model to a case study of a high-performance building to evaluate the life cycle impacts of different building improvement strategies, supplementing physical data collection with qualitative data collected from a post-occupancy survey.

1.3 INTELLECTUAL MERIT

This research is important because it provides a structure for an improved LCA method for whole buildings. Two major categories of improvement are proposed: the incorporation of dynamic life cycle data within a computational framework designed to handle this information, and the inclusion of holistic IEQ impacts in the LCA framework. The latter category requires extending the LCA coverage beyond traditional LCIA human health categories to include non-chemical health and productivity impacts. The evaluation of IEQ impacts is further strengthened by its incorporation into the dynamic framework, facilitating the evaluation of multiple scenarios under differing forecasts of future condition. Particularly with respect to IEQ, the dynamic nature of building operations and occupancy schedules suggests this approach; thus, the two components are highly synergistic. The organization of the proposed research – first, providing the dynamic, computational framework, and then including the additional IEQ impacts – provides an achievable goal with several well-defined objectives, while the proposed case study takes advantages of existing research relationships and large amounts of available data.

2.0 BACKGROUND AND LITERATURE REVIEW

2.1 DYNAMIC LIFE CYCLE ASSESSMENT FOR BUILDINGS

Accurate and complete building assessments are hampered by shortcomings in LCA techniques and data availability. Buildings are complex systems with long lifetimes; the ability to model different scenarios representing system dynamics is recognized as a key need in LCA of buildings (Scheuer et al. 2003). Dynamics of the environment and industrial systems have been considered one of the outstanding problems in LCA (Reap et al. 2008). A number of recent studies have investigated both system dynamics and the use of time horizons or discount rates in the impact characterization step of LCA (Kendall et al. 2009; Levasseur et al. 2010; Pehnt 2006; Struijs et al. 2010; Zhai and Williams 2010). Research has documented the prominence of the operating phase of buildings in most environmental impact categories, but also significant contributions from materials and construction processes which cannot be ignored.

Environmental and industrial dynamics operate on different time scales, all with some relevance to building LCAs (Reap et al. 2008). Environmental dynamics may include long-term or seasonal variation in pollutant fates or population exposures, while industrial dynamics may include changes in the location or type of emissions from different industries, among other factors. Industrial supply chains change their structure over the long term in response to technological, economic and political factors, while shorter-term variations may occur with demand, exemplified by the differences between base load and peak load electrical generation mixes (USDOE 2011b). Environmental emission and consumption factors change over the long term, based on technology and regulatory controls (USEPA 2009b). Long-term changes in emission factors may be taken into account by updates in LCA databases or updates to previously published studies, e.g. (Marceau et al. 2007; Nisbet et al. 2002). In some cases, LCA tools may explicitly include long -term emission trends at the inventory stage (ANL 2010). Short-term environmental dynamics are less often included in LCA, though seasonal and diurnal variations of environmental dynamics are incorporated in some studies of life cycle impact assessment (LCIA) characterization factors (Shah and Ries 2009), and are acknowledged as critical in modeling the environmental impact of some pollutants of importance to many LCIA categories (Bergin et al. 2007).

2.2 LCA AND INDOOR ENVIRONMENTAL QUALITY

Indoor environmental quality (IEQ) is a crucial area of health-related environmental protection because of the large portion of time spent indoors by most people, whether at work, home or in other buildings. IEQ can be affected by chemical pollutants emitted indoors by materials and processes (e.g., carbon monoxide and volatile organic compounds or VOCs), and intake of outdoor ambient pollutants through ventilation (e.g., ozone, nitrogen oxides or NOx, and particulate matter or PM) (ASHRAE 2009). Concentrations of pollutants indoors can be many times greater than outdoors, which compounds the effects of amounts of time spent inside (USEPA 2009a). Reactions between outdoor air pollution and indoor materials can generate so-called secondary indoor emissions, such as the effects of ozone on VOC release from otherwise inert indoor materials. Human beings themselves are the source of infectious biological aerosols (bacteria and virus particles), which cause a variety of acute respiratory illnesses (ARIs). Moisture buildup can lead to the presence of molds and non-contagious biological contaminants, which also affect respiratory function. Many potential exposure mechanisms linked to inadequate ventilation in buildings but causing similar symptoms, such as headaches and respiratory distress, are lumped together under the category of building related illness (BRI) or sick building syndrome (SBS) (Fisk et al. 2009). Though the exact mechanisms are not known, relationships between building variables and impacts on health and well-being have been empirically quantified (Fisk et al. 2009; Seppänen et al. 2006a; Seppänen et al. 2006b) and thus can be integrated into comprehensive environmental and health assessments of building performance. The LCA field has recently begun to recognize the importance of indoor air pollution (Hellweg 2009; Humbert et al. 2011), but these efforts do not extend to indoor environmental quality (IEQ) issues unrelated to pollutant concentrations.

To include IEQ in LCA, it is necessary to categorize its impacts in a manner comparable to existing impact categories. Two major conceptual frameworks exist: the use of a separate category for IEQ, and the integration of IEQ impacts into traditional categories. The former concept has been used in the BEES model (Lippiatt). In BEES, the IEQ category is presented as an additional midpoint alongside the remaining midpoint categories (e.g. global warming potential, eutrophication) taken from TRACI (Bare et al. 2003). It is further limited to indoor air quality (IAQ) and uses a proxy indicator - total VOC emissions per installation or replacement - to model the off-gassing that occurs with certain newly installed products. The performance of whole building systems with respect to IAQ is outside the implicit scope of BEES since it is primarily used for product selection.

The second approach is favored by the midpoint-damage framework developed under the United Nations Environmental Program – Society for Environmental Toxicology and Chemistry (UNEP-SETAC) Life Cycle Initiative and the Impact 2002+/Impact North America life cycle impact assessment method (Humbert et al. 2009; Jolliet et al. 2003; Jolliet 2004). This modeling framework includes the human health midpoint categories of cancer toxicity, non-cancer toxicity, respiratory inorganics, respiratory organics, ionizing radiation, ozone depletion, and photochemical oxidation (smog) (Jolliet et al. 2003). Indoor impacts can be explicitly included in the human health categories (Hellweg 2009), but studies using this approach as well as documentation of emissions rates and indoor concentrations are lacking in the literature. However, building systems contribute to occupants' well-being in a number of ways beyond inhaling or ingesting specific toxic chemical pollutants. Health effects of poor IAQ include acute respiratory illnesses (cold and flu), respiratory allergies and asthma, sick building syndrome (respiratory symptoms not associated with illness or allergies), depression, and stress (Fisk 2002; Singh et al. 2010). The term IAQ is used to indicate the presence of moisture or contaminants in the air (carbon dioxide, VOCs, mold spores, virus particles, etc.) and is a subset of IEQ, which also includes temperature, lighting, acoustics and safety effects. The links between IEQ, health effects and worker productivity has been increasingly studied recently. IEQ may affect productivity through classifiable health effects or through other mechanisms not generally classified as health-related; for instance, employee attitudes toward work. Fisk and others have reviewed studies showing how building ventilation rates affect sick building syndrome (Fisk et al. 2009); generally, increasing ventilation decreases sick building syndrome up to a point.

With respect to productivity, ventilation has been studied more often than other variables with respect to productivity; Seppanen (Seppänen et al. 2006b) summarized nine previous studies reporting quantitative results for the relationship of ventilation to productivity. Seppanen found continuous increases in productivity with ventilation rates from 6.5 l/s/person up to up to 65 l/s/person, with statistically significant increases up to 15 l/s/person. Productivity increases were generally in the vicinity of 1% to 3%, though some have reported higher results. Thermal comfort - temperature, humidity and airflow speeds - has also been shown to have productivity impacts (Seppänen et al. 2006a). The impact of lighting quantity and quality, including daylighting, have been studied, but to a somewhat lesser degree. Abdou (Abdou 1997) and Edwards (Edwards and Torcellini 2002) summarized literature relating to the effects of lighting and daylighting on productivity, but did not attempt to develop quantitative relationships. Heschong et al. showed daylighting improving outcomes in separate studies of retail and school environments (Heschong et al. 2002a, b). A recent publication by Schuster (Schuster 2008) surveys building users' responses to daylighting, finding that perception of lighting quality in day-lit spaces does not necessarily correspond with the lighting levels set for artificial lighting conditions. Other studies have focused on occupants' self-identification of increased productivity due to improvements in general IEQ (Ries et al. 2006; Singh et al. 2010). To date, however, no method has been proposed to incorporate productivity information into a life cycle assessment framework.

2.3 ORGANIZATION OF THESIS

Chapter 3 addresses objective 1, which is to develop a dynamic LCA modeling framework that is capable of handling dynamic variability in building operations and industrial/environmental systems, with results including traditional LCA categories. The framework was developed and then applied to a retrospective and prospective case study of Benedum Hall at the University of Pittsburgh, evaluating the building's performance compared to static LCAs conducted with reference to several milestones (original construction and contemporary renovation). This work was published in the International Journal of Life Cycle Assessment (Collinge et al. 2012b).

Chapters 4 and 5 address objectives 2 and 3, which are to develop IEQ metrics which both complement and extend beyond traditional LCIA categories. Chapter 4 discusses the methods used in the framework, while Chapter 5 discusses data collection and results of the in-depth case study of the Mascaro Center for Sustainable Innovation (MCSI) building at the University of Pittsburgh. The first portion of the framework, relating to indoor chemical impacts, was published along with applicable results from the case study (Chapter 5) in the journal Building and Environment (Collinge et al. 2012a). The remaining portion, relating to nonchemical health impacts and productivity impacts, will be submitted along with additional results from the case study (Chapter 5) for publication in a peer-reviewed journal.

Chapter 6 addresses a portion of objective 4, developing and implementing a post-occupancy survey in the MCSI building to gather qualitative data on occupant perceptions of IEQ and productivity aspects. Results of the survey are presented and compared to results from other post-occupancy surveys. Survey results are also used to guide the development of the scenario analysis focusing on energy-saving strategies, which is presented in Chapter 7. Chapter 7 applies the IEQ+DLCA framework and an empirical parametric energy model of the MCSI building to evaluate strategies for reducing energy use in light of IEQ impacts.

Conclusions of the overall results of this dissertation and recommendations for future work are discussed in Chapter 8.

3.0 DYNAMIC LIFE CYCLE ASSESSMENT MODEL WITH INITIAL RETROSPECTIVE AND PROSPECTIVE CASE STUDY

The following chapter contains material reproduced from an article published in the journal *International Journal of Life Cycle Assessment* with the citation:

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Supporting Information submitted with the *International Journal of Life Cycle Assessment* appears in Appendix A.

3.1 INTRODUCTION

Accurate whole-building LCA is limited by the standard practice of applying static factors throughout the life cycle inventory (LCI) and life cycle impact assessment (LCIA) stages. Since buildings have long useful lifetimes, and the use phase can have large environmental impacts, variations within the use phase can sometimes be greater than the total impacts of materials, construction or end-of-life phases (Aktas and Bilec 2012; Junnila et al. 2006; Scheuer et al. 2003). The ability to accurately model future scenarios is critical for improved building sustainability (Scheuer et al. 2003). Additionally, individual buildings are operated within changing industrial and environmental systems; the simultaneous evaluation of these dynamic interactions during product or building lifetimes is recognized as a key need in LCA (Reap et al. 2008). This chapter provides a framework for including dynamic changes both at the building level and in background industrial and environmental systems.

3.1.1 Time in LCA

Time-related issues affect LCA in numerous ways; broadly, they can be categorized into 1) industrial and environmental dynamics and 2) time horizons and discounting of future emissions (Reap et al. 2008). Temporal variations can be accounted for independently of any discounting of future emissions, using the physical models underlying the inventory data and impact assessment methods (Hellweg and Frischknecht 2004; Hellweg et al. 2003). For industrial and environmental dynamics, one approach is to consider temporal and spatial variability as components of parameter uncertainty in LCA and use probabilistic scenario analysis as a technique for overcoming this uncertainty (Huijbregts 1998; Huijbregts et al. 2001). This approach aggregates temporal and spatial variability with other sources of uncertainty, such as different technologies in use at different industrial facilities, or inaccurate emissions measurements. Another approach is to link explicit modeling of the primary systems of study (e.g. a building or an industrial process) with traditional aggregated LCA datasets, and use additional probabilistic analysis to characterize uncertainty in upstream or downstream material flows or emissions (Reap et al. 2003; Ries 2003; Udo de Haes et al. 2004). Another approach is to shift the focus away from a single product or functional unit to the entire in-use suite of products to capture changes in technology or infrastructure over a given period of interest (Field et al. 2000; Levine et al. 2007; Stasinopoulos et al. 2011).

Recent research has approached different aspects of the time-LCA problem. These studies can be differentiated by whether dynamic methods are applied to the LCI or LCIA steps in the analysis. Several studies have used dynamic LCI data to assess renewable energy systems, considering past and potential technology improvements affecting production efficiencies (Pehnt 2006; Zhai and Williams 2010). For the LCIA step, studies have used atmospheric and other environmental models to calculate time-dependent characterization factors (CFs) on both multi-year scales (Seppälä et al. 2006; Struijs et al. 2010) and seasonal scales (Shah and Ries 2009). The time-dependence of these CFs is a function of background pollutant concentrations or climatic factors. Other studies have investigated the relative impact of emissions timing with respect to a fixed time horizon (e.g. 100-year global warming potential) in the case of land-use change and biofuels (Kendall et al. 2009; Levasseur et al. 2010); vehicle regulations (Kendall and Price 2012) and the institutional building previously studied by Scheuer et al. 2003 (Kendall 2012). In these cases, emissions occurring farther in the future are effectively discounted by their proximity to the overall study time horizon. This effective discounting is distinct from economic discounting or pure time preference discounting. However, few studies so far combine dynamic scenario analysis with temporally explicit LCI data or any type of temporally explicit LCIA method.

3.1.2 Scope and functional unit of this study

The scope of this study was to establish a dynamic LCA (DLCA) approach and test this approach with a case study of an existing institutional building. These results were compared with LCA results from a static approach. The functional unit chosen for this study was an institutional building (Benedum Hall at the University of Pittsburgh) over its assumed lifetime of 75 years (until 2045). Benedum Hall is an existing building that opened in 1971. The system boundary for the study included primarily materials for construction and renovation, and electricity/fuels for building operation. Two separate comparative static versus dynamic analyses were constructed: one for the entire lifetime of the building assuming a 1971 perspective, and one for the remaining life of the building including an actual major renovation and addition, assuming a 2009 perspective. A scenario and sensitivity analysis was conducted for the 2009 dynamic perspective to elicit the effects of changing individual model parameters.

3.2 METHODS

3.2.1 Modeling approach

Heijungs and Suh (Heijungs and Suh 2002) developed a general equation for the environmental impact of a product system for a process-based LCA approach. Mutel and Hellweg restated this equation as shown in Equation 1 (Mutel and Hellweg 2008):

Equation 1

$$h = \mathbf{C} \times \mathbf{B} \times \mathbf{A}^{-1} \times f$$

where h is a vector representing total environmental impacts of the studied system, in some number of impact categories determined by the selected LCIA method; f represents the quantities of outputs from the industrial supply chain (e.g. materials, fuels) required for a specified function of the studied system; **A** is the technosphere matrix representing each unit of output as a function of the inputs to the various processes needed to generate that output; **B** is the biosphere matrix representing the environmental interventions (emissions and resource consumption) required for each process in the supply chain; and **C** (originally **W** in Mutel and Hellweg; changed to **C** herein) is a matrix of CFs which represent the magnitude of the effect of each quantity of emission or other intervention in each impact category. **C** is given here as a matrix rather than a vector or diagonal matrix, to efficiently account for the effect of some emissions in multiple impact categories.

The static approach to LCA often assumes point values for all of the coefficients in the **C**, **B**, and **A** matrices, and is usually structured such that the f vector represents a one-time output of the system (quantity x of product y at an arbitrary time). By contrast, a building is an example of a system whose input requirements vary with time and as a function of changes in its usage. Thus, the demand vector f becomes f_t at any point in time t, as a function of basic operating variables (e.g. occupancy schedules, thermostat setpoints), which are not normally captured in LCA. These operating variables may include material inputs during maintenance, various types of energy inputs required for routine operations based on building schedule and seasons, and replacement of materials and systems at periodic intervals.

Similarly, over the long life of a building, time-related changes may affect the other variables in Equation 1. The technosphere matrix **A** may change over time due to product substitutions, efficiency improvements, or other changes in the structure of the industrial supply chain. The biosphere matrix **B** may also change over time for the above reasons, or due to regulatory controls on emissions. Temporal changes in CFs in the **C** matrix are also possible as evidenced by previous studies, e.g. (Kendall 2012; Seppälä et al. 2006; Shah and Ries 2009; Struijs et al. 2010).

Given the potential for each term in Equation 1 to change over time, a simplified model for DLCA is shown in Figure 1 and represented mathematically by the following:

Equation 2

$$h_t = \sum_{t0}^{te} \mathbf{C}_t \times \mathbf{B}_t \times \mathbf{A}_t^{-1} \times f_t$$

where the t represents a point in time at which the values in the various terms are known, and t_0 and t_e represent the beginning and ending time points of the analysis, usually the beginning and end of the product or system life cycle. The t subscript does not imply that these terms are direct mathematical functions of time; rather, they are functions of their underlying variables that can be represented as a time series. Particularly, the matrix of CFs, $\mathbf{C}_t$ could encompass variations in all the underlying variables (fate, exposure, and effect factors), which must be calculated for each point in time by the physical models applicable to each category. $\mathbf{C}_t$ could also encompass adjustments made to CFs for other reasons, such as proximity to the analysis time horizon, as in Kendall (Kendall 2012). Separate types of changes to CFs could be explicitly documented by constructing several separate **C** matrices (e.g. $\mathbf{C}_{t,\ [fate]}$ or $\mathbf{C}_{t,\ [time\ horizon]}$) and combining these matrices by scalar multiplication (Hadamard product) at the time of analysis.

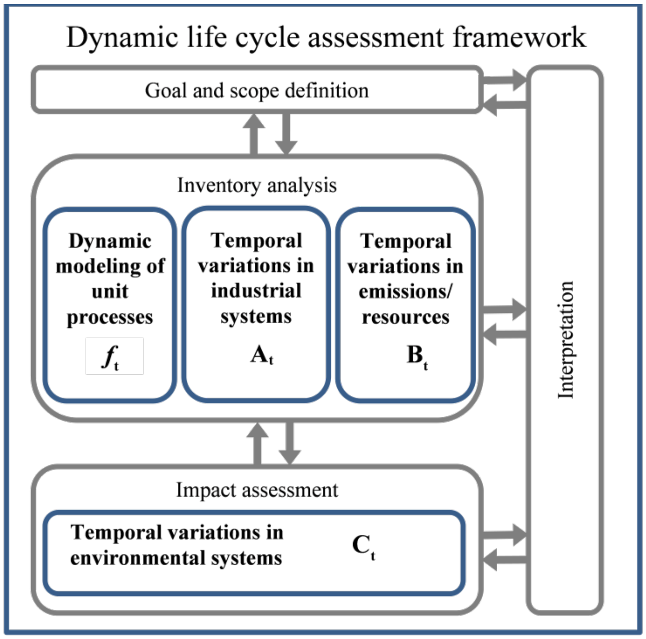


Figure 1 - Conceptual diagram of DLCA framework

There are several considerations to this approach. First, this approach follows an attributional, rather than consequential LCA structure (Ekvall and Weidema 2004). In attributional LCA, the impact of an emission is considered to be the total impact of the product system normalized to a functional unit,, whereas consequential LCA investigates the effects of marginal choices. In the attributional formulation of the DLCA model, the aggregation is performed at the time step level (variations at smaller scales are implicitly averaged). Thus, the terms in eq. 2 are able to vary independently of each other. However, the use of dynamic modeling of system interactions introduces the possibility of feedback loops in which changes occurring in different parts of the system induce mutual changes in each other. The inclusion of feedback loops between variables in Equation 2 (e.g. coefficient $\mathbf{A}_{i,j}$ relating process i to product j as a function of f_j, the quantity of product j required) would move the model partway toward a consequential LCA structure (e.g. marginal effects on power or district heating generation from adding a building to the utility grid). However, a fully consequential LCA requires a general equilibrium economic model with many additional assumptions about changes in industrial relationships based on additional or changed demand for goods and services. A fully consequential LCA structure is sometimes used in large-scale policy analysis but may not be appropriate for the study of individual buildings. For the current study, feedbacks are hypothesized to be significant only within the systems captured by the building energy model that produces the *f* vector. These feedbacks are briefly discussed in Section 2.4.1.

Another consideration is the issue of lag time in the supply chain, where lag time is defined as the difference in timing of processes and emissions at multiple levels in the supply chain (Levine et al. 2007). Some examples are the time difference between the production of a building material and its installation at the construction site, or the time difference between fuel extraction and combustion. For the simplified mathematical model in Equation 2, supply chain functions must be assumed to occur simultaneously in order to invert the **A** matrix. A more complete formulation would involve specifying the lag time for each supply-demand linkage, which would require calculation using a tree structure rather than a matrix structure, as the number of inputs at different time lags would multiply with each step back through the supply chain. This approach could be implemented with an inventory or impact cutoff tolerance. However, data limitations prevented the inclusion of lag times in this study as discussed further in section 3.4.

A prototype DLCA model was constructed using Microsoft Excel and Visual Basic for Applications (VBA). The model used Excel worksheets to store basic data such as process inputs and outputs, emission factors and CFs, while VBA code was used to perform the matrix calculations. The key difference between the prototype model and most standard LCA applications was the use of time series tables to simulate dynamic variation in matrix coefficients representing modeled relationships. With the time series enabled, any coefficient c_i in a vector or

$c_{i,j}$ in a matrix can become $c_{i,j,t}$, where i and j represent the coefficient's position in the matrix in question and t is the current model time step. The model explicitly considered four categories of time series in the LCA calculation, corresponding with the four variables of Equation 2. These categories are outlined in Table 1, along with illustrative examples. Any variable without a time series available due to data limitations was assumed to have a constant value, as in a typical static LCA calculation.

3.2.2 Case study

An existing institutional building – Benedum Hall at the University of Pittsburgh – was selected as the case study for this project. Originally constructed in 1971 to house the engineering program, the Benedum Hall complex includes a twelve-story tower housing laboratories, offices and classrooms; two below-grade floors with additional office and laboratory space, and a two-story auditorium. The two below-grade floors extend under the footprints of both the tower and the auditorium, and support a first-floor level outdoor plaza. The complex underwent a major renovation beginning in 2006, including the construction of a new wing on the first, second and third floors; major upgrade of all mechanical systems; replacement of all the windows and floor coverings; roof replacement including green roof spaces on both the auditorium and a portion of the plaza; and numerous interior space renovations. The additional wing and renovation of the 2nd floor of the tower were completed in November 2009; roof and window replacement on the remaining structure and renovations of the below-grade floors, ground floors and auditorium were completed by August 2010, and renovations of the 3rd-12th floors of the tower are scheduled to be completed by the end of 2012. [UPDATE: 7th floor was completed as of September 2012. Work continues on floor 8-12 as of this writing].

Since the original construction, steam for heating the building has been supplied by a district heating system used by the University and several nearby institutions. Until June 2009, steam was generated using a combination of coal-fired and natural gas-fired boilers at a single plant; in June 2009, a second plant was added and the existing plant was converted to 100% natural gas-fired boilers. Cooling was originally provided by a stand-alone chiller plant on the building's roof, which was replaced by a connection to a new district chilled water plant in 2002.

Table 1. Categories of dynamic life cycle assessment (DLCA) parameters for buildings, examples, and data sources used in the case study.

Category [with parameter from Equation 2 in brackets[a]]	**Examples**	**Data used in case study with associated time interval**
Building Operations [f_t]- initial construction activities; additions, renovations, or major component replacements; changes in usage patterns or energy consumption	Material required for initial construction; material required for replacement of components or reconfiguration of interior spaces; changes in energy consumption	-Benedum Hall original construction plans; 1971 (DRA 1965) -Benedum Hall utility usage (steam, electric, and water); 7/1992-12/2010 -Benedum Hall construction plans for renovation and addition; 2006-2010 (Edge 2007, 2008) -eQUEST model (projected); 2009-2045
Supply chain dynamics[$\mathbf{A}_t$]- changes to upstream processes independent of building management decisions	Changes in fuel mix and efficiency of the electricity grid; changes in origin of natural gas and petroleum supplies; changes in regional waste treatment practices	-District heating plant fuel consumption and steam production; 1/2000-12/2010 -National annual and monthly electric power generation by fuel type; 1970-2008 (USDOE 2010b): (projected); 2009-2045 (USDOE 2010a)
Inventory dynamics [$\mathbf{B}_t$]- changes in resource use or pollutant emissions by processes due to technology, regulation or other factors	Influence of environmental regulations on pollutant emissions; changes in efficiency of industrial processes	-National GHG emissions from electric power generation by fuel type and other major GHG sources; 1990-2008 (USEPA 2010) -National criteria air pollutant (CAP) and hazardous air pollutant (HAP) emissions; 1970-2008 (USEPA 2009, 2011b): (projected); 2009-2016 (USEPA 2011a)
Environmental system dynamics [$\mathbf{C}_t$] – changes in background environmental systems affecting the fate, exposure and effects	Changes in system sensitivity due to background concentrations or distribution of populations; changes in ambient conditions affecting emission fates; consideration of an analysis time horizon	--Time adjusted (global) warming potentials (TAWPs); 2009-2045 (Kendall 2012) -Seasonal characterization factors for photochemical ozone; 2009-2045 (Shah and Ries 2008)

[a] Parameter definitions: [f_t]- vector of outputs from the industrial supply chain (e.g. materials, fuels); [$\mathbf{A}_t$]- matrix representing each unit of output as a function of the inputs to the various processes needed to generate that output; [$\mathbf{B}_t$]- matrix representing the environmental interventions (emissions and resource consumption) required for each process; [$\mathbf{C}_t$] – matrix of characterization factors representing the magnitude of the effect of each quantity of emission or other intervention in each impact category

3.2.3 Static and dynamic LCA comparisons

The DLCA model and a static LCA model were compared over two analysis time frames. The first time frame consisted of the entire lifetime of the building and used a 1971 perspective; while the second time frame consisted of the remaining life of the building using a 2009 perspective. We will refer to these as the “full lifetime” and “remaining lifetime” analyses hereafter. The system boundary for both static and dynamic analyses included building materials and operating fuels/electricity, as well as their respective upstream processes. The system boundary of the DLCA model, including the extent of dynamic processes included, is shown in Figure 2. Material transportation, on-site construction activities, routine maintenance and end-of-life disposition were excluded from the study. Due to the complexity of modeling the entire building, only major systems were selected from the initial construction, and a comparison was made to two previous studies to assess the degree of completeness of the results (Junnila et al. 2006; Scheuer et al. 2003).

The full lifetime of Benedum Hall was assumed to be 75 years, consistent with its current status (recently renovated at 40 years old) and one previous study of an institutional building (Scheuer et al. 2003). It has been noted that arbitrary assumptions about building lifetime can significantly affect LCA results (Aktas and Bilec 2012). The full lifetime DLCA encompassed four distinct phases: 1) initial construction (1971); 2) initial operations (1971-2008); 3) renovation activities (2006-2012); and 4) future operations (2009-2045). The renovation activities were assumed to occur in 2009. Construction material quantities from the original construction, renovation and addition were obtained from the construction drawings and specifications for each project (DRA 1965; Edge 2007, 2008). The full lifetime static LCA coupled the initial construction results with a projection of the initial year’s operations over the

75-year assumed building lifetime, and did not include the renovation/addition. The remaining lifetime DLCA and static LCA included the renovation and future operations phases. The remaining lifetime DLCA was used as the basis for the future scenario analysis (Section 2.5).

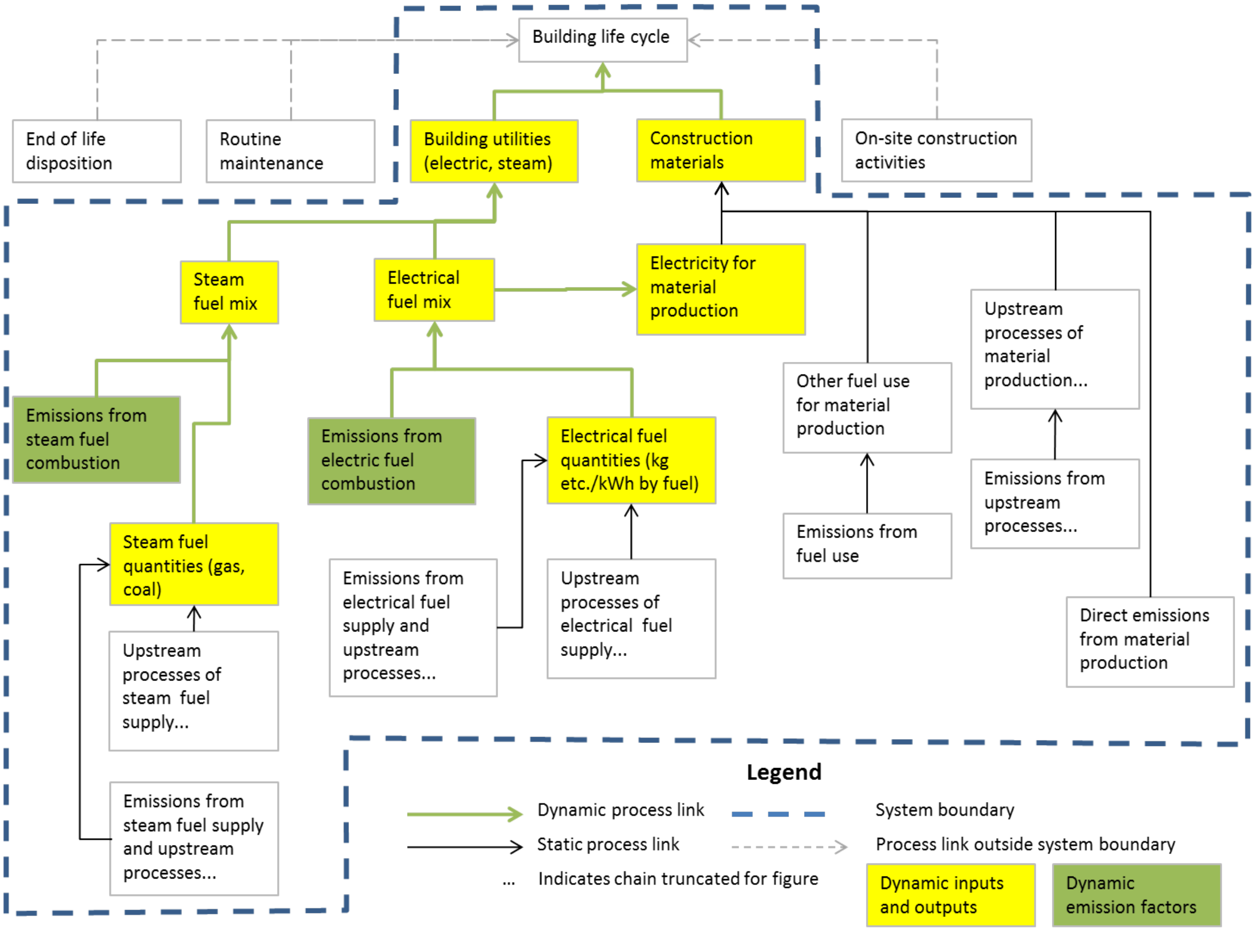


Figure 2 - System boundary and dynamic modeling

For this study, the DLCA model used a monthly time series for several reasons. Historical values for the building's utilities were available on a monthly basis, and fuel mixes for the electricity grid (USDOE 2010) and heating plant were also available on a monthly basis (Section 2.4.2). Annual aggregation of these values would potentially have masked variation in the results due to the timing of variations in energy use and the fuel mix. Emissions factors were typically annual values.

3.2.4 Data collection

Dynamic LCI - building-level data and modeling (f_t) - Historical and future values for the *f* vector were generated specifically for the case study building. Operating energy consumption was taken from utility meter data for Benedum Hall. Data availability varied depending on the individual variables; a summary is provided in Table 1 and a complete list is given in Table 14. For years prior to data availability, the average of the first three available years was used. Future energy consumption was estimated using the U.S. Department of Energy's (USDOE) eQUEST model (Hirsch 2010), adjusting model default parameters to reflect the specific conditions for Benedum Hall. A qualitative comparison of the eQUEST model results and both the extensive pre-renovation and limited post-renovation utility meter data was performed to verify the model's predictive capacity; results of this comparison are presented in Figure 24 and Figure 25.

Dynamic LCI - unit processes ($\mathbf{A}_t$) - Temporally specific historical and projected future unit processes for the **A** matrix were constructed from U.S. Energy Information Agency (EIA) records and projections (USDOE 2010, 2011b) for the national electricity generation mix; and meter data for the central campus steam plant (Table 14). Data sources for each process type are provided in Table 1. Upstream processes without dynamic data available were referred to 1) USLCI unit processes (NREL 2011), for energy and fuels; and 2) the ecoinvent v2.2 database (ecoinvent 2010), for materials. Ecoinvent was chosen over USLCI for materials because some material processes in the USLCI database do not explicitly link to upstream processes, but rather aggregate emissions from all upstream processes into one list. Separation of upstream unit processes was necessary to enable the DLCA model to function properly. However, because ecoinvent consists of mainly European data and does not contain time series, several modifications were made: 1) process electricity requirements from materials in ecoinvent were referred back to the time series described above, and 2) other process energy (e.g. heat, equipment fuel use) were referred to the USLCI energy unit processes. Thus, the material processes used for the 1971 construction were the same as those used for the 2009 renovation/addition, with the exception of changing the fuel mix and emissions for the electricity generation required by these processes.

*Dynamic LCI - emissions factors (**B_t**)* - Temporally specific emissions factors for the **B** matrix were constructed from available industry and environmental data (USEPA 2009b, 2010, 2011b) and Allegheny County Health Department (ACHD) data for the central campus steam plant (Kelly 2011). For example, emission factors for criteria air pollutants (CAPs) from electric power generation were calculated by dividing U.S. Environmental Protection Agency (EPA) historical emissions data (USEPA 2009b, 2011b)by the U.S. Energy Information Agency (EIA) records of power generation by fuel type (USDOE 2011b). Data sources for each variable are provided in Table 1; time series of emission factor results in each LCIA category are presented in Figure 26. Where possible, these values were compared against the USLCI database (NREL 2010) for consistency within the time frames for which the USLCI database applies. Qualitative results of this comparison are also presented in Figure 26.

*Dynamic LCIA - characterization factors (**C_t**)* - Temporally specific CFs are only available in a few LCIA categories. Therefore, for the baseline full lifetime and remaining lifetime DLCA calculations, static factors from the TRACI method were used (Bare et al. 2003). Temporally specific CFs available in the literature include monthly CFs for photochemical ozone in the U.S. (Shah and Ries 2009); annual global CFs for ozone depletion (Struijs et al. 2010), decadal-scale CFs for acidification and eutrophication in Europe (Seppälä et al. 2006), time-horizon adjusted CFs for acidification in Europe (Van Zelm et al. 2007), and time-horizon adjusted CFs for global warming, e.g. (Kendall 2012). The European acidification and eutrophication CFs are not adaptable to the U.S. due to the lack of a U.S.-based database of ecosystem sensitivities (Norris 2003). The lack of any consistent set of temporally variable CFs for the U.S. across multiple impact categories led to the decision not to include them in the baseline analyses for this study. However, example calculations using two sets of dynamic CFs - photochemical ozone from Shah and Ries (Shah and Ries 2009) and global warming (Kendall 2012) have been included in the future scenario analysis (Section 2.5). The compilation of a set of temporally variable CFs across multiple impact categories and time scales for the U.S. is planned as future work.

3.2.5 Future scenario analysis

A future scenario analysis was conducted to probe the sensitivity of the results to changes in assumptions about future trends, building on the remaining lifetime DLCA calculation (2009-2045). The individual and combined influence of end-use energy variations, fuel mixes, and emissions controls was investigated by pairing different combinations of each variable in Eq. 1. For f_t, scenarios were generated using 10% increases and decreases in electricity consumption and steam heat consumption separately. This range was anticipated to be within the capacity of adjustments to existing set points and operating schedules, and thus allowed for some level of uncertainty in occupant usage and behavior. For $\mathbf{A}_t$, the EIA's 47 projected cases from the Annual Energy Outlook (AEO) were examined and the cases which resulted in the greatest variation in generation mixes from the baseline were added to the analysis (USDOE 2010). For $\mathbf{B}_t$, a scenario without the EPA's currently proposed regulations was examined, in which emissions factors remained constant at 2009 levels. The scenario pairing no increase or decrease in energy consumption with no new EPA rules was similar to the static LCA, except that even the EIA's baseline (Reference case) includes expected changes in the future generation mix and is thus dynamic.

Finally, for $\mathbf{C}_t$, calculations were constructed in the GWP category using time-adjusted warming potentials (TAWPs) from Kendall 2012, and in the photochemical ozone category using monthly factors for a typical year from Shah and Ries 2009. Shah and Ries developed CFs at the midpoint level for nitrogen oxides (NOx) and volatile organic compounds (VOC) in terms of ppb O_3*km^2*day/kg emission. To compare with the static TRACI CFs, which use a reference unit of kg NOx eq., the Shah and Ries CFs were normalized by dividing the monthly values for NOx and VOC by the annual average value for NOx from their own study.

3.3 RESULTS AND DISCUSSION

3.3.1 Static LCA validation

Total mass of the materials and embodied energy inputs of the static LCA for the original construction were compared with two previous studies of commercial and/or institutional buildings in the US (Junnila et al. 2006; Scheuer et al. 2003) to validate LCA inputs. Scheuer et al. analyzed a 6-story combination academic and hotel building in Michigan, and Junnila et al. analyzed a 5-story office building in the U.S. midwest. Results of the comparison are summarized in Table 2. A complete comparison of LCI results is given in Table 15. Total normalized mass of Benedum Hall was estimated to be 1,670 kg/m^2 and total embodied energy to be 5,080 MJ/ m^2, compared to 2,000 kg/m^2 and 6,250 MJ/m^2 for Scheuer et al., and 1,290 kg/m^2 and 11,900 MJ/m^2 for Junnila et al. Total annual operating energy was 3,920 MJ/m^2, compared to 4,100 MJ/m^2 for Scheuer et al. and 1,320 MJ/m^2 for Junnila et al.

The results of this study agreed qualitatively with Scheuer et al. in most categories, and with Junnila et al. in some categories. A significant degree of variation is expected even between comparable buildings, due to differences in construction details, selection of system boundaries and the use of different LCI databases. The material systems included in this study for Benedum Hall represented 90% of the results of the Scheuer et al. study by mass, and 74% by embodied energy.

Table 2 - Mass and energy inputs for static LCA model of the building materials and initial energy consumption.

Material and Energy Results	**Case Study: Benedum Hall**		**Scheuer** et al. (2003)		**Junnila** et al. (2006)	
	Mass/ area (kg/m^2)	Energy/ area (MJ/m^2)	Mass/ area (kg/m^2)	Energy/ area (MJ/m^2)	Mass/ area (kg/m^2)	Energy/ area (MJ/m^2)
Total materials	1,670	5,080	2,000	6,250	1,360	11,920
Original construction materials	1,570	4,250	NG	NG	1,290	7,060
Renovation/ addition materials	100	820	NG	NG	70	4,860
Annual operating energy - total	-	3,920	-	4,100	-	1,360
Annual operating energy - electricity	-	3,340	-	NG	-	700
Annual operating energy - heat	-	580	-	NG	-	660

NA = Not applicable NG = Not given (results are presented graphically)

Embodied energy was calculated as total nonrenewable energy. Results from two other LCA studies of commercial or institutional buildings in the US are presented for comparison and validation.

Mass results on a system-by-system basis were comparable to Scheuer et al. (more detail provided in Table 15); the differences in embodied energy can be attributed primarily to 1) the exclusion from this study of internal finish materials, such as carpet and ceiling tiles and 2) the value for embodied energy for steel from the LCI databases used. Finish materials such as carpet and ceiling tile have high embodied energy contents and frequent replacement intervals, and account for a significant portion of the total embodied energy results in Scheuer et al. The amounts of such materials in Benedum Hall are minor by comparison with most buildings and were not considered in this study. Compared with Junnila et al, the lower embodied energy per unit mass can also be attributed in part to the exclusion of interior finishes from this study, since items such as structural steel and concrete had reasonably similar value for total embodied energy per unit area of the building. However, Junnila et al. also used a hybrid process-based and economic input-output (EIO) based LCA model, which may have contributed to the difference. From comparison with both studies, future work on the dynamic LCA model should include finish materials such as paint, carpet and tile for the sake of full compatibility with other studies and to accommodate buildings with larger amounts of these materials than Benedum Hall.

3.3.2 DLCA and static LCA results for full lifetime analysis

The DLCA results were lower than static LCA results in most impact categories with the exception of nonrenewable energy use (NREU; +12%), as shown in Figure 3. The factors affecting the DLCA results in terms of eq. 2 were (1) the building's end-use energy consumption (included in f_t), (2) the electrical generation fuel mix (included in $\mathbf{A}_t$), (3) the steam generation mix (also included in $\mathbf{A}_t$), and (4) emissions factors for the national electrical grid (included in $\mathbf{B}_t$). The results showed reductions of more than half in the categories of acidification (-57%), human health respiratory effects (-61%), photochemical ozone (-55%), eutrophication (-53%)

and carcinogens (-57%). Non-carcinogens and ecotoxicity were reduced by lesser amounts (-27% and -9% respectively). Global warming potential (GWP) decreased by 2%.

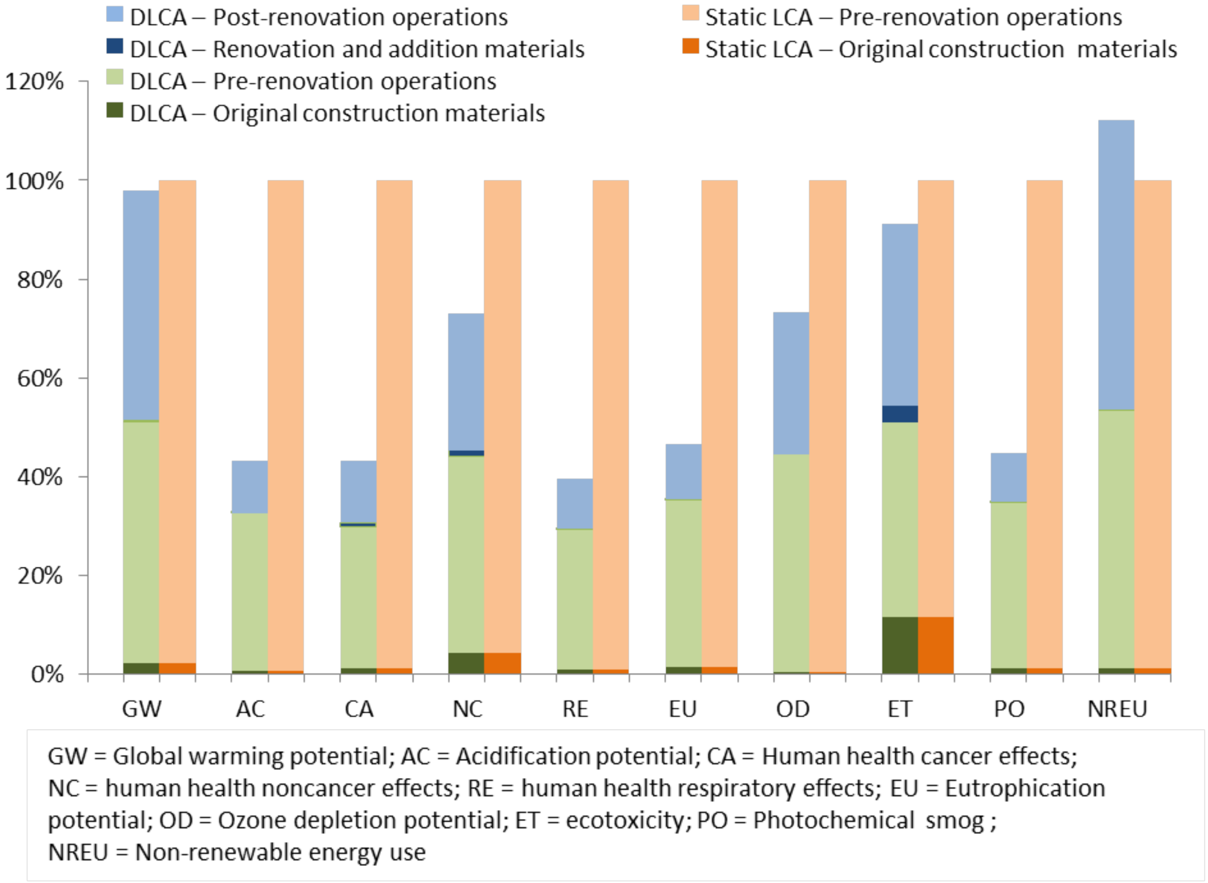


Figure 3 - Comparison of results from static and DLCA models, using the TRACI method.

Results are normalized to the total static LCA results for each category. Static LCA results were calculated as the total of the initial construction and projection of the initial year's operating energy consumption for the 75-year life of the building. DLCA results are classified into four categories: Original construction materials; Pre-renovation operations (operating energy consumption through 2008); Renovation and addition materials; and Post-renovation operations (operating energy consumption 2009 through end of lifetime).

The largest differences in the results were due to the lowering of emission factors for CAPs from 1970 to the present, documented by EPA's extensive historical estimation of CAP trends and continuing projected reduction in the near future through 2015 due to the EPA's proposed Transport and Toxics Rules. Data for hazardous air pollutants (HAPs) also exist in EPA's historical estimates and future projections, though coverage dates are generally more limited (1990-2008). No such national database for water pollution was found, though estimates are noted in the literature (Bare 2011). Therefore, the water emissions estimated herein are primarily static values from the ecoinvent and USLCI databases. Additionally, water pollution related categories such as eutrophication and ecotoxicity may be under-represented because wastewater from the building was not included in the study.

The three toxic pollutant LCIA categories (human health cancer, human health noncancer, and ecotoxicity) are typically affected by both air and water emissions of hazardous metals and organic compounds. However, air emissions of metals from coal combustion dominated the results in the three toxics categories. In accordance with EPA modeling documentation, combustion-related air emissions of metals were projected proportionately to particulate matter <2.5 µm (PM2.5) and organic compounds were projected proportionately to total VOCs (USEPA 2011a). Non-carcinogens and ecotoxicity were affected to a higher degree than carcinogens by water emissions, and thus do not show as much reduction from historical levels, due to the use of static data for water emissions. Material production processes for the construction and renovation had a proportionately greater impact in the non-carcinogens and ecotoxicity categories than the other categories; however, operating energy consumption still had the greatest impact. For ozone depletion, all processes considered in this LCA are minor sources, and thus neither the static nor dynamic results were considered to be significant.

Changes in emissions factors had the greatest influence on the LCIA results, but the remaining variables in eq. 2 (f_t, $\mathbf{A}_t$) were also important, particularly in the GWP and NREU categories. Figure 4 shows the DLCA results as cumulative time series in each LCIA category, normalized to the cumulative totals in each category as of 2008. Impacts from construction and renovation are represented at a single point in time; realistically, these impacts occur over the span of several years. The time scale associated with these activities is shorter than that for building operations, even when operations are classified into phases between major renovations. Since the temporal changes incorporated into the current analysis are mainly gradual and on the order of decades, the treatment of material- and construction-related emissions as pulses were not expected to influence the overall results.

Electrical energy consumption increased gradually during the period of pre-renovation meter data availability, growing 10% from 1993-1994 through 2007-2008. Steam consumption remained essentially constant during this same period. The cause of the increased electrical usage was not known, but it was assumed to be from increases in laboratory and office equipment demand, including computers. If electrical energy consumption was due to increased use of the overall building (e.g. extended hours, increased ventilation etc.), it would be expected to result in an increase in steam use as well. For the renovated building, modeled energy consumption of both types increased. An increase in overall building footprint, coupled with increased heating, cooling and fan usage demands from increased space ventilation requirements were responsible for the increased energy consumption.

In the GWP category, the increasing trend in energy consumption was offset by a decreasing trend in greenhouse gas (GHG) emissions from the energy supply chain. While the electrical generation mix continues to rely heavily on coal-fired power plants, GWP for the electrical generation sector decreased 11% from 0.72 kg CO2 eq/kWh in 1970, to 0.64 kg CO2 eq/kWh in 2008. GWP of the district steam production decreased 39% from 2.3 to 1.4 kg CO2 eq/kg steam, following the switch from mixed coal- and gas-fired generation to 100% gas in June

2009. However, the modest decrease in GWP/kWh from electrical generation was offset by the modest increase in electrical usage over the building's lifetime to date, and the larger decrease in GWP/kg steam was offset by the larger increase in projected steam usage following the renovation as noted above. Because the heating fuel switch and renovations occurred at nearly the same time, the slope of the NREU curve in Figure 4 is higher post-renovation than pre-renovation, while the slope of the GWP curve in Figure 4 remains the same. Because natural gas emits fewer CAPs and HAPs than coal, the heating fuel switch also affected the curves in Figure 4, combining with the reduced emissions factors from electric power generation to reduce the slope of the future curves.

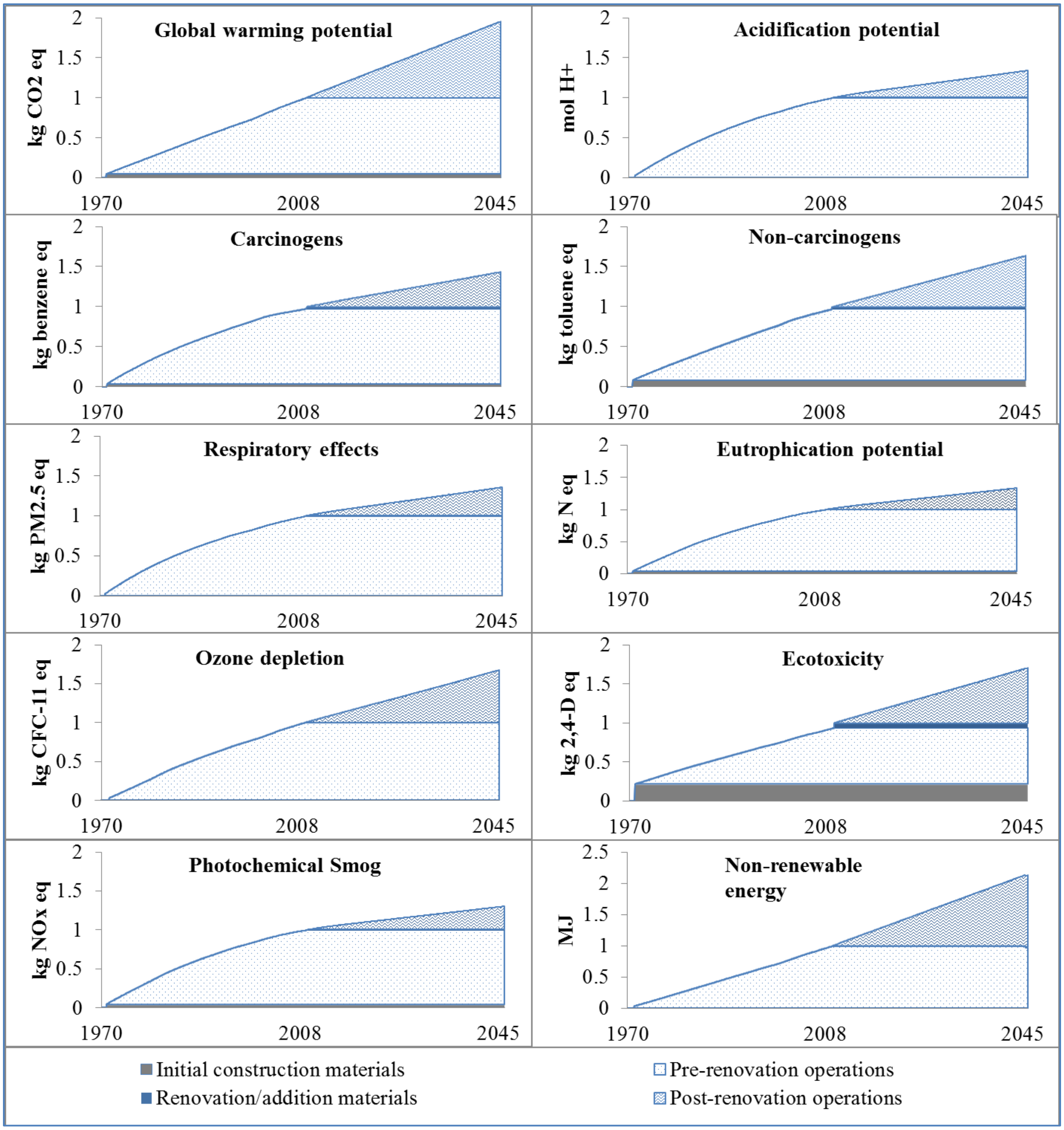


Figure 4 – Cumulative time series of DLCA results in TRACI impact categories and nonrenewable energy use. Cumulative totals are normalized to year 2008 totals (prior to renovation).

3.3.3 DLCA and Static LCA results for remaining lifetime analysis

The DLCA results for the remaining lifetime analysis were lower than the static LCA results in every impact category shown in Figure 5. As with the full lifetime analysis, the static LCA used energy mixes and emission factors from the year of analysis (2009) projected through the remaining lifetime. However in contrast with the full lifetime analysis, the building's end use energy consumption was the same for both static and dynamic analyses, since no actual energy data were available yet. Reductions in impacts from largest to smallest were: acidification (-17%), photochemical ozone (-16%), human health respiratory effects (-15%), eutrophication (-14%), carcinogens (-5%), NREU (-4%), non-carcinogens (-3%), ecotoxicity (-3%), and GWP (-2%). As with the full lifetime analysis, the largest decreases were caused by a reduction in emissions factors following environmental regulations (the proposed EPA Transport and Toxics rules). The reductions in global warming potential and nonrenewable energy use were due to changes in the electrical fuel generation mix.

3.3.4 Future scenario analysis

The maximum variations from the baseline for the different DLCA scenarios are shown as error bars on the DLCA results in Figure 5. These error bars represent the scenarios contributing to the minimum and maximum impacts in each category. Other types of uncertainty and variability (not shown) include parameter uncertainty (e.g. emissions factors) and spatial variations. These uncertainties can be elicited by Monte Carlo analysis (e.g. Dale et al. 2013) and could be shown as an additional set of error bars, applied to both the static and dynamic LCA results. For the baseline energy use case, the minimum and maximum variability from the static

LCA due to combining variability in projected energy mixes and emissions factors were: acidification (+39%/-18%), photochemical ozone (+36%/-15%), human health respiratory effects (+35%/-22%), eutrophication (+32%/-20%), carcinogens (+20%/-34%), non-carcinogens (+10%/-12%) and ecotoxicity (+9%/-9%). The minimum and maximum variability for categories depending only on energy mixes were nonrenewable energy use (+7%/-15%) and global warming potential (+10%/-17%).

Figure 6 shows selected time series for the global warming and photochemical ozone impact categories, representing scenarios with different combinations of variation from the baseline, for each term in eq. 2. The remaining series are presented in Figure 29. Of the variations in the *f* vector, the 10%+/- electricity scenarios had greater influence than the 10% +/- heat scenarios, due to 1) the larger overall energy use represented by electricity for this building, and 2) the larger impact in most categories per unit energy of electricity, due to the use of coal as a fuel. The variations in the *f* vector are a simple scaling of the baseline results, but are qualitatively illustrative of uncertainty in building use, such as hours of operation, user behavior, or HVAC system setpoints. They are also a point of reference in Figure 6 for the relative changes in impact due to the scenarios representing variations of the A, B and C matrices.

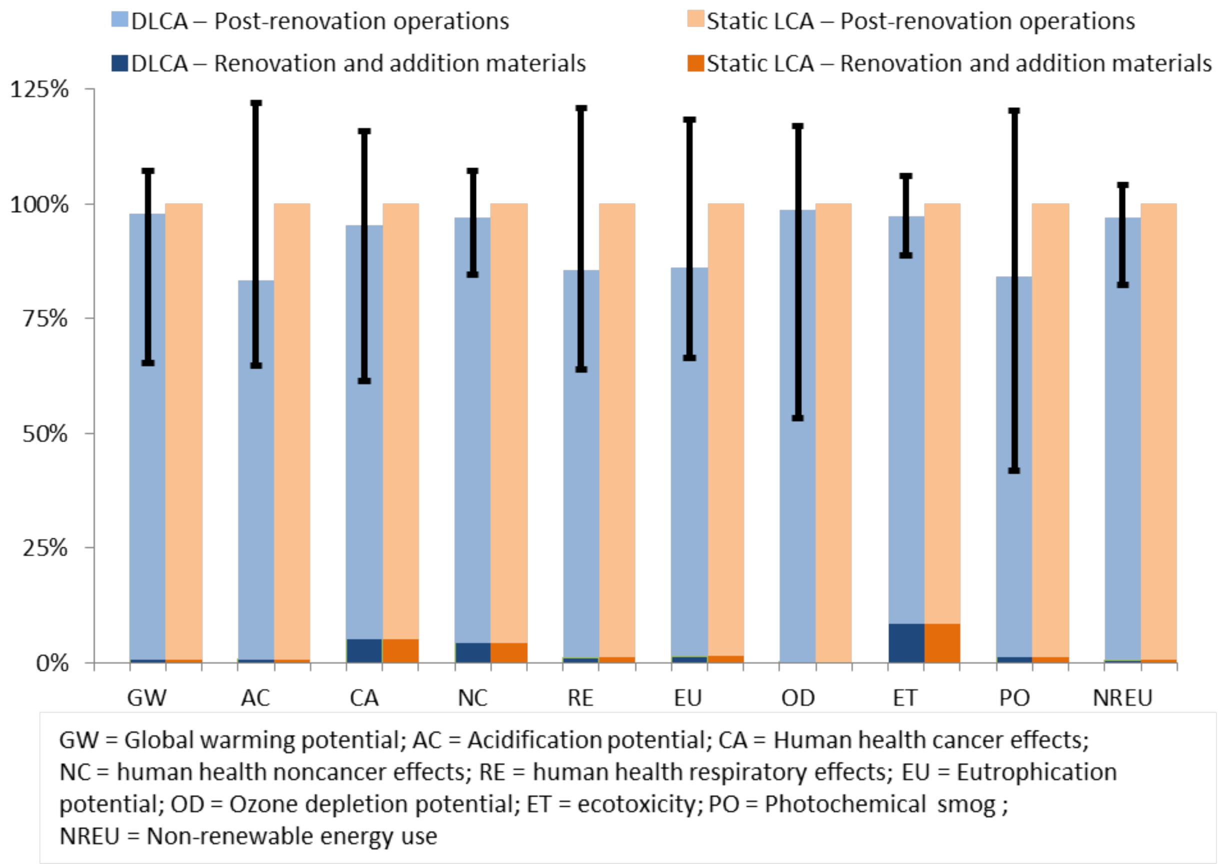
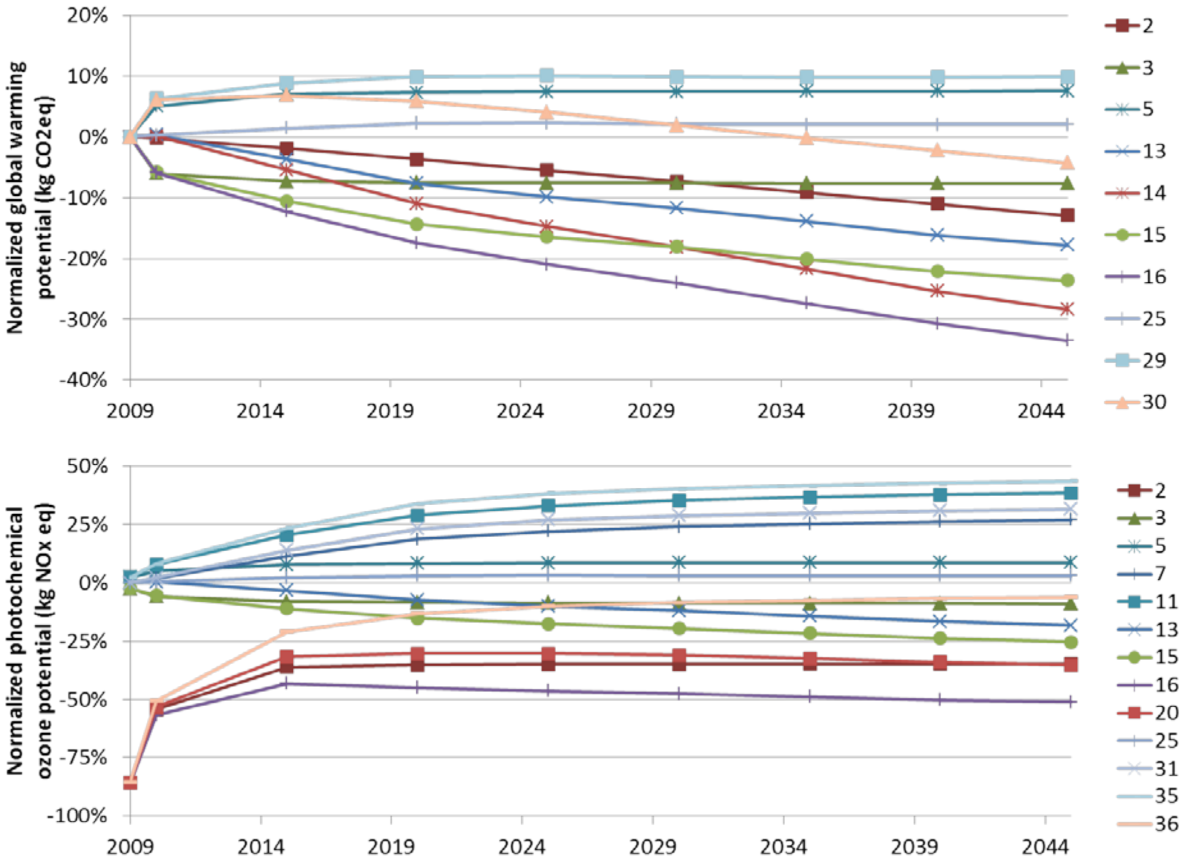


Figure 5 - Comparison of predicted results for from static and DLCA models for the renovation and post-renovation operations.

Error bars on the DLCA results indicate the minimum and maximum values associated with different scenarios from the sensitivity analysis. For the GW and PO categories, the error bars include consideration of dynamic characterization factors at the impact assessment step. Error bars for all other categories include only variation in the life cycle inventory.



Scenario Legend

1 – (Not shown) Baseline all cases
2 – Baseline electricity, EIA reference, EPA rules, Dynamic CF
3 – 90% electricity, EIA reference, EPA rules, Static CF
5 – 110% electricity, EIA reference, EPA rules, Static CF
7 – Baseline electricity, EIA reference, No EPA rules, Static CF
11 – 110% electricity, EIA reference, No EPA rules, Static CF
13 – Baseline electricity, EIA GHG price, EPA rules, Static CF
14 – Baseline electricity, EIA GHG price, EPA rules, Dynamic CF
15 – 90% electricity, EIA GHG price, EPA rules, Static CF
16 – 90% electricity, EIA GHG price, EPA rules, Dynamic CF
20 – Baseline electricity, EIA GHG Price, EPA rules, Dynamic CF
25 – Baseline electricity, EIA Low Shale, EPA rules, Static CF
29 – 110% electricity, EIA Low Shale, EPA rules, Static CF
30 – 110% electricity, EIA Low Shale, EPA rules, Dynamic CF
31 – Baseline electricity, EIA Low Shale, No EPA rules, Static CF
35 – 110% electricity, EIA Low Shale, No EPA rules, Static CF
36 – 110% electricity, EIA Low Shale, No EPA rules, Static CF

Figure 6 - Time series of DLCA results for the sensitivity analysis, shown as cumulative percent deviations from the baseline scenario for the global warming potential and photochemical smog categories.

Time series plots of the deviations from baseline for the remaining TRACI impact categories are presented in Figure 29.

Of the 47 electricity grid mix scenarios drawn from the EIA AEO (represented in the **A** matrix), the greatest decrease in impact in most categories was the “GHG price economywide” scenario, representing a future in which coal use drops steeply due its greater CO_2 emissions than other fuels. The AEO scenario with the greatest increase in impacts was the “low shale resource” scenario, in which estimated unproven resources (EURs) are assumed to be half those in the Reference case. The low availability of shale gas in this scenario leads to a reduced use of gas and a corresponding increase in coal for electric power generation.

For any combination of *f* and **A** scenarios, eliminating the introduction of the new EPA regulations (represented in the **B** matrix) showed increased impact in most categories associated with CAPs (and some HAPs, such as metals from coal-fired power plants) compared to the baseline DLCA case. Scenarios eliminating the new EPA regulations combined with low gas resources - and hence increased coal use for power generation without significant new emission controls - showed increased impacts in these categories compared even to the static LCA.

The effect of including dynamic CFs is shown in the odd-numbered curves in Figure 6, and is reflected in the error bars in the global warming and photochemical ozone categories in Figure 5. In both cases, the addition of dynamic CFs reduced the total impacts compared to static CFs, though for different reasons. For global warming potential, the dynamic CFs, or TAWPs, reduced the cumulative impacts for any combination of other variables by approximately 13% at the year 2045. This reduction represents the application of a fixed 100-year time horizon for integrating radiative forcing of GHGs, applied over the 36-year lifetime of the building. For example, CO_2 emissions in 2045 treated in this manner have a TAWP of 0.71, instead of 1. For more information on TAWPs, see Kendall (2012). Although TAWPs for different GHGs vary differently with time, CO_2 was by far the dominant GHG in this analysis. Since the TAWP is calculated on an annual basis, any process with a total lag time of less than 1 year is accurately represented, which should capture the bulk of energy extraction and supply processes.

For photochemical ozone, the inclusion of dynamic CFs reduced the individual scenarios resulting from the combination of the other variables by 26% to 50%. The reduction was lowest for low emissions scenarios (e.g. Scenario 16 in Figure 6; 90% electricity with AEO GHG price and new EPA rules) and highest for high emissions scenarios (e.g. Scenario 36; 110% electricity with AEO low shale resources and no new EPA rules). The overall reductions are explained by the fact that higher emissions of ozone precursors - mainly NOx in this case - occurred during winter months, when the dynamic CFs are lowest. This was due to 1) overall increased demand for energy in the winter, due to heating needs and 2) relatively constant year-round electrical demand, but with a higher percentage of coal-fired power generation in winter months. Since the photochemical ozone CFs vary on a scale of months, it is possible that including lag times could affect this calculation. However, uncertainty in the supply chain required assuming an annual average CF for all upstream processes, while using the monthly CFs for combustion. This formulation implicitly resulted in a variable lag time of up to 1 year between upstream processes and combustion.

3.3.5 Limitations

Additional dynamic CFs - CF variations were not considered in most categories because no applicable source of temporally CFs was found in the literature. The lack of characterization methods incorporating both short-term and long-term temporal variability is a shortcoming of current LCA practice, and could be remedied by additional LCIA method development. Temporally variable CFs need to take into account changes in background chemical concentrations, environmental systems and the distributions of exposed populations, as well as time horizon relevance. The examples used in this study represent one instance of a time horizon related CF (TAWP) and one instance of a physical system variation (photochemical ozone). In the case of the latter, additional investigation into the combination of daily, seasonal and long-term factors is needed (Reap et al. 2008).

Data availability - Dynamic variation in industrial processes and emission factors is hampered by a lack of available data. In this case study, unit energy use for industrial processes and emissions factors from fuel use other than in electrical power plants, were not able to be modeled dynamically. This resulted in lower energy use and emissions associated with building material production for the initial construction. However, in LCIA categories that were highly influenced by energy use, these contributions were small relative to the impacts of operating energy. With respect to emissions factors, it is noted that continued increases in data quality are expected to provide additional accuracy in results. Efforts to track and control toxic pollutants have historically lagged behind CAPs, and thus there is greater uncertainty in the temporal trends in toxic-related impact categories. With respect to lag times, the inclusion of supply chain lag times as an additional variable in LCI databases is critical for the accurate application of temporally varying CFs. However, the uncertainty related to upstream production functions may require annual averaging of most processes except those occurring in the building itself, which can be known with some detail, or those which are predictable based on system characteristics, such as energy and fuel supplies.

Spatial variability - Significant spatial uncertainty exists in LCA. The definition proposed herein for DLCA includes consideration of spatial variability, though it has not been directly addressed yet in this analysis. Noting that the term dynamic usually connotes temporal changes, it should be considered that spatial patterns of industrial activity and environmental impacts change over time; the NEI and other databases provide explicit spatial detail related to emissions, and LCIA methods with spatially explicit CFs are available. For North America, both TRACI and Impact models have some spatial resolution, though additional detail is needed in most categories. Related to spatial variation, it has been noted that there is extensive regional variation in the electrical generation mix. The national generation mix has been used herein, but regional or even sub-state-level mixes have been used in some studies. However, it has been shown that power trading between regions tends to drive the mix toward a national average (Weber et al. 2010); thus, the use of non-spatially explicit factors may be warranted in this case. More so than for electricity, the concentration of major producers in some industries (e.g. petroleum refineries, mining) in specific regions with CFs different from the national average may lead to a case for regionalization of LCA results even when the exact supply chain is uncertain.

Uncertainty of future scenarios - The outlook of this chapter comprises both historical temporal variations and predicted future variations. However, it is likely that the primary use for LCA of buildings will continue to be predictive. Uncertainty in future scenarios depends on both building-level variables (e.g. occupancy levels, renovations) and external variables such as emissions controls and environmental background conditions. Since Benedum Hall was recently renovated, projection of past building-level trends into the future was limited to assuming as-is operations of the building and district heating plants (since the building recently underwent a full renovation), with variation in energy usage of +/-10% to accommodate occupant behavior. However, exact knowledge of future occupant needs or renovation schedules will not usually be available to the LCA practitioner, even with DLCA modeling. There are also predictive assumptions built into the models used by EIA and EPA to forecast future energy mixes and emissions. Though uncertainty in prediction cannot be fully avoided, considering multiple future scenarios can illuminate possible environmental tradeoffs; for example, the often-cited tradeoff between embodied energy in construction materials and use-phase operating energy is changed somewhat when a DLCA model with varying energy supply background conditions is used. Alternatively, a conditional probability approach could be used - explicitly accounting for the choice of externally imposed scenarios to generate a scenario-independent DLCA result which would include the other types of uncertainty (e.g. spatial, parameter) while still eliciting expected changes from a static LCA over time (e.g. building systems performance).

3.4 CONCLUSION

This chapter explicitly uses dynamic LCA (DLCA) and illustrates the potential importance of the method using a simplified case study of an institutional building. The results show that the environmental impacts of the building over its lifetime vary significantly from what would be predicted if temporal changes were not taken into account. Particularly, the results indicate the importance of changes in building usage, energy sources and environmental regulations in calculating the overall environmental impacts of the building. Given that temporal changes are rarely accounted for in LCA practice, it seems clear that LCA could be improved by incorporating a more dynamic focus. Previous whole-building LCAs have demonstrated the relative importance of the operations phase in most impact categories, compared to the materials, construction and end-of-life phases. The DLCA results suggest an additional conclusion; that in some cases, changes in building usage, or changes in external conditions such as energy mixes or environmental regulations during a building's lifetime, can influence the LCA results to a greater degree than the material and construction phases. Correspondingly, adapting LCA to a more dynamic approach as demonstrated herein seems likely to increase the usefulness of the method in assessing the performance of buildings and other complex systems in the built environment.

Future research needs include characterization of uncertainty related to building systems modeling (e.g. future occupant needs and maintenance/renovation schedules); additional exploration of the interactions with dynamic, temporally evolving (and themselves uncertain) LCI and LCIA background variables, and development of additional dynamic CFs and dynamic parameters for LCI databases.

Establishing a DLCA framework for whole buildings was considered to be an essential prerequisite for incorporating indoor environmental quality (IEQ) effects into whole-building LCA. The factors affecting IEQ impacts, particularly occupancy and operational schedules, are subject to significant changes on daily and seasonal bases, as well as over the long term. The following chapters deal with the incorporation of IEQ into the DLCA model and comparison of internal to external effects.

4.0 INTEGRATING INDOOR ENVIRONMENTAL QUALITY INTO THE DLCA FRAMEWORK FOR WHOLE BUILDINGS

The following chapter contains material reproduced from an article published in the journal *Building and Environment* with the citation:

Collinge, W.O., A.E. Landis, A.K. Jones, L.A. Schaefer and M.M. Bilec (2013), "Indoor Environmental Quality in a Dynamic Life Cycle Assessment Framework for Whole Buildings: Focus on Human Health Chemical Impacts." *Building and Environment* 62 pp. 182-190.

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Portions of the Supporting Information submitted with *Building and Environment* appear in this chapter and Chapter 5, and the remaining portions appear in Appendix B.

4.1 INTRODUCTION

The aim of this chapter is to outline a framework for incorporating IEQ into whole-building LCA. Methods for empirically quantifying IEQ impacts generally fall into two types: single variable relationships between building-related parameters and measured occupant health or performance outcomes (Fisk and Mirer 2009; Heschong et al. 2002a; Mendell and Mirer 2009; Milton 2000; Seppänen et al. 2006c; Sahakian et al. 2009; Mendell 2003) and multivariate indices with single-value or reduced-parameter predictors of occupant outcomes (Mendell 2003; Sekhar et al. 2003; Sofuoglu and Moschandreas 2003; Wong et al. 2007).

Recent research integrating IEQ in LCA has focused on incorporating indoor chemical pollutant intake into the existing human health toxicity life cycle impact assessment (LCIA) categories (Demou et al. 2009; Hellweg et al. 2009; Humbert et al. 2011; Wenger et al. 2012). In these approaches, the impacts of indoor pollutant emissions are estimated based on emission rates from indoor materials or processes and building-level variables, such as ventilation and occupancy rates. A benefit of these approaches is integration within existing conventional LCIA categories. However, when extending the approach to consider whole-building IEQ features, additional factors need to be included. These factors can be grouped into three categories: 1) indoor intake of outdoor pollution due to a building's location and ventilation characteristics, 2) indoor generation of biological/biochemical contaminants, and 3) non-IAQ related influences on occupants' health and productivity (e.g. eye strain and mood impacts due to poor lighting quality). Though the latter two factors may extend the boundaries of conventional LCA practice, there is precedent for inclusion of similar effects in the LCA literature; e.g. noise, workplace accidents (Cucurachi et al. 2012; Pettersen and Hertwich 2008). In the case of whole buildings and other built environment systems, the case for including these system-dependent impacts is made stronger by the function of the system under study (e.g. housing or transporting human beings).

The overarching goal of this research project is to develop a dynamic LCA (DLCA) tool for building analysis that incorporates metrics of relevance to building design. In Chapter 3, a working definition of DLCA was proposed as “an approach to LCA which explicitly incorporates dynamic process modeling in the context of temporal and spatial variations in the surrounding industrial and environmental systems”, and its application was evaluated with a simplified case study. The research questions addressed in the next two chapters are: “How do we incorporate IEQ into LCA, and how significantly does IEQ affect conventional LCA results?” To answer these questions, we developed a framework for including IEQ impacts in whole-building LCA, separating chemical-specific impacts that align with traditional LCIA categories from non chemical-specific impacts, and identifying potential gaps or overlaps. Chapter 4 outlines the complete framework, and Chapter 5 applies the framework to a case study of an existing LEED Gold academic building. We then compare these internal impacts to the external impacts resulting from the DLCA model applied to the building’s energy use.

4.2 METHODS

4.2.1 General framework for Indoor Environmental Quality + Dynamic Life Cycle Assessment (IEQ+DLCA)

The indoor environmental quality + dynamic life cycle assessment (IEQ+DLCA) framework developed herein is illustrated in Figure 7. Beginning at the top of the figure, the first distinction is between internal and external building impacts, which is a crucial element of the framework. Internal impacts are defined as those occurring within the study building, whereas external impacts are those occurring outside of the study building.

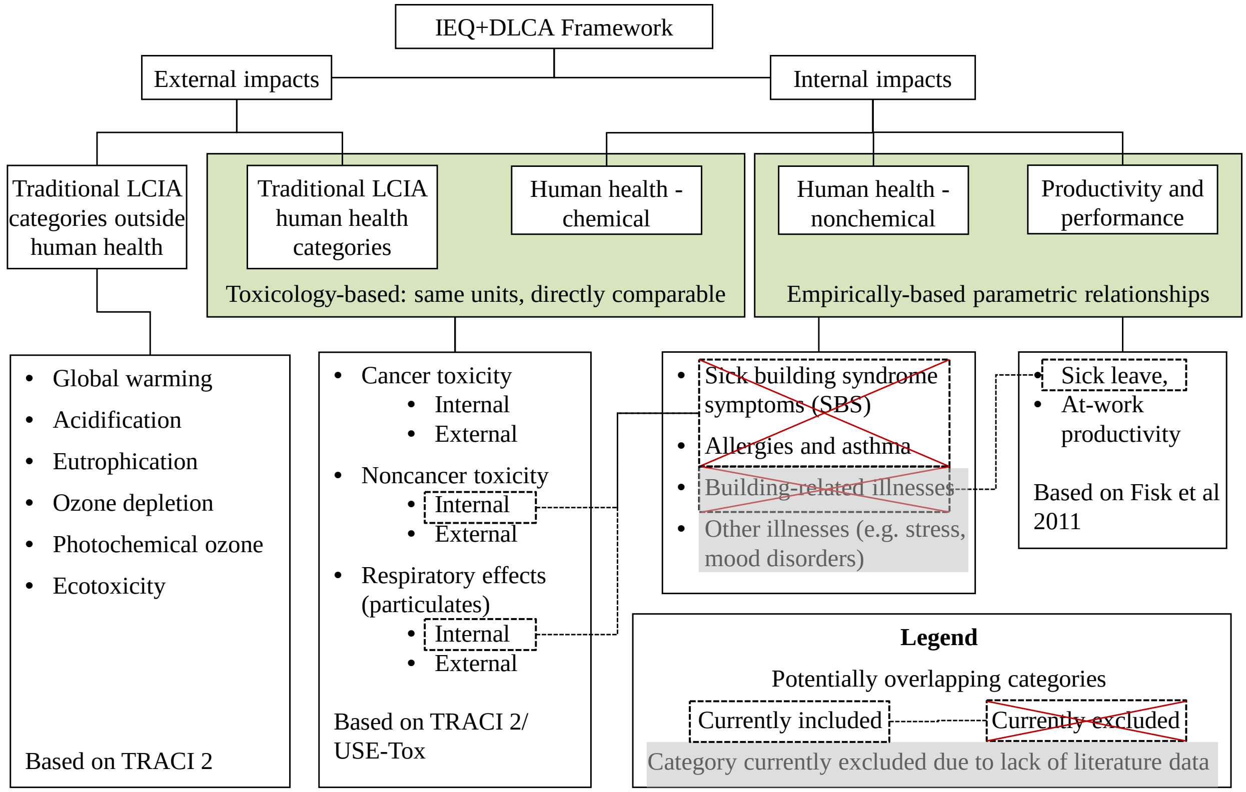


Figure 7 - IEQ+DLCA framework.

External LCA impact categories are shown on the left; internal impact categories are shown on the right.

For external impacts, shown on the left side of Figure 7, the IEQ+DLCA framework builds on the dynamic LCA (DLCA) model developed in the previous chapter (Collinge et al. 2012a). A dynamic approach, considering the time variation in building-related measurements, can reduce the uncertainty introduced by static estimates of building usage, as well as accounting for variation in industrial and environmental systems. Inputs to the DLCA model are typical for LCA - quantities of energy or materials required for building operations and maintenance - but are input as time series to maintain correspondence with dynamic unit processes and emissions factors. The DLCA model contains a standard set of impact assessment categories based on TRACI 2.0 (Bare 2011), with optional dynamic characterization factors (CFs) limited to those few categories for which values are available in the literature. Dynamic CFs are not currently available for human health categories. TRACI 2.0 employs CFs from the UseTox model for cancer and noncancer toxicity (Rosenbaum 2008b; Rosenbaum et al. 2011), and its own CFs for respiratory effects, all of which are static values. If dynamic CFs for these categories are developed in the future (e.g. seasonal and spatial variation in fate and exposure factors), these could be incorporated into the DLCA model. With respect to human health, external impacts could include impacts inside other buildings, such as occupational exposures related to industrial processes in the supply chain. However, most LCIA methods do not yet explicitly consider such impacts, though research is being undertaken toward this goal (Demou et al. 2009; Hellweg et al. 2009; Humbert et al. 2011); thus, their inclusion is not examined here.

Internal impacts are limited to human health impacts, since the remaining categories in conventional LCA accrue to species or environmental systems (e.g. global climate). As defined herein, internal impacts - shown on the right side of Figure 7 - affect users or occupants of the building, during the time they are inside the building. In the external categories, human health impacts accrue to either the global or continental population as specified in the underlying Use-Tox LCIA model (Rosenbaum 2008b). Since the internal impacts are specific to the population of occupants of the subject building, there will be some finite but small overlap between these populations. Herein we assume that this overlap is negligible, and its potential effects are discussed in the next section.

Internal impacts are further separated into three types; 1) human health chemical impacts, 2) human health nonchemical impacts, and 3) performance or productivity impacts. For all three categories, a specific set of dynamic building data is required (Figure 8), including indoor and outdoor air temperatures (ambient and supply air); ventilation and recirculation airflows and filtration or other treatments; humidity; lighting; and noise levels. Evaluation of chemical impacts also requires indoor pollutant emissions, or indoor and outdoor pollutant concentrations. For all types of internal impacts, the dynamic estimation of building occupancy levels is critical to calculate temporally specific exposures. Chemical impacts are disaggregated into 3 categories; respiratory effects, cancer toxicity, and noncancer toxicity. These categories are the same in terms of dose-response or effect factors as their external (conventional) counterparts (Figure 8), but with different methods used to calculate exposure, described in more detail in section 4.2.2.

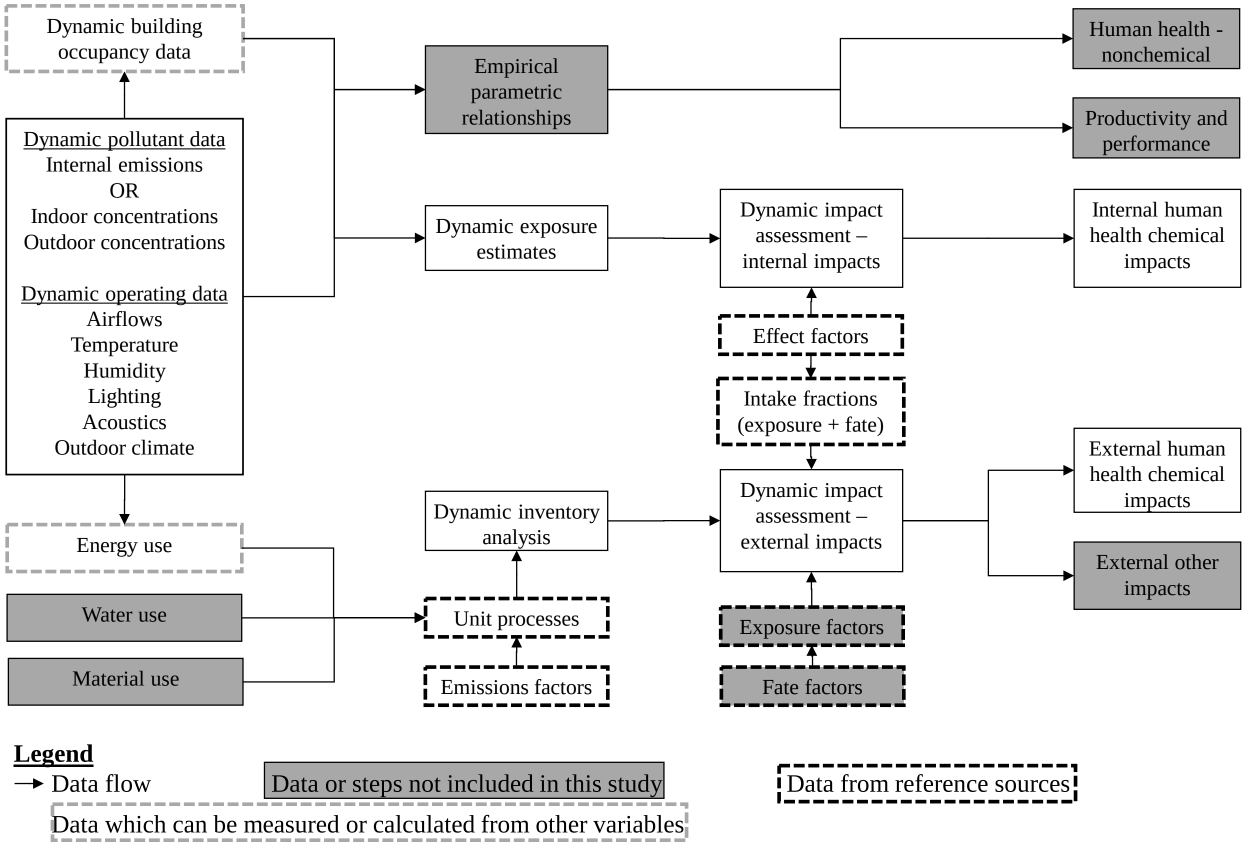


Figure 8 - Flowchart showing inputs, calculation steps and outputs for internal human health-chemical impact categories and external LCA impact categories.

4.2.2 Whole building exposure approach for chemical impacts

The general approach to LCIA consists of multiplying emissions collected in the LCI by CFs, which relate emissions to health impacts through the use of fate, exposure and effect modeling (Rosenbaum et al. 2011). This approach is incorporated in the IEQ+DLCA framework for internal and external chemical impacts, as shown in Figure 8. The CFs can be broken down into a fate factor (FF), an exposure factor (XF), and an effect factor (EF). The expression FF x XF is often defined as the intake fraction (iF) - the total fraction of an emission inhaled or ingested through multiple exposure pathways (Bennett et al. 2002). An advantage of the iF approach is that it combines temporally and spatially explicit environmental (fate and exposure) modeling into a single parameter, while maintaining the use of separate EFs derived from toxicological studies.

However, emissions factors for indoor materials and processes during a building's use phase are often lacking in LCA (Verbeeck and Hens 2010a, b). Conditions under which contaminants are emitted from building materials or indoor processes may be highly site-specific, and may depend on reactions with outdoor pollution, sunlight, humidity or other factors. Herein, the single-compartment box model developed by Hellweg et al. (Hellweg et al. 2009) is modified to use measured concentrations as opposed to emissions factors, and expanded to permit the use of a multi-compartment model appropriate for a standard modern office building with separate ducted supply and return air systems. It is possible to consider such a building as a set of well-mixed compartments where the infiltration, exfiltration and inter-compartment air exchange rates are small in comparison to the mechanical air circulation rate (ASHRAE 2009). Typically, interior air is circulated to a central air handler through the return ductwork, where some fraction of the return air is exhausted to the outdoors and the remainder is combined with fresh outdoor air. The mixed air is filtered or otherwise treated to remove contaminants and then supplied to the interior space, with the supply and return air to each compartment approximately balanced to avoid inter-compartment mixing (ASHRAE 2009). Figure 9 shows a schematic of this type of system.

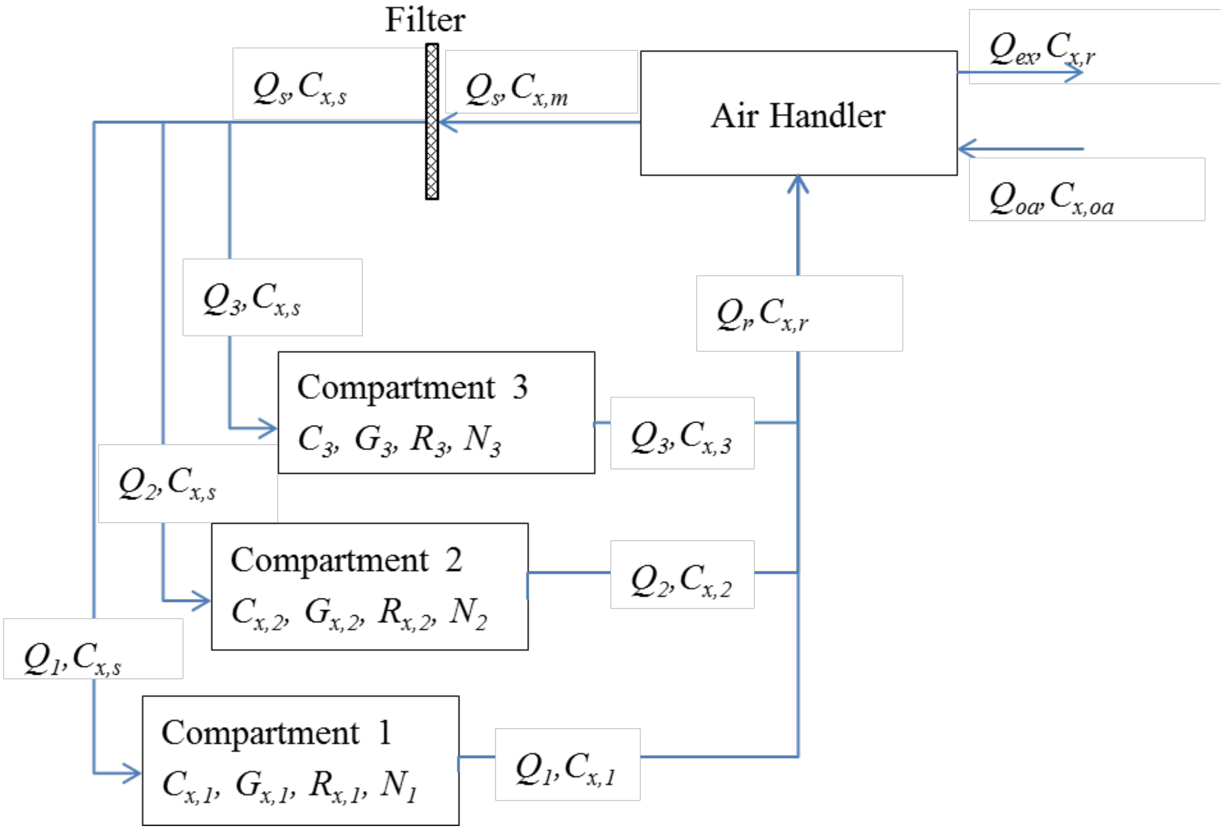


Figure 9 - Schematic of multicompartment IAQ model.

Variables are the following: Q = airflows (m^3/min), C = concentrations (ppm or µg/m^3), G = emissions rate (g/min), R = removal rate (g/min), N = persons, subscript x denotes a specific contaminant, and the subscript s, r, m, ex and oa denote supply air, return air, mixed air, exhaust air and outside air, respectively.

Beginning with the single-compartment box model, the steady-state intake fraction for indoor emissions is written by Hellweg et al. (Hellweg et al. 2009):

Equation 3

$$iF = \frac{\partial C_x}{\partial G_x} N \times IR = \frac{\partial (G_x / Q)}{\partial G_x} N \times IR = \frac{IR}{Q} N = \frac{IR}{V \times k_{ex}} N$$

where C_x is the concentration of airborne contaminant x (kg/m3) in the compartment, G_x is the emission of contaminant x in the compartment (kg/day), N is the number of persons exposed, IR is the average inhalation rate (m^3/person*day), Q is the ventilation rate (m^3/day), V is the volume of the compartment (m^3), and k_{ex} is the air exchange rate (day^{-1}). This terminology is extended to express the total impact h_x for contaminant x in a single LCIA category by Equation 4:

Equation 4

$$h_x = G_x \times iF \times EF = G_x \times \frac{IR}{V \times k_{ex}} N \times EF$$

If the variables N, IR and EF in Equation 4 are known, and can be supplemented with measured concentrations C_x, then by the definitions in Equation 3, Equation 4 can be rewritten:

Equation 5

$$h_x = C_x \times IR \times N \times EF_x$$

One potential advantage of a measured-concentration approach is its ability to incorporate indoor exposure from outdoor ambient pollution. Indoor exposure may occur because of the intake of outdoor contamination into the building, such as combustion emissions from nearby roadway traffic. This contamination depends upon the building's location and is the result of many processes both related and unrelated to the life cycle of the building. However, for whole-building LCA we may wish to estimate the building-specific exposure due to intake of outdoor emissions, regardless of the source. This exposure, while not attributable to individual building materials, can be considered part of the LCA of the building for the purpose of comparison to a baseline, or the evaluation of alternative building designs.

For a multi-compartment model, a modified version of Equation 5 can be written:

Equation 6

$$h_x = \sum_{i,t} C_{x,i,t} \times IR \times N_{i,t} \times EF_x$$

where the subscript *i* refers to individual compartments in the building, and the subscript *t* refers to the time interval at which the concentrations and occupancy are measured. In the case of internal building emissions vented to the outdoor environment, additional populations may be exposed. The multi-compartment model can be extended to this case by considering an additional compartment to represent the local environment, with an effective mixing volume based on local meteorological characteristics. In the multi-compartment model, using indoor emissions factors instead of measured concentration data requires additional computation, since in the case of air recirculation, the concentration in every compartment is related to emissions in each other compartment.

Figure 9 shows the case of a typical office building with separate ducted supply and return air systems. We consider the building as a set of well-mixed compartments where the inter-compartment air exchange rate is small in comparison to the mechanical air circulation rate. Typically, interior air is brought back to a central air handler through the return ductwork, where some fraction of it is exhausted to the outdoors and the remainder is combined with fresh outdoor air. The mixed air is filtered to remove contaminants and then supplied to the interior space, with the supply and return air to each compartment approximately balanced to maintain similar space pressures, thereby avoiding inter-compartment mixing.

Assuming negligible pressure differences throughout, so that mass flows can be considered proportional to measured volumetric flows, we can write a mass balance for the whole building:

Equation 7

$$Q_s = Q_r = Q_{rc} + Q_{oa} = Q_{rc} + Q_{ex}$$

where Q_s is the supply air flow from the air handler, Q_r is the return air flow from all compartments, Q_{rc} is the recirculated air flow, Q_{oa} is the outside air intake, and Q_{ex} is the exhaust air flow to the outdoors. With balanced compartments, the supply and return flow to each compartment i will be Q_i.

The concentration of any given contaminant x in compartment i is $C_{x,i}$, and is affected by the concentrations in the recirculated air (C_r) and the outdoor air (C_{oa}), as well as the indoor emissions $G_{x,i}$ in compartment i, removal $R_{x,i}$ in compartment i due to settling, adsorption, chemical reaction or other means. We can perform a mass-balance for contaminant x in compartment i as the following:

Equation 8

$$\frac{dm_{x,i}}{dt} = \frac{dC_{x,i}}{dt} V_i = G_{x,i} - R_{x,i} + Q_i C_{x,s} - Q_i C_{x,i}$$

where $m_{x,i}$ is the mass of contaminant x in compartment i and Vi is the mixed volume of the compartment. We assume each compartment is well-mixed, such that the concentration in the exhaust air stream is equal to the concentration in the compartment $C_{x,i}$. The concentration in the return air at the air handler will be the weighted average by flow of the concentrations in the individual compartments:

Equation 9

$$C_{x,r} = \frac{\sum_i Q_i C_{x,i}}{Q_r}$$

The concentration of contaminant in the supply air will be influenced by the building-wide ratio of recirculated air to outside air, as well as filtration or other removal at the air handler or in the ductwork:

Equation 10

$$C_{x,s} = \frac{C_{x,r} Q_{rc} + C_{x,oa} Q_{oa}}{Q_s} FF_x$$

where the term FF_x represents the fraction of contaminant retained in the supply airstream after filtration or other removal.

Combining Equation 8 through Equation 10, we can write the mass balance for compartment *i*:

Equation 11

$$\frac{dC_{x,i}}{dt} V_i = G_{x,i} - R_{x,i} + Q_i \left(\frac{\frac{\sum_i Q_i C_{x,i}}{Q_r} Q_{rc} + C_{x,oa} Q_{oa}}{Q_s} FF_x - C_{x,i} \right)$$

Solution in the case of known concentrations and flows- For steady-state conditions, $dC/dt = 0$ and if the Q and C terms are known, Equation 12 can be solved straightforwardly to obtain $G - R$. For a time-varying condition, if the concentrations $C_{x,i}$ and Q_i are measured at some time interval Δt, an approximate solution for the quantity $G_{x,i} - R_{x,i}$ representing net emissions of contaminant x in compartment i can be written as the following:

Equation 12

$$(C_{x,i,t} - C_{x,i,t-\Delta t})V_i = G_{x,i,t} - R_{x,i,t} + Q_{i,t}\left(\frac{\dfrac{\sum_i Q_{i,t}C_{x,i,t}}{Q_{r,t}}Q_{rc} + C_{x,oa,t}Q_{oa,t}}{Q_{s,t}}FF_x - C_{x,i,t-\Delta t} \right)$$

In some cases, it may be practical to ignore compartmental removal rates $R_{x,i}$ and consider the emissions equal to the net emissions. This is the case in the example of measuring occupancy levels from CO_2 concentrations and airflows, discussed below.

Intake fraction solution in the case of known emission rates- While Equation 12 can be solved separately for (G - R) for each compartment given values for the C and Q terms, it is not possible to solve it for C given G, R and Q. For steady state conditions, expanding the summation term in Equation 11, substituting $Q_r = Q_s$ and rearranging yields:

Equation 13

$$G_{x,i} - R_{x,i} + \left(\frac{Q_{rc}}{Q_s}Q_1C_{x,1} + \ldots + \frac{Q_{rc}}{Q_s}Q_nC_{x,n} + C_{x,oa}Q_{oa} \right)\frac{Q_i}{Q_s}FF_x - Q_iC_{x,i} = 0$$

Writing Equation 13 for each compartment i = 1,2,3…n results in a system of n linear equations and n unknown concentrations, assuming net generation and removal rates are known along with compartment sizes, airflows and the outdoor concentration $C_{x,oa}$. The system can be solved simultaneously to yield concentrations. Equation 13 can be rewritten for the whole building in matrix notation:

Equation 14

$$\mathbf{g} - \mathbf{r} - \mathbf{Ac} = \mathbf{0}$$

where g, r, and c are nx1 vectors representing the emissions, removal and concentration in the n compartments and $\boldsymbol{A}$ is an nxn matrix of the coefficients applied to the concentration terms, calculated from the remaining flow and ratio terms in Equation 13. If in-compartment removal rates area small, r can be neglected, and solving for the vector of concentrations *c* yields:

Equation 15

$$\mathbf{c} = \mathbf{A}^{-1}\mathbf{g}$$

To obtain the whole-building intake fraction for emissions in any compartment we first must calculate the change in the concentration vector as a function of the change in $G_{x,i}$:

Equation 16

$$\frac{\partial c}{\partial G_{x,i}} = \mathbf{A}^{-1} \frac{\partial g}{\partial G_{x,i}}$$

All terms in the right hand side of Equation 16 are zero (since the emission rates in the different compartments are independent) except for the term related to $G_{x,i}$ (since $\partial G_{x,i} / \partial G_{x,i} = 1$); thus:

Equation 17

$$\frac{\partial c}{\partial G_{x,i}} = \mathbf{A}_i^{-1}$$

where $\mathbf{A}_i^{-1}$ represents row *i* of the $\mathbf{A}^{-1}$ inverse matrix.

The intake fraction associated with an emission in compartment *i* is calculated by combining Equations 3 and 17, where **n** is now a vector of the number of persons in each compartment:

Equation 18

$$iF = \frac{\partial c}{\partial G_{x,i}} \mathbf{n} \times IR = \mathbf{A}_i^{-1} \mathbf{n} \times IR$$

Outdoor and indoor exposure and overlaps - Impacts of indoor emissions vented to the outdoors could be represented by the addition of an outdoor compartment with mixing characteristics established from local meteorology, along with local population data.

There will be some finite overlap of the population exposed to indoor pollution and the population exposed to outdoor pollution. We can consider a building located in a default continental or urban box as outlined by the Use-Tox model (Hellweg et al. 2009). The external intake is thus *life cycle emissions x per capita intake fraction x external(urban or continental) population.* Concurrently, the internal intake considering exposure to outdoor pollution, is *indoor concentration x per capita indoor intake x internal population (occupancy)*. The key to the overlap being small is that internal population must be small compared to external population, and the life cycle emissions within the continental or urban box volume must be small compared to the ambient pollution levels. The internal to external population ratio is further reduced by the ratio of the average amount of time the occupants spend indoors versus outdoors. In the case of a geographically isolated building with high on-site emissions, the overlap would be substantial. In the case of a medium-sized building in a large urban area, with a spatially diverse supply chain (e.g. the electrical grid) the overlap would be small, which is the case represented in the current chapter.

4.2.2.1 Estimating occupancy using CO_2 concentrations

A measurement or estimate of occupancy is necessary to calculate intake fractions or total intakes by Equation 3 and Equation 5. Occupancy can be calculated using measured CO_2 concentrations, HVAC system airflows and known values of human respiratory CO_2 output, as long as no other significant sources or sinks of CO_2 exist within the compartment (e.g. combustion or passive ventilation). Equation 12 can be used to determine CO_2 emissions in each compartment given R_{CO2} = 0 (no interior removal) and FF_{CO2} = 1 (no filtration). Rewritten explicitly for CO_2, Equation 12 becomes:

Equation 19

$$(C_{CO2,i,t} - C_{CO2,i,t-\Delta t})V_i = G_{CO2,i,t} + Q_{i,t}\left(\frac{\dfrac{\sum_i Q_{i,t}C_{CO2,i,t}}{Q_{r,t}}Q_{rc} + C_{CO2,oa,t}Q_{oa,t}}{Q_{s,t}} - C_{CO2,i,t-\Delta t}\right)$$

The rate of CO2 production (r_{CO2})due to human respiration under office building-type conditions is approximately 0.026 kg CO_2/hr, with a low estimate of 0.018 kg/hr and a high estimate of 0.036 kg/hr (Emmerich and Persily 1997).

Equation 19 was solved for each 20-minute time step corresponding to the OptiNet sampling rate. Due to the scope of the data collection, several additional assumptions were made:

- The air handler serving the 2nd and 3rd floors of the MCSI addition also feeds other areas of the building, some of which are monitored for CO_2 concentration and some of which are not. The concentration of CO_2 in the return air at the air handler (corresponding to the summation term in Equation 19 divided by Q_r) was not directly measured, but was assumed to be the same as calculated applying the same formula to the sample of rooms where the in-room concentrations were monitored. In other words, the average concentration in non-monitored areas was assumed to be the same as the average concentration in monitored areas, for the same time step.
- Outside air and recirculated airflows were not directly measured, but were estimated based on the total supply airflow and the economizer percent open ($EO_{\%}$) at the air handler, which varied from its preset minimum of 20% outside air to 100% outside air under favorable outside temperatures. The concentration of CO_2 ($C_{CO2,s}$) in the supply air was calculated by:

Equation 20

$$C_{x,s} = C_{x,r}Q_s \times (1 - EO_{\%}) + C_{x,oa}Q_s \times EO_{\%}$$

After solving Equation 19 for $G_{CO2,i,t}$, the number of persons in each compartment ($N_{i,t}$) was calculated by Equation 21:

Equation 21

$$Ni,t = \frac{G_{CO_2,i,t}}{r_{CO_2}}$$

4.2.2.2 VOC Speciation and inhalation toxicity

The USE-Tox model, developed for the UNEP-SETAC Life Cycle Initiative, contains estimates of human toxicity in cancer and noncancer effects categories (Rosenbaum 2008a). USE-Tox calculates intake fractions (iF) and effect factors (EF) for use in Eq. 2. In the indoor model, iFs are calculated from primary data, but require the use of independent EFs to aggregate the effects from multiple substances into these categories. The same substance-specific EFs are used in Eq. 3 to calculate impacts in the multicompartment model with known concentrations and occupancy. The USE-Tox model documentation provides a list of already-calculated EFs for many common organic (including VOCs) and inorganic substances, and is available at www.usetox.org. A list of the USE-Tox EFs for all VOCs in this study is given in Table 18.

To estimate the overall inhalation toxicity of an air volume, the individual VOC mass concentrations were multiplied against their EF (cases/mass inhaled) to give a result in terms of cases/volume of air inhaled, which can be considered an ambient air-specific EF:

Equation 22

$$EF_{air} = \sum_{x} CM_x \times EF_x$$

where EF_{air} is the ambient air-specific EF, CM_x is the mass/volume concentration of contaminant x, and EF_x is the effect factor for contaminant x in either the carcinogen or non-carcinogen category.

The 10.6 electron-volt (eV) photoionization detector used in the OptiNet system generates a total VOC (TVOC) reading in equivalent ppm of isobutylene. For individual species, conversion factors may be applied to estimate the equivalent TVOC reading generated by a known concentration. PID conversion factors are listed in Table 18.

The equivalent TVOC measurement in ppm isobutylene for a given mixture of VOCs is given by Equation 23:

Equation 23

$$C_{TVOC} = \sum_x C_x \times PID_x$$

where C_x is the concentration in ppm of each VOC species x and PID_x is the corresponding PID equivalency factor. If concentrations are given in mass units, e.g. μg/m^3, the conversion becomes :

Equation 24

$$C_{TVOC} = \sum_x CM_x \times PID_x \times \frac{0.024}{MW_x}$$

where MW_x is the molecular weight in g/mol. A list of the applied PID equivalency factors and molecular weights of all VOCs in this study is given inTable 18.

We separately estimated speciation of indoor and outdoor VOCs using measurements available from other sources:

- Pittsburgh Air Quality Study (PAQS); (Millet et al. 2005) - All outdoor VOCs.
- Allegheny County Health Department's (ACHD) 2010 Annual Air Quality Report (data from 2009 and 2010) - Hazardous outdoor VOCs (ACHD 2011).
- EPA BASE Study - Indoor VOCs (USEPA 2005).

The two outdoor studies were selected based on the regional location of the data collection, while the BASE study was selected for indoor comparison due to its large number of building sites in many locations. None of these studies includes every possible VOC species that could be encountered in the indoor or outdoor air mixture. Instead, the combination of VOC species from all three studies was used to generate a master list of probable VOCs for this study, which is the list in Table 18. The process used to generate probable VOC concentrations from each reference is described in Appendix B.

4.2.3 Extending the IEQ+DLCA framework beyond chemical impacts

4.2.3.1 Nonchemical health impacts

For chemical impacts, the LCIA model TRACI 2 incorporates CFs from the UNEP-SETAC life cycle initiative, or USE-Tox, human and ecological toxicity model (Rosenbaum 2008a; Rosenbaum et al. 2011). The USE-Tox human toxicity CFs or human toxicity potentials (HTPs) can be separated into fate factors (FFs), exposure factors (XFs) and effect factors (EFs). The units for HTP are disease cases/kg emitted, and the units for EFs are disease cases/kg intake (generally inhalation or ingestion). Other LCIA methods have attempted to represent varying disease severities, but due to high uncertainty in this area, the USE-Tox authors decided not to weight cases by severity. Thus, when assessing probable impacts, a case of one type of disease carries equal weight to a case of another type of disease, except that cancer is given its own category. Typical LCIA results in TRACI/USE-Tox will show one total for cancer cases and one total for noncancer cases.

The use of cases in TRACI/USE-Tox may represent an opportunity to bring “non-chemical” impacts into the LCIA toolbox for whole building LCA, or for LCA of any built environment system where impacts can be considered internal or external. For instance, the design and operation of buildings can influence transmission of pathogens, thus making cases of contagious illness a possible metric of building performance (Sundell et al. 2011). Previous work relating IAQ to incidence of disease or illness of different types has used “avoided cases” as a metric to describe the benefit of IAQ improvements (Fisk 2002). Recent work has also expressed benefits in terms of relative symptom prevalence (RSP) in building occupants, in which “symptom” is analogous to “case” (Fisk et al. 2011). In the absence of severity weighting, it seems reasonable to include several other categories of human health impacts alongside cancer-related and noncancer-related chemical toxicity in the LCIA framework for whole buildings (e.g. contagious illnesses, mood disorders).

Sick building syndrome - Sick building syndrome (SBS) includes “eye, nose, or throat irritation, headache, and fatigue, that are associated with occupancy in a specific building” (Fisk et al. 2009). Though it has been frequently studied, no clear cause of SBS has been identified, though its occurrence has been associated with buildings with low ventilation rates (Fisk et al. 2009). Reduction of SBS symptoms is a quantified benefit of several of the IAQ improvement strategies exploredd by Fisk et al. (Fisk et al. 2011) related to ventilation and thermal comfort. However, SBS symptoms overlap strongly with the reported symptoms from toxicological testing of many of the chemicals classified in the noncancer toxicity category in USE-Tox. Although no single chemical compound or group of compounds has been deemed causal to SBS, it is possible that many instances of SBS are related to one or more of the compounds characterized in USE-Tox noncancer toxicity. Due to this potential overlap and the desire to retain the USE-Tox noncancer toxicity category as an internal building metric to match the external metric, an SBS category was not included in our framework at this time.

Allergies and asthma - Though different, allergies and asthma are sometimes grouped together as a category of IAQ impacts (Fisk 2002) due to similarity of triggers and symptoms. Many common triggers for these illnesses are generated or enhanced by indoor conditions; e.g. environmental tobacco smoke, dust mites, pet dander. Studies have shown that at least in residences, inadequate ventilation is associated with increased prevalence of these symptoms (Sundell et al. 2011). However, few enough studies exist and no general relationship has been developed between ventilation or other building variables and allergies or asthma. It is noted that lists of asthmagens - asthma-inducing substances, including chemical and biological substances - exist, but a substance-specific approach to this category was precluded by the potential overlap of substances (e.g. formaldehyde, toluene, particulate matter) and symptoms to those included in the USE-Tox database. It is expected that a full investigation of the toxicological basis of this overlap would be required, which was beyond the scope of this study.

Building-related illnesses - This term sometimes includes SBS, allergies and asthma, but is often more narrowly used to describe illnesses caused by infectious agents which can be related to the building; e.g. pathogens in air conditioning systems. A subset of these illnesses is communicable (acute) respiratory infections such as the common cold and various types of pneumonia. The agents causing these illnesses are biological and are thus excluded from potential overlaps with USE-Tox or other LCIA databases. It has been demonstrated in some cases that building conditions have led to above average rates of infection (Sundell et al. 2011), usually by building elements harboring pathogens or by insufficient ventilation (which mimics an “overcrowded” condition). However, no empirical relationships were found in the literature to link any specific building parameters to rates of infection of these types. (Absenteeism, which may be a proxy for acute respiratory illnesses is discussed in a later section).

Noncommunicable, non-inhalation illnesses - There are many conditions or illnesses that could potentially be attributed to building conditions, which are not physically communicable and for which inhalation is not the primary trigger. Excluding ingestion of toxins or pathogens (the former of which is covered in USE-Tox), some brief examples are: mood effects of poor lighting or insufficient daylighting (Singh et al. 2011); eyestrain or headache effects from lighting; discomfort due to temperature or work positions; or relationships mediated through an understood physiological mechanism, such as health effects of insufficient vitamin D in office workers (Vu et al. 2011). scant quantitative literature exists on these topics, and no meta analyses or other literature summaries were encountered. Further research on these topics would be beneficial to IEQ+DLCA, because potentially significant effects from plausible pathways exist which do not correspond to any impact category in conventional LCIA.

4.2.3.2 Performance and productivity impacts

Absenteeism - Absenteeism, or sick leave, is a potential proxy for multiple IEQ effects in workplaces, though it seems plausible that it more strongly represents acute illnesses, particularly respiratory illnesses, e.g. colds, influenza - than long term conditions such as SBS (Fisk 2002). Absenteeism also represents a real economic loss to the employer in a work situation, and in cases where it represents some level of incapacitation, an economic loss to the employee as well. It is also easily quantified in many workplaces with regular or mandatory schedules. Milton et al. (Milton 2000) provide a quantitative reference for a relationship between ventilation and short-term sick leave, based on a large cross-sectional study of 40 buildings with different characteristics. Milton et al. also found a relationship between IEQ complaints and short-term sick leave; IEQ complaints were also associated with SBS. Particularly in light of the exclusion of SBS and allergies/asthma categories due to potential overlaps with established LCIA categories, sick leave category in the IEQ+DLCA framework was included.

Productivity - There is extensive literature on IEQ and performance or productivity (hereafter, productivity) impacts, e.g. (Heschong et al. 2002a, b; Seppänen et al. 2006c, a). Though productivity impacts require different measurement units than health impacts, and may accrue to different entities (an employer's economic bottom line vs. an individual's health), there is potential to include productivity impacts in LCA of buildings. When comparing different design or operational decisions, the relative impacts on productivity and the internal and external environment can be simultaneously evaluated and tradeoffs identified. Perhaps as important, productivity impacts may be a partial proxy for health impacts, as illnesses affecting building occupants during work hours may impact productivity even at levels below those required for a health diagnosis. Another way to say this is that overlaps between nonchemical health impacts and productivity impacts may exist, such as reduced productivity due to working while sick. One advantage of including both productivity and absenteeism as hybrid metrics representing health and economic impacts is that they are mutually exclusive; studies establishing IEQ/productivity relationships have typically excluded missed workdays from the analysis.

Inclusion of metrics in the framework - Given the types of impacts discussed, only two metrics were added beyond human health chemical impacts: absenteeism and productivity. This represents a significant exercise of judgment, and other researchers may come to different conclusions. the potential overlap of SBS and allergy/asthma impacts with the TRACI/USE-Tox categories of respiratory effects and noncancer toxicity was an influencing factor. By comparison, communicable illnesses (BRI) and noncommunicable, non-inhalation illnesses represent two additional categories which could be included given sufficient additional case study data, though likely a choice between the BRI and absenteeism categories would have to be made. The categories and their status within the framework pursuant to this discussion are listed at the bottom of Figure 7.

Equations used to relate IEQ parameters with internal building impacts are incorporated from reference sources as cited in Fisk et al. 2011 and are the following:

- Ventilation and performance (Seppänen et al. 2006b)

Equation 25

$$RWP_v = \exp[(-76.38v^{-1} - 0.78x\ln(v) + 3.87v - y_0)/1000];6.5 < v < 47$$

Equation 26

$$y_0 = -76.38V_{r,WP}{}^{-1} - 0.78V_{r,WP}\ln(V_{r,WP}) + 3.87V_{r,WP};V_{r,WP} = 10$$

- Temperature and performance (Seppänen et al. 2006a)

Equation 27

$$RWP_T = -0.469 + 0.165T - 5.83x10^{-5}T^2 + 6.23X10^{-5}T^3;15 < T < 31.5$$

- Ventilation and absenteeism (Milton 2000)

Equation 28

$$RSLR_v = -.029(v - V_{r,SL});12 < v < 24;V_{r,SL} = 12$$

In the above equations, RWP_v is relative work performance related to ventilation rate v in L/sec/person, y_0 is the reference point for RWP_v, $V_{r,WP}$ is the reference ventilation rate for work performance of 10 l/s/person, RWP_v is relative work performance related to temperature T in degrees C, $RSLR_v$ is the relative sick leave rate related to v, and $V_{r,WP}$ is the reference ventilation rate for sick leave of 12 l/s/person (Fisk et al. 2011; Milton 2000).

4.2.4 Framework summary

A recap of the framework and summary of the data used herein is presented in Table 3.

Table 3 - Summary of IEQ+DLCA framework data and calculations

Impact type	Trigger variable	Equations
Respiratory	PM2.5	Equation 5 (EF = 1)
Cancer toxicity	VOC	Equation 5 Equation 34, Equation 35 for EF
Noncancer toxicity		
Absenteeism	Ventilation	Equation 28
Productivity	Ventilation	Equation 25, Equation 26
	Temperature	Equation 27

4.3 CONCLUSION

This chapter outlined the framework for including IEQ impacts in the DLCA model, addressing both chemical-specific impacts aligned with traditional LCIA categories, as well as health and productivity effects beyond the traditional categories. Some non chemical-specific health categories were excluded from consideration in the model at this time, based on potential overlap with chemical-specific categories. Chapter 5 illustrates the application of the framework to a detailed case study of the MCSI building at the University of Pittsburgh, with a focus on comparing internal to external effects in the chemical-specific categories.

5.0 IN-DEPTH CASE STUDY: MASCARO CENTER FOR SUSTAINABLE INNOVATION

The following chapter contains material reproduced from an article published in the journal *Building and Environment* with the citation:

Collinge, W.O., A.E. Landis, A.K. Jones, L.A. Schaefer and M.M. Bilec (2013), “Indoor Environmental Quality in a Dynamic Life Cycle Assessment Framework for Whole Buildings: Focus on Human Health Chemical Impacts.” *Building and Environment* 62 pp. 182-190.

The article appears as published per the copyright agreement with Elsevier, publisher of *Building and Environment.*

Portions of the Supporting Information submitted with *Building and Environment* appear in this chapter and Chapter 5, and the remaining portions appear in Appendix B.

5.1 DATA COLLECTION

The Mascaro Center for Sustainable Innovation (MCSI) building at the University of Pittsburgh was chosen as an illustrative case study for the IEQ+DLCA framework. MCSI is a LEED Gold certified facility combining 1,900 m^2 of new construction with 2,300 m^2 of renovation of the second floor of an existing building, Benedum Hall. As a part of this research, the MCSI building was equipped with an advanced energy consumption and indoor air quality sensing system. Energy consumption is sensed with multiple panel-based electrical meters and HVAC system flowmeters, while IEQ data are collected using the AirCuity OptiNet system (AirCuity). OptiNet is an indoor air quality sensing system which features a central sensor suite and unique structured cables housing air sampling tubes and control wires. Vacuum pumps continuously bring air from the sample locations through the tubes to the sensor suite for analysis.

The OptiNet system was selected due to its compatibility with the existing campus-wide building automation system and its ability to measure air quality data at a high level of temporal resolution at multiple locations within the building. A drawback of the system is that the level of chemical detail captured by the system’s sensors is less than that required by LCIA methods; thus, additional data sources were required to provide LCI-ready data, as outlined in Chapter 4 and again in this chapter. Figure 10 provides an overview of the OptiNet system and the collection of necessary supplementary data. The types of supplementary data used are either reference studies or air quality monitoring data. These types of data are available for many urban areas in the US via the US Environmental Protection Agency (USEPA), and thus could be used in applying this framework to other locations.

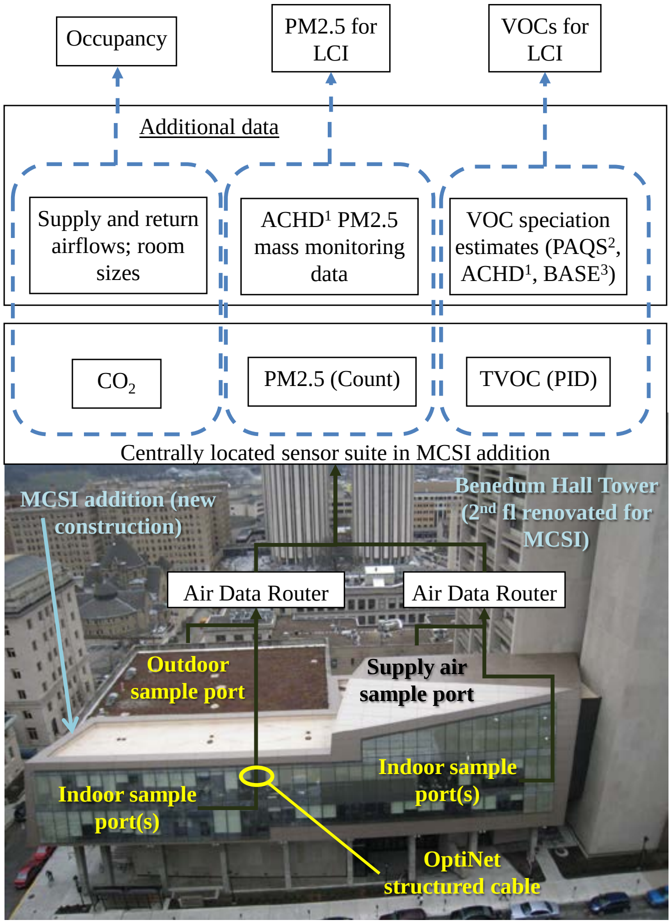


Figure 10 - Data collection and flow for MCSI IAQ sampling.

The MCSI building comprises the MCSI addition (3 floors, shown in the foreground) and the renovated 2nd floor of the Benedum Hall tower (shown at upper right). Only the addition was used in this study.

For this study, the MCSI building and the outdoor air were monitored for CO$_2$, particulate matter less than 2.5 µm in diameter (PM2.5), total volatile organic compounds (TVOC); HVAC system data including airflows, temperature and humidity; and energy consumption for heating, cooling and electricity use. The study time period was January 1, 2012, to December 31, 2012, although some measurements were not available for all portions of that period, as described in the following paragraphs. All measurements were taken at 20-minute or smaller intervals. Six indoor sample points (four open offices and two conference rooms), one outdoor sample point and one sample point for filtered outdoor air were monitored.

External LCIA categories - External impacts from the building in human health respiratory effects, cancer toxicity and noncancer toxicity LCIA categories were calculated using the DLCA model (Collinge et al. 2012a), updated to include characterization factors for human toxicity from TRACI/Use-Tox (Bare 2011; Rosenbaum 2008a). TRACI results for the human health respiratory category are expressed in PM2.5 equivalents (eq), aggregating direct PM10 and PM2.5 with secondary PM from SO_2, NOx and NH_3 emissions. Because this TRACI category extends only to the reference substance midpoint of PM2.5 eq, the intake fractions for PM from Humbert et al. (Humbert et al. 2011) were subsequently applied to the TRACI results. DLCA results in the selected categories were compared to the analogous internal categories. The DLCA model was evaluated for the upstream impacts of the case study building's energy consumption during the study time period. Building materials, construction and end-of-life impacts were excluded due to the short time frame, and since the authors' previous study as well as several earlier studies indicated the generally lower impacts of these processes compared to operating energy use (Junnila et al. 2006; Scheuer et al. 2003; Aktas and Bilec 2012; Rajagopalan et al. 2009). To evaluate the uncertainty in the spatial location of upstream processes, the calculation was repeated assuming 100% rural, 100% urban, or 50% rural/50% urban upstream emissions to air (emissions to water are not separated by a rural/urban distinction in TRACI/UseTox).

Occupancy Measurement - Occupancy data is necessary to calculate impacts in all of the internal IEQ+DLCA categories. Occupancy was estimated using ventilation rates from the MCSI building automation system (BAS) and CO_2 concentrations measured by OptiNet. CO_2 concentration data were available for March 1-June 30 and September 1-December 31, 2012. Equation 19 and Equation 20 were used to estimate CO_2 emissions rates in each compartment at an hourly time step, where each hourly value was determined as the average for samples taken in the previous or following 30 minutes. A reference value of 0.026 kg CO_2/hr/person was used to convert emissions estimates into occupancy rates (Emmerich and Persily 1997) (see Equation 21). This method provides an approximate estimate of occupancy using the mass balance of CO_2 in each compartment (inflow - outflow = net generation). The compartments are assumed to be well-mixed, such that outflow can be calculated by assuming the exhaust air concentration is the same as the concentration in the compartment. Inflow is calculated by an airflow-weighted average of exhaust air concentrations and the outdoor air concentration, in accordance with Figure 9.

Internal Respiratory Effects - Particulate matter (PM2.5) was measured by OptiNet's optical particle counter, which has a range of 0.3 to 2.5 µm. PM2.5 concentration data were available for March 1-June 30 and Sept 1-Dec 31, 2012. Since most LCI databases report PM2.5 measurements in mass units, correlation factors for mass and particle number were obtained by performing a linear regression of the measured outdoor data against hourly PM2.5 mass data from the Allegheny County Health Department's (ACHD) Lawrenceville (Pittsburgh), Pennsylvania site, located approximately 2.4 km from MCSI, during the aforementioned period (see B.2.2). This linear relationship was applied to the outdoor particle counts to estimate outdoor mass concentration at the study site. The outdoor mass estimates were scaled by the hourly indoor/outdoor particle count ratios from the OptiNet data to generate indoor mass concentration estimates. PM2.5 mass intake was estimated using the derived occupancy rates, the indoor mass concentration estimates, and a reference respiration rate of 0.54 m^3/person/hour (Humbert et al. 2011). The use of the measured indoor/outdoor particle count ratio may overestimate PM2.5 mass intake, since the filters should have a higher efficiency toward the large end of the 0.3 to 2.5 µm range. To account for this potential bias, a lower bound estimate of indoor PM2.5 mass was constructed by applying a 95% removal rate to the outdoor particle count before converting to mass, consistent with the high end of the efficiency range for the building's ASHRAE 52.2 MERV 13 air filters. An alternate scenario of a lower-performance building was constructed using an indoor/outdoor mass ratio of 0.56, the median value from the EPA BASE study.

Internal Cancer and Noncancer Toxicity - VOC concentrations were measured by OptiNet's photo ionization detector (PID), which reports total VOCs (TVOC) as equivalent parts per million by volume (ppm) of isobutylene. TVOC concentration data from the PID were available for March 1-June 30, 2012. Because the concentrations of individual VOCs were not known, a sample of possible representative VOCs of both outdoor and indoor origin was constructed as described in Chapter 4. For species of outdoor origin, data from the Pittsburgh Air Quality Study (PAQS) (Millet et al. 2005) and ACHD annual monitoring data (ACHD 2011) were used. For species of indoor origin, EPA BASE Study data (USEPA 2005) were used. The fractional composition of TVOC levels for outdoor air was assumed to be equal to the combination of PAQS and ACHD data, whereas indoor air composition was assumed to be represented by the distribution of BASE study buildings. For each reference study, concentration-adjusted toxicity potentials were constructed (cases/m3 inhaled x ppm as isobutylene - see Equation 34 and Equation 35). Published PID correction factors (Table 18) were used to convert the VOC species concentrations to equivalent PID readings. The results were then summed to create a PID-equivalent TVOC value (ppm as isobutylene) for each reference study.

Effect factors (EFs) from the TRACI/UseTox model (Bare 2011; Rosenbaum 2008a) for each VOC species were used to calculate human health cancer and noncancer toxicity potentials (cases/m3 inhaled) for each reference study. The toxicity potentials were divided by the PID-equivalent TVOC values to obtain the normalized toxicity potentials. Estimated occupancy rates and the reference respiration value were used to estimate the total volume of indoor air inhaled during the study period. Due to the uncertainty of the building-specific speciation for VOCs of indoor origin, a range of toxicity potentials from the BASE study was used representing the 25th, 50th and 75th percentile values from all buildings in the dataset. Finally, normalized toxicity potentials for each relevant reference (PAQS + ACHD for outdoor; BASE 25%/50%/75% for indoor) were multiplied by the actual TVOC readings from the OptiNet system, the estimated occupancy rates and the reference respiration rate, to calculate the estimated health impacts.

Estimating data for missing periods - In order to provide a complete, year-round analysis, data were estimated for periods when specific datapoints were unavailable. Estimates were generated by season and hour of the day. For CO_2-based occupancy, January and February levels were estimated for each hour and day of the week based on the average readings at those times and weekdays for December 1-21 and March 1-11 and 17-21 (to avoid including the Christmas holiday and the University spring break in the averages); and July and August were estimated in the same manner using data from June 1-30. Outdoor PM2.5 readings were estimated similarly to CO2 except the full months of December and March were used. For indoor PM, the relationship to the economizer described in Section 7.3.1 was applied to the estimated outdoor data. For outdoor and indoor TVOC, the hourly and weekday averages were computed from March 1 through June 30 and applied to the remainder of the year.

5.2 RESULTS AND DISCUSSION

Results for the illustrative case study building illustrated the feasibility of including one component of IEQ into LCA - whole-building chemical impacts. During the study time period, internal human health chemical impacts in the three categories varied from lower to higher than external results in the analogous categories. Primary measured or estimated results of the internal building monitoring are discussed first, followed by results of the comparison between internal and external impacts. Figure 11 shows average weekday profiles of the results of measurements and estimated occupancy from the study period.

5.2.1 Occupancy and estimated internal impact

Estimated occupancy rates ranged from zero at night to an average of just over 30 people near mid-day on weekdays, and from zero to 5 on weekends, see Figure 11. The average weekday occupancy rates agreed qualitatively with the building’s size and the number of employees housed.

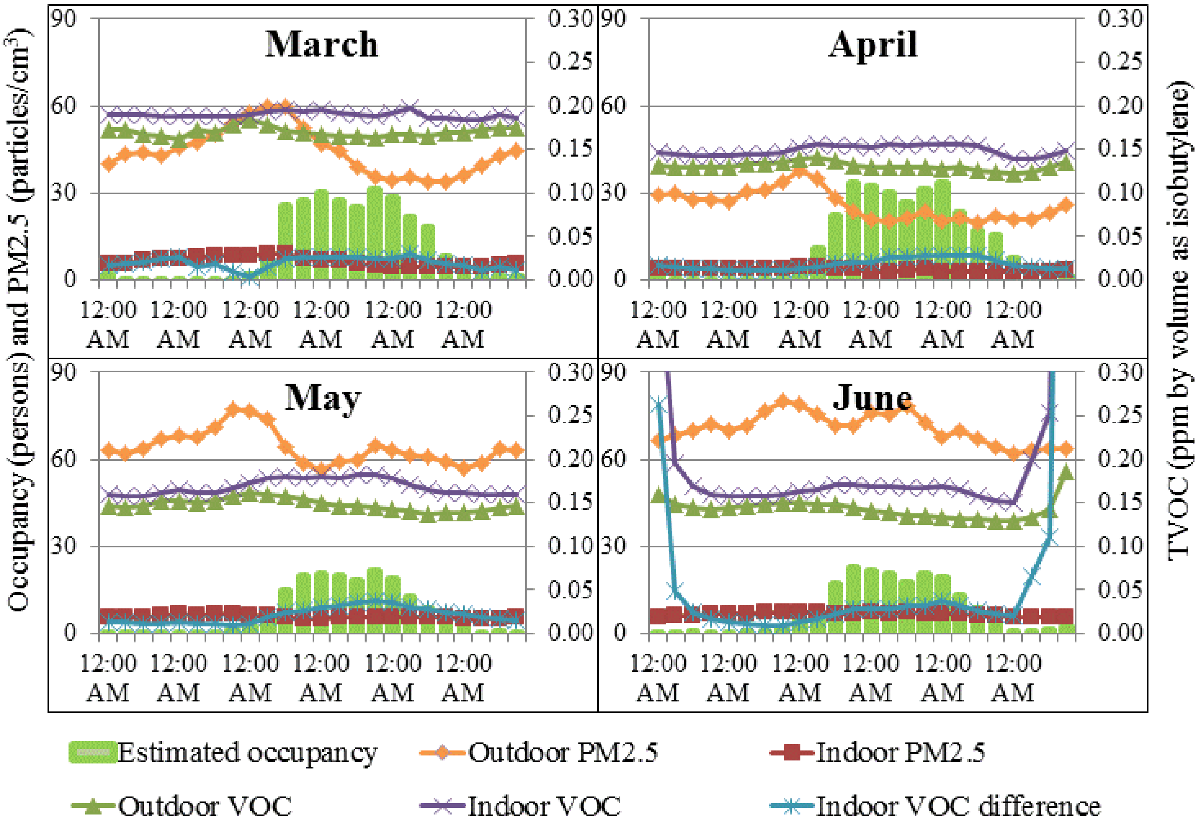


Figure 11 - Average weekday values by month for March-June 2012 for PM2.5, TVOC, and estimated occupancy based on CO_2 measurements and HVAC system monitoring data.

PM2.5 and occupancy are shown on the left axis and TVOC is shown on the right axis.

PM2.5 was primarily of outdoor origin due to the similarity between interior measurements and measurements of the filtered supply airstream, in contrast to the much greater outdoor levels, also illustrated in Figure 11. Outdoor particle counts peaked on weekdays near 8AM, suggesting a possible correlation with nearby traffic sources. Otherwise, particle counts were generally lower during the daytime and higher at night. The mean and median ratio of indoor to outdoor particle count was 0.14, and it varied depending on the economizer use. This result is consistent with the MERV 13 (ASHRAE 52.2) filters installed at MCSI, which are designed to have a removal of >75% for particulates greater than 0.3 µm, the smallest size sensed by the OptiNet system (ASHRAE 2010). The lack of a much greater (>90%) removal may indicate the majority of particles were at the smaller end of the range of 0.3 to 2.5 µm, which is consistent with the results of Stanier et al's previous study for the Pittsburgh region (Stanier et al. 2004). Though Stanier et al. did not find a correlation between particle number and particle mass for the Pittsburgh region, the linear regression fit to mass concentrations from the ACHD site yielded a statistically significant correlation ($p < 0.05$), with an R^2 value of 0.39.

TVOC was of majority outdoor origin with some indoor contribution, as indicated by indoor levels consistently similar to but slightly higher than outdoor levels (Figure 11). As with PM2.5, outdoor VOC levels were generally higher at night than during the daytime, and had a mean value of 0.15 ppm as isobutylene. Some background indoor sources of VOCs, such as building materials, are suggested by the small but nearly uniform increase in indoor average TVOC measurements compared to outdoors, approximately 0.01 ppm as isobutylene. Another potential indoor VOC source was correlated with occupancy in the form of a mid-weekday increase of an additional 0.01 to 0.02 ppm. Whether this source is related to indoor processes (e.g. office or laboratory equipment) or the occupants themselves (e.g. personal care products) is not known, as source verification was not part of the study. VOC speciation estimates from Millet et al. (Millet et al. 2005) and ACHD annual monitoring reports for hazardous air pollutants (HAPs) (ACHD 2011) are shown along with concentration-weighted effect factors (EFs) from Use-Tox for cancer and noncancer toxicity in Figure 12.

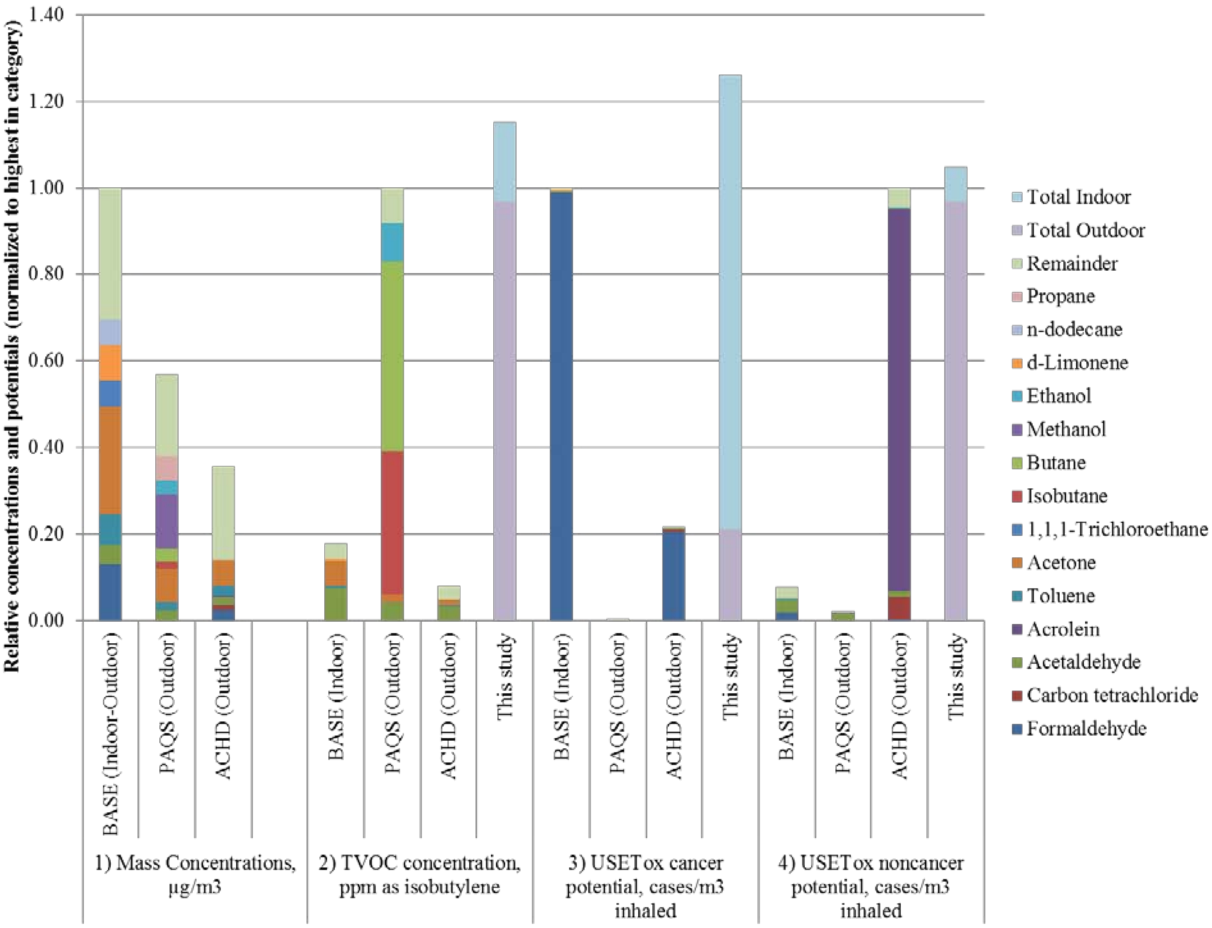


Figure 12 - Relative VOC concentrations and toxicity potentials for March-June 2012 and reference studies.

For each category 1-4 on the x-axis, results were normalized to the highest of the 3 reference studies (BASE, PAQS and ACHD). No result is shown under 1) for this study since mass concentrations were not directly measured. Toxicity potentials 3) and 4) were estimated for this study by combining TVOC measurements 2) with toxicity potentials from reference studies. Toxicity potentials shown from the BASE study are median values.

Total VOC mass intake was estimated after species estimation and calculation of PID equivalencies. The PID-equivalent outdoor TVOC concentration from the PAQS was 0.15 ppm (Millet et al. 2005), which was identical to the average outdoor concentration measured in this study. TVOC measurements of filtered outdoor air were nearly identical to the unfiltered air, suggesting very little removal of these compounds by adsorption onto the filters.

5.2.2 Comparison of internal and external impact assessment results

A comparison of the estimated building-specific internal results to the external results is shown in Figure 13. Internal building results in the human health respiratory effects category (representative of PM2.5 intake by the building's occupants) were 2.6×10^{-5} kg inhaled, approximately 2.3% of the external results (representing external PM2.5 intake due to the building's energy supply processes) of 1.1×10^{-3} kg inhaled. Internal building results for cancer toxicity were 5 times greater than external results (5.7x10-4 cases vs. 1.1x10-4 cases), but external results for noncancer toxicity were an order of magnitude higher than internal results (1.7×10^{-2} cases vs. 1.2×10^{-4} cases).

For internal impacts alone, the source of contaminants resulting in indoor exposure varied between categories. Internal building respiratory effects were predominantly of outdoor origin and noncancer toxicity was estimated at 90% outdoor origin; the source of these effects was the intake of outdoor air for ventilation. The internal respiratory impacts were noticeable alongside external impacts in spite of outdoor air filtration and negligible internal emissions, due to the relatively high outdoor air concentrations at the building's urban location. For noncancer toxicity, the chemical causing the majority of the noncancer toxicity was acrolein. Though the higher levels of pollutants in the outdoor air are not attributable to the building's supply chain, the impacts of their intake on the building's occupants are allocated to the building's operations, since they are highly influenced by design and operating parameters. Cancer toxicity was estimated at 90% indoor origin; due to estimated levels of formaldehyde based on the BASE study-derived correlation for formaldehyde to the measured total VOC reading. Indoor sources of formaldehyde are diverse, but include building materials and furnishings, such as compressed wood products, insulation, carpets, adhesives and fabrics for partitions and chairs. The remaining 10% of cancer toxicity estimated of outdoor origin was 46% of the external result.

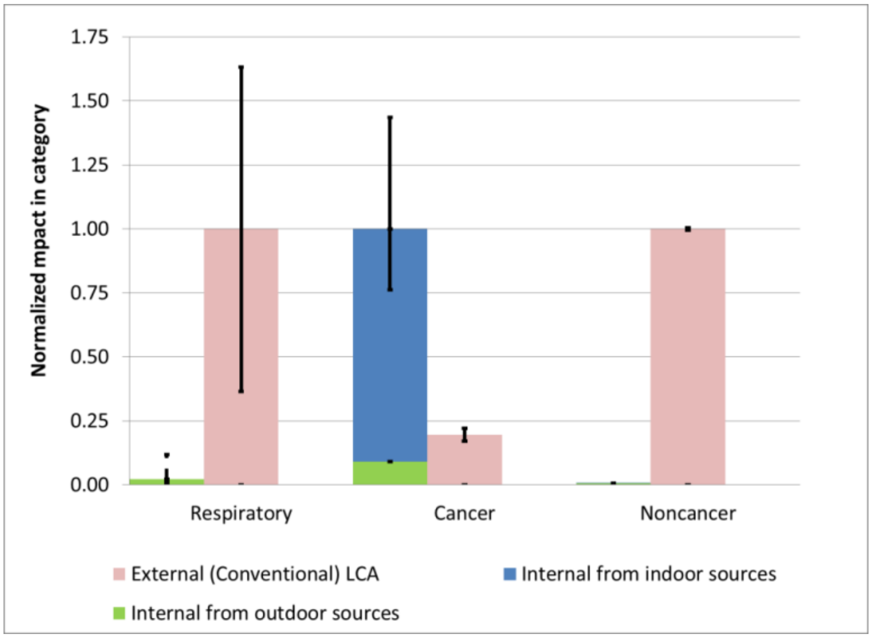


Figure 13 - Results of comparison of internal building impacts to external (conventional) LCA impacts**.**

All values are normalized to the highest in each category of external vs. total internal. Error bars represent the following: Internal respiratory effects - efficiency of particle mass removal by size range, with point value shown at 85% removal,lower bound at 95% removal, and upper bound (dashed) illustrating a lower-performing building corresponding to the median 0.56 indoor/outdoor PM2.5 mass concentration ratio from the BASE study; Internal cancer and noncancer effects - 25th to 75th percentile toxicity of TVOC mixture from the BASE study, with point value shown at the median; External (conventional) LCA - uncertainty in the spatial distribution of emissions, from 100% rural to 100% urban, with the point value shown at 50/50.

Uncertainty in the comparative results was modeled by including factors believed to account for significant variation in the fate and exposure assessment steps, including the geographic location of upstream emissions, VOC speciation estimates, and particle number to mass ratios. For the external categories, point estimates in Figure 13 represent an assumption of 50% urban/50% rural location of air emissions, whereas the lower and upper bounds represent 100% rural and 100% urban emission locations. For internal building respiratory effects, the point estimate represents assuming the mass/particle number ratio of indoor PM2.5 was the same as outdoor PM2.5 and thus that the calculated filtration rate of 86% by particle number could be applied to the mass as well. The lower bound represents the assumption that the filters removed 95% of outdoor PM2.5 by mass. The upper bound illustrates a scenario of a lower-performance building, represented by the median BASE study indoor/outdoor PM2.5 mass ratio of 0.56. The lower bound, point estimate and upper bound for indoor sources of VOC in the cancer and noncancer toxicity categories represent the 25th, 50th and 75th percentile toxicity values for indoor sources calculated from the BASE study. For respiratory effects, the internal impacts from the lower-performing building scenario exceeded the lower bound of the external impacts, indicating the possibility of buildings whose internal impacts are greater than external.

5.2.3 Absenteeism and productivity impacts

Absenteeism and productivity impacts were calculated according to Equation 25 through Equation 28. Ventilation rates did not fall below the 24 l/s/person upper limit of Equation 28 during the study period, so the relative absenteeism rate was calculated to be zero. Calculated productivity (relative work performance) rates by location within the building are shown in Table 4. Room temperatures were maintained within a range that kept them near the maximum relative productivity value of 1.003, which occurs at 21.8º C (Seppänen et al. 2006a). Ventilation rates were generally above the 47 l/s/person necessary for the maximum relative productivity value of 1.0264, but dipped below this rate at times of peak occupancy in warmer weather, when the economizer was at its minimum setting of 20%, suggesting that adding a demand-controlled ventilation (DCV) feature could potentially improve productivity slightly.

Table 4 - Relative productivity by room for the MCSI building

	Room						
Productivity Metrics	**225A**	**225E**	**225N**	**341B**	**341C**	**341N**	**Total**
Temperature-related productivity ratio (RWP -Equation 27) Mean	1.001	0.998	1.002	1.002	1.002	1.001	1.001
Std Dev	*0.001*	*0.002*	*0.001*	*0.001*	*0.001*	*0.002*	*0.002*
Ventilation-related productivity ratio (RWP -Equation 25) Mean	1.017	1.024	1.025	1.023	1.021	1.026	1.023
Std Dev	*0.051*	*0.033*	*0.030*	*0.033*	*0.023*	*0.006*	*0.032*

5.2.4 Limitations

Limitations of the DLCA portion of the framework were discussed in Section 3.3.5. Limitations of the IEQ portion include the occupancy estimate based on CO_2 alone, the PM2.5 particle count/mass estimation, and the assumed VOC speciation from reference sources.. For occupancy, a more robust estimate would combine CO_2 with other proxy indicators of occupancy, such as thermal load, acoustical measurements, or network and workstation use - as well as a validation period against directly observed occupancy; see e.g. (Dong et al. 2010 (In Press)). For internal building PM2.5 intake, the conversion from PM2.5 to particle number was based on a site-specific, empirical relationship to outdoor levels. As previously mentioned this may bias the results since filtration will likely reduce mass to a greater extent than particle number. Further investigation at this and other building sites could include using mobile devices to develop particle number to mass relationships or size distributions for both outdoor and indoor air; e.g. (Wang et al. 2010). On the other hand, recent literature indicates that particle number intake may be as important for respiratory effects as particle mass for some types of health impacts (Atkinson et al. 2010). If LCA research moves toward incorporating particle number effects, the need to convert to mass-based data could become less important.

For VOC related impacts, the lack of site-specific speciation data could be overcome by performing spot-checks on the TVOC composition using mobile devices or grab samples; e.g. (Wu et al. 2011b). The priority of testing could be indicated by the prevalence of certain species in the available estimates of outdoor and indoor air referenced in this chapter, i.e. the compounds listed in Figure 5. Care would need to be taken to distinguish between indoor VOC sources contributing to baseline (24-hour) levels, and sources contributing to fluctuating levels as discussed above. The dominance of formaldehyde in the cancer toxicity category is due to its high effect factor in Use-Tox and relative prominence in both the ACHD and BASE study data. Additional research is needed to determine the correlation between formaldehyde levels and TVOC readings, since formaldehyde is not detected by the PID. Seasonal variation in all types of impacts could be explored through additional data collection.

Another limitation of this study and the overall framework is that it is a comparison between estimated results based on actual measurement of indoor pollutants, with verifiable exposure factors, against model results invoking highly aggregated pollutant concentrations and exposure factors. Although many other significant sources of uncertainty exist along the LCA calculation chain (e.g. emissions factors, dose-response functions), it is at least in theory possible to reduce the uncertainty associated with indoor exposure in a specific building by directly measuring it. Although herein the exposure has only been estimated, its verifiability results in a qualitatively large discrepancy in uncertainty between internal and external impacts.

For productivity impacts, the empirical relationships used herein are quantitative, but are based on limited data. Since the calculated changes in productivity are small even for a tightly regulated building such as MCSI, more application-specific relationships would be warranted. Sensor information related to zone temperatures and ventilation airflows is relatively sparse -

ideally, a characterization of these variables would be undertaken at an individual occupant level, such as in Choi et al. (Choi et al. 2012). However, Choi et al. did not measure productivity or attempt to develop quantitative relationships. Also, the temperature-performance relationship expressed in Equation 27 appears to be mainly based on cold-weather heating applications, and conflicts somewhat with the recommendation from Choi et al. to increase warm weather (air conditioning) set point temperatures relative to current practice. In order to better characterize the potentially site-specific productivity impacts from the MCSI building on its occupants, a post-occupancy survey was carried out, and is discussed in Chapter 6.

6.0 POST-OCCUPANCY SURVEY OF THE MCSI BUILDING

6.1 INTRODUCTION

A post-occupancy survey was developed and administered to MCSI building occupants to collect data about occupant perceptions of the building's IEQ performance. Post-occupancy surveys, also known as occupant satisfaction surveys, are used to provide feedback about the occupants' perceptions of a building's performance, generally focusing on indoor comfort and satisfaction aspects (Frontczak et al. 2012). These surveys are used to help evaluate the performance of individual buildings as well as for more basic research, and are often coupled with physical measurements of indoor conditions (Choi et al. 2012). Surveys have the advantage of being less expensive and easier to implement than physical data collection, as well as a focus on outcomes; however they are subjective, reflecting differences in occupant's perception due to factors which may not be controllable or related to the building under study.

The survey undertaken here was modeled after similar surveys conducted by the authors, e.g. Ries et al. 2006, with modifications designed for specifics of the MCSI building. These surveys share many characteristics with a variety of surveys which have been used by researchers (Peretti and Schiavon 2011). The survey was approved by the University of Pittsburgh's Institutional Review Board and administered via email to occupants of the MCSI building, both the Annex and the 2nd floor of the Benedum Hall tower. The main research question addressed by the survey and coupled analysis is “How can qualitative data related to occupant perceptions be synthesized with physical measurements in an LCA framework?”

6.2 METHODS

Development of the survey questionnaire was guided by available reference materials and prior experience, e.g. (Ries et al. 2006). General data were collected such as age, gender, job title (faculty, graduate student, staff, undergraduate student, or researcher), length of job tenure and number of hours worked per week. General data about the work location were also collected: part of the building (1st, 2nd or 3rd floor Annex, 2nd floor tower East or North offices, and wet lab), space type (open floor plan, private office, or laboratory area), and proximity to windows. Detailed questions regarding IEQ satisfaction were grouped under four headings: thermal comfort, air quality, lighting/daylighting, and acoustics. After answering the IEQ questions, occupants were asked to evaluate 1) their perception of IEQ impacts on their productivity and 2) their estimation of how potential IEQ-related changes to the building (scenarios) would affect their productivity. IEQ and productivity questions used a 7-point, Likert-type scale, with responses arranged from “strongly disagree” or “strong negative effect”, through neutral or “no effect”, to “strongly agree” or “strong positive effect.” The scenario-related questions used the same 7-point scale, except an additional option of “I don’t know” was provided in order to allow survey respondents to use the “neutral” rating to indicate anticipation that the change would not have an effect on their productivity. The structure of the survey is summarized in Table 5 and the complete text of the survey and all responses, except for age, gender and length of job tenure, are given in Appendix C.

Table 5 - Summary of post-occupancy survey question types

Section topic	**Question format**	**Number of questions**
General questions (age, gender, title, job tenure, work area descriptions)	Multiple choice	11
IEQ satisfaction - thermal comfort	7 point Likert-type (1-7)	10
IEQ satisfaction - air quality		4
IEQ satisfaction - lighting		6
IEQ satisfaction - acoustics		5
IEQ and productivity		6
IEQ and productivity - scenarios	7 point Likert-type (1-7) with "Don't know" option	7

6.3 SURVEY RESULTS

The survey was sent to 74 occupants, with 48 completed surveys returned, a 65% response rate. The breakdown of responses by general category is given in Table 6. There is significant overlap between job titles, location in the building, space types and where applicable, window direction, due to the assignment of space by duties. Generally, faculty and staff offices are private offices on either the 1st floor of the Annex or the 2nd floor of the tower; the remaining spaces are primarily occupied by graduate students, with some undergraduate students and research assistants, as well as several visiting scholars who are identified as faculty.

Table 6 - Breakdown of survey results by general category

Question	Number of responses	Categories and number of responses in category					
What is your age?	48	Under 21	21 to 30	31 to 40	41 to 50	51 to 60	61 to 65
		1	28	9	7	2	1
What is your gender?	48	Male	Female				
		35	13				
How long have you been working in the MCSI building?[1]	49	Less than 1 year	1 to 2 years	2 to 3 years	More than 3 years or since the building was opened		
		7	11	8	23		
What is your job title?	48	Staff	Graduate student	Faculty	Postdoctoral researcher	Undergraduate student	Other[2]
		4	31	10	2	1	1
How many hours a week do you spend at MCSI?	49	<10	10-20	20-30	30-40	>40	
		0	6	6	17	20	
In which area of the building is your primary work area located?	49	First floor MCSI wing[1]	2nd floor MCSI wing[1]	3rd floor MCSI wing[1]	2nd floor Benedum Hall - Wet Lab	2nd floor Benedum Hall - East offices[1]	2nd floor Benedum Hall - North offices[1]
		3	15	16	8	3	4
Which option best describes your work area?	48	Laboratory benches	Open office with partitions	Private office	Other (please specify)[3]		
		8	29	9	2		
Do you have outside views from your work area while either standing or seated?[3]	49	Yes	No				
		41	8				
Which direction does the window face?	44	North (O'Hara Street)	East (Thackeray Street)	South (Fifth Avenue)	West (Bouquet Street)		
		33	7	3	1		
Is there a corridor or hallway between your seat and the nearest window?	49	Yes	No				
		12	37				
In my work area, I can personally adjust or control the following. (Check all that apply):							
Daylight level i.e., with window blinds or shades	33						
Electric light level, i.e., with a switch or dimmer	29						
Air supply temperature i.e., with a thermostat	8						
Air supply volume and/or direction i.e., with an adjustable vent	3						
None of the above	10						
Other	0						

1. Research assistant (1 response)
2. Open laboratory (1 response); Reception area (1 response)

IEQ Results - Results for the IEQ questions are summarized in Tables 5-8, and distributions of results for key questions are presented in Figure 14. Occupants were generally neutral relating to thermal comfort, somewhat more satisfied with air quality and lighting, and neutral to moderately satisfied with acoustics. Some categories had noticeable variation across the different areas of the building; temperature and thermal comfort were rated higher by occupants of the Annex (mean 4.4) than the tower offices or wet lab (3.1 and 3.6 respectively). Air quality was rated positively by Annex and wet lab occupants (5.6, 5.3) and slightly negatively by tower office occupants (3.9). Lighting quality was rated higher by Annex and tower office occupants (5.4, 5.6) than wet lab occupants (3.9), Acoustical quality decreased from Annex to tower offices and again to the wet lab (4.6, 4.0, 2.9).

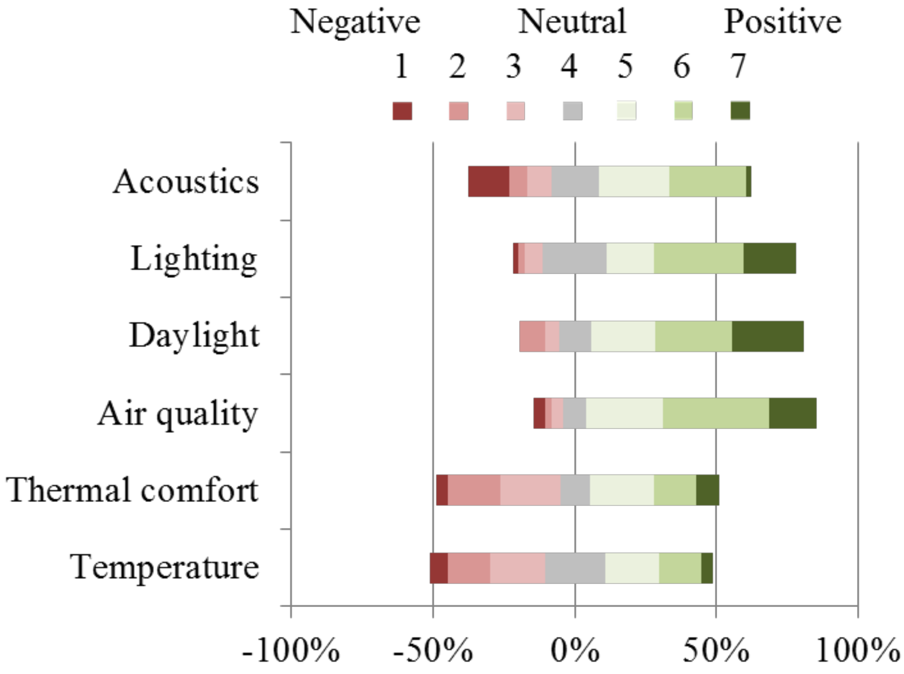


Figure 14- Distribution of results for occupant satisfaction in IEQ categories.

Table 7 - Post-occupancy survey results: IEQ - thermal comfort

Question	**Number of responses**	**Mean** *(Median)*	**Mean responses by area**		
			Annex: All floors *(1st 2nd, 3rd floors)*	**Tower offices**	**Wet lab**
During warmer weather, I am satisfied with the temperature in my work area.	48	**3.7** *(4.0)*	**4.1** *(4.0, 3.9, 4.2)*	2.6	3.0
During cooler weather, I am satisfied with the temperature in my work area.	48	**4.0** *(4.0)*	**4.1** *(3.5, 3.7, 4.6)*	3.4	4.1
I am generally satisfied with the temperature in my work area.	47	**3.9** *(4.0)*	**4.1** *(4.0, 3.8, 4.5)*	3.6	3.4
During warmer weather, I believe the air is too humid in my work area.	48	**3.0** *(3.0)*	**2.8** *(3.0, 2.5, 2.9)*	3.6	3.8
During cooler weather, I believe the air is too dry in my work area.	48	**3.7** *(4.0)*	**3.6** *(5.0, 3.3, 3.6)*	4.0	3.9
I am generally satisfied with the humidity in my work area.	47	**4.9** *(5.0)*	**5.1** *(4.0, 5.6, 4.8)*	4.7	4.5
During warmer weather, I am satisfied with the air flow speed (not too drafty or too stagnant) in my work area.	48	**4.6** *(5.0)*	**4.7** *(4.5, 4.7, 4.8)*	4.9	3.9
During cooler weather, I am satisfied with the air flow speed (not too drafty or too stagnant) in my work area.	47	**4.7** *(5.0)*	**4.8** *(4.5, 4.9, 4.8)*	4.8	4.1
I am generally satisfied with the air flow speed (not too drafty or too stagnant) in my work area.	47	**4.7** *(5.0)*	**4.8** *(4.5, 4.9, 4.8)*	4.7	4.1
Recalling the previous questions related to temperature, humidity, and air flow speed, I am generally satisfied with the thermal comfort in my work area.	48	**4.1** *(4.0)*	**4.4** *(4.0, 4.0, 4.8)*	3.1	3.6

Table 8 - Post-occupancy survey results: IEQ - air quality

Question	**Number of responses**	**Mean** *(Median)*	**Mean responses by area**		
			Annex: All floors *(1st 2nd, 3rd floors)*	**Tower offices**	**Wet lab**
I believe the air in my work area is not stuffy or stale.	48	**5.3** *(6.0)*	**5.5** *(5.5, 5.3, 5.7)*	4.7	5.1
I believe the air in my work area is clean.	48	**5.3** *(6.0)*	**5.6** *(5.0, 5.6, 5.8)*	4.3	4.9
I believe the air in my work area is generally free from odors.	48	**5.2** *(6.0)*	**5.5** *(5.0, 5.4, 5.8)*	3.7	5.3
Recalling the previous questions related to stuffiness/staleness, cleanliness and odor, I am generally satisfied with the air quality in my work area.	48	**5.3** *(6.0)*	**5.6** *(5.5, 5.5, 5.8)*	3.9	5.3

Table 9 - Post-occupancy survey results: IEQ - lighting

Question	**Number of responses**	**Mean** *(Median)*	**Mean responses by area**		
			Annex: All floors *(1st 2nd, 3rd floors)*	**Tower offices**	**Wet lab**
My work area is too bright.	48	**2.7** *(2.0)*	**2.6** *(2.0, 2.9, 2.5)*	2.4	3.4
My work area is too dark.	48	**2.8** *(2.0)*	**2.6** *(2.0, 2.5, 2.7)*	2.0	4.4
There is an adequate amount of daylight in my area (leave blank if none).	44	**5.3** *(6.0)*	**5.4** *(6.5, 5.1, 5.4)*	5.4	4.8
There is an adequate amount of electric light in my area.	48	**5.7** *(6.0)*	**5.9** *(6.0, 5.8, 5.9)*	5.9	5.1
There is a problem with glare, reflections or contrast in my work area.	48	**3.1** *(3.0)*	**3.3** *(3.0, 2.5, 4.0)*	2.6	2.9
Recalling the previous questions related to lighting and daylighting, I am generally satisfied with the lighting quality in my work area.	48	**5.2** *(5.5)*	**5.4** *(5.5, 5.3, 5.5)*	5.6	3.9

Table 10 - Post-occupancy survey results: IEQ - acoustics

Question	**Number of responses**	**Mean** *(Median)*	**Mean responses by area**		
			Annex: All floors *(1st 2nd, 3rd floors)*	**Tower offices**	**Wet lab**
My work area is too loud due to other people's conversations.	48	**4.0** *(4.0)*	**3.9** *(5.5, 3.8, 3.6)*	4.3	4.3
My work area is too loud due to background noise other than conversations (e.g. mechanical equipment, outdoor noises).	48	**4.2** *(5.0)*	**4.1** *(4.5, 4.0, 4.1)*	3.3	5.6
My work area is too quiet.	48	**2.5** *(2.0)*	**2.5** *(2.0, 2.4, 2.8)*	2.7	2.0
There is a problem with acoustics in my work area other than generally too loud or too quiet.	48	**2.9** *(2.0)*	**2.4** *(2.0, 2.7, 2.3)*	3.7	4.0
If you agree, please explain:[1]	6				
Recalling the previous questions related to acoustics, I am generally satisfied with the acoustical quality in my work area.	48	**4.2** *(5.0)*	**4.6** *(4.0, 4.6, 4.6)*	4.0	2.9

Productivity results - Results for the productivity questions are summarized in Table 11 and a distribution of responses is shown in Figure 15. Overall, occupants rated IEQ as having a near-neutral effect on their productivity, thermal comfort and acoustics as having a slight negative effect, air quality as having a slight positive effect, and lighting and outdoor views as having a stronger positive effect. Annex occupants' mean rankings in every category were higher than tower office or wet lab occupants' rankings. For thermal comfort, Annex occupants gave neutral ratings, while both tower office and wet lab occupants gave somewhat negative ratings. Air quality was rated to have a positive effect by Annex occupants, neutral by wet lab occupants and a negative effect by tower office occupants. Lighting and outdoor views were rated to have positive effects by Annex and tower office occupants, and having a negative effect by wet lab occupants. Acoustics was rated near neutral by Annex and tower office occupants and having a negative effect by wet lab occupants.

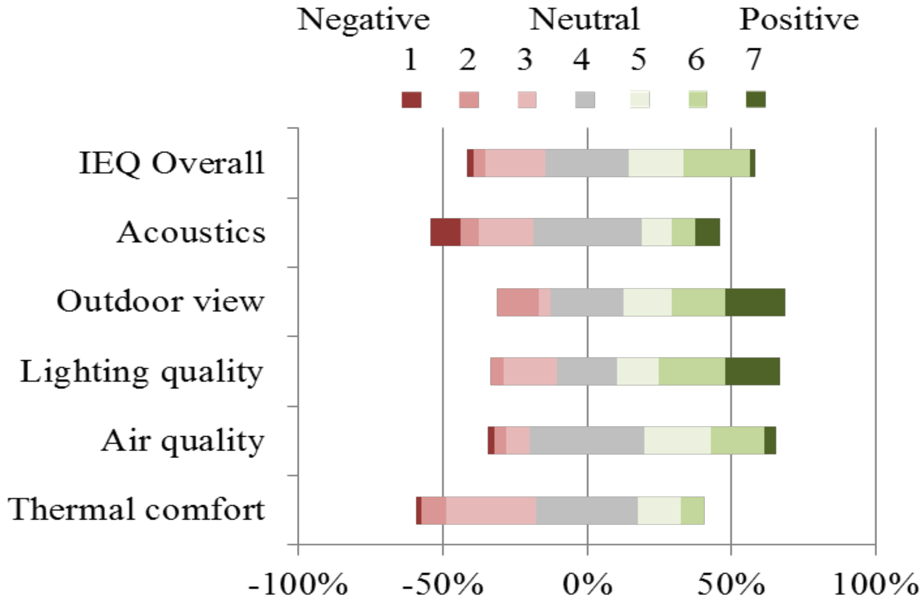


Figure 15- Distribution of results for occupants' perceived productivity impacts from IEQ.

Table 11 - Post-occupancy survey results: productivity

Question	**Number of responses**	**Mean** *(Median)*	**Mean responses by area**		
			Annex: All floors *(1st 2nd, 3rd floors)*	**Tower offices**	**Wet lab**
How does the thermal comfort (remember, this includes temperature, humidity and airspeed) in your work area affect your productivity?	48	**3.8** *(4.0)*	**4.0** (*4.0 4.1 3.9*)	3.1	3.4
How does the air quality (remember, this includes stuffiness/staleness, cleanliness and odors) in your work area affect your productivity?	48	**4.5** *(4.0)*	**4.9** (*4.0, 5.0, 4.9*)	3.0	4.1
How does the lighting quality (remember, this includes both daylighting and artifical - both overhead, and task-based) in your work area affect your productivity?	48	**4.9** *(5.0)*	**5.4** (*5.0, 5.5, 5.3*)	4.6	3.3
How does the outdoor view, or lack of an outdoor view, in your work area affect your productivity?	48	**4.8** *(5.0)*	**5.2** (*5.0, 5.1, 5.3*)	4.6	3.6
How does the acoustical quality or noise level in your work area affect your productivity?	48	**3.9** *(4.0)*	**4.2** (*3.5, 4.5, 4.0*)	3.9	2.8
Recalling the previous questions related to indoor environmental quality (including thermal comfort, air quality, lighting and acoustics), how does the overall indoor environmental quality in your work area affect your productivity?	48	**4.3** (*4.0*)	**4.8** (*4.0, 5.1, 4.7*)	3.4	3.3

Scenario results - Results indicated somewhat positive impacts from raising summer temperatures, moderate to strong negative effects from lowering winter temperatures or decreasing daylighting (nearly uniform across building areas), somewhat negative effects from decreasing ventilation (also uniform), moderate to strong positive effects from including operable windows and increasing daylighting, and perceived neutral to slightly positive effects from reducing overhead lighting when sufficient daylight was present (daylighting controls).

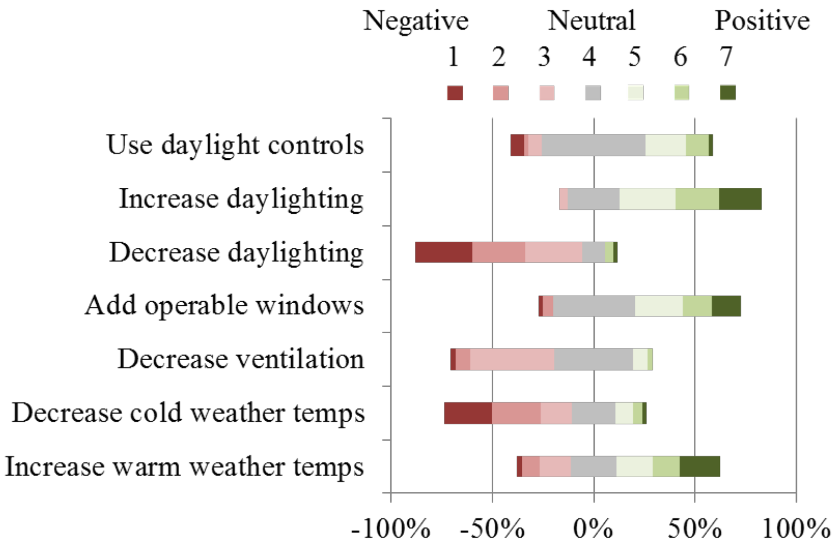


Figure 16- Distribution of results for occupants' anticipated productivity impacts from scenarios.

Table 12 - Post-occupancy survey results: scenarios

Question	**Number of responses**	**Mean** *(Median)*	**Mean responses by area**		
			Annex: All floors *(1st 2nd, 3rd floors)*	**Tower offices**	**Wet lab**
How do you think increasing the temperature in your work area by several degrees in warmer weather would affect your productivity?	48	**4.6** (*4.0*)	**4.6** (*3.5, 4.9, 4.7*)	5.1	4.0
How do you think decreasing the temperature in your work area by several degrees in cooler weather would affect your productivity?	48	**2.9** (*2.5*)	**3.1** (*4.5, 3.1, 2.9*)	2.9	2.0
How do you think decreasing the ventilation in your work area would affect your productivity?	48	**3.5** (*3.0*)	**3.4** (*3.0, 3.3, 3.6*)	3.6	3.4
How do you think including operable windows in your work area would affect your productivity?	47	**4.8** (*4.0*)	**4.8** (*5.5, 4.6, 4.8*)	5.4	4.2
How do you think decreasing the amount of daylighting in your work area would affect your productivity?	47	**2.5** (*2.0*)	**2.5** *(2.5 2.6 2.4)*	2.1	2.9
How do you think increasing the amount of daylighting in your work area would affect your productivity?	48	**5.3** (*5.0*)	**5.5** (*5.0 6.0 5.1)*	4.7	5.0
How do you think automatically turning off overhead lighting in your work area when there is sufficient daylight would affect your productivity?	48	4.1 (*4.0*)	**4.4** (*4.5 4.7 4.1*)	3.4	3.8

Raising summer temperatures was rated positively in the Annex and tower offices and neutral in the wet lab. The anticipated negative effects from lowering winter temperatures or decreasing daylighting were nearly uniform across building areas, as were the somewhat negative effects from decreasing ventilation. Increasing daylighting was rated highest in the Annex, while including operable windows was rated highest in the tower offices. Daylighting controls were rated positively in the Annex, negatively in the tower offices, and near neutral in the wet lab.

Results by identifying characteristic - Several of the results were stratified by identifying characteristics, where evidence from previous studies or the researchers' judgment suggested a possible relationship. Choi et al. suggest that "gender matters - increase summer set points" (Choi et al. 2012). In the MCSI building, the mean satisfaction with temperature in warmer weather was 2.8 for female occupants (n=12) and 3.9 (n=35) for male occupants, which was significant at a 90% confidence level (p = 0.07 using a two-tailed t-test assuming unequal variances). Mean satisfaction in cooler weather was 3.9 for both genders, and 3.5 female/4.1 male overall, though the overall value was not statistically significant. This result corroborates the findings of Choi et al. Frontczak et al. find that "Office workers will be most satisfied with their workspace and building when located close to a window in a private office" (Frontczak et al. 2012). Statistically significant differences were found between open office occupants (n=29) and private occupants (n=9) for thermal comfort impacts on productivity (p=0.04), air quality effects on productivity (p=0.001) and overall IEQ impacts on productivity (p=0.05), with the open office occupants reporting more positive effects for all three questions. No statistically significant differences were found between open office and private office occupants' responses to questions about IEQ perception not related to productivity. These results suggest that in this case, there may be factors other than office type and location that influence occupants' perception of IEQ impacts on their productivity. Possible factors include job status (e.g. most open office occupants are graduate students, and most private office occupants are facults), or an inverted building-specific relationship of office type and percieved IEQ (poorer in the tower offices). The wet lab area was not included in this comparison.

Overall, the survey results indicated general satisfaction with lighting and daylighting aspects, and some dissatisfaction with acoustics and thermal comfort aspects, with near neutral results for air quality. Open-ended responses for possible building improvements included reducing echoes and mechanical noise, providing better control over temperature including too-cold temperatures in the summer, mitigating cooking odors from a basement-level restaurant, and increasing automatic lighting shut-off delay.

Results of the survey were used to qualitatively inform the scenario analysis described in Chapter 7; i.e. to provide additional support for scenarios which were identified as positive or neutral – e.g. raising summer temperature set points, using daylighting controls, and demand-controlled ventilation, but disallowing scenarios that were identified as negative – e.g. lowering winter temperature set points or reducing ventilation. Operable windows were not able to be analyzed using the empirical energy model developed herein, whereas general increases or decreases in daylighting were not considered in the scenario analysis because they would require extensive modifications to the building.

7.0 SCENARIO ANALYSIS: ENERGY-SAVING STRATEGIES

7.1 INTRODUCTION

A scenario analysis was conducted using the IEQ+DLCA model, along with empirically-derived energy and IEQ relationships for the MCSI building, to explore the tradeoffs or synergies resulting from changes in building operating parameters. Saving energy - thus reducing external impacts - while reducing or maintaining constant internal impacts was the main criterion for the scenarios. Four scenarios were investigated: 1) demand-controlled ventilation (DCV), which ties outdoor air intake to occupancy levels; 2) raising the cooling season (warm weather) indoor temperature set point; 3) adding daylighting controls to dim overhead lighting when adequate daylight was present, and 4) a combined scenario using all three options.

For all scenarios, energy savings were estimated with an empirically-derived energy model, and IEQ impacts were calculated using parametric relationships developed herein. These energy savings were input into the DLCA model to calculate the external impacts. Internal chemical impacts were calculated using the derived building-specific parametric relationships, and internal non-chemical impacts were limited to ensuring no decrease in relative productivity.

7.2 METHODS

The data collection and analysis described in Section 5.1 were used to establish building-specific parametric relationships. Herein, the development of these relationships is restricted to the new construction portion, or “annex”. The parametric relationships were used to model the energy and IEQ consequences of possible building operation scenarios designed to save energy.

Empirical energy model – An empirical energy model was constructed for the MCSI annex, using the available measurement data. A schematic of the model is shown in Figure 17, and a summary-level relationship for the model is expressed in Equation 34:

Equation 29

$$q_E = q_{INT} + q_{VENT} + q_{SA} + q_{HW} + q_{H,FAN}$$

where q_E is the estimated heat gain through the building envelope, q_{INT} is the summary of all internal heat gains (electrical appliances, lighting, and occupants), q_{VENT} is the heat gain from conditioning the ventilation (outdoor) air to the internal conditions, q_{SA} is the additional heat gain from conditioning the supply air (outdoor + recycled), q_{HW} is the hot water space heating gain (supply air reheat terminals and radiators), and $q_{H,FAN}$ is the heat gain from the supply fan at the air handler (all q terms are in units of power, typically kW). q_{SA} represents the sum of cooling coil (chilled water) and heating coil (steam) loads, which are mutually exclusive.

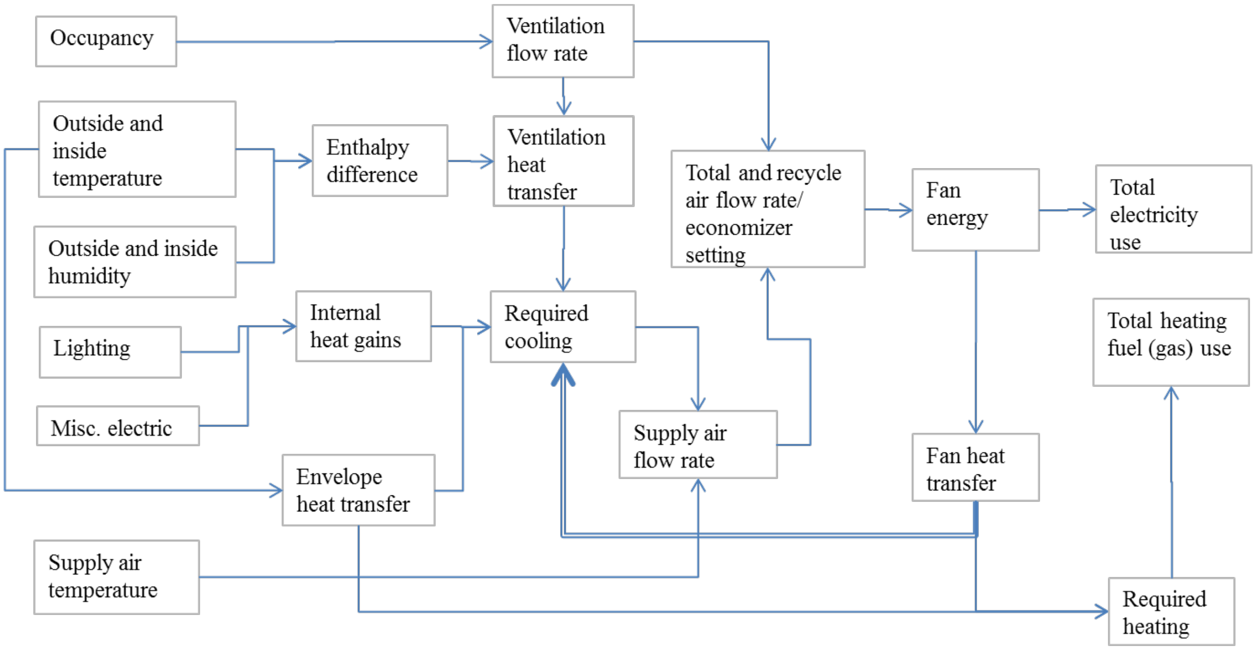


Figure 17 - Schematic of parametric energy model for the MCSI Annex

The air handler serving the MCSI annex is a return air system with economizer (Figure 9), which also serves other portions of the Benedum Hall complex. Airflows were measured both at the air handler and at the variable-air-volume (VAV) units serving the different compartments of the MCSI space. Loads measured at the air handler (cooling water use, steam use and fan electrical consumption) were allocated to the MCSI annex by multiplying them by the ratio of the total airflow at the MCSI VAV units to the total airflow at the air handler. The ventilation rate was calculated by multiplying the airflow by the economizer percent open, which was measured by a sensor. During warm weather, the economizer was operated at 20% open.

The variable heat gain associated with ventilation air was calculated using the enthalpy difference of the outdoor air and indoor air, multiplied by the ventilation mass flow rate. Even at zero ventilation, further cooling is required in moderate and warm weather to offset heat gain at the building envelope and indoor thermal loads, such as appliances and occupants, as well as heat gain introduced by the supply fan. This cooling was calculated using the enthalpy difference of the indoor air and supply air, multiplied by the supply air mass flow rate, and is independent of the ventilation rate:

Equation 30

$$q_{VENT} = (h_{OA} - h_{RA}) * \dot{m}_{OA}$$

where *h* is the enthalpy of moist air, calculated in accordance with the ASHRAE handbook (ASHRAE 2009). Assuming conduction through the building envelope as the primary pathway for the additional cooling, the calculated load was expressed as a function of the temperature difference between the outdoor and indoor air, and linear regression was used to estimate the coefficients.

Ventilation and indoor particulate intake - Indoor particle concentrations were observed to be almost always lower than outdoor concentrations, and to be highly correlated with outdoor concentrations. Since the building's MERV 13 air filters are capable of reducing the majority of PM2.5, it was hypothesized that the ratio of indoor particle levels to outdoor particle counts was dependent on the status of the economizer. Least-squares regression was performed to establish a relationship between economizer percent open and indoor/outdoor particle count ratio. This relationship was used in the subsequent scenario analysis to estimate changes in occupant intake of particulate matter due to changes in ventilation.

Indoor TVOC emissions - Indoor TVOC emissions were calculated by the same method used to calculate CO_2 emissions and occupancy (Equation 19). Using the measured outdoor and indoor TVOC concentrations and the airflow rates, a quasi-steady state mass balance model was used to estimate the TVOC emissions in each compartment as the mass accumulation after inflow and outflow. TVOC emissions estimated in this way were compared against occupancy and ventilation rates to determine if any relationship could be found.

Scenarios - Four scenarios were investigated: 1) demand-controlled ventilation (DCV), which ties outdoor air intake to occupancy levels; 2) raising the summer temperature set point by 1.1º C (2º F); 3) adding daylighting controls to dim overhead lighting when adequate daylight was present, and 4) a combined scenario using all three options. Scenarios and controlling criteria are outlined in Table 13.

Table 13 - Energy-saving scenarios and controlling criteria

Scenario	**Controlling parameters**	**Parameter values**
1 - DCV	Ventilation rate	0.3 l/s/m^2 floor area; 45 l/s/person
2 - Summer temperature	Indoor temperature set point	Recorded range (Mean 21.5, Std dev 0.88) + 1.1 deg C
3 - Daylighting control	Lighting power load	Hourly maximum of: • Actual recorded value • Mean daily minimum + 0.75*mean daily range
4 - Combined	All of the above	All of the above

For the DCV scenario, inspection of the building operating data, described in detail in the results section, showed that the building was usually operated at ventilation rates higher than the upper limits in Equation 25 and Equation 28. The DCV scenario attempted to maintain the ventilation at 45 l/s/person to achieve maximum productivity according to Eq. 1, given the occupancy calculated from the CO_2 data. An area-specific minimum ventilation rate of 0.3 l/s/(m^2 floor area) was added in accordance with ASHRAE Standard 62.1-2010 (ASHRAE 2010).

7.3 RESULTS AND DISCUSSION

7.3.1 Building-specific parametric relationships

Energy – Building-specific parametric relationships were developed for the relationship of envelope heat transfer (Q_E) and indoor/outdoor temperature difference (Figure 18), and AHU fan power and mass flow rate (Figure 19).

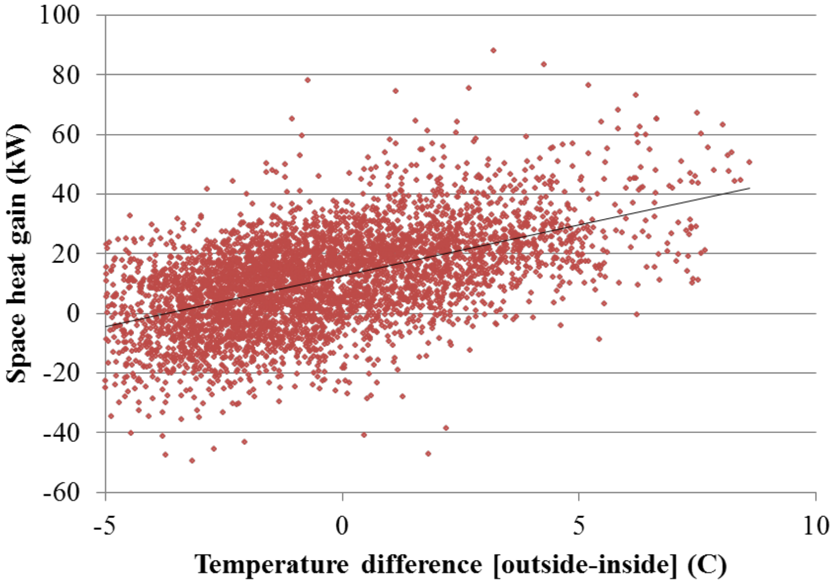


Figure 18 - MCSI Annex envelope heat transfer as a function of inside-outside temperature difference.

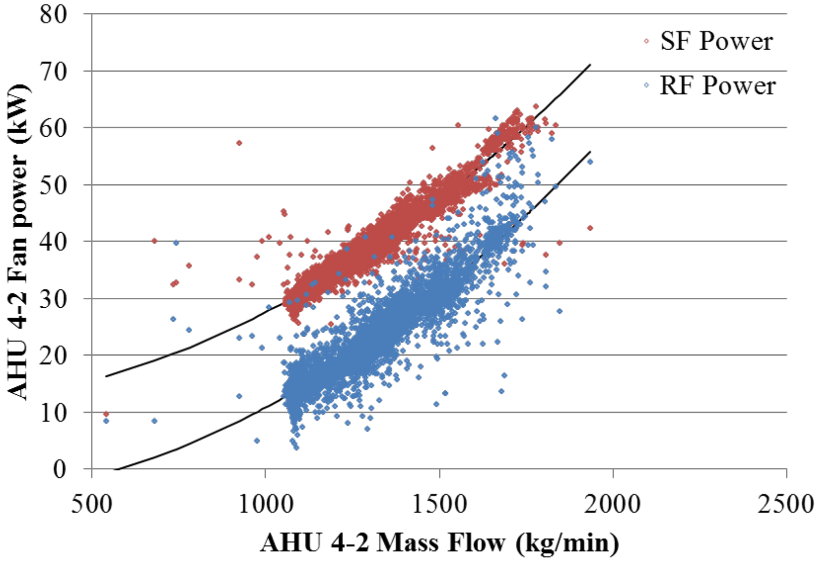


Figure 19 - MCSI Annex supply and return fan power as a function of supply air mass flow.

Least-squares regression was used to fit a linear relationship for heat gain and temperature difference (Equation 31), and a parabolic relationship for supply fan power and mass flow (Equation 32):

Equation 31

$$Q_E = 3.42 * (T_o - T_i) + 12.55$$
$$(T_o - T_i) > -5$$

Equation 32

$$Q_{SF} = 1.59 \times 10^{-5} * m_{SA} + 11.70$$
$$m_{SA} > 500$$

Both relationships were determined to be statistically significant at the 95% level using the F-test. Although a statistically significant relationship for return fan power was also established, extrapolating it below the empirically established range resulted in physically impossible negative values, and therefore it was not used in the scenario analysis.

IAQ - The building-specific parametric relationships for ventilation and indoor/outdoor particle count ratios are shown in Figure 20 and have the form:

Equation 33

$$PM2.5_{In} / PM2.5_{Out} = a * (m_{OA} / m_{SA})^{b}$$

where the quantity m_{OA}/m_{SA} is equivalent to the economizer percent open, and the coefficients a and b varied somewhat between individual compartments in the model, with b approximately equal to 0.5 in most cases. All of these relationships were determined to be statistically significant at the 95% level using the F-test. No statistically significant relationships were found for indoor VOC emissions when evaluated agains either occupancy or ventilation rate.

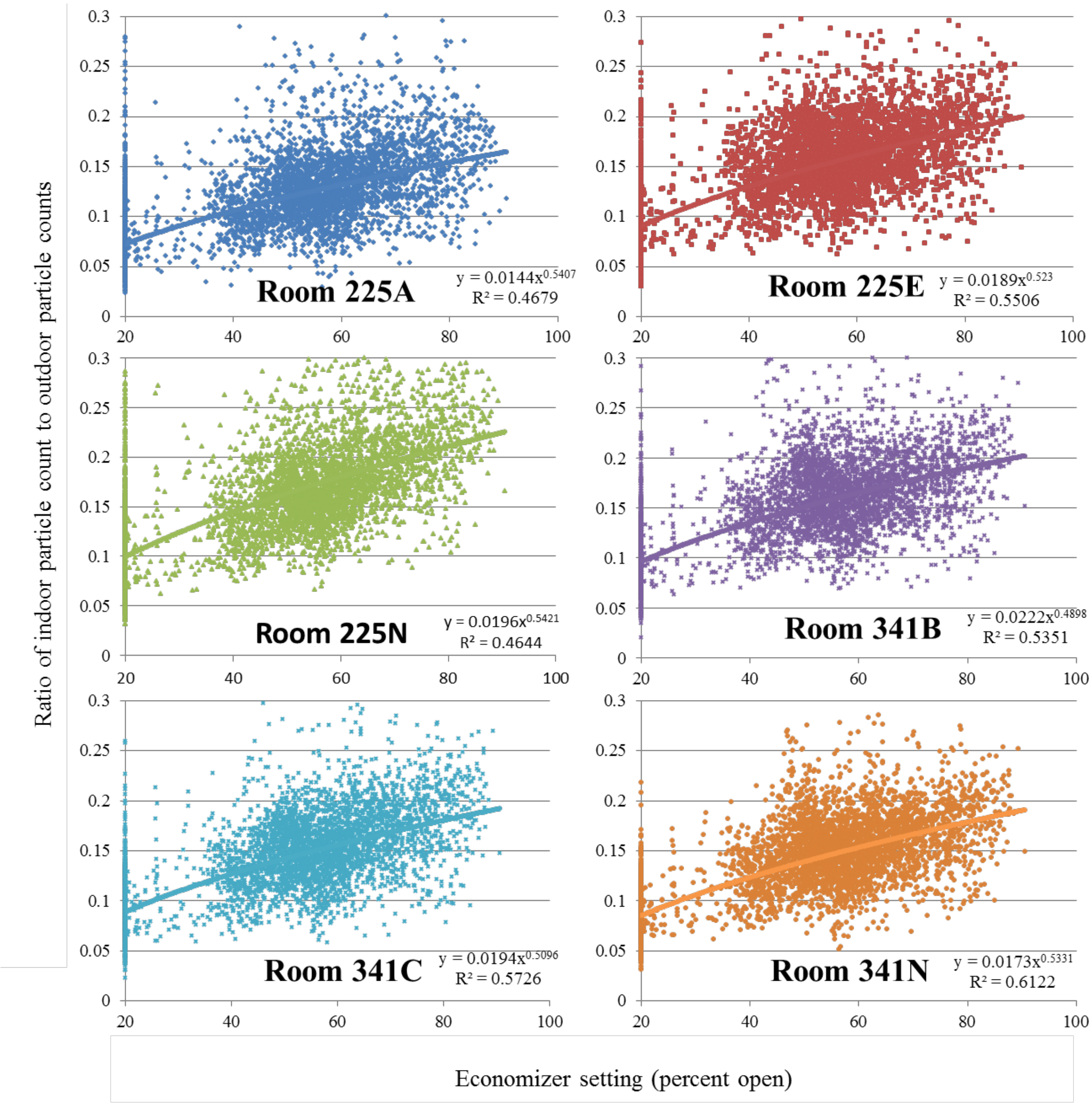


Figure 20 - Room-level empirical relationships for indoor/outdoor particle count ratio and economizer setting.

7.3.2 Energy savings and life cycle impacts

Figure 21 shows a time-series comparison of the cooling savings from the baseline for each of the four scenarios. Scenario 1 saved 50% of the building's ventilation-related cooling demand, by reducing the ventilation rate generally during hot summer nights, when the building was virtually unoccupied. Even at the relatively high rate of 45 l/s/person used to maintain productivity in accordance with Equation 25, the summertime maximum (daytime) ventilation for the rarely exceeded the baseline scenario ventilation. The reduction in ventilation rate allowed a reduction in the overall supply air demand, reducing supply fan power, with a corresponding reduction in heating of the supply air stream at the fan (see the recursive loop in Figure 17). The combined effects of these reductions resulted in a total savings of 11% of total cooling energy and 6% of total electricity use (from cooling and fans).

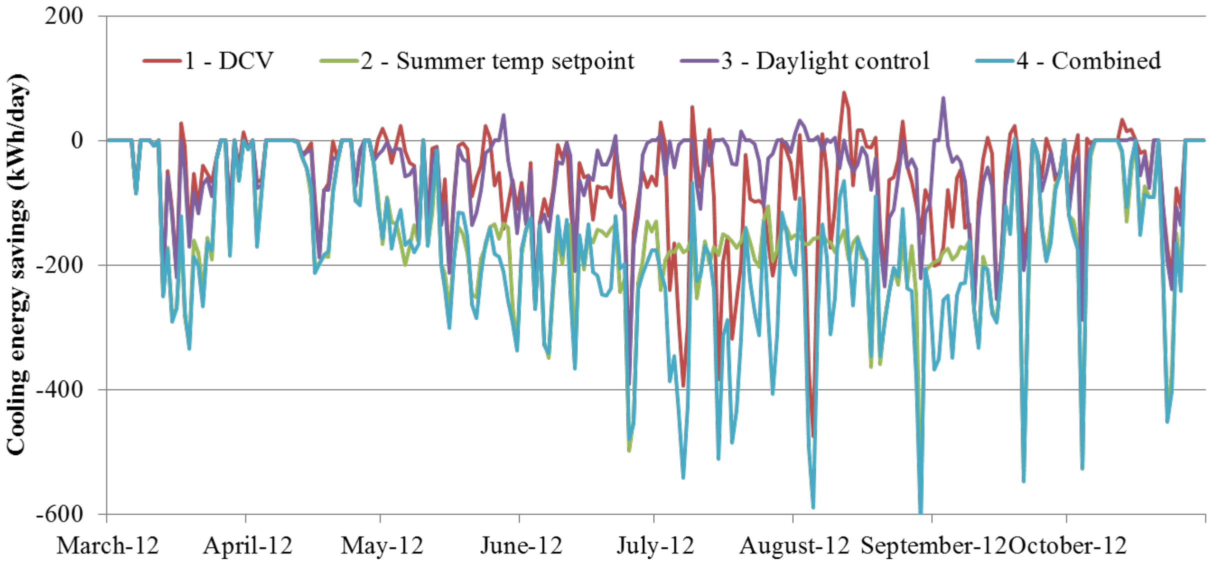


Figure 21 - Scenario results for ventilation-related cooling energy consumption from March through October 2012.

Although measured temperatures in occupied spaces rarely varied from a narrow range around the optimum performance temperature in Equation 27, feedback from the occupant survey indicated an acceptable increase in space temperature in warmer weather. Scenario 2, modeling a 1.1º C (2º F) increase in indoor temperature when temperatures outside were higher than inside, resulted in a 24% reduction in cooling energy and a 9% reduction in total electricity use. The cooling energy reduction was slightly offset by an increase in supply fan energy to take advantage of the additional range of free cooling. Scenario 3, allowing electric light levels to dim when daylight was available during cooling season led to an 8% decrease in lighting energy use and a corresponding 2% decrease in cooling energy use, for a total reduction of 4% of total electric use. When the three strategies were combined - Scenario 4 - the savings were 8%, 29%, 19% and 14% for lighting, chilled water, supply fan and total electricity respectively.

Monthly time series of IEQ+DLCA model results are shown in Figure 22 for selected impact categories. External impacts of all types were reduced by decreasing the energy consumption and generally followed the monthly distribution shown for global warming, for a total reduction of approximately 14%, with some categories affected slightly more than others by the timing of the reductions with respect to the dynamic electrical grid mix. The slightly greater reduction in the photochemical ozone category of 15%, and the different monthly distribution was due to the use of dynamic CFs from Shah et al. 2008, which are higher in the summer months, corresponding to the timing of the larger reductions.

Internal respiratory impacts were increased from baseline for all but Scenario 1, because the lower cooling demand meant that less air recirculation was necessary to meet the cooling needs at a constant supply air enthalpy. Less air recirculation, while reducing the overall air flow rate, increased the economizer open percent and increased the average indoor particle count in accordance with Equation 33 and Figure 20. Increases were 5.5%, 1.8% and 4.5% for Scenarios 2, 3 and 4, respectively. Conversely, estimated internal cancer and noncancer impacts due to internal VOC sources were reduced by the increased economizer settings in all but Scenario 1. Changes in these two categories were 22%, -6.3%, -2.1%, and 18% in Scenarios 1, 2, 3 and 4 respectively. From a seasonal standpoint, indoor respiratory impacts were greatest during cool to moderate weather, when outdoor air supply was the greatest, and indoor VOC effects were greatest during hot weather when outdoor air supply was the lowest.

Figure 23 shows the full summary of results from the IEQ+DLCA model for the study period, including all external and internal chemical categories. Productivity categories - absenteeism and at-work performance - are not included in Figure 23 because the baseline conditions for the MCSI building were near the upper limits for the ventilation-based relationships, and near the optimum value for the temperature-based relationships included in the model. A condition of “no change relative to baseline” can be assumed for all scenarios in the productivity categories. For this case study and time period (~1 year), dynamic variation LCI and LCIA data did not strongly affect the differences between scenarios. Internal cancer impacts from indoor sources were sufficiently greater than external cancer impacts, that variations between scenarios were of the same magnitude as the total external impacts.

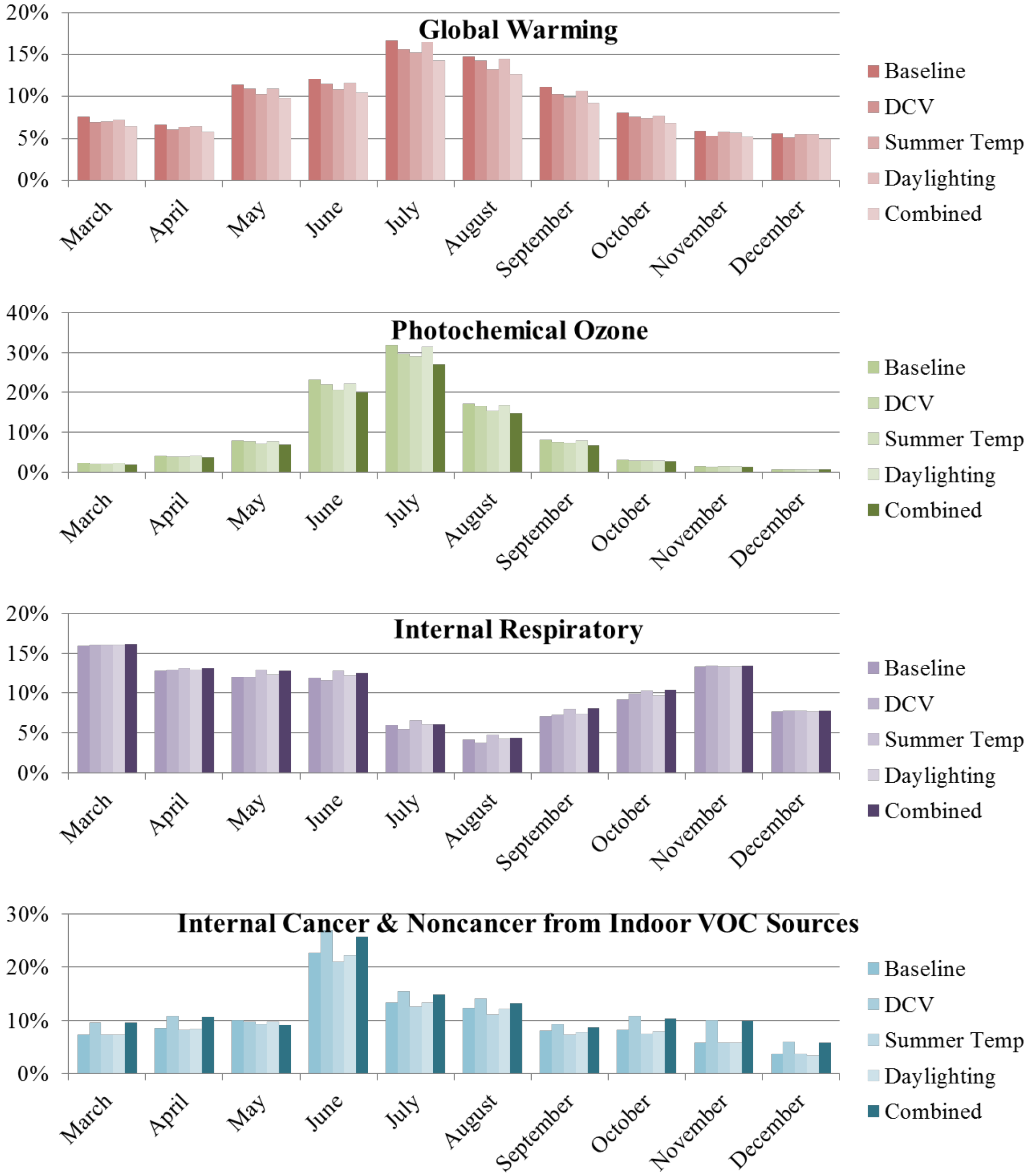


Figure 22 - Monthly baseline and scenario results for the MCSI annex in selected impact categories from the IEQ+DLCA model.

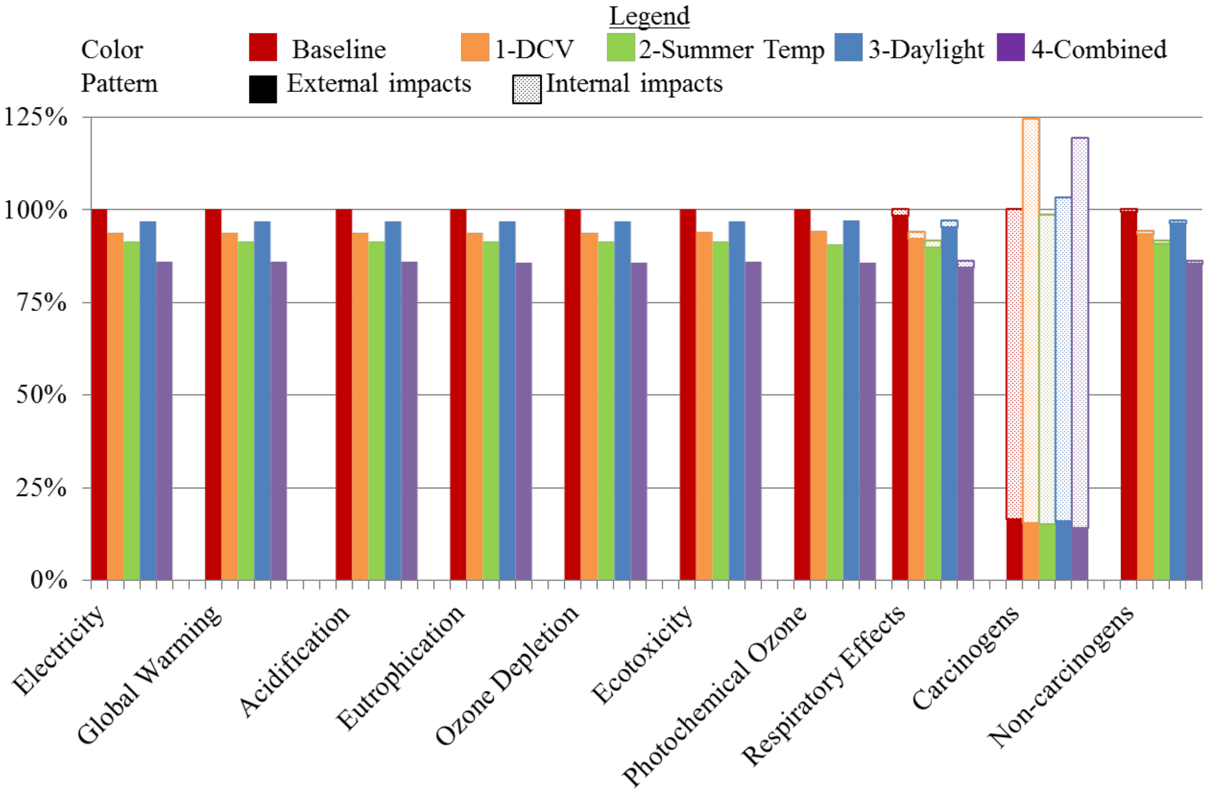


Figure 23 - Full LCIA results for the MCSI annex scenario analysis from the IEQ+DLCA model.

Results are normalized to the internal + external total from the baseline scenario.

8.0 CONCLUSIONS

8.1 SUMMARY

The goal of this study was to improve LCA methods for whole buildings by developing a dynamic model and integrating building-level indoor environmental impacts, including both human health and productivity. The first portion of this study developed the basic dynamic LCA (DLCA) framework and illustrated the potential importance of the method using a simplified retrospective and prospective case study of an institutional building (Benedum Hall). The results showed that the environmental impacts of the building over its lifetime varied from what would be predicted if temporal changes were not taken into account. Particularly, the results indicated the importance of changes in building usage, energy sources and environmental regulations in calculating the overall environmental impacts of the building. Given that temporal changes are rarely accounted for in LCA practice, it seems clear that LCA could be improved by moving to a more dynamic framework. Previous whole-building LCAs have demonstrated the relative importance of the operations phase in most impact categories, compared to the materials, construction and end-of-life phases. The DLCA results suggested an additional conclusion; that in some cases, changes in building usage, or changes in external conditions such as energy mixes or environmental regulations during a building's lifetime, can influence the LCA results to a greater degree than the material and construction phases. Correspondingly, adapting LCA to a more dynamic approach as demonstrated herein seems likely to increase the usefulness of the method in assessing the performance of buildings and other complex systems in the built environment.

The second portion of this work outlined a framework for including whole-building IEQ effects in LCA. The framework added three types of impacts to the LCA matrix: internal chemical impacts, internal non-chemical health impacts, and performance/productivity impacts. Indoor chemical impacts included impacts from indoor emissions as well as the intake of outdoor pollution. Indoor chemical impacts were categorized so as to be directly comparable to existing LCIA categories, which are conventionally used for external impacts only. These categories are respiratory effects, cancer toxicity and noncancer toxicity. Indoor nonchemical impacts were disaggregated into health and productivity impacts. After analysis of the potential overlap between chemical-specific health effects and the remaining health effects, it was concluded that some categories of nonchemical health impacts (e.g. SBS) could not be included in the framework without potential double-counting. Furthermore, the remaining nonchemical health impacts (e.g. BRI and impacts not related to air quality) have not been studied sufficiently to permit the development of empirical parametric relationships for inclusion in the framework. However, productivity impacts related to absenteeism and at-work performance were able to be included, and could potentially capture some of the missing health impacts.

The complete IEQ+DLCA framework was evaluated using a case study of a LEED Gold academic building - the MCSI building at the University of Pittsburgh, a combination annex to and renovation of a portion of Benedum Hall, the subject of the first case study. Extensive data were collected on energy consumption and IEQ variables, and a post-occupancy survey was performed to evaluate occupant perceptions of IEQ and its effects on productivity. Results of the case study suggest that in some instances, internal effects can be comparable to internal effects. For internal building respiratory effects, the performance of the mechanical filtration system can influence the results by several orders of magnitude. For example, although the internal respiratory effects in this study were lower than the external respiratory effects, they would have been greater without the building's MERV 13 filters; for instance, many commercial buildings may only employ a MERV 8 filter, which has minimal removal of PM2.5. An illustrative scenario of a lower-performing building showed that internal effects could be greater than external effects in some cases. This could be due to some combination of poor filtration and/or indoor sources of particulate matter. For cancer toxicity, the estimated internal effects were greater than external effects. In other words, the estimated exposure of building occupants, even in a building achieving LEED certification, could be greater than the total exposure of external populations due to the upstream processes of the building's operating energy supply.

Indoor source control via low-VOC building materials, furnishings and maintenance items is believed to be very important for VOC exposure; this was corroborated by the relatively low indoor contribution to TVOC levels for the case study building compared to the BASE study. This was expected since as a LEED Gold building the case study was designed with indoor source control as a key element. Ventilation complements indoor source control by removing internally generated pollutants from both occupants and building materials; however, increased ventilation without much greater attention to filtration or other treatment of outdoor and recirculated air carries the risk of increased impacts in some categories (e.g., respiratory effects and non-carcinogenic toxicity) offsetting gains in other categories (e.g. carcinogens). These relationships are site-specific, so tradeoffs will vary on a case-by-case basis. Incorporating both chemical and non-chemical health and productivity impacts into the IEQ+DLCA framework demonstrated the need to carefully consider IEQ consequences when making decisions related to energy savings. Limits on operational changes were revealed, underscoring the potential importance of design features.

The post-occupancy survey supplemented the physical analysis of the building and the existing literature on occupants' perceptions of IEQ and its relationship to their productivity. Previously documented relationships between IEQ and productivity indicate a positive correlation with ventilation and an optimal temperature range. However, the survey results suggested some degree of flexibility with respect to indoor temperature set points during the cooling season, which corresponded with the results of another previous qualitative study. Daylighting was confirmed to be a critical variable for IEQ satisfaction. As with the chemical impacts, the non-chemical health and productivity impacts may be site and population-specific, varying with the setting and occupant type, even when building design features are similar.

8.2 FUTURE WORK

Future research needs include aspects of both the dynamic features and IEQ categories in LCA, as well as refinements to the underlying human health functions. For DLCA, additional needs are characterization of uncertainty related to building systems modeling (e.g. future occupant needs and maintenance/renovation schedules); additional exploration of the interactions with dynamic, temporally evolving (and themselves uncertain) LCI and LCIA background variables; and development of additional dynamic CFs and dynamic parameters for LCI databases. The variability in these tradeoffs may support greater attention to the development of more sophisticated building modeling and the application of regional criteria in green building rating systems.

With respect to IEQ, overlaps between chemical-specific, toxicologically-based effect factors from LCIA methods, and empirically derived relationships from the IAQ literature, indicate a need for interdisciplinary efforts targeted at merging the two knowledge bases. There is a need for serious consideration of threshold doses in LCIA models so that insignificant increases in impact can be excluded as negligible.

Future work on the current project includes the exploration of an additional high-performance building case study - the Center for Sustainable Landscapes at Phipps Conservatory in Pittsburgh, as well as the continued development of the IEQ+DLCA model toward a building-level dashboard system, with improvements from both a sensing and computational standpoint. A long-term goal is to develop a reference set of estimates using data from studies such as this and the BASE study to provide design-level estimates of the tradeoffs between internal and external impacts.

8.3 OUTLOOK

Overall, LCA could be improved as a design tool for whole buildings by including a thorough analysis of the IEQ effects of design decisions, as well as internal and external system changes over a building's lifetime. Understanding the uncertainties with respect to both LCIA internal building results and external (conventional) LCA results, we conclude that for LCA of whole buildings, including dynamic modeling and building-level IEQ categories is important. The findings of this study, while underscoring the importance of internal impacts, may support the use of green building rating systems, which include the benefits of enhanced IEQ from better filtration, indoor chemical source control and attention to non-chemical environmental variables such as lighting and acoustics. As these impacts accrue to different populations (building occupants versus the world at large), the overall vision is to reduce environmental impacts related to the built environment.

APPENDIX A

INPUTS AND RESULTS FOR INITIAL DLCA CASE STUDY

A.1 BUILDING MATERIAL AND ENERGY DATA

Table 14 - Actual and estimated energy data for Benedum Hall.

Month and Year	Boiler Plant Data				Benedum Hall Consumption			eQUEST Simulated Data(4)		
	Steam Generation (Gg)	Coal for steam (Gg)	Gas for steam (10^6 m^3)	Steam energy content (MJ/kg)(1)	Steam (Mg)(3)	Electricity (MWh)(3)	Steam (GJ)(3)	Steam (Mg)	Electricity (MWh)	Steam (GJ)
Jul-92	---	---	---	---(2)	260	1090	690	400	1060	1060
Aug-92	---	---	---	---	250	820	670	401	1090	1060
Sep-92	---	---	---	---	210	1050	580	591	1130	1650
Oct-92	---	---	---	---	410	860	1090	589	930	1570
Nov-92	---	---	---	---	710	880	1850	867	800	2260
Dec-92	---	---	---	---	980	790	2550	1324	780	3430
Jan-93	---	---	---	---	1010	750	2640	1673	720	4370
Feb-93	---	---	---	---	1030	840	2700	1536	740	4050
Mar-93	---	---	---	---	810	870	2100	885	920	2300
Apr-93	---	---	---	---	520	870	1420	546	910	1490
May-93	---	---	---	---	320	810	860	413	870	1130
Jun-93	---	---	---	---	250	1010	740	394	1050	1150
Jul-93	---	---	---	---	180	1170	480	398	1060	1060
Aug-93	---	---	---	---	210	1070	560	401	1090	1060
Sep-93	---	---	---	---	220	1080	620	591	1130	1650
Oct-93	---	---	---	---	380	880	1010	589	930	1570
Nov-93	---	---	---	---	710	840	1850	867	800	2260
Dec-93	---	---	---	---	1220	800	3160	1324	780	3430
Jan-94	---	---	---	---	1340	830	3490	1673	720	4370
Feb-94	---	---	---	---	1000	860	2630	1536	740	4050
Mar-94	---	---	---	---	750	1050	1940	885	920	2300
Apr-94	---	---	---	---	430	930	1160	546	910	1490
May-94	---	---	---	---	380	890	1030	413	870	1130
Jun-94	---	---	---	---	290	1190	840	394	1050	1150
Jul-94	---	---	---	---	290	940	780	398	1060	1060
Aug-94	---	---	---	---	330	1040	860	401	1090	1060
Sep-94	---	---	---	---	250	900	710	591	1130	1650
Oct-94	---	---	---	---	320	790	860	589	930	1570
Nov-94	---	---	---	---	500	900	1310	867	800	2260
Dec-94	---	---	---	---	720	630	1860	1324	780	3430
Jan-95	---	---	---	---	1010	820	2640	1673	720	4370
Feb-95	---	---	---	---	1010	710	2670	1536	740	4050
Mar-95	---	---	---	---	850	970	2200	885	920	2300
Apr-95	---	---	---	---	610	790	1650	546	910	1490
May-95	---	---	---	---	280	750	780	413	870	1130
Jun-95	---	---	---	---	230	1100	680	394	1050	1150
Jul-95	---	---	---	---	230	890	600	398	1060	1060
Aug-95	---	---	---	---	180	1170	480	401	1090	1060
Sep-95	---	---	---	---	170	920	480	591	1130	1650
Oct-95	---	---	---	---	360	870	970	589	930	1570
Nov-95	---	---	---	---	900	880	2350	867	800	2260
Dec-95	---	---	---	---	1150	720	2990	1324	780	3430
Jan-96	---	---	---	---	1210	650	3150	1673	720	4370
Feb-96	---	---	---	---	1010	810	2670	1536	740	4050
Mar-96	---	---	---	---	970	720	2520	885	920	2300
Apr-96	---	---	---	---	580	720	1580	546	910	1490
May-96	---	---	---	---	320	800	880	413	870	1130
Jun-96	---	---	---	---	230	850	670	394	1050	1150
Jul-96	---	---	---	---	230	1080	620	398	1060	1060
Aug-96	---	---	---	---	250	820	670	401	1090	1060

Table 14 (Continued)

Sep-96	---	---	---	---	330	840	910	591	1130	1650
Oct-96	---	---	---	---	420	930	1130	589	930	1570
Nov-96	---	---	---	---	950	700	2470	867	800	2260
Dec-96	---	---	---	---	990	720	2560	1324	780	3430
Jan-97	---	---	---	---	1020	870	2660	1673	720	4370
Feb-97	---	---	---	---	860	710	2260	1536	740	4050
Mar-97	---	---	---	---	790	810	2050	885	920	2300
Apr-97	---	---	---	---	610	870	1660	546	910	1490
May-97	---	---	---	---	320	760	880	413	870	1130
Jun-97	---	---	---	---	310	790	890	394	1050	1150
Jul-97	---	---	---	---	340	1020	900	398	1060	1060
Aug-97	---	---	---	---	300	810	790	401	1090	1060
Sep-97	---	---	---	---	320	970	890	591	1130	1650
Oct-97	---	---	---	---	510	840	1370	589	930	1570
Nov-97	---	---	---	---	870	770	2260	867	800	2260
Dec-97	---	---	---	---	1000	830	2580	1324	780	3430
Jan-98	---	---	---	---	970	740	2520	1673	720	4370
Feb-98	---	---	---	---	880	770	2330	1536	740	4050
Mar-98	---	---	---	---	820	890	2140	885	920	2300
Apr-98	---	---	---	---	400	840	1080	546	910	1490
May-98	---	---	---	---	200	790	550	413	870	1130
Jun-98	---	---	---	---	180	850	520	394	1050	1150
Jul-98	---	---	---	---	200	1080	530	398	1060	1060
Aug-98	---	---	---	---	290	970	760	401	1090	1060
Sep-98	---	---	---	---	290	1030	800	591	1130	1650
Oct-98	---	---	---	---	480	930	1290	589	930	1570
Nov-98	---	---	---	---	960	920	2490	867	800	2260
Dec-98	---	---	---	---	960	910	2490	1324	780	3430
Jan-99	---	---	---	---	1280	760	3350	1673	720	4370
Feb-99	---	---	---	---	1060	940	2800	1536	740	4050
Mar-99	---	---	---	---	1290	920	3360	885	920	2300
Apr-99	---	---	---	---	680	850	1860	546	910	1490
May-99	---	---	---	---	540	890	1460	413	870	1130
Jun-99	---	---	---	---	410	1120	1200	394	1050	1150
Jul-99	---	---	---	---	460	980	1230	398	1060	1060
Aug-99	---	---	---	---	460	1070	1220	401	1090	1060
Sep-99	---	---	---	---	610	1130	1700	591	1130	1650
Oct-99	---	---	---	---	910	1010	2430	589	930	1570
Nov-99	---	---	---	---	980	940	2540	867	800	2260
Dec-99	---	---	---	---	1310	1040	3400	1324	780	3430
Jan-00	98.61	4.95	3.49	2.61	1420	1020	3690	1676	720	4370
Feb-00	79.11	4.33	2.86	2.75	1610	1010	4420	1475	740	4050
Mar-00	65.13	4.53	1.71	2.73	1280	1130	3510	841	920	2300
Apr-00	50.85	3.25	1.61	2.80	1220	950	3420	531	910	1490
May-00	31.77	2.21	1.06	3.01	760	860	2290	375	870	1130
Jun-00	24.28	1.65	0.91	3.13	420	1170	1310	367	1050	1150
Jul-00	27.34	1.26	1.15	2.76	460	940	1260	382	1060	1060
Aug-00	26.64	1.14	1.15	2.72	440	1060	1200	389	1090	1060
Sep-00	28.95	1.56	1.18	2.91	510	1040	1480	566	1130	1650
Oct-00	46.17	3.21	1.31	2.82	730	980	2060	558	930	1570
Nov-00	73.27	4.45	2.23	2.67	1450	910	3890	844	800	2260
Dec-00	107.17	6.04	3.75	2.75	1510	860	4160	1249	780	3430
Jan-01	99.28	6.33	2.73	2.64	1660	950	4370	1655	720	4370
Feb-01	80.34	5.18	2.08	2.60	1390	890	3610	1558	740	4050

Table 14 (Continued)

Mar-01	85.55	4.90	2.15	2.39	1440	880	3440	963	920	2300
Apr-01	51.18	3.40	1.29	2.62	840	1120	2190	568	910	1490
May-01	35.89	2.66	0.71	2.60	720	890	1880	434	870	1130
Jun-01	27.76	1.73	0.76	2.61	410	1150	1060	441	1050	1150
Jul-01	25.88	1.87	0.52	2.57	400	940	1030	410	1060	1060
Aug-01	24.45	1.46	0.72	2.61	450	1140	1170	405	1090	1060
Sep-01	28.88	1.40	1.06	2.61	540	1040	1400	630	1130	1650
Oct-01	47.63	3.11	1.20	2.59	900	930	2330	606	930	1570
Nov-01	56.74	3.71	1.38	2.56	1010	900	2590	883	800	2260
Dec-01	78.12	5.60	1.56	2.55	1140	800	2910	1344	780	3430
Jan-02	86.31	6.18	1.82	2.59	1350	1070	3500	1689	720	4370
Feb-02	79.40	5.03	2.05	2.57	1220	630	3120	1579	740	4050
Mar-02	76.95	5.30	1.92	2.67	1160	850	3100	862	920	2300
Apr-02	54.70	4.06	1.30	2.76	1300	1090	3570	540	910	1490
May-02	45.66	3.15	1.04	2.59	1140	350	2950	435	870	1130
Jun-02	29.59	2.28	0.86	3.03	540	1030	1630	380	1050	1150
Jul-02	25.54	1.17	0.99	2.62	90	940	230	402	1060	1060
Aug-02	26.65	1.29	0.95	2.57	190	1100	480	410	1090	1060
Sep-02	25.48	1.59	0.85	2.83	190	1060	540	581	1130	1650
Oct-02	53.47	3.36	1.44	2.60	930	920	2420	606	930	1570
Nov-02	74.67	5.30	1.58	2.58	1280	850	3300	875	800	2260
Dec-02	97.35	5.79	2.52	2.47	1870	810	4630	1387	780	3430
Jan-03	115.57	6.08	3.37	2.43	2300	820	5590	1800	720	4370
Feb-03	99.65	5.38	3.05	2.52	2140	810	5380	1609	740	4050
Mar-03	77.02	5.03	1.98	2.61	1820	660	4760	881	920	2300
Apr-03	53.68	3.80	1.31	2.70	1470	560	3970	551	910	1490
May-03	41.78	3.23	0.91	2.76	940	990	2600	410	870	1130
Jun-03	33.26	2.50	0.91	2.92	560	1320	1650	394	1050	1150
Jul-03	28.59	2.06	0.93	3.05	530	850	1620	346	1060	1060
Aug-03	30.07	1.88	0.97	2.79	570	1000	1580	378	1090	1060
Sep-03	34.31	2.11	1.00	2.65	690	950	1830	621	1130	1650
Oct-03	55.79	3.52	1.34	2.49	1190	900	2980	630	930	1570
Nov-03	65.11	4.48	1.54	2.62	1250	850	3270	861	800	2260
Dec-03	96.29	5.96	2.60	2.58	2030	780	5220	1331	780	3430
Jan-04	118.24	6.12	4.09	2.61	2160	820	5660	1671	720	4370
Feb-04	95.15	5.84	2.54	2.55	1940	800	4940	1590	740	4050
Mar-04	78.54	5.48	2.02	2.72	1560	560	4250	845	920	2300
Apr-04	59.64	4.51	1.22	2.66	1190	560	3170	558	910	1490
May-04	38.68	2.71	0.78	2.51	640	560	1610	449	870	1130
Jun-04	31.46	2.20	0.75	2.65	330	560	880	433	1050	1150
Jul-04	27.97	1.79	0.84	2.75	130	670	350	383	1060	1060
Aug-04	29.71	1.52	1.00	2.56	160	1000	400	413	1090	1060
Sep-04	30.66	1.60	0.98	2.53	300	950	750	651	1130	1650
Oct-04	46.02	3.16	1.16	2.67	970	900	2590	588	930	1570
Nov-04	65.31	4.33	1.61	2.59	1480	850	3840	870	800	2260
Dec-04	94.89	5.80	2.78	2.64	1930	780	5100	1298	780	3430
Jan-05	106.15	5.61	3.79	2.68	2110	720	5660	1628	720	4370
Feb-05	89.25	5.00	3.28	2.80	1830	810	5120	1446	740	4050
Mar-05	94.94	4.74	3.46	2.64	1790	560	4730	871	920	2300
Apr-05	55.96	2.85	2.14	2.73	960	560	2620	544	910	1490
May-05	46.00	2.31	1.65	2.62	920	560	2420	431	870	1130
Jun-05	32.32	1.64	1.12	2.59	490	560	1260	444	1050	1150
Jul-05	33.29	2.15	0.75	2.47	360	560	900	427	1060	1060
Aug-05	33.16	2.18	0.71	2.46	350	1000	860	428	1090	1060

Table 14 (Continued)

Sep-05	35.52	2.45	0.80	2.57	380	920	980	640	1130	1650
Oct-05	52.88	2.80	1.80	2.62	1010	900	2650	599	930	1570
Nov-05	73.06	4.16	2.35	2.65	1260	900	3350	852	800	2260
Dec-05	108.15	5.03	4.33	2.69	2150	890	5800	1274	780	3430
Jan-06	90.78	4.23	3.50	2.64	1720	860	4550	1655	720	4370
Feb-06	95.60	4.16	3.85	2.63	1700	830	4470	1541	740	4050
Mar-06	88.14	4.35	3.28	2.65	1490	920	3960	867	920	2300
Apr-06	57.02	3.31	1.87	2.70	890	920	2400	551	910	1490
May-06	46.73	2.69	1.45	2.62	710	900	1850	431	870	1130
Jun-06	36.58	2.11	1.17	2.67	380	810	1000	431	1050	1150
Jul-06	35.51	2.40	1.06	2.83	360	800	1020	373	1060	1060
Aug-06	34.77	2.14	1.06	2.69	330	880	900	392	1090	1060
Sep-06	38.82	2.50	1.12	2.71	370	880	1010	607	1130	1650
Oct-06	59.15	3.92	1.76	2.79	910	910	2530	564	930	1570
Nov-06	71.48	3.21	2.61	2.52	1170	950	2940	896	800	2260
Dec-06	86.54	4.68	2.95	2.65	850	840	2250	1293	780	3430
Jan-07	84.52	4.78	2.80	2.68	960	880	2580	1631	720	4370
Feb-07	110.86	4.53	4.68	2.64	1090	950	2880	1537	740	4050
Mar-07	84.37	4.65	2.93	2.70	800	930	2160	851	920	2300
Apr-07	70.26	4.46	2.00	2.67	720	910	1920	557	910	1490
May-07	45.59	3.04	1.15	2.63	360	970	930	430	870	1130
Jun-07	37.27	2.68	0.97	2.78	280	810	770	414	1050	1150
Jul-07	35.00	2.46	0.91	2.74	230	800	620	384	1060	1060
Aug-07	33.79	2.28	0.94	2.74	190	880	520	384	1090	1060
Sep-07	35.44	1.74	1.33	2.66	210	870	570	618	1130	1650
Oct-07	47.27	2.34	1.68	2.59	400	1020	1030	606	930	1570
Nov-07	79.30	4.35	2.72	2.68	810	920	2180	843	800	2260
Dec-07	105.27	5.69	3.67	2.68	1080	860	2900	1278	780	3430
Jan-08	100.10	5.28	3.52	2.66	1100	950	2920	1642	720	4370
Feb-08	98.39	4.96	3.59	2.65	990	960	2630	1528	740	4050
Mar-08	103.33	5.36	3.66	2.65	960	880	2530	868	920	2300
Apr-08	66.85	3.98	1.99	2.62	570	990	1500	567	910	1490
May-08	55.46	3.36	1.71	2.69	310	850	830	420	870	1130
Jun-08	40.88	2.62	1.22	2.74	140	840	370	420	1050	1150
Jul-08	40.51	2.54	1.43	2.91	110	940	330	362	1060	1060
Aug-08	40.79	2.14	1.30	2.53	120	830	300	418	1090	1060
Sep-08	41.56	2.42	1.20	2.55	50	890	120	644	1130	1650
Oct-08	65.33	3.49	2.26	2.66	350	980	920	592	930	1570
Nov-08	93.61	4.81	3.45	2.69	600	820	1620	839	800	2260
Dec-08	117.56	5.81	4.46	2.69	840	800	2260	1277	780	3430
Jan-09	105.32	5.47	3.63	2.61	1880	950	4900	2519	750	6580
Feb-09	88.84	4.63	3.00	2.59	1260	1740	3270	2583	780	6690
Mar-09	97.21	4.82	3.37	2.57	1260	560	3250	1562	960	4010
Apr-09	74.93	4.18	2.28	2.56	760	910	1940	1123	940	2870
May-09	53.89	3.32	1.48	2.59	610	770	1570	624	900	1610
Jun-09	38.79	1.91	1.50	2.70	390	850	1070	527	1130	1420
Jul-09	44.35	0	3.30	2.86	370	990	1060	468	1130	1340
Aug-09	40.33	0	2.99	2.85	290	910	830	445	1170	1270
Sep-09	45.07	0	3.19	2.71	290	700	780	801	1200	2170
Oct-09	69.24	0	5.18	2.87	550	1360	1580	977	970	2810
Nov-09	70.60	0	5.14	2.79	840	930	2340	1488	830	4160
Dec-09	68.76	0	5.05	2.82	1430	1050	4030	1988	810	5600
Jan-10	77.89	0	5.75	2.83	1810	920	5140	2323	750	6580
Feb-10	73.55	0	5.42	2.83	4470	920	12620	2367	780	6690

Table 14 (Continued)

Mar-10	52.58	0	3.79	2.77	1860	920	5150	1449	960	4010
Apr-10	36.03	0	2.57	2.74	1410	1090	3860	1048	940	2870
May-10	25.21	0	1.83	2.79	1270	920	3530	579	900	1610
Jun-10	24.79	0	1.79	2.76	1040	1060	2870	515	1130	1420
Jul-10	24.51	0	1.75	2.74	1050	1030	2880	489	1130	1340
Aug-10	22.08	0	1.52	2.65	1100	980	2900	478	1170	1270
Sep-10	25.37	0	1.95	2.95	1150	1050	3390	737	1200	2170
Oct-10	43.49	0	3.21	2.83	1460	960	4140	992	970	2810
Nov-10	59.39	0	4.42	2.85	2170	1010	6210	1456	830	4160
Dec-10	80.70	0	5.99	2.85	2900	1030	8260	1968	810	5600
Jan-11	78.21	0	5.76	2.83	3020	970	8540	2330	750	6580
Feb-11	61.29	0	4.48	2.81	2460	1000	6910	2384	780	6690

Table 14 Notes:

1) Steam energy content was calculated using values of 24.8 MJ/kg for coal and 38.4 MJ/m3 for gas. This represents primary energy content and includes all energy losses during steam generation, distribution and use.

2) For the years 1971 through 1999, steam energy content was assumed to be the average of years 2000-2002 on a month-by-month basis.

3) For the years 1971 through June 1992, electrical and steam usage were assumed to be the average of years 1993-1995 on a month-by-month basis.

4) The eQUEST model was constructed for the original building and compared with actual data from years 1993-2001 (prior to removal of electric chillers from the building's roof). Once this model was completed, the renovation changes were added and results of the renovated building model were used from March 2011 onward.

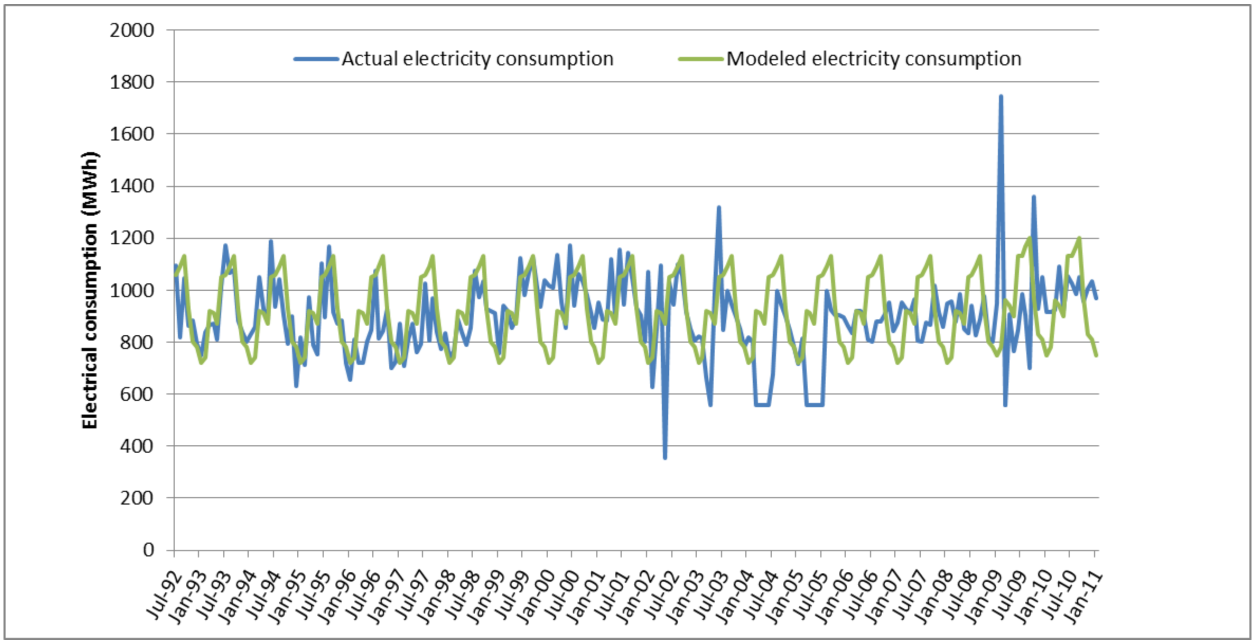


Figure 24 - Comparison of actual electrical usage and eQUEST model results for Benedum Hall**.**

Actual usage from 2002-2011 does not include cooling since the building was connected to the central campus chilled water plant in 2002.

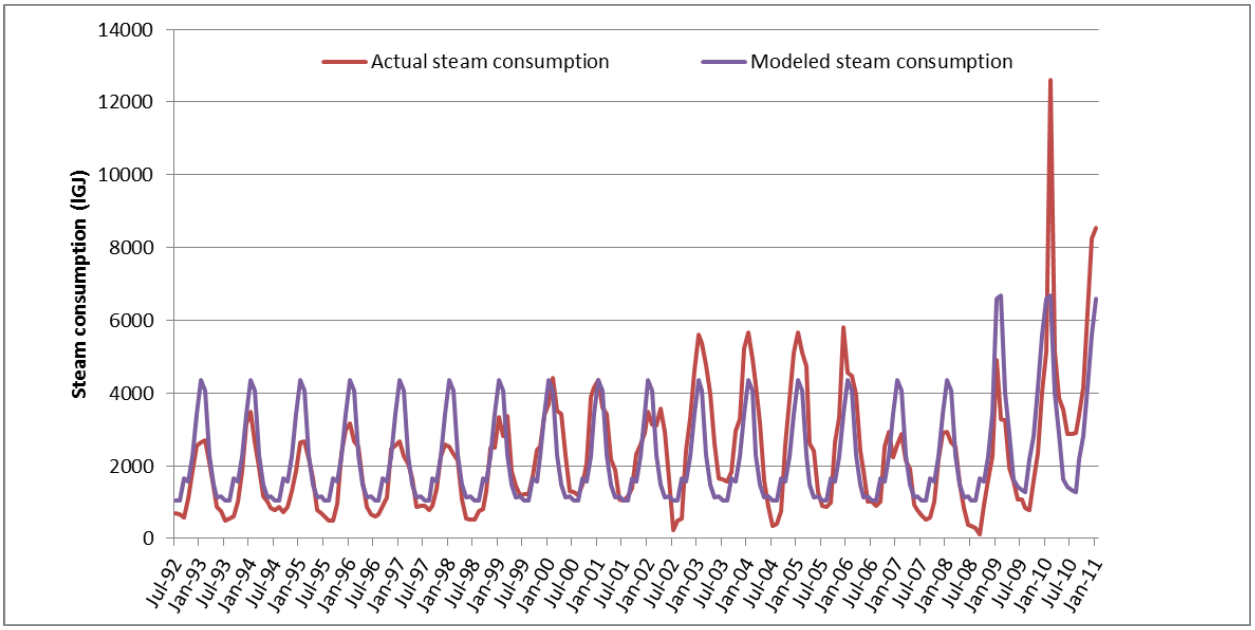


Figure 25 - Comparison of steam usage and eQUEST model results for Benedum Hall

A.2 LIFE CYCLE INVENTORY

Table 15 - Mass and embodied energy inputs for static LCA model of Benedum Hall materials compared to two other studies

Case Study: Benedum Hall			**Scheuer 2003**			**Junnila 2006**	
Building lifetime	75 Years		Building lifetime	75 Years		Building lifetime	50 Years
Floor area	37,000 m^2		Floor area	7,300 m^2		Floor area	4,400 m^2
	Mass/area (kg/m2)	Energy/area (MJ/m2)	**Materials**	Mass/area (kg/m2)	Energy/area (MJ/m2)	**Materials**	Energy/area (MJ/m2)
Structural steel (piling and rebar)	77	1,870	Steel, electric arc furnace	65	790	Rebar and steel stairs	1,080
Structural concrete	1180	820	Cement (in concrete) Sand (concrete and backfill) Gravel (concrete)	180 1100 320	670 660 64	Concrete	700
Concrete masonry unit walls	250	190	NA^2	NA	NA	NA	NA
Steel studs, doors, and frames^3	22	600	Steel, primary, cold rolled Steel, secondary, hot rolled	12 10	322 139	Steel studs, doors, frames and grid	890
Steel piping and ductwork (galvanized and stainless)	18	600	Steel, primary, electrogalvanized	10	319	Steel, piping and ductwork	1,400
Cast iron piping^3	6.7	160	Cast iron	6.7	220	Incl. in steel piping	NA
Copper tubing and wire^3	4.5	140	Copper, primary, extruded Copper tube	2.9 1.6	206 108	Copper tubing and wire	250
Aluminum (window frames, cladding panels)	0.49	56	Aluminum, primary	2.1	425	Aluminum	18
Exterior masonry (limestone)	86	2.4	Exterior masonry (brick)	53	143	NA	NA
Resilient floor tile	3.2	190	NA	NA	NA	Ceramic tile	250
Glass (windows)	5.5	71	Glass	6.4	44	Glass	780
Gypsum board	5.4	31	Kraft paper Gypsum, primary Gypsum, secondary	8.4 10 10	315 8 0	Gypsum board Mineral fiber board ceiling tile	340 210

Table 15 (Continued)

Extruded polystyrene insulation	0.19	20	Polyisocyanurate Polystyrene	1.2 0.8	86 78	Extruded polystyrene insulation	20
Fiberglass insulation	0.45	21	Glass fiber, primary	2.9	51	Fiberglass insulation	710
HVAC multizone units	10	270	NA	NA	NA	HVAC multizone units	420
GFRC panels	0.04	0.14	NA	NA	NA	NA	NA
Polyethylene (cladding panels)	0.2	16	NA	NA	NA	NA	NA
Total materials	**1670**	**5,080**	**Total materials**	**2,000**	**6,250**	**Total materials**	**11,900**
Original construction materials	*1570*	*4,250*				*Original construction materials*	*7,060*
Renovation materials	*100*	*820*				*Renovation materials*	*4,860*
			Total shown here[4]	1,780	4,640	Total shown here[4]	7,100
			% Total shown here	90%	74%	% Total shown here	59%
Total operating energy		**3,920**	**Total operating energy**		**4,100**	**Total operating energy**	**1,360**
Electricity		3,340					700
Heating		580					660

Table 15 Notes:

1.This table attempts to provide comparable items in rows going across, where possible. There is overlap between some categories across the studies, but not within studies.

2. NA = Not applicable - generally, not present in the subject building.

3. Values from Scheuer et al. for mass/area were used herein for these material categories.

4. Major items excluded from “Total shown here” are the following: For Scheuer et al. - carpet, roofing materials, fireproofing and paint; For Junnila et al. - carpet, roofing materials, ceiling tile, elevator and paint. Fireproofing is NA for Benedum Hall; carpeting and ceiling tile are minimal, and roofing and paint were excluded due to lack of data.

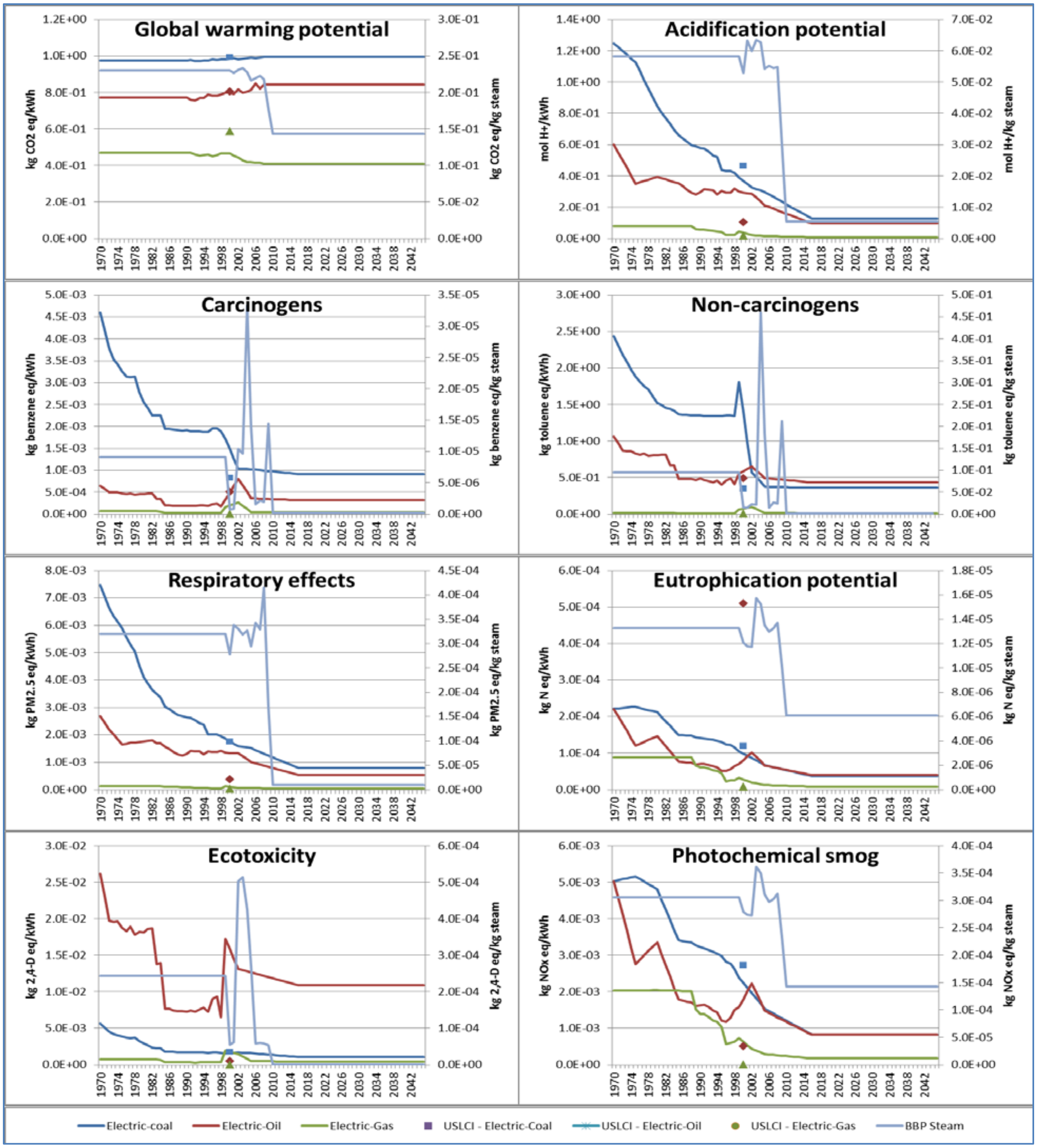


Figure 26 - Time series of derived emissions factors for fossil fuel electric power generation and Bellefield Boiler Plant (BBP) steam heat.

TRACI categories are shown except for ozone depletion.

Figure 26 Notes:

1) Electric power generation quantities by fuel type from EIA and emissions totals from EPA.

2) Years outside EPA HAP emission estimates (pre-1998, and post-2005 for some HAPS were calculated by assuming constant relationships between organic gases/ total VOCs, and non-mercury metallic haps/PM2.5.

3) BBP emissions data from Allegheny County Health Department for the years 2000-2010.

4) US LCI totals (for combustion only, not including upstream processes) are shown for qualitative comparison. USLCI totals are arbitrarily shown at the year 2000.

A.3 LIFE CYCLE IMPACT ASSESSMENT

Table 16 - Results of life cycle impact assessment (LCIA) for Benedum Hall original construction and renovation materials.

TRACI Category	**Global Warming**	**Acidification**	**Carcinogens**	**Non carcinogens**	**Respiratory effects**	**Eutrophication**	**Ozone depletion**	**Ecotoxicity**	**Smog**
Units	**kg CO2 eq**	**H+ moles eq**	**kg benzene eq**	**kg toluene eq**	**kg PM2.5 eq**	**kg N eq**	**kg CFC-11 eq**	**kg 2,4-D eq**	**kg NOx eq**
Original construction – Unit processes by LCA data source (1)									
ecoinvent - air	8.1E+06	6.9E+05	1.0E+04	3.3E+07	1.1E+04	4.6E+02	0.0E+00	1.8E+06	1.0E+04
ecoinvent - water	0.0E+00	0.0E+00	1.8E+02	4.7E+06	0.0E+00	2.7E+01	0.0E+00	1.8E+04	0.0E+00
uslci - air	6.4E+06	1.8E+06	3.3E+03	3.9E+06	3.7E+03	7.8E+02	8.4E-03	1.2E+05	1.8E+04
uslci - water	0.0E+00	0.0E+00	1.6E+03	3.9E+07	0.0E+00	1.6E+02	0.0E+00	1.0E+06	0.0E+00
Renovation – Unit processes by LCA data source (1)									
ecoinvent - air	7.1E+05	1.2E+05	1.1E+04	1.6E+07	2.8E+03	6.6E+01	0.0E+00	7.1E+05	1.5E+03
ecoinvent - water	0.0E+00	0.0E+00	7.5E+01	2.2E+06	0.0E+00	9.2E+00	0.0E+00	3.2E+03	0.0E+00
uslci - air	9.6E+05	2.9E+05	4.6E+02	4.9E+05	6.5E+02	1.1E+02	5.4E-04	1.8E+04	2.6E+03
uslci - water	0.0E+00	0.0E+00	2.8E+02	6.5E+06	0.0E+00	2.8E+01	0.0E+00	1.7E+05	0.0E+00

Table 16 Notes:

LCA data source categories are as follows: ecoinvent – air and ecoinvent – water represent emissions from material production to air and water respectively, excluding emissions from fuel used in material production; uslci – air and uslci – water represent emissions from fuel consumption used in material production, such as direct fuel combustion or electricity use. This method was used for two reasons: a) take advantage of ecoinvent’s larger database of material processes and b) maintain the use of US-specific data for emissions from fuel combustion.

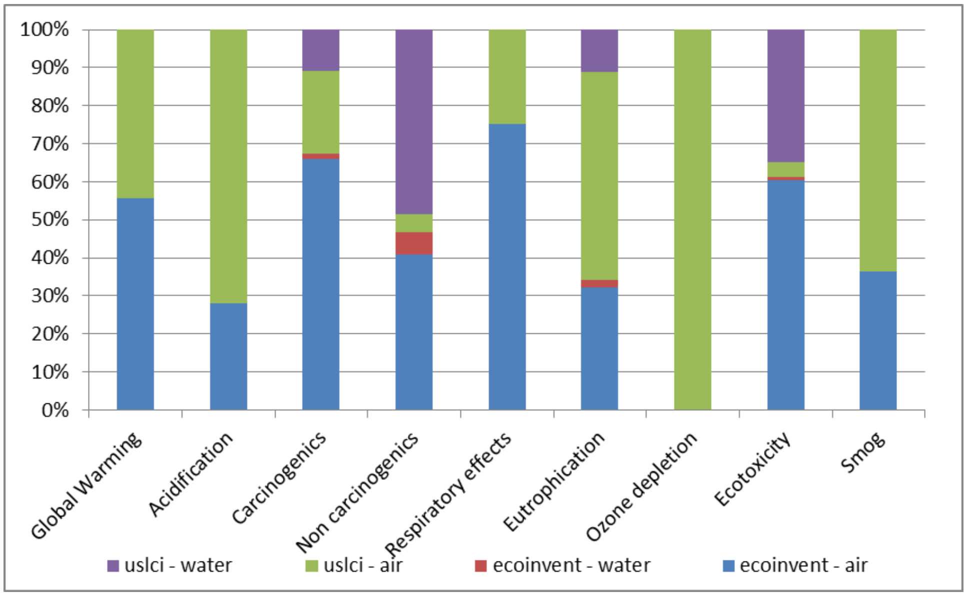


Figure 27 - Normalized TRACI results from Benedum Hall original construction materials showing percentage contributions from unit processes.

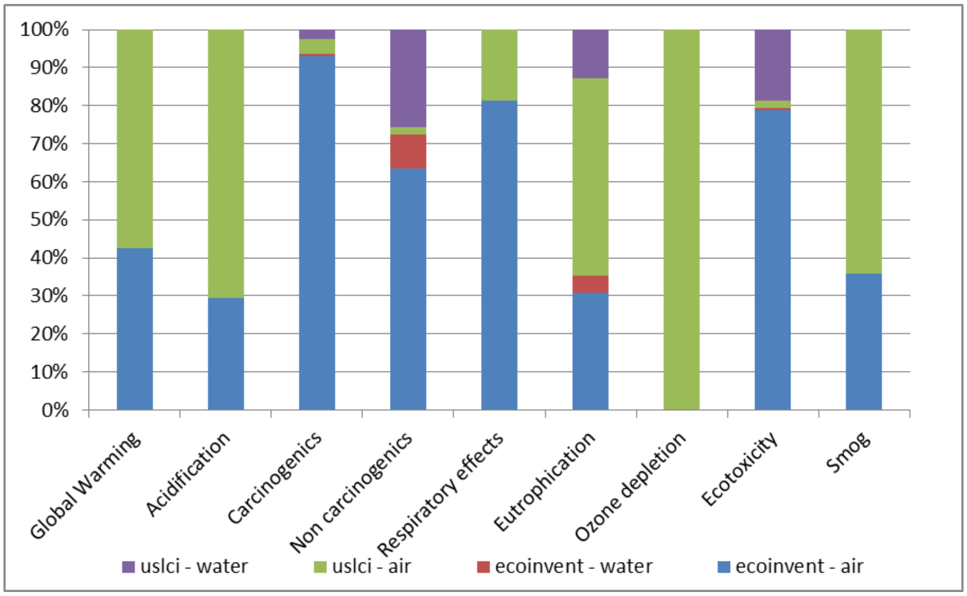


Figure 28 - Normalized TRACI results from Benedum Hall renovation materials showing percentage contributions from unit processes.

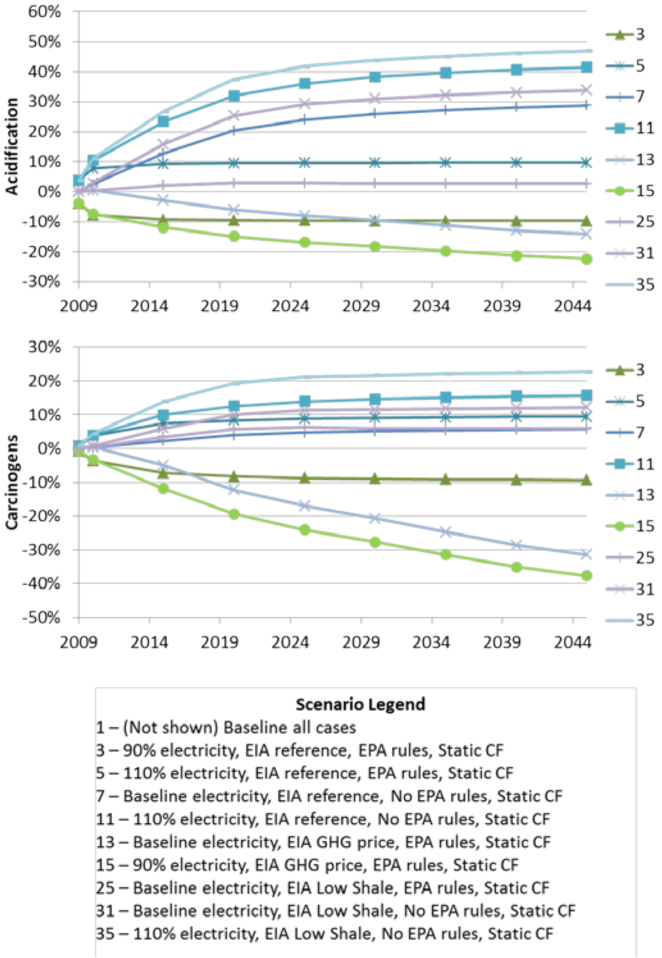


Figure 29 - (1 of 4) Time series of DLCA results for the sensitivity analysis, shown as cumulative percent deviations from the baseline scenario for the remaining categories not shown in Figure 6.

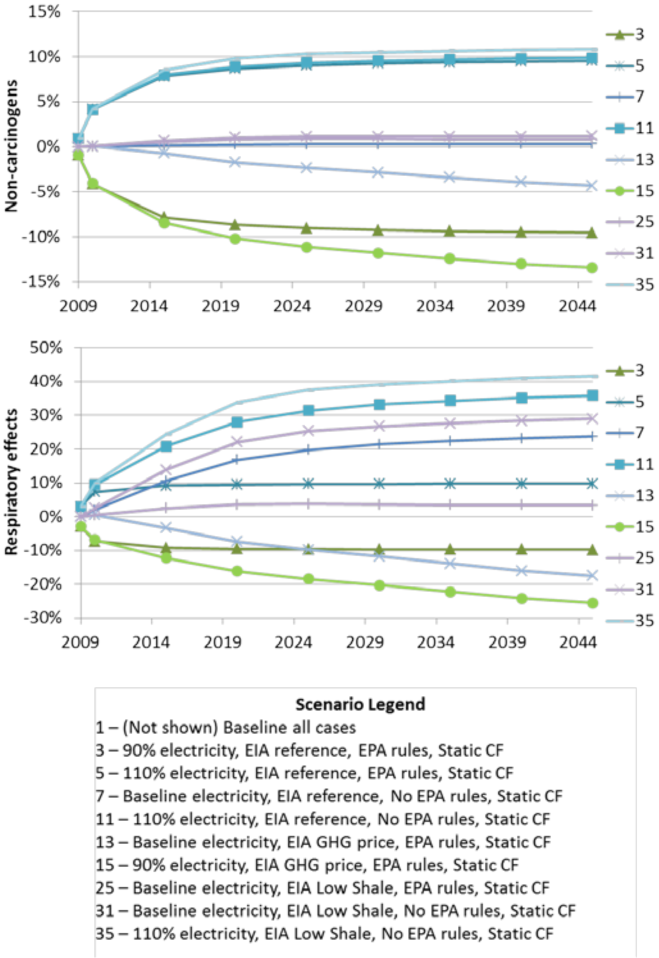
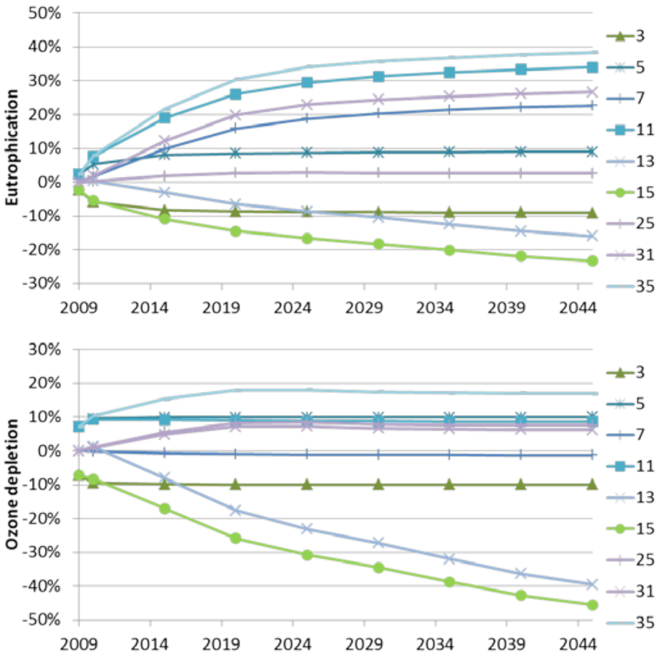


Figure 29 - (2 of 4) Time series of DLCA results for the sensitivity analysis, shown as cumulative percent deviations from the baseline scenario for the remaining categories not shown in Figure 6.



Scenario Legend

1 – (Not shown) Baseline all cases
3 – 90% electricity, EIA reference, EPA rules, Static CF
5 – 110% electricity, EIA reference, EPA rules, Static CF
7 – Baseline electricity, EIA reference, No EPA rules, Static CF
11 – 110% electricity, EIA reference, No EPA rules, Static CF
13 – Baseline electricity, EIA GHG price, EPA rules, Static CF
15 – 90% electricity, EIA GHG price, EPA rules, Static CF
25 – Baseline electricity, EIA Low Shale, EPA rules, Static CF
31 – Baseline electricity, EIA Low Shale, No EPA rules, Static CF
35 – 110% electricity, EIA Low Shale, No EPA rules, Static CF

Figure 29 - (3 of 4) Time series of DLCA results for the sensitivity analysis, shown as cumulative percent deviations from the baseline scenario for the remaining categories not shown in Figure 6.

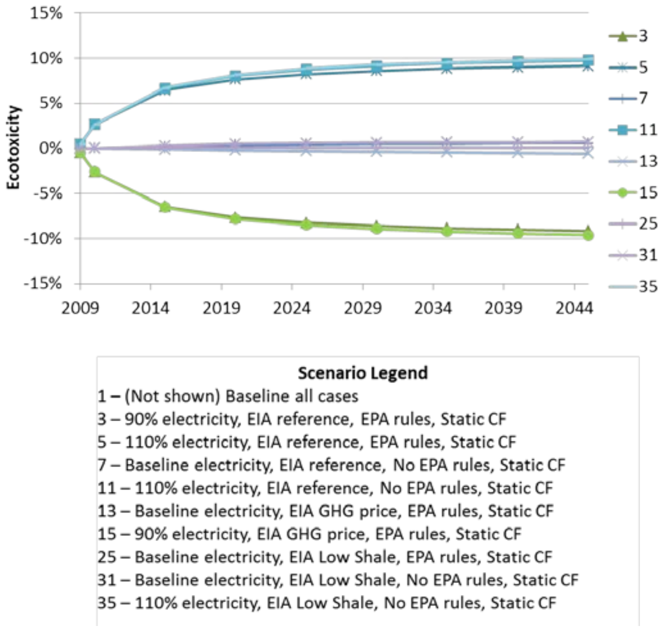


Figure 29 - (4 of 4) Time series of DLCA results for the sensitivity analysis, shown as cumulative percent deviations from the baseline scenario for the remaining categories not shown in Figure 6.

APPENDIX B

DATA COLLECTION FOR THE IN-DEPTH MCSI CASE STUDY

B.1 MCSI BUILDING DATA

B.1.1 Data collection and organization

A floor plan of the MCSI annex is shown in Figure 30 on the following page. Raw data and model calculations from the study period are organized in a series of text (.csv) files and Excel spreadsheets, as indicated in Table 17.

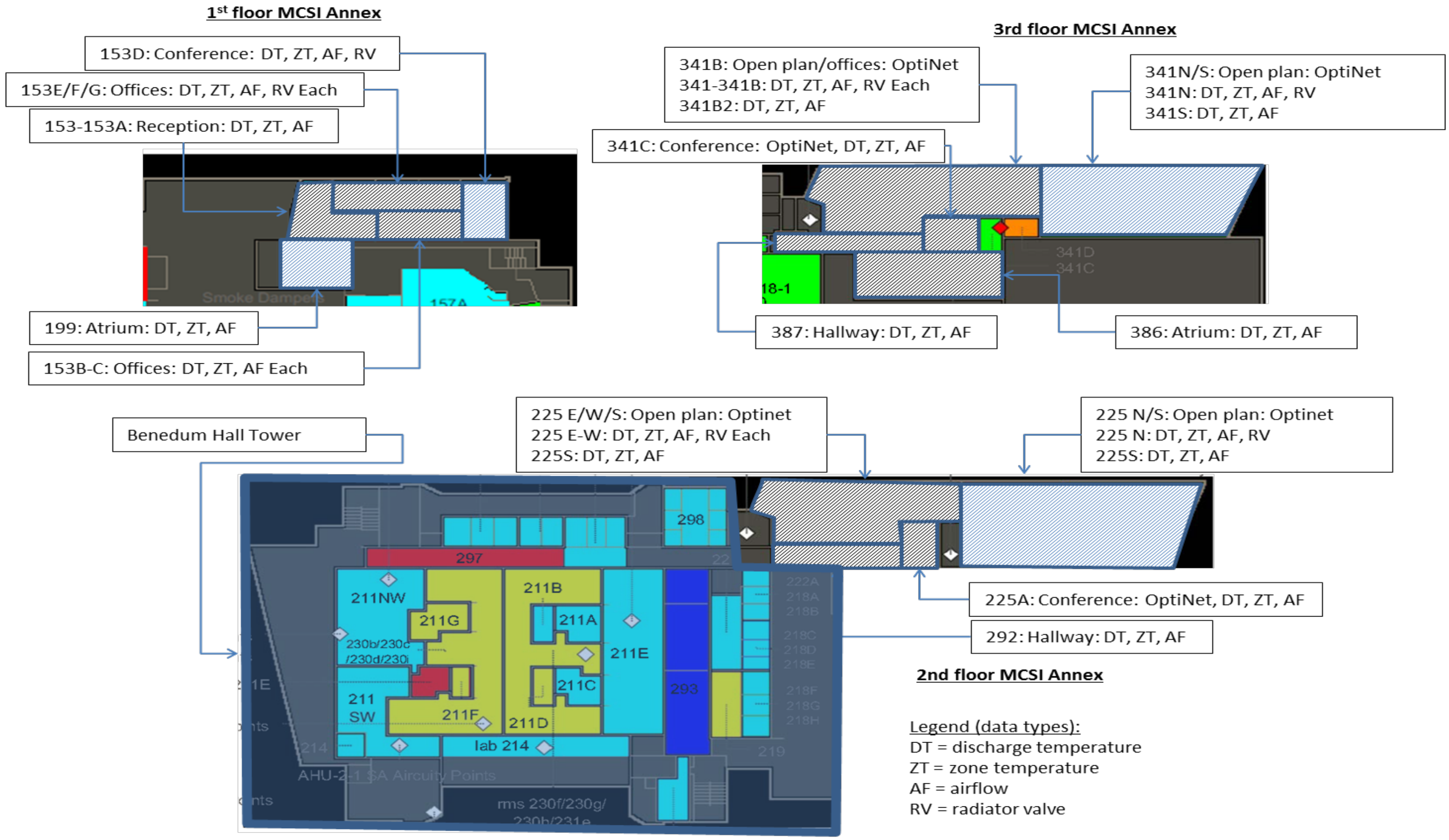
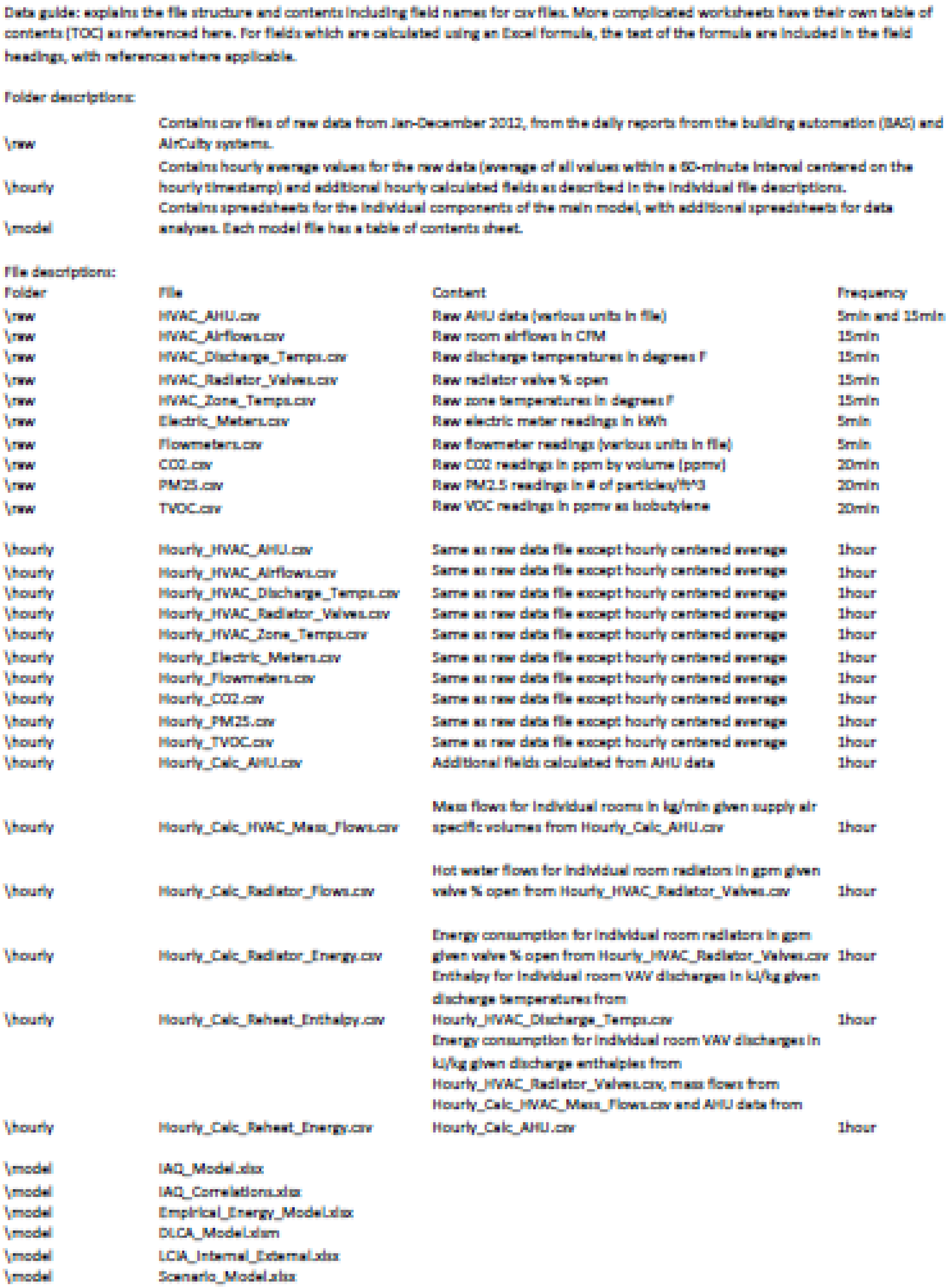


Figure 30 - Floor plan of the MCSI annex showing data collection points.

Table 17- Data organization and file structure



Data guide: explains the file structure and contents including field names for csv files. More complicated worksheets have their own table of contents (TOC) as referenced here. For fields which are calculated using an Excel formula, the text of the formula are included in the field headings, with references where applicable.

Folder descriptions:

\raw	Contains csv files of raw data from Jan-December 2012, from the daily reports from the building automation (BAS) and AirCuity systems.
\hourly	Contains hourly average values for the raw data (average of all values within a 60-minute interval centered on the hourly timestamp) and additional hourly calculated fields as described in the individual file descriptions.
\model	Contains spreadsheets for the individual components of the main model, with additional spreadsheets for data analyses. Each model file has a table of contents sheet.

File descriptions:

Folder	File	Content	Frequency
\raw	HVAC_AHU.csv	Raw AHU data (various units in file)	5min and 15min
\raw	HVAC_Airflows.csv	Raw room airflows in CFM	15min
\raw	HVAC_Discharge_Temps.csv	Raw discharge temperatures in degrees F	15min
\raw	HVAC_Radiator_Valves.csv	Raw radiator valve % open	15min
\raw	HVAC_Zone_Temps.csv	Raw zone temperatures in degrees F	15min
\raw	Electric_Meters.csv	Raw electric meter readings in kWh	5min
\raw	Flowmeters.csv	Raw flowmeter readings (various units in file)	5min
\raw	CO2.csv	Raw CO2 readings in ppm by volume (ppmv)	20min
\raw	PM25.csv	Raw PM2.5 readings in # of particles/ft^3	20min
\raw	TVOC.csv	Raw VOC readings in ppmv as isobutylene	20min
\hourly	Hourly_HVAC_AHU.csv	Same as raw data file except hourly centered average	1hour
\hourly	Hourly_HVAC_Airflows.csv	Same as raw data file except hourly centered average	1hour
\hourly	Hourly_HVAC_Discharge_Temps.csv	Same as raw data file except hourly centered average	1hour
\hourly	Hourly_HVAC_Radiator_Valves.csv	Same as raw data file except hourly centered average	1hour
\hourly	Hourly_HVAC_Zone_Temps.csv	Same as raw data file except hourly centered average	1hour
\hourly	Hourly_Electric_Meters.csv	Same as raw data file except hourly centered average	1hour
\hourly	Hourly_Flowmeters.csv	Same as raw data file except hourly centered average	1hour
\hourly	Hourly_CO2.csv	Same as raw data file except hourly centered average	1hour
\hourly	Hourly_PM25.csv	Same as raw data file except hourly centered average	1hour
\hourly	Hourly_TVOC.csv	Same as raw data file except hourly centered average	1hour
\hourly	Hourly_Calc_AHU.csv	Additional fields calculated from AHU data	1hour
\hourly	Hourly_Calc_HVAC_Mass_Flows.csv	Mass flows for individual rooms in kg/min given supply air specific volumes from Hourly_Calc_AHU.csv	1hour
\hourly	Hourly_Calc_Radiator_Flows.csv	Hot water flows for individual room radiators in gpm given valve % open from Hourly_HVAC_Radiator_Valves.csv	1hour
\hourly	Hourly_Calc_Radiator_Energy.csv	Energy consumption for individual room radiators in gpm given valve % open from Hourly_HVAC_Radiator_Valves.csv	1hour
\hourly	Hourly_Calc_Reheat_Enthalpy.csv	Enthalpy for individual room VAV discharges in kJ/kg given discharge temperatures from Hourly_HVAC_Discharge_Temps.csv	1hour
\hourly	Hourly_Calc_Reheat_Energy.csv	Energy consumption for individual room VAV discharges in kJ/kg given discharge enthalpies from Hourly_HVAC_Radiator_Valves.csv, mass flows from Hourly_Calc_HVAC_Mass_Flows.csv and AHU data from Hourly_Calc_AHU.csv	1hour
\model	IAQ_Model.xlsx		
\model	IAQ_Correlations.xlsx		
\model	Empirical_Energy_Model.xlsx		
\model	DLCA_Model.xlsm		
\model	LCIA_Internal_External.xlsx		
\model	Scenario_Model.xlsx		

B.2 EXTERNAL REFERENCE DATA FOR IEQ MODEL

B.2.1 Allegheny County Health Department (ACHD) PM2.5

Figure 31 shows the correlation obtained from a linear least-squares fit of the ACHD hourly particle mass monitoring data versus the hourly average outdoor particle count from this study. The best-fit line shown in Figure 31 was applied to the hourly outdoor particle counts to generate hourly PM2.5 outdoor mass estimates. The mass estimates were further multiplied by the ratio at each hourly interval of the indoor particle count in each compartment to the outdoor particle count, to generate indoor mass concentration estimates for each compartment. The indoor mass concentration estimates were multiplied by the occupancy estimates and respiration rate in order to estimate intake in each compartment at each interval.

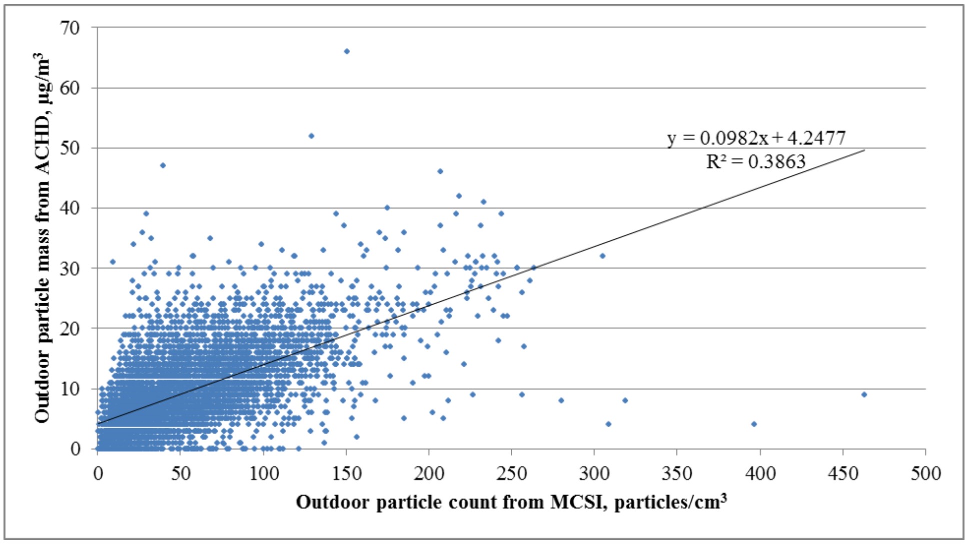


Figure 31 - Linear regression of outdoor particle number from this study and particle mass from ACHD during the study time period

B.2.2 VOC SPECIATION

Table 18 gives the master list of VOCs used in this study. It represents a compilation of all VOCs listed in the ACHD, PAQS and BASE reference studies, along with parameters necessary for conversion of TVOC readings to LCIA results: molecular weights, PID correction factors, and USE-Tox effect factors, and calculated values for TVOC equivalents and toxicity potentials.

Outdoor Estimate - The average outdoor TVOC concentration from this study was 0.15 ppm, and the calculated value from the PAQS was also 0.15 ppm. From this comparison, we assumed that the PAQS data were reasonably representative of the concentrations of outdoor species during our study period. The majority of the estimated PID reading for the PAQS data was comprised of butane and isobutane, two relatively nontoxic species. By contrast, the ACHD report lists only hazardous air pollutants (HAPs), and does not include butane, isobutane or other species not listed as HAPs by EPA. The total estimated PID reading for the ACHD data was 0.012 ppm, of which 92% was comprised of the compounds also found in the PAQS data, which in turn was 95% of the estimated PID reading from the PAQS data for those compounds.

Given the strong similarities across individual compound concentrations between the PAQS and ACHD data, we assumed that these data represented separate samples of a very similar population of VOCs, with one sample (PAQS) focused on mass and one sample (ACHD) focused on toxicity. We note that if one simply added the PID equivalents of the remaining HAPs from ACHD to the PAQS total, the result would be the same to two significant digits.

Equation 34 was used to calculate the ambient outdoor air EFs for cancer and noncancer effects based on the speciation of the ACHD data:

Equation 34

$$EF_{oa,\,t} = \frac{C_{TVOC,\,oa,\,t}}{C_{TVOC,\,PAQS}} \sum_{x} CM_{x,\,ACHD} \times EF_{x}$$

where $EF_{oa,t}$ is the estimated effect factor for cancer or noncancer effects for the outdoor air in our study at time t, $C_{TVOC,oa,t}$ is the outdoor air TVOC reading at time t, $C_{TVOC,PAQS}$ is the PID equivalent TVOC concentration for the PAQS (0.13 ppm), and $CM_{x,ACHD}$ is the mass concentration of VOC species x from the ACHD data. With the time-averaged value $C_{TVOC,oa}$ equal to $C_{TVOC,PAQS}$, the average estimated values for EF_{oa} for this study were 2.3 x 10^{-9} cases/m3 inhaled for cancer effects and 4.5 x 10^{-9} for noncancer effects. Over 99% of the cancer value was due to formaldehyde, while 91% of the noncancer value was due to acrolein.

Indoor Estimate - We obtained the EPA BASE study raw data from the EPA’s Indoor Environments Division. BASE study VOC sampling was conducted at 100 buildings with typically 2 outdoor and 4 indoor time-integrated samples conducted at each site. A total of 80 VOCs (including formaldehyde and acetaldehyde, which are labeled aldehydes and not VOCs in BASE study terminology) were analyzed, though not every building was tested for every VOC. All 80 of these VOCs are listed in Table 18.

EPA provided a breakdown of indoor and outdoor VOC concentrations by 5-percentile increments across the sample population (Min, 5th%, 10th%...95th%, Max) but did not report the quantity [Indoor - Outdoor] for each site. Since indoor concentrations for most VOCs at most sites were higher than outdoor concentrations, we computed the quantity [Average Indoor - Average Outdoor] concentration for each VOC at each site. Equation 24 was then used to estimate PID equivalent TVOC concentrations as ppm isobutylene for each site. The median PID equivalent concentration for the BASE study was 0.027 ppm, whereas the measured average value for our study was 0.028 ppm (Figure 12). A cumulative distribution of the estimated PID values from the BASE study is shown in Figure 32.

The ambient air effect factors EF_{air} were calculated for each building using Equation 20 for the outdoor and [indoor - outdoor] concentrations for each VOC species. The outdoor values, while of interest, were not used further in this study due to the existence of the location-specific PAQS and ACHD datasets. A cumulative distribution of the EF_{air} values for cancer and noncancer effects is shown in Figure 33. The median EFs were 1.1 x 10^{-8} cases/m3 inhaled for cancer effects and 3.6 x 10^{-10} for noncancer effects.

Equation 35 was used to calculate compartment and time specific EFs for this study:

Equation 35

$$EF_{i,t} = \frac{(C_{TVOC,i,t} - C_{TVOC,oa,t})}{C_{TVOC,BASE}} EF_{BASE,i-o}$$

where $C_{TVOC,BASE}$ and $EF_{BASE,i\text{-}o}$ are the median values reported above.

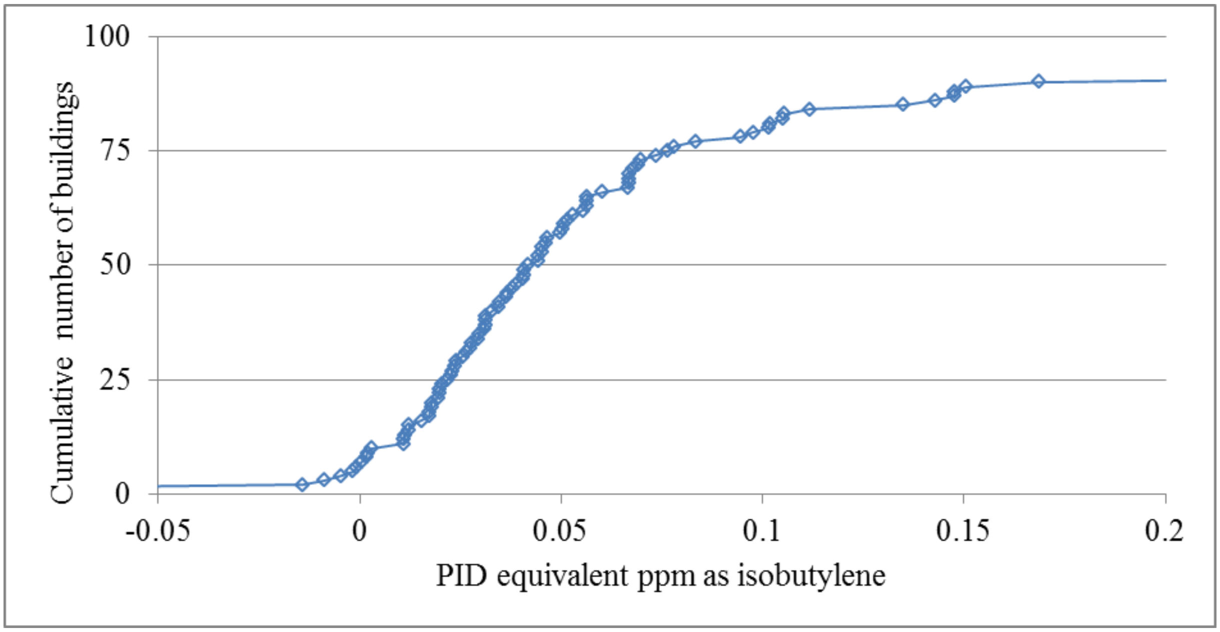


Figure 32 - Cumulative distribution of indoor - outdoor PID equivalent TVOC concentrations from EPA BASE study

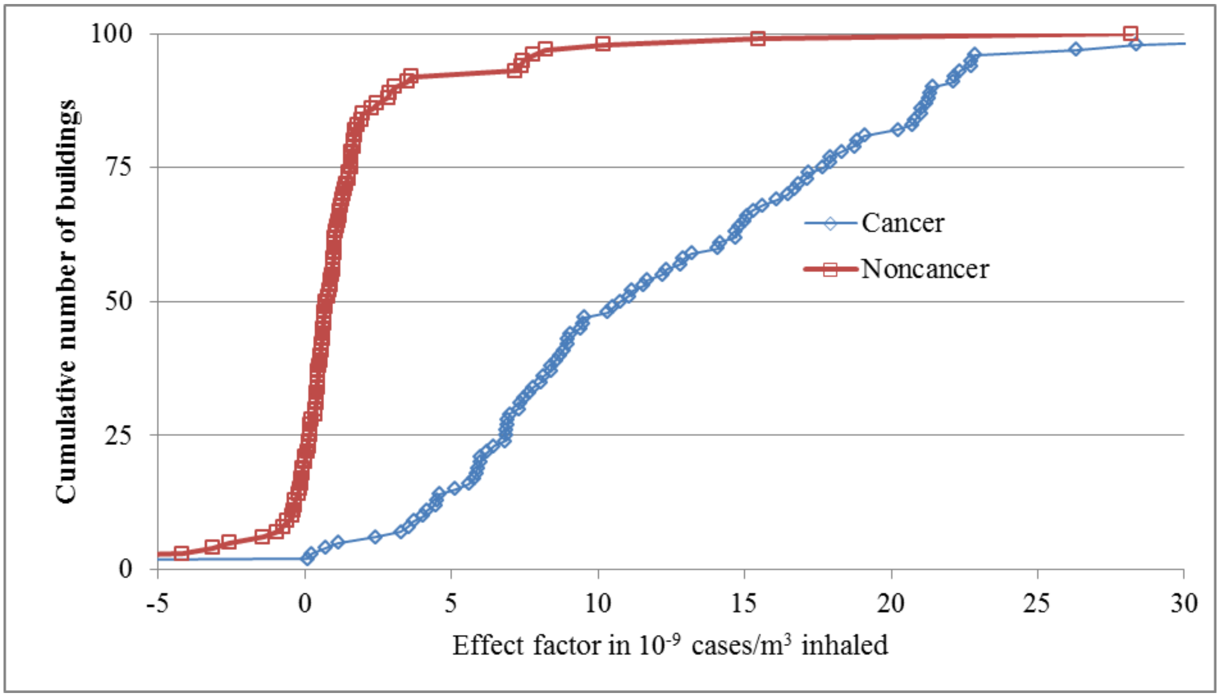


Figure 33 - Cumulative distribution of indoor - outdoor effect factors from EPA BASE study

Table 18 - List of VOCs, properties factors and reference values

				Use-Tox Effect and Characterization Factors					
Compound	CAS Number	Mol. Wt	PID Correction	USE-Tox EF Cancer	USE-Tox EF Noncancer	CF Cancer Urban Air	CF Cancer Rural Air	CF Noncancer Urban Air	CF Noncancer Rural Air
Units->		g/mol	ppm isobuylene (isobutylene)/	cases/kg inhaled	cases/kg inhaled	cases/kg emitted	cases/kg emitted	cases/kg emitted	cases/kg emitted
1,1,1-Trichloroethane	71-55-6	133	Not detected	0.00E+00	1.08E-04	0.00E+00	0.00E+00	1.90E-08	1.64E-08
1,1,2,2-Tetrachloroethane	79-34-5	168	Not detected	5.33E-02	n/a	2.04E-06	7.50E-07	n/a	n/a
1,1,2-Trichloro-1,2,2-trifluoroethane	76-13-1	187	Not detected	0.00E+00	1.14E-04	0.00E+00	0.00E+00	4.12E-07	4.09E-07
1,1,2-Trichloroethane	79-00-5	133	Not detected	3.71E-02	1.16E-01	1.52E-06	6.16E-07	4.73E-06	1.92E-06
1,1-Dichloroethane	75-34-3	99	Not listed	0.00E+00	n/a	0.00E+00	0.00E+00	n/a	n/a
1,1-Dichloroethylene	75-35-4	97	0.82	5.90E-02	9.45E-03	1.47E-06	9.59E-08	2.36E-07	1.54E-08
1,2,4-Trichlorobenzene	120-82-1	181	0.46	n/a	8.59E-03	n/a	n/a	3.43E-07	1.35E-07
1,2,4-Trimethylbenzene	95-63-6	120	Not listed	2.63E-04	n/a	5.89E-09	1.59E-10	n/a	n/a
1,2-Dibromoethane	106-93-4	188	1.7	7.25E-01	4.71E-03	2.84E-05	1.08E-05	1.84E-07	7.01E-08
1,2-Dichloro-1,1,2,2-tetrafloroethane	76-14-2	171	Not listed	Not listed	Not listed	Not listed	Not listed	Not listed	Not listed
1,2-Dichlorobenzene	95-50-1	147	0.47	0.00E+00	1.48E-03	0.00E+00	0.00E+00	5.75E-08	2.16E-08
1,2-Dichloroethane	107-06-2	99	Not detected	1.42E-02	n/a	5.87E-07	2.43E-07	n/a	n/a
1,2-Dichloropropane	78-87-5	113	0	7.39E-03	1.03E+00	2.82E-07	1.02E-07	3.92E-05	1.43E-05
1,3,5-Trimethylbenzene	108-67-8	120	0.35	n/a	n/a	n/a	n/a	n/a	n/a
1,3-Butadiene	106-99-0	54	0.85	5.65E-02	8.45E-02	1.13E-06	1.66E-08	1.68E-06	2.49E-08
1,3-Dichlorobenzene	541-73-1	147	0	n/a	n/a	n/a	n/a	n/a	n/a
1,4-Dichlorobenzene	106-46-7	147	Not listed	7.53E-03	2.23E-03	3.06E-07	1.24E-07	9.13E-08	3.72E-08
1-butanol	71-36-3	74	4.7	n/a	2.03E-03	n/a	n/a	5.27E-08	5.03E-09
1-butene	106-98-9	56	0.9	Not listed	Not listed	Not listed	Not listed	Not listed	Not listed
1-Ethyl-4-methylbenzene	622-96-8	120	Not listed	Not listed	Not listed	Not listed	Not listed	Not listed	Not listed
1-pentene	109-67-1	70	Not listed	Not listed	Not listed	Not listed	Not listed	Not listed	Not listed
2,2,4-trimethyl-1,3-pentanediol diisobutyrate	6846-50-0	286	Not listed	Not listed	Not listed	Not listed	Not listed	Not listed	Not listed
2,2,4-trimethyl-1,3-pentanediol monoisobutyrate	25265-77-4	216	Not listed	n/a	n/a	n/a	n/a	n/a	n/a
2-butoxyethanol	111-76-2	118	1.2	1.19E-03	7.92E-03	2.93E-08	2.49E-09	2.02E-07	2.40E-08
2-ethyl-1-hexanol	104-76-7	130	1.9	1.21E-03	n/a	3.07E-08	2.66E-09	n/a	n/a
2-methyl-1-butene	563-46-2	70	Not listed	Not listed	Not listed	Not listed	Not listed	Not listed	Not listed
2-methyl-1-propanol	78-83-1	74	Not listed	n/a	8.04E-04	n/a	n/a	2.14E-08	2.45E-09
2-methylpropene	115-11-7	56	1	3.23E-04	n/a	6.75E-09	1.23E-10	n/a	n/a
3-methyl-1-butene	563-45-1	70	Not listed	Not listed	Not listed	Not listed	Not listed	Not listed	Not listed
3-methylfuran	930-27-8	82	Not listed	Not listed	Not listed	Not listed	Not listed	Not listed	Not listed
4-phenylcyclohexene	4994-16-5	158	Not listed	Not listed	Not listed	Not listed	Not listed	Not listed	Not listed
Acetaldehyde	75-07-0	44	6	7.49E-03	3.85E-02	1.81E-07	9.18E-09	9.29E-07	4.71E-08
Acetone	67-64-1	58	1.1	n/a	2.82E-04	n/a	n/a	9.67E-09	2.83E-09
Acetonitrile	75-05-8	41	Not detected	0.00E+00	2.79E-03	0.00E+00	0.00E+00	9.72E-08	2.96E-08
Acrolein	107-02-8	56	3.9	0.00E+00	5.97E+01	0.00E+00	0.00E+00	1.41E-03	5.56E-05
Acrylonitrile	107-13-1	53	Not detected	1.28E-01	3.52E-01	3.54E-06	4.89E-07	9.68E-06	1.27E-06
a-pinene	80-56-8	136	0.31	n/a	n/a	n/a	n/a	n/a	n/a
Benzene	71-43-2	78	0.53	1.47E-02	3.72E-03	4.74E-07	1.20E-07	1.20E-07	3.04E-08
Benzyl chloride	100-44-7	127	0.6	3.32E-02	n/a	9.52E-07	1.56E-07	n/a	n/a
Bromodichloromethane	75-27-4	164	Not listed	4.28E-02	5.05E-02	2.23E-06	1.20E-06	2.64E-06	1.41E-06
Bromoform	75-25-2	253	2.5	1.77E-03	1.42E-02	7.80E-08	3.51E-08	6.26E-07	2.82E-07
Bromomethane	74-83-9	95	1.7	0.00E+00	1.51E+00	0.00E+00	0.00E+00	1.14E-04	7.72E-05
Butanal	123-72-8	72	1.8	n/a	n/a	n/a	n/a	n/a	n/a
Butane	106-97-8	58	67	Not listed	Not listed	Not listed	Not listed	Not listed	Not listed
Butyl acetate	123-86-4	116	2.6	n/a	n/a	n/a	n/a	n/a	n/a
Butylated hydroxytoluene	128-37-0	220	Not listed	3.13E-03	n/a	7.83E-08	7.37E-09	n/a	n/a
c-2-butene	107-01-7	56	Not listed	Not listed	Not listed	Not listed	Not listed	Not listed	Not listed
Carbon disulfide	75-15-0	76	1.2	n/a	2.64E-01	n/a	n/a	5.31E-05	4.67E-05
Carbon tetrachloride	56-23-5	154	Not detected	1.08E-01	3.58E-01	4.80E-05	4.54E-05	1.59E-04	1.50E-04
Chlorobenzene	108-90-7	113	0.4	4.64E-03	4.81E-03	1.61E-07	4.89E-08	1.67E-07	5.06E-08
Chloroethane	75-00-3	65	Not detected	1.13E-03	4.18E-05	4.42E-08	1.68E-08	1.64E-09	6.25E-10
Chloroethene	75-01-4	63	2	1.93E-01	6.69E-02	5.03E-06	4.63E-07	1.74E-06	1.61E-07
Chloroform	67-66-3	119	Not detected	5.64E-03	3.25E-02	2.99E-07	1.62E-07	1.71E-06	9.27E-07
Chloromethane	74-87-3	50	Not detected	n/a	8.84E-03	n/a	n/a	6.56E-07	4.41E-07
cis-1,2-dichloroethene	156-59-2	97	0.8	Not listed	Not listed	Not listed	Not listed	Not listed	Not listed
cis-1,2-Dichloroethene	540-59-0	97	0.8	n/a	n/a	n/a	n/a	n/a	n/a
cis-1,3-Dichloro-1-propene	52-75-6	111	0.96	Not listed	Not listed	Not listed	Not listed	Not listed	Not listed
cis-1,3-dichloropropene	10061-01-5	111	Not listed	n/a	n/a	n/a	n/a	n/a	n/a
Cyclohexane	110-82-7	84	1.4	n/a	8.26E-04	n/a	n/a	2.14E-08	1.86E-09

Table 18 (Continued)

				Use-Tox Effect and Characterization Factors					
Compound	CAS Number	Mol. Wt	PID Correction	USE-Tox EF Cancer	USE-Tox EF Noncancer	CF Cancer Urban Air	CF Cancer Rural Air	CF Noncancer Urban Air	CF Noncancer Rural Air
Units->		g/mol	ppm isobuylene (isobutylene)/	cases/kg inhaled	cases/kg inhaled	cases/kg emitted	cases/kg emitted	cases/kg emitted	cases/kg emitted
Cyclopentane	287-92-3	70	15	n/a	n/a	n/a	n/a	n/a	n/a
Cyclopentene	142-29-0	68	Not listed	Not listed	Not listed	Not listed	Not listed	Not listed	Not listed
Dibrochloromethane	124-48-1	208	5.3	1.47E-02	1.19E-02	6.72E-07	3.16E-07	5.44E-07	2.55E-07
Dichlorodifluoromethane	75-71-8	121	Not detected	0.00E+00	8.47E-03	0.00E+00	0.00E+00	2.32E-05	2.30E-05
dimethy disulfide	624-92-0	94	0.2	Not listed	Not listed	Not listed	Not listed	Not listed	Not listed
Dimethylsulfide	75-18-3	62	0.44	n/a	n/a	n/a	n/a	n/a	n/a
d-limonene	5989-27-5	136	0.33	5.62E-03	n/a	8.59E-08	6.68E-10	n/a	n/a
Ethanol	64-17-5	46	10	1.26E-04	n/a	3.64E-09	6.38E-10	n/a	n/a
Ethyl acetate	141-78-6	88	4.6	n/a	2.82E-04	n/a	n/a	8.63E-09	1.82E-09
Ethylbenzene	100-41-4	106	0.52	2.36E-02	3.85E-04	6.13E-07	5.55E-08	1.01E-08	9.44E-10
Formaldehyde	50-00-0	30	Not detected	1.06E+00	8.47E-03	2.54E-05	1.39E-06	2.67E-07	7.54E-08
Heptane	142-82-5	100	2.8	n/a	n/a	n/a	n/a	n/a	n/a
Hexachloro-1,3-butadiene	87-68-3	261	Not listed	1.74E-02	n/a	2.10E-06	1.68E-06	n/a	n/a
Hexanal	66-25-1	100	Not listed	n/a	n/a	n/a	n/a	n/a	n/a
Hexane	110-54-3	86	4.3	6.74E-05	9.16E-03	1.79E-09	1.93E-10	2.44E-07	2.62E-08
Isobutane	75-28-5	58	100	Not listed	Not listed	Not listed	Not listed	Not listed	Not listed
Isopentane	78-78-4	72	8.2	Not listed	Not listed	Not listed	Not listed	Not listed	Not listed
Isoprene	78-79-5	68	0.63	7.45E-03	n/a	1.35E-07	1.46E-09	n/a	n/a
Isopropyl alcohol	67-63-0	60	6	0.00E+00	n/a	0.00E+00	0.00E+00	n/a	n/a
m & p- Xylene	1330-20-7	106	0.44	Not listed	Not listed	Not listed	Not listed	Not listed	Not listed
Methacrolein	78-85-3	70	Not listed	Not listed	Not listed	Not listed	Not listed	Not listed	Not listed
Methanol	67-56-1	32	Not detected	n/a	5.08E-04	n/a	n/a	1.63E-08	4.13E-09
Methyl butyl ketone	591-78-6	100	Not listed	n/a	n/a	n/a	n/a	n/a	n/a
Methyl ethyl ketone	78-93-3	72	0.9	n/a	3.02E-05	n/a	n/a	1.27E-09	5.38E-10
Methyl isobutyl ketone	108-10-1	100	0.8	n/a	1.63E-04	n/a	n/a	3.98E-09	2.16E-10
Methyl tert-butyl ether	1634-04-4	88	0.9	3.86E-03	6.46E-04	1.10E-07	1.77E-08	1.85E-08	2.99E-09
Methylene chloride	75-09-2	85	Not detected	1.86E-03	2.17E-02	8.92E-08	4.42E-08	1.04E-06	5.16E-07
Methylpentanes	96-14-0	86	Not listed	Not listed	Not listed	Not listed	Not listed	Not listed	Not listed
Methylvinylketone	78-94-4	70	Not listed	n/a	n/a	n/a	n/a	n/a	n/a
naphthalene	91-20-3	128	0.42	5.19E-02	7.19E-02	1.22E-06	5.15E-08	1.68E-06	6.40E-08
n-decane	124-18-5	142	1.4	n/a	n/a	n/a	n/a	n/a	n/a
n-dodecane	112-40-3	170	Not listed	Not listed	Not listed	Not listed	Not listed	Not listed	Not listed
n-heptanal	111-71-7	114	Not listed	Not listed	Not listed	Not listed	Not listed	Not listed	Not listed
n-nonanal	124-19-6	142	Not listed	Not listed	Not listed	Not listed	Not listed	Not listed	Not listed
n-octane	111-65-9	114	1.8	n/a	n/a	n/a	n/a	n/a	n/a
nonane	111-84-2	128	1.4	Not listed	Not listed	Not listed	Not listed	Not listed	Not listed
n-undecane	1120-21-4	156	2	Not listed	Not listed	Not listed	Not listed	Not listed	Not listed
o-xylene	95-47-6	106	0.46	n/a	n/a	n/a	n/a	n/a	n/a
o-Xylene	1330-20-7	106	0.46	Not listed	Not listed	Not listed	Not listed	Not listed	Not listed
Pentanal	110-62-3	86	Not listed	n/a	n/a	n/a	n/a	n/a	n/a
Pentane	109-66-0	72	8.4	n/a	n/a	n/a	n/a	n/a	n/a
phenol	108-95-2	94	1	0.00E+00	3.29E-03	0.00E+00	0.00E+00	8.41E-08	1.32E-08
Propane	74-98-6	44	Not detected	Not listed	Not listed	Not listed	Not listed	Not listed	Not listed
Propene	115-07-1	42	1.4	0.00E+00	n/a	0.00E+00	0.00E+00	n/a	n/a
Propionaldehyde	123-38-6	58	1.9	n/a	n/a	n/a	n/a	n/a	n/a
Propyne	74-99-7	40	Not listed	Not listed	Not listed	Not listed	Not listed	Not listed	Not listed
Styrene	100-42-5	104	0.4	4.92E-02	9.84E-03	1.01E-06	1.66E-08	2.01E-07	3.32E-09
t-2-pentene	646-04-8	70	Not listed	Not listed	Not listed	Not listed	Not listed	Not listed	Not listed
Tetrachloroethylene	127-18-4	165	0.57	8.50E-03	3.23E-02	4.29E-07	2.23E-07	1.62E-06	8.40E-07
Tetrahydrofuran	109-99-9	72	1.7	2.82E-03	n/a	6.79E-08	3.39E-09	n/a	n/a
Toluene	108-88-3	92	0.5	0.00E+00	3.64E-03	3.17E-12	3.18E-12	9.62E-08	9.90E-09
trans-1,3-dichloropropene	10061-02-6	111	Not listed	Not listed	Not listed	Not listed	Not listed	Not listed	Not listed
Trichloroethylene	79-01-6	131	0.54	1.72E-03	n/a	5.06E-08	9.36E-09	n/a	n/a
Trichlorofluoromethane	75-69-4	137	Not listed	0.00E+00	1.46E-03	0.00E+00	0.00E+00	1.81E-06	1.77E-06
TOTALS									

Table 18 (Continued)

		PAQS (Millet et al) data and calculations									
Compound	CAS Number	Summer		Winter		Annual Median Concentration, ppt	PID Equivalent Concentration, ppm isobutylene	% Total PID Value	Annual Median Mass concentration µg/m3	Cancer toxicity potential (Cases/m3 air inhaled)	Noncancer toxicity potential (Cases/m3 air inhaled)
Units->		Median, ppt	IQR, d ppt	Median, ppt	IQR,d						
1,1,1-Trichloroethane	71-55-6	Not listed	Not listed	Not listed	Not listed	0	0.00E+00	0.0%	0.000	0.00E+00	0.00E+00
1,1,2,2-Tetrachloroethane	79-34-5	Not listed	Not listed	Not listed	Not listed	0	0.00E+00	0.0%	0.000	0.00E+00	0.00E+00
1,1,2-Trichloro-1,2,2-trifluoroethane	76-13-1	Not listed	Not listed	Not listed	Not listed	0	0.00E+00	0.0%	0.000	0.00E+00	0.00E+00
1,1,2-Trichloroethane	79-00-5	Not listed	Not listed	Not listed	Not listed	0	0.00E+00	0.0%	0.000	0.00E+00	0.00E+00
1,1-Dichloroethane	75-34-3	Not listed	Not listed	Not listed	Not listed	0	0.00E+00	0.0%	0.000	0.00E+00	0.00E+00
1,1-Dichloroethylene	75-35-4	Not listed	Not listed	Not listed	Not listed	0	0.00E+00	0.0%	0.000	0.00E+00	0.00E+00
1,2,4-Trichlorobenzene	120-82-1	Not listed	Not listed	Not listed	Not listed	0	0.00E+00	0.0%	0.000	0.00E+00	0.00E+00
1,2,4-Trimethylbenzene	95-63-6	Not listed	Not listed	Not listed	Not listed	0	0.00E+00	0.0%	0.000	0.00E+00	0.00E+00
1,2-Dibromoethane	106-93-4	Not listed	Not listed	Not listed	Not listed	0	0.00E+00	0.0%	0.000	0.00E+00	0.00E+00
1,2-Dichloro-1,1,2,2-tetrafloroethane	76-14-2	Not listed	Not listed	Not listed	Not listed	0	0.00E+00	0.0%	0.000	0.00E+00	0.00E+00
1,2-Dichlorobenzene	95-50-1	Not listed	Not listed	Not listed	Not listed	0	0.00E+00	0.0%	0.000	0.00E+00	0.00E+00
1,2-Dichloroethane	107-06-2	Not listed	Not listed	Not listed	Not listed	0	0.00E+00	0.0%	0.000	0.00E+00	0.00E+00
1,2-Dichloropropane	78-87-5	Not listed	Not listed	Not listed	Not listed	0	0.00E+00	0.0%	0.000	0.00E+00	0.00E+00
1,3,5-Trimethylbenzene	108-67-8	Not listed	Not listed	Not listed	Not listed	0	0.00E+00	0.0%	0.000	0.00E+00	0.00E+00
1,3-Butadiene	106-99-0	Not listed	Not listed	Not listed	Not listed	0	0.00E+00	0.0%	0.000	0.00E+00	0.00E+00
1,3-Dichlorobenzene	541-73-1	Not listed	Not listed	Not listed	Not listed	0	0.00E+00	0.0%	0.000	0.00E+00	0.00E+00
1,4-Dichlorobenzene	106-46-7	Not listed	Not listed	Not listed	Not listed	0	0.00E+00	0.0%	0.000	0.00E+00	0.00E+00
1-butanol	71-36-3	Not listed	Not listed	Not listed	Not listed	0	0.00E+00	0.0%	0.000	0.00E+00	0.00E+00
1-butene	106-98-9	57	40 – 83	62	44 – 88	59.5	5.36E-05	0.0%	0.136	0.00E+00	0.00E+00
1-Ethyl-4-methylbenzene	622-96-8	Not listed	Not listed	Not listed	Not listed	0	0.00E+00	0.0%	0.000	0.00E+00	0.00E+00
1-pentene	109-67-1	36	24 – 56	20	14 – 32	28	0.00E+00	0.0%	0.080	0.00E+00	0.00E+00
2,2,4-trimethyl-1,3-pentanediol diisobutyrate	6846-50-0	Not listed	Not listed	Not listed	Not listed	0	0.00E+00	0.0%	0.000	0.00E+00	0.00E+00
2,2,4-trimethyl-1,3-pentanediol monoisobutyrate	25265-77-4	Not listed	Not listed	Not listed	Not listed	0	0.00E+00	0.0%	0.000	0.00E+00	0.00E+00
2-butoxyethanol	111-76-2	Not listed	Not listed	Not listed	Not listed	0	0.00E+00	0.0%	0.000	0.00E+00	0.00E+00
2-ethyl-1-hexanol	104-76-7	Not listed	Not listed	Not listed	Not listed	0	0.00E+00	0.0%	0.000	0.00E+00	0.00E+00
2-methyl-1-butene	563-46-2	16	11 – 25	42	22 – 74	29	0.00E+00	0.0%	0.083	0.00E+00	0.00E+00
2-methyl-1-propanol	78-83-1	Not listed	Not listed	Not listed	Not listed	0	0.00E+00	0.0%	0.000	0.00E+00	0.00E+00
2-methylpropene	115-11-7	38	32 – 51	NQf	NQf	38	3.80E-05	0.0%	0.087	2.81E-14	0.00E+00
3-methyl-1-butene	563-45-1	6	5 – 10	19	12 – 35	12.5	0.00E+00	0.0%	0.036	0.00E+00	0.00E+00
3-methylfuran	930-27-8	<DLg	<DLg	10	6 – 16	10	0.00E+00	0.0%	0.034	0.00E+00	0.00E+00
4-phenylcyclohexene	4994-16-5	Not listed	Not listed	Not listed	Not listed	0	0.00E+00	0.0%	0.000	0.00E+00	0.00E+00
Acetaldehyde	75-07-0	538	403 – 729	1559	1103 – 2150	1048.5	6.29E-03	4.2%	1.887	1.41E-11	7.26E-11
Acetone	67-64-1	943	655 – 1385	4031	3128 – 4894	2487	2.74E-03	1.8%	5.900	0.00E+00	1.67E-12
Acetonitrile	75-05-8	NQf	NQf	131	105 – 155	131	0.00E+00	0.0%	0.220	0.00E+00	6.12E-13
Acrolein	107-02-8	Not listed	Not listed	Not listed	Not listed	0	0.00E+00	0.0%	0.000	0.00E+00	0.00E+00
Acrylonitrile	107-13-1	Not listed	Not listed	Not listed	Not listed	0	0.00E+00	0.0%	0.000	0.00E+00	0.00E+00
a-pinene	80-56-8	<DLg	<DLg	16	10 – 29	16	4.96E-06	0.0%	0.089	0.00E+00	0.00E+00
Benzene	71-43-2	279	231 – 355	215	143 – 405	247	1.31E-04	0.1%	0.788	1.16E-11	2.93E-12
Benzyl chloride	100-44-7	Not listed	Not listed	Not listed	Not listed	0	0.00E+00	0.0%	0.000	0.00E+00	0.00E+00
Bromodichloromethane	75-27-4	Not listed	Not listed	Not listed	Not listed	0	0.00E+00	0.0%	0.000	0.00E+00	0.00E+00
Bromoform	75-25-2	Not listed	Not listed	Not listed	Not listed	0	0.00E+00	0.0%	0.000	0.00E+00	0.00E+00
Bromomethane	74-83-9	Not listed	Not listed	Not listed	Not listed	0	0.00E+00	0.0%	0.000	0.00E+00	0.00E+00
Butanal	123-72-8	NQf	NQf	91	64 – 122	91	1.64E-04	0.1%	0.268	0.00E+00	0.00E+00
Butane	106-97-8	1333	978 – 1799	632	375 – 1106	982.5	6.58E-02	43.8%	2.331	0.00E+00	0.00E+00
Butyl acetate	123-86-4	Not listed	Not listed	Not listed	Not listed	0	0.00E+00	0.0%	0.000	0.00E+00	0.00E+00
Butylated hydroxytoluene	128-37-0	Not listed	Not listed	Not listed	Not listed	0	0.00E+00	0.0%	0.000	0.00E+00	0.00E+00
c-2-butene	107-01-7	27	18 – 44	20	15 – 28	23.5	0.00E+00	0.0%	0.054	0.00E+00	0.00E+00
Carbon disulfide	75-15-0	Not listed	Not listed	Not listed	Not listed	0	0.00E+00	0.0%	0.000	0.00E+00	0.00E+00
Carbon tetrachloride	56-23-5	Not listed	Not listed	Not listed	Not listed	0	0.00E+00	0.0%	0.000	0.00E+00	0.00E+00
Chlorobenzene	108-90-7	Not listed	Not listed	Not listed	Not listed	0	0.00E+00	0.0%	0.000	0.00E+00	0.00E+00
Chloroethane	75-00-3	Not listed	Not listed	Not listed	Not listed	0	0.00E+00	0.0%	0.000	0.00E+00	0.00E+00
Chloroethene	75-01-4	Not listed	Not listed	Not listed	Not listed	0	0.00E+00	0.0%	0.000	0.00E+00	0.00E+00
Chloroform	67-66-3	11	10 – 13	17	13 – 30	14	0.00E+00	0.0%	0.068	3.84E-13	2.21E-12
Chloromethane	74-87-3	Not listed	Not listed	Not listed	Not listed	0	0.00E+00	0.0%	0.000	0.00E+00	0.00E+00
cis-1,2-dichloroethene	156-59-2	Not listed	Not listed	Not listed	Not listed	0	0.00E+00	0.0%	0.000	0.00E+00	0.00E+00
cis-1,2-Dichloroethene	540-59-0	Not listed	Not listed	Not listed	Not listed	0	0.00E+00	0.0%	0.000	0.00E+00	0.00E+00
cis-1,3-Dichloro-1-propene	52-75-6	Not listed	Not listed	Not listed	Not listed	0	0.00E+00	0.0%	0.000	0.00E+00	0.00E+00
cis-1,3-dichloropropene	10061-01-5	Not listed	Not listed	Not listed	Not listed	0	0.00E+00	0.0%	0.000	0.00E+00	0.00E+00
Cyclohexane	110-82-7	Not listed	Not listed	Not listed	Not listed	0	0.00E+00	0.0%	0.000	0.00E+00	0.00E+00

Table 18 (Continued)

		PAQS (Millet et al) data and calculations									
Compound	CAS Number	Summer		Winter		Annual Median Concentration, ppt	PID Equivalent Concentration, ppm isobutylene	% Total PID Value	Annual Median Mass concentration µg/m3	Cancer toxicity potential (Cases/m3 air inhaled)	Noncancer toxicity potential (Cases/m3 air inhaled)
Units->		Median, ppt	IQR, d ppt	Median, ppt	IQR,d						
Cyclopentane	287-92-3	53	35 – 92	47	36 – 72	50	7.50E-04	0.5%	0.143	0.00E+00	0.00E+00
Cyclopentene	142-29-0	NQf	NQf	3	0 – 8	3	0.00E+00	0.0%	0.008	0.00E+00	0.00E+00
Dibrochloromethane	124-48-1	Not listed	Not listed	Not listed	Not listed	0	0.00E+00	0.0%	0.000	0.00E+00	0.00E+00
Dichlorodifluoromethane	75-71-8	Not listed	Not listed	Not listed	Not listed	0	0.00E+00	0.0%	0.000	0.00E+00	0.00E+00
dimethy disulfide	624-92-0	Not listed	Not listed	Not listed	Not listed	0	0.00E+00	0.0%	0.000	0.00E+00	0.00E+00
Dimethylsulfide	75-18-3	NQf	NQf	7	5 – 10	7	3.08E-06	0.0%	0.018	0.00E+00	0.00E+00
d-limonene	5989-27-5	Not listed	Not listed	Not listed	Not listed	0	0.00E+00	0.0%	0.000	0.00E+00	0.00E+00
Ethanol	64-17-5	989	673 – 1416	1722	1017 – 3567	1355.5	1.36E-02	9.0%	2.550	3.21E-13	0.00E+00
Ethyl acetate	141-78-6	Not listed	Not listed	Not listed	Not listed	0	0.00E+00	0.0%	0.000	0.00E+00	0.00E+00
Ethylbenzene	100-41-4	47	34 – 69	71	44 – 141	59	3.07E-05	0.0%	0.256	6.03E-12	9.86E-14
Formaldehyde	50-00-0	Not listed	Not listed	Not listed	Not listed	0	0.00E+00	0.0%	0.000	0.00E+00	0.00E+00
Heptane	142-82-5	Not listed	Not listed	Not listed	Not listed	0	0.00E+00	0.0%	0.000	0.00E+00	0.00E+00
Hexachloro-1,3-butadiene	87-68-3	Not listed	Not listed	Not listed	Not listed	0	0.00E+00	0.0%	0.000	0.00E+00	0.00E+00
Hexanal	66-25-1	34	22 – 52	NQf	NQf	34	0.00E+00	0.0%	0.139	0.00E+00	0.00E+00
Hexane	110-54-3	147	116 – 199	129	81 – 231	138	5.93E-04	0.4%	0.485	3.27E-14	4.45E-12
Isobutane	75-28-5	668	479 – 953	323	212 – 634	495.5	4.96E-02	33.0%	1.175	0.00E+00	0.00E+00
Isopentane	78-78-4	575	448 – 809	649	409 – 1139	612	5.02E-03	3.3%	1.802	0.00E+00	0.00E+00
Isoprene	78-79-5	<DLg	<DLg	619	153 – 1475	619	3.90E-04	0.3%	1.722	1.28E-11	0.00E+00
Isopropyl alcohol	67-63-0	131	86 – 199	235	147 – 432	183	1.10E-03	0.7%	0.449	0.00E+00	0.00E+00
m & p- Xylene	1330-20-7	113	76 – 176	163	89 – 306	138	6.07E-05	0.0%	0.598	0.00E+00	0.00E+00
Methacrolein	78-85-3	<DLg	<DLg	266	178 – 366	266	0.00E+00	0.0%	0.762	0.00E+00	0.00E+00
Methanol	67-56-1	3760	2347 – 5773	10717	7122 – 14601	7238.5	0.00E+00	0.0%	9.474	0.00E+00	4.82E-12
Methyl butyl ketone	591-78-6	Not listed	Not listed	Not listed	Not listed	0	0.00E+00	0.0%	0.000	0.00E+00	0.00E+00
Methyl ethyl ketone	78-93-3	215	153 – 299	559	408 – 674	387	3.48E-04	0.2%	1.140	0.00E+00	3.44E-14
Methyl isobutyl ketone	108-10-1	Not listed	Not listed	Not listed	Not listed	0	0.00E+00	0.0%	0.000	0.00E+00	0.00E+00
Methyl tert-butyl ether	1634-04-4	10	7 – 14	31	19 – 61	20.5	1.85E-05	0.0%	0.074	2.85E-13	4.76E-14
Methylene chloride	75-09-2	NQf	NQf	79	48 – 145	79	0.00E+00	0.0%	0.275	5.10E-13	5.97E-12
Methylpentanes	96-14-0	268	203 – 368	276	183 – 506	272	0.00E+00	0.0%	0.957	0.00E+00	0.00E+00
Methylvinylketone	78-94-4	<DLg	<DLg	463	273 – 665	463	0.00E+00	0.0%	1.326	0.00E+00	0.00E+00
naphthalene	91-20-3	Not listed	Not listed	Not listed	Not listed	0	0.00E+00	0.0%	0.000	0.00E+00	0.00E+00
n-decane	124-18-5	Not listed	Not listed	Not listed	Not listed	0	0.00E+00	0.0%	0.000	0.00E+00	0.00E+00
n-dodecane	112-40-3	Not listed	Not listed	Not listed	Not listed	0	0.00E+00	0.0%	0.000	0.00E+00	0.00E+00
n-heptanal	111-71-7	Not listed	Not listed	Not listed	Not listed	0	0.00E+00	0.0%	0.000	0.00E+00	0.00E+00
n-nonanal	124-19-6	Not listed	Not listed	Not listed	Not listed	0	0.00E+00	0.0%	0.000	0.00E+00	0.00E+00
n-octane	111-65-9	Not listed	Not listed	Not listed	Not listed	0	0.00E+00	0.0%	0.000	0.00E+00	0.00E+00
nonane	111-84-2	Not listed	Not listed	Not listed	Not listed	0	0.00E+00	0.0%	0.000	0.00E+00	0.00E+00
n-undecane	1120-21-4	Not listed	Not listed	Not listed	Not listed	0	0.00E+00	0.0%	0.000	0.00E+00	0.00E+00
o-xylene	95-47-6	Not listed	Not listed	Not listed	Not listed	0	0.00E+00	0.0%	0.000	0.00E+00	0.00E+00
o-Xylene	1330-20-7	60	41 – 89	52	29 – 93	56	2.58E-05	0.0%	0.243	0.00E+00	0.00E+00
Pentanal	110-62-3	NQf	NQf	137	98 – 193	137	0.00E+00	0.0%	0.482	0.00E+00	0.00E+00
Pentane	109-66-0	355	279 – 493	352	213 – 613	353.5	2.97E-03	2.0%	1.041	0.00E+00	0.00E+00
phenol	108-95-2	Not listed	Not listed	Not listed	Not listed	0	0.00E+00	0.0%	0.000	0.00E+00	0.00E+00
Propane	74-98-6	2960	2087 – 4307	1787	992 – 3540	2373.5	0.00E+00	0.0%	4.271	0.00E+00	0.00E+00
Propene	115-07-1	214	147 – 306	219	159 – 336	216.5	3.03E-04	0.2%	0.372	0.00E+00	0.00E+00
Propionaldehyde	123-38-6	Not listed	Not listed	Not listed	Not listed	0	0.00E+00	0.0%	0.000	0.00E+00	0.00E+00
Propyne	74-99-7	29	22 – 40	7	5 – 12	18	0.00E+00	0.0%	0.029	0.00E+00	0.00E+00
Styrene	100-42-5	Not listed	Not listed	Not listed	Not listed	0	0.00E+00	0.0%	0.000	0.00E+00	0.00E+00
t-2-pentene	646-04-8	19	12 – 33	44	33 – 62	31.5	0.00E+00	0.0%	0.090	0.00E+00	0.00E+00
Tetrachloroethylene	127-18-4	18	12 – 25	22	13 – 41	20	1.14E-05	0.0%	0.135	1.15E-12	4.36E-12
Tetrahydrofuran	109-99-9	Not listed	Not listed	Not listed	Not listed	0	0.00E+00	0.0%	0.000	0.00E+00	0.00E+00
Toluene	108-88-3	331	248 – 494	443	274 – 902	387	1.94E-04	0.1%	1.456	0.00E+00	5.29E-12
trans-1,3-dichloropropene	10061-02-6	Not listed	Not listed	Not listed	Not listed	0	0.00E+00	0.0%	0.000	0.00E+00	0.00E+00
Trichloroethylene	79-01-6	Not listed	Not listed	Not listed	Not listed	0	0.00E+00	0.0%	0.000	0.00E+00	0.00E+00
Trichlorofluoromethane	75-69-4	Not listed	Not listed	Not listed	Not listed	0	0.00E+00	0.0%	0.000	0.00E+00	0.00E+00
TOTALS							0.150	100%	43.53	4.73E-11	1.05E-10

Table 18 (Continued)

		ACHD Air Quality Report Data									
Compound	CAS Number	2009	2009	2010	2010	2009-2010 Average ppb	PID Equivalent Concentration, ppm isobutylene	% Total PID Value	Annual Median Mass concentration µg/m3	Cancer toxicity potential (Cases/m3 air inhaled)	Noncancer toxicity potential (Cases/m3 air
Units->		Average (ppb)	24-Hour Maximum (ppb)	Average (ppb)	24-Hour Maximum (ppb)						
1,1,1-Trichloroethane	71-55-6	0.02	0.08	0.02	0.03	0.02	0.00E+00	0.0%	0.109	0.00E+00	1.17E-14
1,1,2,2-Tetrachloroethane	79-34-5	0	0.01	0	0.01	0	0.00E+00	0.0%	0.000	0.00E+00	0.00E+00
1,1,2-Trichloro-1,2,2-trifluoroethane	76-13-1	0.13	0.25	0.1	0.14	0.115	0.00E+00	0.0%	0.880	0.00E+00	1.00E-13
1,1,2-Trichloroethane	79-00-5	0	0.01	0	0.01	0	0.00E+00	0.0%	0.000	0.00E+00	0.00E+00
1,1-Dichloroethane	75-34-3	0	0.01	0	0.01	0	0.00E+00	0.0%	0.000	0.00E+00	0.00E+00
1,1-Dichloroethylene	75-35-4	0	0.01	0	0.01	0	0.00E+00	0.0%	0.000	0.00E+00	0.00E+00
1,2,4-Trichlorobenzene	120-82-1	0.01	0.01	0	0.01	0.005	2.30E-06	0.0%	0.037	0.00E+00	3.18E-13
1,2,4-Trimethylbenzene	95-63-6	0.07	0.45	0.06	0.28	0.065	0.00E+00	0.0%	0.319	8.41E-14	0.00E+00
1,2-Dibromoethane	106-93-4	0	0.01	0	0.01	0	0.00E+00	0.0%	0.000	0.00E+00	0.00E+00
1,2-Dichloro-1,1,2,2-tetrafloroethane	76-14-2	0.02	0.03	0.02	0.03	0.02	0.00E+00	0.0%	0.140	0.00E+00	0.00E+00
1,2-Dichlorobenzene	95-50-1	0	0.02	0	0.01	0	0.00E+00	0.0%	0.000	0.00E+00	0.00E+00
1,2-Dichloroethane	107-06-2	0.02	0.03	0.02	0.04	0.02	0.00E+00	0.0%	0.081	1.15E-12	0.00E+00
1,2-Dichloropropane	78-87-5	0	0.02	0.01	0.02	0.005	0.00E+00	0.0%	0.023	1.71E-13	2.38E-11
1,3,5-Trimethylbenzene	108-67-8	0.02	0.12	0.02	0.06	0.02	7.00E-06	0.1%	0.098	0.00E+00	0.00E+00
1,3-Butadiene	106-99-0	0.06	0.32	0.06	0.2	0.06	5.10E-05	0.4%	0.133	7.48E-12	1.12E-11
1,3-Dichlorobenzene	541-73-1	0	0.01	0	0.01	0	0.00E+00	0.0%	0.000	0.00E+00	0.00E+00
1,4-Dichlorobenzene	106-46-7	0.06	0.27	0.07	0.2	0.065	0.00E+00	0.0%	0.391	2.94E-12	8.72E-13
1-butanol	71-36-3	Not listed	Not listed	Not listed	Not listed	0	0.00E+00	0.0%	0.000	0.00E+00	0.00E+00
1-butene	106-98-9	0	0	0	0	0	0.00E+00	0.0%	0.000	0.00E+00	0.00E+00
1-Ethyl-4-methylbenzene	622-96-8	0.02	0.13	0.02	0.18	0.02	0.00E+00	0.0%	0.098	0.00E+00	0.00E+00
1-pentene	109-67-1	0	0	0	0	0	0.00E+00	0.0%	0.000	0.00E+00	0.00E+00
2,2,4-trimethyl-1,3-pentanediol diisobutyrate	6846-50-0	Not listed	Not listed	Not listed	Not listed	0	0.00E+00	0.0%	0.000	0.00E+00	0.00E+00
2,2,4-trimethyl-1,3-pentanediol monoisobutyrate	25265-77-4	Not listed	Not listed	Not listed	Not listed	0	0.00E+00	0.0%	0.000	0.00E+00	0.00E+00
2-butoxyethanol	111-76-2	0	0	0	0	0	0.00E+00	0.0%	0.000	0.00E+00	0.00E+00
2-ethyl-1-hexanol	104-76-7	0	0	0	0	0	0.00E+00	0.0%	0.000	0.00E+00	0.00E+00
2-methyl-1-butene	563-46-2	0	0	0	0	0	0.00E+00	0.0%	0.000	0.00E+00	0.00E+00
2-methyl-1-propanol	78-83-1	Not listed	Not listed	Not listed	Not listed	0	0.00E+00	0.0%	0.000	0.00E+00	0.00E+00
2-methylpropene	115-11-7	0	0	0	0	0	0.00E+00	0.0%	0.000	0.00E+00	0.00E+00
3-methyl-1-butene	563-45-1	0	0	0	0	0	0.00E+00	0.0%	0.000	0.00E+00	0.00E+00
3-methylfuran	930-27-8	0	0	0	0	0	0.00E+00	0.0%	0.000	0.00E+00	0.00E+00
4-phenylcyclohexene	4994-16-5	Not listed	Not listed	Not listed	Not listed	0	0.00E+00	0.0%	0.000	0.00E+00	0.00E+00
Acetaldehyde	75-07-0	0.78	1.63	0.9	1.84	0.84	5.04E-03	42.3%	1.512	1.13E-11	5.81E-11
Acetone	67-64-1	1.93	5.58	1.86	4.68	1.895	2.08E-03	17.5%	4.495	0.00E+00	1.27E-12
Acetonitrile	75-05-8	0.14	0.28	0.3	0.75	0.22	0.00E+00	0.0%	0.369	0.00E+00	1.03E-12
Acrolein	107-02-8	0.02	0.09	0.04	0.14	0.03	1.17E-04	1.0%	0.069	0.00E+00	4.10E-09
Acrylonitrile	107-13-1	0.03	0.1	0.01	0.09	0.02	0.00E+00	0.0%	0.043	5.55E-12	1.53E-11
a-pinene	80-56-8	0	0	0	0	0	0.00E+00	0.0%	0.000	0.00E+00	0.00E+00
Benzene	71-43-2	0.41	1.55	0.36	1.72	0.385	2.04E-04	1.7%	1.228	1.80E-11	4.56E-12
Benzyl chloride	100-44-7	0	0.01	0	0.04	0	0.00E+00	0.0%	0.000	0.00E+00	0.00E+00
Bromodichloromethane	75-27-4	0.01	0.01	0.01	0.03	0.01	0.00E+00	0.0%	0.067	2.87E-12	3.39E-12
Bromoform	75-25-2	0	0.01	0	0.01	0	0.00E+00	0.0%	0.000	0.00E+00	0.00E+00
Bromomethane	74-83-9	0.01	0.02	0.01	0.02	0.01	1.70E-05	0.1%	0.039	0.00E+00	5.87E-11
Butanal	123-72-8	0	0	0	0	0	0.00E+00	0.0%	0.000	0.00E+00	0.00E+00
Butane	106-97-8	0	0	0	0	0	0.00E+00	0.0%	0.000	0.00E+00	0.00E+00
Butyl acetate	123-86-4	Not listed	Not listed	Not listed	Not listed	0	0.00E+00	0.0%	0.000	0.00E+00	0.00E+00
Butylated hydroxytoluene	128-37-0	Not listed	Not listed	Not listed	Not listed	0	0.00E+00	0.0%	0.000	0.00E+00	0.00E+00
c-2-butene	107-01-7	0	0	0	0	0	0.00E+00	0.0%	0.000	0.00E+00	0.00E+00
Carbon disulfide	75-15-0	0.02	0.07	0.02	0.09	0.02	2.40E-05	0.2%	0.062	0.00E+00	1.64E-11
Carbon tetrachloride	56-23-5	0.11	0.13	0.1	0.12	0.105	0.00E+00	0.0%	0.661	7.14E-11	2.37E-10
Chlorobenzene	108-90-7	0	0.01	0	0.02	0	0.00E+00	0.0%	0.000	0.00E+00	0.00E+00
Chloroethane	75-00-3	0.01	0.06	0.07	0.12	0.04	0.00E+00	0.0%	0.106	1.20E-13	4.45E-15
Chloroethene	75-01-4	0	0.01	0	0.01	0	0.00E+00	0.0%	0.000	0.00E+00	0.00E+00
Chloroform	67-66-3	0.03	0.08	0.03	0.06	0.03	0.00E+00	0.0%	0.146	8.23E-13	4.74E-12
Chloromethane	74-87-3	0.69	0.84	0.67	0.86	0.68	0.00E+00	0.0%	1.391	0.00E+00	1.23E-11
cis-1,2-dichloroethene	156-59-2	Not listed	Not listed	Not listed	Not listed	0	0.00E+00	0.0%	0.000	0.00E+00	0.00E+00
cis-1,2-Dichloroethene	540-59-0	0	0.01	0	0.01	0	0.00E+00	0.0%	0.000	0.00E+00	0.00E+00
cis-1,3-Dichloro-1-propene	52-75-6	0	0.01	0	0.01	0	0.00E+00	0.0%	0.000	0.00E+00	0.00E+00
cis-1,3-dichloropropene	10061-01-5	Not listed	Not listed	Not listed	Not listed	0	0.00E+00	0.0%	0.000	0.00E+00	0.00E+00
Cyclohexane	110-82-7	0.05	0.18	0.04	0.14	0.045	6.30E-05	0.5%	0.155	0.00E+00	1.28E-13

Table 18 (Continued)

		ACHD Air Quality Report Data									
Compound	CAS Number	2009	2009	2010	2010	2009-2010	PID Equivalent		Annual Median Mass	Cancer toxicity potential	Noncancer toxicity
Units->		Average (ppb)	24-Hour Maximum (ppb)	Average (ppb)	24-Hour Maximum (ppb)	Average ppb	Concentration, ppm isobutylene	% Total PID Value	concentration µg/m3	(Cases/m3 air inhaled)	potential (Cases/m3 air
Cyclopentane	287-92-3	0	0	0	0	0	0.00E+00	0.0%	0.000	0.00E+00	0.00E+00
Cyclopentene	142-29-0	0	0	0	0	0	0.00E+00	0.0%	0.000	0.00E+00	0.00E+00
Dibrochloromethane	124-48-1	0	0.01	0	0.01	0	0.00E+00	0.0%	0.000	0.00E+00	0.00E+00
Dichlorodifluoromethane	75-71-8	0.65	0.74	0.61	0.72	0.63	0.00E+00	0.0%	3.118	0.00E+00	2.64E-11
dimethy disulfide	624-92-0	Not listed	Not listed	Not listed	Not listed	0	0.00E+00	0.0%	0.000	0.00E+00	0.00E+00
Dimethylsulfide	75-18-3	0	0	0	0	0	0.00E+00	0.0%	0.000	0.00E+00	0.00E+00
d-limonene	5989-27-5	0	0	0	0	0	0.00E+00	0.0%	0.000	0.00E+00	0.00E+00
Ethanol	64-17-5	0	0	0	0	0	0.00E+00	0.0%	0.000	0.00E+00	0.00E+00
Ethyl acetate	141-78-6	0.02	0.15	0.03	0.15	0.025	1.15E-04	1.0%	0.090	0.00E+00	2.54E-14
Ethylbenzene	100-41-4	0.05	0.32	0.06	0.19	0.055	2.86E-05	0.2%	0.238	5.62E-12	9.19E-14
Formaldehyde	50-00-0	1.49	4.27	1.85	5.33	1.67	0.00E+00	0.0%	2.049	2.17E-09	1.74E-11
Heptane	142-82-5	0.07	0.33	0.09	1.02	0.08	2.24E-04	1.9%	0.327	0.00E+00	0.00E+00
Hexachloro-1,3-butadiene	87-68-3	0.01	0.01	0	0.01	0.005	0.00E+00	0.0%	0.053	9.30E-13	0.00E+00
Hexanal	66-25-1	0	0	0	0	0	0.00E+00	0.0%	0.000	0.00E+00	0.00E+00
Hexane	110-54-3	0.2	1.27	0.21	1.46	0.205	8.82E-04	7.4%	0.721	4.86E-14	6.61E-12
Isobutane	75-28-5	0	0	0	0	0	0.00E+00	0.0%	0.000	0.00E+00	0.00E+00
Isopentane	78-78-4	0	0	0	0	0	0.00E+00	0.0%	0.000	0.00E+00	0.00E+00
Isoprene	78-79-5	0	0	0	0	0	0.00E+00	0.0%	0.000	0.00E+00	0.00E+00
Isopropyl alcohol	67-63-0	0.36	1.06	0.32	0.99	0.34	2.04E-03	17.1%	0.834	0.00E+00	0.00E+00
m & p- Xylene	1330-20-7	0.06	0.41	0.06	0.23	0.06	2.64E-05	0.2%	0.260	0.00E+00	0.00E+00
Methacrolein	78-85-3	0	0	0	0	0	0.00E+00	0.0%	0.000	0.00E+00	0.00E+00
Methanol	67-56-1	0	0	0	0	0	0.00E+00	0.0%	0.000	0.00E+00	0.00E+00
Methyl butyl ketone	591-78-6	0.01	0.04	0.01	0.05	0.01	0.00E+00	0.0%	0.041	0.00E+00	0.00E+00
Methyl ethyl ketone	78-93-3	0.28	0.68	0.34	1.47	0.31	2.79E-04	2.3%	0.913	0.00E+00	2.76E-14
Methyl isobutyl ketone	108-10-1	0.01	0.06	0.02	0.06	0.015	1.20E-05	0.1%	0.061	0.00E+00	1.00E-14
Methyl tert-butyl ether	1634-04-4	0	0.01	0	0.01	0	0.00E+00	0.0%	0.000	0.00E+00	0.00E+00
Methylene chloride	75-09-2	0.19	0.47	0.24	1.87	0.215	0.00E+00	0.0%	0.747	1.39E-12	1.62E-11
Methylpentanes	96-14-0	0	0	0	0	0	0.00E+00	0.0%	0.000	0.00E+00	0.00E+00
Methylvinylketone	78-94-4	0	0	0	0	0	0.00E+00	0.0%	0.000	0.00E+00	0.00E+00
naphthalene	91-20-3	Not listed	Not listed	Not listed	Not listed	0	0.00E+00	0.0%	0.000	0.00E+00	0.00E+00
n-decane	124-18-5	0	0	0	0	0	0.00E+00	0.0%	0.000	0.00E+00	0.00E+00
n-dodecane	112-40-3	0	0	0	0	0	0.00E+00	0.0%	0.000	0.00E+00	0.00E+00
n-heptanal	111-71-7	Not listed	Not listed	Not listed	Not listed	0	0.00E+00	0.0%	0.000	0.00E+00	0.00E+00
n-nonanal	124-19-6	0	0	0	0	0	0.00E+00	0.0%	0.000	0.00E+00	0.00E+00
n-octane	111-65-9	Not listed	Not listed	Not listed	Not listed	0	0.00E+00	0.0%	0.000	0.00E+00	0.00E+00
nonane	111-84-2	0	0	0	0	0	0.00E+00	0.0%	0.000	0.00E+00	0.00E+00
n-undecane	1120-21-4	0	0	0	0	0	0.00E+00	0.0%	0.000	0.00E+00	0.00E+00
o-xylene	95-47-6	Not listed	Not listed	Not listed	Not listed	0	0.00E+00	0.0%	0.000	0.00E+00	0.00E+00
o-Xylene	1330-20-7	0.16	1.14	0.16	0.67	0.16	7.36E-05	0.6%	0.694	0.00E+00	0.00E+00
Pentanal	110-62-3	0	0	0	0	0	0.00E+00	0.0%	0.000	0.00E+00	0.00E+00
Pentane	109-66-0	0	0	0	0	0	0.00E+00	0.0%	0.000	0.00E+00	0.00E+00
phenol	108-95-2	0	0	0	0	0	0.00E+00	0.0%	0.000	0.00E+00	0.00E+00
Propane	74-98-6	0	0	0	0	0	0.00E+00	0.0%	0.000	0.00E+00	0.00E+00
Propene	115-07-1	0	0	0	0	0	0.00E+00	0.0%	0.000	0.00E+00	0.00E+00
Propionaldehyde	123-38-6	0.17	0.39	0.19	0.36	0.18	3.42E-04	2.9%	0.427	0.00E+00	0.00E+00
Propyne	74-99-7	0	0	0	0	0	0.00E+00	0.0%	0.000	0.00E+00	0.00E+00
Styrene	100-42-5	0.03	0.13	0.03	0.13	0.03	1.20E-05	0.1%	0.128	6.28E-12	1.26E-12
t-2-pentene	646-04-8	0	0	0	0	0	0.00E+00	0.0%	0.000	0.00E+00	0.00E+00
Tetrachloroethylene	127-18-4	0.03	0.14	0.03	0.17	0.03	1.71E-05	0.1%	0.202	1.72E-12	6.54E-12
Tetrahydrofuran	109-99-9	0.01	0.05	0.01	0.07	0.01	1.70E-05	0.1%	0.029	8.29E-14	0.00E+00
Toluene	108-88-3	0.51	2.81	0.46	2.22	0.485	2.43E-04	2.0%	1.825	0.00E+00	6.64E-12
trans-1,3-dichloropropene	10061-02-6	Not listed	Not listed	Not listed	Not listed	0	0.00E+00	0.0%	0.000	0.00E+00	0.00E+00
Trichloroethylene	79-01-6	0.02	0.75	0.01	0.05	0.015	8.10E-06	0.1%	0.080	1.38E-13	0.00E+00
Trichlorofluoromethane	75-69-4	0.32	0.48	0.3	0.35	0.31	0.00E+00	0.0%	1.737	0.00E+00	2.53E-12
TOTALS							0.012	100%	27.23	2.31E-09	4.64E-09

Table 18 (Continued)

		EPA BASE Study Data									
Compound	CAS Number	Reported BASE Study concentrations, μg/m3			Recalculated BASE Study concentrations, μg/m3[1]			BASE In-Out PID eq ppm as isobutylene	% Total PID Value	Cancer toxicity potential (Cases/m3 air	Noncancer toxicity potential (Cases/m3 air
Units->		Median Indoor	Median Outdoor	Median In-Median Out	Median Indoor	Median Outdoor	Median In-Median				
1,1,1-Trichloroethane	71-55-6	3.1	0.63	2.47	5.1	0.9	4.7	0.000	0.0%	0.00E+00	5.08E-13
1,1,2,2-Tetrachloroethane	79-34-5	Not listed	Not listed	0	0.0	0.0	0.0	0.000	0.0%	0.00E+00	0.00E+00
1,1,2-Trichloro-1,2,2-trifluoroethane	76-13-1	< LOQ	< LOQ	0	0.0	0.0	0.0	0.000	0.0%	0.00E+00	0.00E+00
1,1,2-Trichloroethane	79-00-5	Not listed	Not listed	0	0.0	0.0	0.0	0.000	0.0%	0.00E+00	0.00E+00
1,1-Dichloroethane	75-34-3	< LOQ	< LOQ	0	0.0	0.0	0.0	0.000	0.0%	0.00E+00	0.00E+00
1,1-Dichloroethylene	75-35-4	< LOQ	< LOQ	0	0.0	0.0	0.0	0.000	0.0%	0.00E+00	0.00E+00
1,2,4-Trichlorobenzene	120-82-1	< LOQ	< LOQ	0	0.0	0.0	0.0	0.000	0.0%	0.00E+00	0.00E+00
1,2,4-Trimethylbenzene	95-63-6	1.9	0.97	0.93	3.1	2.1	1.5	0.000	0.0%	3.92E-13	0.00E+00
1,2-Dibromoethane	106-93-4	< LOQ	< LOQ	0	0.0	0.0	0.0	0.000	0.0%	0.00E+00	0.00E+00
1,2-Dichloro-1,1,2,2-tetrafloroethane	76-14-2	< LOQ	< LOQ	0	0.0	0.0	0.0	0.000	0.0%	0.00E+00	0.00E+00
1,2-Dichlorobenzene	95-50-1	< LOQ	< LOQ	0	0.0	0.0	0.0	0.000	0.0%	0.00E+00	0.00E+00
1,2-Dichloroethane	107-06-2	< LOQ	< LOQ	0	0.0	0.0	0.0	0.000	0.0%	0.00E+00	0.00E+00
1,2-Dichloropropane	78-87-5	Not listed	Not listed	0	0.0	0.0	0.0	0.000	0.0%	0.00E+00	0.00E+00
1,3,5-Trimethylbenzene	108-67-8	0.54	0.24	0.3	0.0	0.0	0.0	0.000	0.0%	0.00E+00	0.00E+00
1,3-Butadiene	106-99-0	< LOQ	< LOQ	0	0.0	0.0	0.0	0.000	0.0%	0.00E+00	0.00E+00
1,3-Dichlorobenzene	541-73-1	Not listed	Not listed	0	0.0	0.0	0.0	0.000	0.0%	0.00E+00	0.00E+00
1,4-Dichlorobenzene	106-46-7	0.54	< LOQ	0.54	0.0	0.0	0.0	0.000	0.0%	0.00E+00	0.00E+00
1-butanol	71-36-3	2.1	< LOQ	2.1	0.0	0.0	0.0	0.000	0.0%	0.00E+00	0.00E+00
1-butene	106-98-9	Not listed	Not listed	0	0.0	0.0	0.0	0.000	0.0%	0.00E+00	0.00E+00
1-Ethyl-4-methylbenzene	622-96-8	0.77	0.33	0.44	0.0	0.0	0.0	0.000	0.0%	0.00E+00	0.00E+00
1-pentene	109-67-1	Not listed	Not listed	0	0.0	0.0	0.0	0.000	0.0%	0.00E+00	0.00E+00
2,2,4-trimethyl-1,3-pentanediol diisobutyrate	6846-50-0	0.74	< LOQ	0.74	0.0	0.0	0.0	0.000	0.0%	0.00E+00	0.00E+00
2,2,4-trimethyl-1,3-pentanediol monoisobutyrate	25265-77-4	2.5	< LOQ	2.5	0.0	0.0	0.0	0.000	0.0%	0.00E+00	0.00E+00
2-butoxyethanol	111-76-2	5.5	< LOQ	5.5	0.0	0.0	0.0	0.000	0.0%	0.00E+00	0.00E+00
2-ethyl-1-hexanol	104-76-7	1.2	< LOQ	1.2	0.0	0.0	0.0	0.000	0.0%	0.00E+00	0.00E+00
2-methyl-1-butene	563-46-2	Not listed	Not listed	0	0.0	0.0	0.0	0.000	0.0%	0.00E+00	0.00E+00
2-methyl-1-propanol	78-83-1	< LOQ	< LOQ	0	0.0	0.0	0.0	0.000	0.0%	0.00E+00	0.00E+00
2-methylpropene	115-11-7	Not listed	Not listed	0	0.0	0.0	0.0	0.000	0.0%	0.00E+00	0.00E+00
3-methyl-1-butene	563-45-1	Not listed	Not listed	0	0.0	0.0	0.0	0.000	0.0%	0.00E+00	0.00E+00
3-methylfuran	930-27-8	Not listed	Not listed	0	0.0	0.0	0.0	0.000	0.0%	0.00E+00	0.00E+00
4-phenylcyclohexene	4994-16-5	< LOQ	< LOQ	0	0.0	0.0	0.0	0.000	0.0%	0.00E+00	0.00E+00
Acetaldehyde	75-07-0	7.2	2.6	4.6	7.2	3.4	3.4	0.011	42.4%	2.53E-11	1.30E-10
Acetone	67-64-1	30	7.8	22.2	43.0	21.1	18.9	0.009	33.0%	0.00E+00	5.35E-12
Acetonitrile	75-05-8	Not listed	Not listed	0	0.0	0.0	0.0	0.000	0.0%	0.00E+00	0.00E+00
Acrolein	107-02-8	Not listed	Not listed	0	0.0	0.0	0.0	0.000	0.0%	0.00E+00	0.00E+00
Acrylonitrile	107-13-1	Not listed	Not listed	0	0.0	0.0	0.0	0.000	0.0%	0.00E+00	0.00E+00
a-pinene	80-56-8	0.57	< LOQ	0.57	0.0	0.0	0.0	0.000	0.0%	0.00E+00	0.00E+00
Benzene	71-43-2	3.6	2.9	0.7	3.5	2.7	0.6	0.000	0.4%	8.44E-12	2.14E-12
Benzyl chloride	100-44-7	Not listed	Not listed	0	0.0	0.0	0.0	0.000	0.0%	0.00E+00	0.00E+00
Bromodichloromethane	75-27-4	Not listed	Not listed	0	0.0	0.0	0.0	0.000	0.0%	0.00E+00	0.00E+00
Bromoform	75-25-2	Not listed	Not listed	0	0.0	0.0	0.0	0.000	0.0%	0.00E+00	0.00E+00
Bromomethane	74-83-9	< LOQ	< LOQ	0	0.0	0.0	0.0	0.000	0.0%	0.00E+00	0.00E+00
Butanal	123-72-8	Not listed	Not listed	0	0.0	0.0	0.0	0.000	0.0%	0.00E+00	0.00E+00
Butane	106-97-8	Not listed	Not listed	0	0.0	0.0	0.0	0.000	0.0%	0.00E+00	0.00E+00
Butyl acetate	123-86-4	1.5	< LOQ	1.5	0.0	0.0	0.0	0.000	0.0%	0.00E+00	0.00E+00
Butylated hydroxytoluene	128-37-0	< LOQ	< LOQ	0	0.0	0.0	0.0	0.000	0.0%	0.00E+00	0.00E+00
c-2-butene	107-01-7	Not listed	Not listed	0	0.0	0.0	0.0	0.000	0.0%	0.00E+00	0.00E+00
Carbon disulfide	75-15-0	< LOQ	0.98	0	1.6	0.0	0.0	0.000	0.0%	0.00E+00	0.00E+00
Carbon tetrachloride	56-23-5	< LOQ	< LOQ	0	0.0	0.0	0.0	0.000	0.0%	0.00E+00	0.00E+00
Chlorobenzene	108-90-7	< LOQ	< LOQ	0	0.0	0.0	0.0	0.000	0.0%	0.00E+00	0.00E+00
Chloroethane	75-00-3	< LOQ	< LOQ	0	0.0	0.0	0.0	0.000	0.0%	0.00E+00	0.00E+00
Chloroethene	75-01-4	< LOQ	< LOQ	0	0.0	0.0	0.0	0.000	0.0%	0.00E+00	0.00E+00
Chloroform	67-66-3	< LOQ	< LOQ	0	0.0	0.0	0.0	0.000	0.0%	0.00E+00	0.00E+00
Chloromethane	74-87-3	2.5	2.3	0.2	2.5	2.2	0.2	0.000	0.0%	0.00E+00	1.33E-12
cis-1,2-dichloroethene	156-59-2	Not listed	Not listed	0	0.0	0.0	0.0	0.000	0.0%	0.00E+00	0.00E+00
cis-1,2-Dichloroethene	540-59-0	Not listed	Not listed	0	0.0	0.0	0.0	0.000	0.0%	0.00E+00	0.00E+00
cis-1,3-Dichloro-1-propene	52-75-6	Not listed	Not listed	0	0.0	0.0	0.0	0.000	0.0%	0.00E+00	0.00E+00
cis-1,3-dichloropropene	10061-01-5	< LOQ	< LOQ	0	0.0	0.0	0.0	0.000	0.0%	0.00E+00	0.00E+00
Cyclohexane	110-82-7	Not listed	Not listed	0	0.0	0.0	0.0	0.000	0.0%	0.00E+00	0.00E+00

Table 18 (Continued)

		EPA BASE Study Data									
Compound	CAS Number	Reported BASE Study concentrations, µg/m3			Recalculated BASE Study concentrations, µg/m3[1]			BASE In-Out PID eq ppm as isobutylene	% Total PID Value	Cancer toxicity potential (Cases/m3 air	Noncancer toxicity potential (Cases/m3 air
Units->		Median Indoor	Median Outdoor	Median In-Median Out	Median Indoor	Median Outdoor	Median In-Median				
Cyclopentane	287-92-3	Not listed	Not listed	0	0.0	0.0	0.0	0.000	0.0%	0.00E+00	0.00E+00
Cyclopentene	142-29-0	Not listed	Not listed	0	0.0	0.0	0.0	0.000	0.0%	0.00E+00	0.00E+00
Dibrochloromethane	124-48-1	Not listed	Not listed	0	0.0	0.0	0.0	0.000	0.0%	0.00E+00	0.00E+00
Dichlorodifluoromethane	75-71-8	6.8	4.4	2.4	6.3	4.3	1.7	0.000	0.0%	0.00E+00	1.44E-11
dimethy disulfide	624-92-0	< LOQ	< LOQ	0	0.0	0.0	0.0	0.000	0.0%	0.00E+00	0.00E+00
Dimethylsulfide	75-18-3	Not listed	Not listed	0	0.0	0.0	0.0	0.000	0.0%	0.00E+00	0.00E+00
d-limonene	5989-27-5	7.1	0.19	6.91	7.7	0.0	6.2	0.000	1.4%	3.46E-11	0.00E+00
Ethanol	64-17-5	79	25	54	0.0	0.0	0.0	0.000	0.0%	0.00E+00	0.00E+00
Ethyl acetate	141-78-6	2	0.26	1.74	2.0	0.0	1.9	0.002	9.2%	0.00E+00	5.40E-13
Ethylbenzene	100-41-4	1.5	0.7	0.8	2.6	0.0	0.8	0.000	0.3%	1.79E-11	2.92E-13
Formaldehyde	50-00-0	15	3	12	15.5	3.1	9.9	0.000	0.0%	1.05E-08	8.41E-11
Heptane	142-82-5	Not listed	Not listed	0	0.0	0.0	0.0	0.000	0.0%	0.00E+00	0.00E+00
Hexachloro-1,3-butadiene	87-68-3	Not listed	Not listed	0	0.0	0.0	0.0	0.000	0.0%	0.00E+00	0.00E+00
Hexanal	66-25-1	4.1	0.5	3.6	0.0	0.0	0.0	0.000	0.0%	0.00E+00	0.00E+00
Hexane	110-54-3	2.5	1.3	1.2	0.0	0.0	0.0	0.000	0.0%	0.00E+00	0.00E+00
Isobutane	75-28-5	Not listed	Not listed	0	0.0	0.0	0.0	0.000	0.0%	0.00E+00	0.00E+00
Isopentane	78-78-4	Not listed	Not listed	0	0.0	0.0	0.0	0.000	0.0%	0.00E+00	0.00E+00
Isoprene	78-79-5	Not listed	Not listed	0	0.0	0.0	0.0	0.000	0.0%	0.00E+00	0.00E+00
Isopropyl alcohol	67-63-0	30	3.5	26.5	0.0	0.0	0.0	0.000	0.0%	0.00E+00	0.00E+00
m & p- Xylene	1330-20-7	Not listed	Not listed	0	0.0	0.0	0.0	0.000	0.0%	0.00E+00	0.00E+00
Methacrolein	78-85-3	Not listed	Not listed	0	0.0	0.0	0.0	0.000	0.0%	0.00E+00	0.00E+00
Methanol	67-56-1	Not listed	Not listed	0	0.0	0.0	0.0	0.000	0.0%	0.00E+00	0.00E+00
Methyl butyl ketone	591-78-6	Not listed	Not listed	0	0.0	0.0	0.0	0.000	0.0%	0.00E+00	0.00E+00
Methyl ethyl ketone	78-93-3	2.6	1.4	1.2	5.0	3.5	1.0	0.000	1.1%	0.00E+00	2.87E-14
Methyl isobutyl ketone	108-10-1	1	< LOQ	1	0.0	0.0	0.0	0.000	0.0%	0.00E+00	0.00E+00
Methyl tert-butyl ether	1634-04-4	< LOQ	< LOQ	0	0.0	0.0	0.0	0.000	0.0%	0.00E+00	0.00E+00
Methylene chloride	75-09-2	2.9	< LOQ	2.9	3.3	0.0	1.5	0.000	0.0%	2.76E-12	3.23E-11
Methylpentanes	96-14-0	1.4	0.82	0.58	1.9	0.0	0.0	0.000	0.0%	0.00E+00	0.00E+00
Methylvinylketone	78-94-4	Not listed	Not listed	0	0.0	0.0	0.0	0.000	0.0%	0.00E+00	0.00E+00
naphthalene	91-20-3	0.73	0.22	0.51	0.0	0.0	0.0	0.000	0.0%	0.00E+00	0.00E+00
n-decane	124-18-5	2.9	0.48	2.42	4.7	2.2	2.5	0.001	2.3%	0.00E+00	0.00E+00
n-dodecane	112-40-3	3.5	< LOQ	3.5	6.9	0.0	4.7	0.000	0.0%	0.00E+00	0.00E+00
n-heptanal	111-71-7	< LOQ	< LOQ	0	0.0	0.0	0.0	0.000	0.0%	0.00E+00	0.00E+00
n-nonanal	124-19-6	3.6	0.94	2.66	0.0	0.0	0.0	0.000	0.0%	0.00E+00	0.00E+00
n-octane	111-65-9	0.85	0.25	0.6	1.3	0.0	1.0	0.000	1.4%	0.00E+00	0.00E+00
nonane	111-84-2	0.94	0.28	0.66	1.4	0.0	0.7	0.000	0.7%	0.00E+00	0.00E+00
n-undecane	1120-21-4	4	0.31	3.69	7.8	3.5	3.3	0.001	3.8%	0.00E+00	0.00E+00
o-xylene	95-47-6	2.1	0.89	1.21	3.0	1.7	1.7	0.000	0.7%	0.00E+00	0.00E+00
o-Xylene	1330-20-7	Not listed	Not listed	0	0.0	0.0	0.0	0.000	0.0%	0.00E+00	0.00E+00
Pentanal	110-62-3	1.2	< LOQ	1.2	0.0	0.0	0.0	0.000	0.0%	0.00E+00	0.00E+00
Pentane	109-66-0	Not listed	Not listed	0	0.0	0.0	0.0	0.000	0.0%	0.00E+00	0.00E+00
phenol	108-95-2	1.8	1.1	0.7	0.0	0.0	0.0	0.000	0.0%	0.00E+00	0.00E+00
Propane	74-98-6	Not listed	Not listed	0	0.0	0.0	0.0	0.000	0.0%	0.00E+00	0.00E+00
Propene	115-07-1	Not listed	Not listed	0	0.0	0.0	0.0	0.000	0.0%	0.00E+00	0.00E+00
Propionaldehyde	123-38-6	Not listed	Not listed	0	0.0	0.0	0.0	0.000	0.0%	0.00E+00	0.00E+00
Propyne	74-99-7	Not listed	Not listed	0	0.0	0.0	0.0	0.000	0.0%	0.00E+00	0.00E+00
Styrene	100-42-5	0.91	0.24	0.67	0.0	0.0	0.0	0.000	0.0%	0.00E+00	0.00E+00
t-2-pentene	646-04-8	Not listed	Not listed	0	0.0	0.0	0.0	0.000	0.0%	0.00E+00	0.00E+00
Tetrachloroethylene	127-18-4	1.5	0.56	0.94	4.0	0.0	2.1	0.000	0.7%	1.75E-11	6.64E-11
Tetrahydrofuran	109-99-9	Not listed	Not listed	0	0.0	0.0	0.0	0.000	0.0%	0.00E+00	0.00E+00
Toluene	108-88-3	8.7	3.7	5	16.9	9.6	5.4	0.001	2.7%	0.00E+00	1.98E-11
trans-1,3-dichloropropene	10061-02-6	< LOQ	< LOQ	0	0.0	0.0	0.0	0.000	0.0%	0.00E+00	0.00E+00
Trichloroethylene	79-01-6	0.29	< LOQ	0.29	0.0	0.0	0.0	0.000	0.0%	0.00E+00	0.00E+00
Trichlorofluoromethane	75-69-4	3.9	< LOQ	3.9	4.3	0.0	3.0	0.000	0.0%	0.00E+00	4.41E-12
TOTALS		257.080	68.790	189.270	160.404	60.058	76.433	0.027	100%	1.06E-08	3.62E-10

B.3 LIFE CYCLE INVENTORY

B.3.1 National Renewable Energy Laboratory (NREL) dynamic grid mix

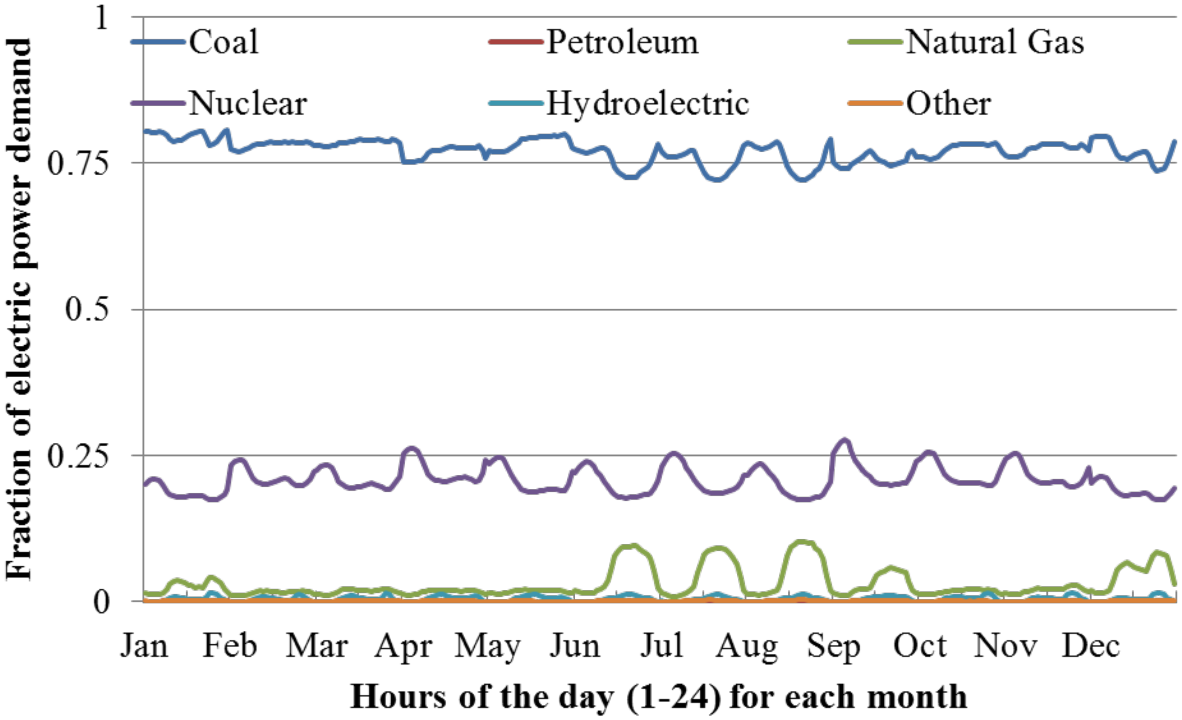


Figure 34 - Dynamic electrical generation mix at load point (courtesy of NREL)

APPENDIX C

POST-OCCUPANCY SURVEY QUESTIONS AND RESPONSES

Table 19 - Post-occupancy survey questions and individual results

RespondentID		2468709672	2467042000	2465413150	2465307176	2424782001	2463689908	2463645788
What is your job title?	Response	Staff	Graduate student	Graduate student	Graduate student	Graduate student	Graduate student	Graduate student
	Other (please specify)							
How many hours a week do you spend at MCSI?	Response	10-20	>40	30-40	>40	30-40	30-40	30-40
In which area of the building is your primary work area located?	Response	2nd floor Benedum Hall - Wet Lab	2nd floor MCSI wing (grad student space or dry lab)	3rd floor MCSI wing (grad student space)	2nd floor Benedum Hall - Wet Lab	2nd floor MCSI wing (grad student space or dry lab)	3rd floor MCSI wing (grad student space)	2nd floor Benedum Hall - Wet Lab
Which option best describes your work area?	Response	Laboratory benches	Laboratory benches	Open office with partitions	Laboratory benches	Open office with partitions	Open office with partitions	Laboratory benches
	Other (please specify)							
Do you have outside views from your work area while either standing or seated, including windows above eye level?	Response	Yes	No	Yes	Yes	Yes	Yes	No
Which direction does the window face?	Response	North (O'Hara Street)	East (Thackeray Street)	North (O'Hara Street)	South (Fifth Avenue)	North (O'Hara Street)	North (O'Hara Street)	West (Bouquet Street)
Is there a corridor or hallway between your seat and the nearest window?	Response	No	Yes	No	No	No	No	No
In my work area, I can personally adjust or control the following. (Check all that apply):	Daylight level i.e., with window blinds or shades	x		x	x	x		
	Electric light level, i.e., with a switch or dimmer	x		x		x		
	Air supply temperature i.e., with a thermostat							
	Air supply volume and/or direction i.e., with an adjustable vent				x			
	None of the above		x				x	x
	Other							
During warmer weather, I am satisfied with the temperature in my work area.		3	6	1	5	3	5	1
During cooler weather, I am satisfied with the temperature in my work area.		3	6	3	6	4	5	1
I am generally satisfied with the temperature in my work area.		3		2	4	6	5	1
During warmer weather, I believe the air is too humid in my work area.		3	2	1	4	2	3	4
During cooler weather, I believe the air is too dry in my work area.		4	2	6	4	2	3	4
I am generally satisfied with the humidity in my work area.		4	6	1	6	7	5	6
During warmer weather, I am satisfied with the air flow speed (not too drafty or too stagnant) in my work area.		3	6	2	6	6	5	1
During cooler weather, I am satisfied with the air flow speed (not too drafty or too stagnant) in my work area.	1 = Strongly disagree; 4 = Neutral; 7 = Strongly agree	5	6	2	6	6	5	1
I am generally satisfied with the air flow speed (not too drafty or too stagnant) in my work area.		5	6	2	6	6	5	1
Recalling the previous questions related to temperature, humidity, and air flow speed, I am generally satisfied with the thermal comfort in my work area.		3	6	2	5	2	5	1
I believe the air in my work area is not stuffy or stale.		5	6	3	6	1	5	7
I believe the air in my work area is clean.		4	6	4	6	7	5	7
I believe the air in my work area is generally free from odors.		5	6	3	6	7	5	6
Recalling the previous questions related to stuffiness/staleness, cleanliness and odor, I am generally satisfied with the air quality in my work area.		5	6	3	6	7	5	6
What type of lighting is provided at your work area? (Check all that apply.)	Daylighting (sunlight entering the building through windows, glass roof, or glass doors)	x		x	x	x	x	
	Overhead lighting (lighting provided by the fixtures on the ceiling or on the walls)	x	x	x	x	x	x	x
	Task lighting (lighting provided by personal fixtures at one's work area, such as desk lights)	x		x				
	Other (please specify)							
My work area is too bright.		4	2	5	3	5	3	5
My work area is too dark.		4	7	1	3	1	5	3
There is an adequate amount of daylight in my area (leave blank if none).		4		5	7	7	5	
There is an adequate amount of electric light in my area.	1 = Strongly disagree; 4 = Neutral; 7 = Strongly agree	5	3	4	7	7	5	5
There is a problem with glare, reflections or contrast in my work area.		5	1	6	3	2	5	5
Recalling the previous questions related to lighting and daylighting, I am generally satisfied with the lighting quality in my work area.		4	4	5	6	7	4	4

Table 19 (Continued)

RespondentID		2468709672	2467042000	2465413150	2465307176	2424782001	2463689908	2463645788
My work area is too loud due to other people's conversations.	1 = Strongly disagree; 4 = Neutral; 7 = Strongly agree	5	5	4	4	5	3	5
My work area is too loud due to background noise other than conversations (e.g. mechanical equipment, outdoor noises).		5	4	6	6	2	3	5
My work area is too quiet.		3	3	4	4	1	2	1
There is a problem with acoustics in my work area other than generally too loud or too quiet.		4	2	4	4	1	3	5
	If you agree, please explain:							generally noisy or loud
Recalling the previous questions related to acoustics, I am generally satisfied with the acoustical quality in my work area.	1 = Strongly disagree; 4 = Neutral; 7 = Strongly agree	4	6	5	5	6	5	3
How does the thermal comfort (remember, this includes temperature, humidity and airspeed) in your work area affect your productivity?	1 = Strong negative effect; 4 = Neutral; 7 = Strong positive effect	3	5	3	4	2	4	2
How does the air quality (remember, this includes stuffiness/staleness, cleanliness and odors) in your work area affect your productivity?		3	5	3	4	7	4	5
How does the lighting quality (remember, this includes both daylighting and artifical - both overhead, and task-based) in your work area affect your productivity?		3	3	3	4	7	3	3
How does the outdoor view, or lack of an outdoor view, in your work area affect your productivity?		2	3	5	6	7	5	4
How does the acoustical quality or noise level in your work area affect your productivity?		2	4	3	3	5	6	3
Recalling the previous questions related to indoor environmental quality (including thermal comfort, air quality, lighting and acoustics), how does the overall indoor environmental quality in your work area affect your productivity?		2	6	5	4	6	5	3
How do you think increasing the temperature in your work area by several degrees in warmer weather would affect your productivity?	1 = Strong negative effect; 4 = Neutral; 7 = Strong positive effect; 0 = I don't know	2	5	7	4	7	3	6
How do you think decreasing the temperature in your work area by several degrees in cooler weather would affect your productivity?		3	4	3	4	2	3	2
How do you think decreasing the ventilation in your work area would affect your productivity?		3	4	3	4	2	4	4
How do you think including operable windows in your work area would affect your productivity?		5	5	0	5	2	2	0
How do you think decreasing the amount of daylighting in your work area would affect your productivity?		3	3	3	3	1	2	4
How do you think increasing the amount of daylighting in your work area would affect your productivity?		5	5	5	6	7	6	5
How do you think automatically turning off overhead lighting in your work area when there is sufficient daylight would affect your productivity?		4	4	0	4	3	4	4

Table 19 (Continued)

RespondentID		2463595868	2463456757	2459886333	2457993679	2457977220	2456121623	2453710317
What is your job title?	Response	Graduate student	Graduate student	Graduate student	Graduate student	Graduate student	Graduate student	Graduate student
	Other (please specify)							
How many hours a week do you spend at MCSI?	Response	30-40	10-20	30-40	30-40	10-20	>40	20-30
In which area of the building is your primary work area located?	Response	2nd floor MCSI wing (grad student space or dry lab)	2nd floor MCSI wing (grad student space or dry lab)	3rd floor MCSI wing (grad student space)	2nd floor MCSI wing (grad student space or dry lab)	2nd floor Benedum Hall - Wet Lab	2nd floor Benedum Hall - Wet Lab	3rd floor MCSI wing (grad student space)
Which option best describes your work area?	Response	Open office with partitions	Open office with partitions	Open office with partitions	Open office with partitions	Laboratory benches	Laboratory benches	Open office with partitions
	Other (please specify)							
Do you have outside views from your work area while either standing or seated, including windows above eye level?	Response	Yes	Yes	Yes	Yes	No	Yes	Yes
Which direction does the window face?	Response	North (O'Hara Street)	North (O'Hara Street)	North (O'Hara Street)	North (O'Hara Street)		South (Fifth Avenue)	North (O'Hara Street)
Is there a corridor or hallway between your seat and the nearest window?	Response	No	Yes	Yes	No	Yes	Yes	Yes
In my work area, I can personally adjust or control the following. (Check all that apply):	Daylight level i.e., with window blinds or shades	x		x	x			
	Electric light level, i.e., with a switch or dimmer			x	x			x
	Air supply temperature i.e., with a thermostat	x						
	Air supply volume and/or direction i.e., with an adjustable vent							
	None of the above		x			x	x	
	Other							
During warmer weather, I am satisfied with the temperature in my work area.		4	2	6	2	2	6	4
During cooler weather, I am satisfied with the temperature in my work area.		4	3	7	5	6	6	6
I am generally satisfied with the temperature in my work area.		4	3	7	4	4	6	6
During warmer weather, I believe the air is too humid in my work area.		4	2	4	2	5	4	1
During cooler weather, I believe the air is too dry in my work area.		5	2	4	4	5	5	1
I am generally satisfied with the humidity in my work area.		5	6	7	6	5	3	7
During warmer weather, I am satisfied with the air flow speed (not too drafty or too stagnant) in my work area.		5	3	7	2	5	5	6
During cooler weather, I am satisfied with the air flow speed (not too drafty or too stagnant) in my work area.	1 = Strongly disagree; 4 = Neutral; 7 = Strongly agree	5	3	7	5	5	5	6
I am generally satisfied with the air flow speed (not too drafty or too stagnant) in my work area.		5	3	7	3	5	5	6
Recalling the previous questions related to temperature, humidity, and air flow speed, I am generally satisfied with the thermal comfort in my work area.		5	2	7	3	5	6	6
I believe the air in my work area is not stuffy or stale.		6	6	6	7	6	3	7
I believe the air in my work area is clean.		6	6	5	7	3	6	7
I believe the air in my work area is generally free from odors.		6	6	6	6	3	6	7
Recalling the previous questions related to stuffiness/staleness, cleanliness and odor, I am generally satisfied with the air quality in my work area.		6	6	6	7	4	6	7
What type of lighting is provided at your work area? (Check all that apply.)	Daylighting (sunlight entering the building through windows, glass roof, or glass doors)	x	x	x	x		x	x
	Overhead lighting (lighting provided by the fixtures on the ceiling or on the walls)	x	x	x	x	x	x	x
	Task lighting (lighting provided by personal fixtures at one's work area, such as desk lights)							
	Other (please specify)							
My work area is too bright.		2	2	4	1	5	2	1
My work area is too dark.		2	1	4	1	4	5	4
There is an adequate amount of daylight in my area (leave blank if none).		6	6	5	6		4	2
There is an adequate amount of electric light in my area.	1 = Strongly disagree; 4 = Neutral; 7 = Strongly agree	6	6	6	7	7	5	7
There is a problem with glare, reflections or contrast in my work area.		2	1	1	1	2	2	2
Recalling the previous questions related to lighting and daylighting, I am generally satisfied with the lighting quality in my work area.		6	6	6	7	3	4	4

Table 19 (Continued)

RespondentID		2463595868	2463456757	2459886333	2457993679	2457977220	2456121623	2453710317
My work area is too loud due to other people's conversations.	1 = Strongly disagree; 4 = Neutral; 7 = Strongly agree	2	3	4	3	1	7	1
My work area is too loud due to background noise other than conversations (e.g. mechanical equipment, outdoor noises).		2	5	5	4	7	6	1
My work area is too quiet.		6	2	4	2	1	2	6
There is a problem with acoustics in my work area other than generally too loud or too quiet.		2	2	4	2	2	4	1
	If you agree, please explain:							
Recalling the previous questions related to acoustics, I am generally satisfied with the acoustical quality in my work area.	1 = Strongly disagree; 4 = Neutral; 7 = Strongly agree	6	6	5	5	2	2	6
How does the thermal comfort (remember, this includes temperature, humidity and airspeed) in your work area affect your productivity?	1 = Strong negative effect; 4 = Neutral; 7 = Strong positive effect	6	3	5	4	3	5	4
How does the air quality (remember, this includes stuffiness/staleness, cleanliness and odors) in your work area affect your productivity?		6	6	7	6	4	5	4
How does the lighting quality (remember, this includes both daylighting and artifical - both overhead, and task-based) in your work area affect your productivity?		6	5	7	7	3	3	6
How does the outdoor view, or lack of an outdoor view, in your work area affect your productivity?		6	4	4	7	2	4	6
How does the acoustical quality or noise level in your work area affect your productivity?		6	4	7	6	4	1	4
Recalling the previous questions related to indoor environmental quality (including thermal comfort, air quality, lighting and acoustics), how does the overall indoor environmental quality in your work area affect your productivity?		6	6	6	6	3	3	4
How do you think increasing the temperature in your work area by several degrees in warmer weather would affect your productivity?	1 = Strong negative effect; 4 = Neutral; 7 = Strong positive effect; 0 = I don't know	3	5	0	6	4	0	4
How do you think decreasing the temperature in your work area by several degrees in cooler weather would affect your productivity?		3	2	6	4	1	0	4
How do you think decreasing the ventilation in your work area would affect your productivity?		4	2	4	3	3	0	3
How do you think including operable windows in your work area would affect your productivity?		4	4	5	4	0	0	7
How do you think decreasing the amount of daylighting in your work area would affect your productivity?		1	3	6	1	1	3	2
How do you think increasing the amount of daylighting in your work area would affect your productivity?		7	5	6	6	7	4	7
How do you think automatically turning off overhead lighting in your work area when there is sufficient daylight would affect your productivity?		5	5	5	6	6	3	6

Table 19 (Continued)

RespondentID		2453034559	2452104034	2452005526	2451968040	2451873253	2449203632	2435366623
What is your job title?	Response	Faculty	Graduate student	Postdoctoral researcher	Graduate student	Faculty	Staff	Faculty
	Other (please specify)							
How many hours a week do you spend at MCSI?	Response	30-40	30-40	30-40	>40	>40	30-40	>40
In which area of the building is your primary work area located?	Response	2nd floor Benedum Hall - East offices (facing plaza & Thackeray Street)	3rd floor MCSI wing (grad student space)	2nd floor Benedum Hall - North offices (facing O'Hara Street)	2nd floor Benedum Hall - Wet Lab	2nd floor Benedum Hall - East offices (facing plaza & Thackeray Street)	First floor MCSI wing (Mascaro suite)	2nd floor Benedum Hall - North offices (facing O'Hara Street)
Which option best describes your work area?	Response	Private office	Open office with partitions	Laboratory benches	Open office with partitions	Laboratory benches	Other (please specify)	Private office
	Other (please specify)						reception area	
Do you have outside views from your work area while either standing or seated, including windows above eye level?	Response	Yes	Yes	Yes	No	Yes	Yes	Yes
Which direction does the window face?	Response	East (Thackeray Street)	North (O'Hara Street)	North (O'Hara Street)		East (Thackeray Street)	North (O'Hara Street)	North (O'Hara Street)
Is there a corridor or hallway between your seat and the nearest window?	Response	No	No	Yes	No	No	No	No
In my work area, I can personally adjust or control the following. (Check all that apply):	Daylight level i.e., with window blinds or shades	x	x	x		x		x
	Electric light level, i.e., with a switch or dimmer	x	x	x		x	x	x
	Air supply temperature i.e., with a thermostat		x			x	x	
	Air supply volume and/or direction i.e., with an adjustable vent							x
	None of the above				x			
	Other							
During warmer weather, I am satisfied with the temperature in my work area.		5	5	1	2	2	2	2
During cooler weather, I am satisfied with the temperature in my work area.		5	5	5	2	2	2	2
I am generally satisfied with the temperature in my work area.		5	5	5	2	3	2	2
During warmer weather, I believe the air is too humid in my work area.		2	3	5	4	4	4	1
During cooler weather, I believe the air is too dry in my work area.		3	3	7	4	2	4	1
I am generally satisfied with the humidity in my work area.		5	6	3	4	3	4	7
During warmer weather, I am satisfied with the air flow speed (not too drafty or too stagnant) in my work area.		5	4	3	2	4	3	7
During cooler weather, I am satisfied with the air flow speed (not too drafty or too stagnant) in my work area.	1 = Strongly disagree; 4 = Neutral; 7 = Strongly agree	5	4	3	2		3	7
I am generally satisfied with the air flow speed (not too drafty or too stagnant) in my work area.		5	4	3	2	4	3	7
Recalling the previous questions related to temperature, humidity, and air flow speed, I am generally satisfied with the thermal comfort in my work area.		5	6	3	2	2	2	3
I believe the air in my work area is not stuffy or stale.		6	5	3	4	2	5	7
I believe the air in my work area is clean.		6	6	2	4	1	4	7
I believe the air in my work area is generally free from odors.		5	6	3	5	1	4	7
Recalling the previous questions related to stuffiness/staleness, cleanliness and odor, I am generally satisfied with the air quality in my work area.		5	6	3	5	1	5	7
What type of lighting is provided at your work area? (Check all that apply.)	Daylighting (sunlight entering the building through windows, glass roof, or glass doors)	x	x	x		x	x	x
	Overhead lighting (lighting provided by the fixtures on the ceiling or on the walls)	x	x	x	x	x	x	x
	Task lighting (lighting provided by personal fixtures at one's work area, such as desk lights)							
	Other (please specify)							
My work area is too bright.		2	2	1	1	4	2	1
My work area is too dark.		1	1	1	7	4	2	1
There is an adequate amount of daylight in my area (leave blank if none).		6	7	7		3	7	7
There is an adequate amount of electric light in my area.	1 = Strongly disagree; 4 = Neutral; 7 = Strongly agree	6	7	7	2	2	6	7
There is a problem with glare, reflections or contrast in my work area.		2	5	4	2	6	4	1
Recalling the previous questions related to lighting and daylighting, I am generally satisfied with the lighting quality in my work area.		6	7	7	1	3	5	7

Table 19 (Continued)

RespondentID		2453034559	2452104034	2452005526	2451968040	2451873253	2449203632	2435366623
My work area is too loud due to other people's conversations.	1 = Strongly disagree; 4 = Neutral; 7 = Strongly agree	6	3	1	3	7	6	5
My work area is too loud due to background noise other than conversations (e.g. mechanical equipment, outdoor noises).		5	6	1	7	7	4	1
My work area is too quiet.		3	4	7	2	1	2	2
There is a problem with acoustics in my work area other than generally too loud or too quiet.		1	2	1	6	7	2	5
	If you agree, please explain:					mechanical noises from HVAC		Hallway outside office seems to resemble a reverberation chamber
Recalling the previous questions related to acoustics, I am generally satisfied with the acoustical quality in my work area.	1 = Strongly disagree; 4 = Neutral; 7 = Strongly agree	4	4	6	1	1	4	3
How does the thermal comfort (remember, this includes temperature, humidity and airspeed) in your work area affect your productivity?	1 = Strong negative effect; 4 = Neutral; 7 = Strong positive effect	4	5	2	4	3	4	3
How does the air quality (remember, this includes stuffiness/staleness, cleanliness and odors) in your work area affect your productivity?		4	5	2	4	1	4	4
How does the lighting quality (remember, this includes both daylighting and artifical - both overhead, and task-based) in your work area affect your productivity?		3	6	7	2	3	5	5
How does the outdoor view, or lack of an outdoor view, in your work area affect your productivity?		4	6	2	4	6	5	7
How does the acoustical quality or noise level in your work area affect your productivity?		4	4	7	3	1	4	3
Recalling the previous questions related to indoor environmental quality (including thermal comfort, air quality, lighting and acoustics), how does the overall indoor environmental quality in your work area affect your productivity?		4	6	3	4	3	4	4
How do you think increasing the temperature in your work area by several degrees in warmer weather would affect your productivity?	1 = Strong negative effect; 4 = Neutral; 7 = Strong positive effect; 0 = I don't know	2	5	7	6	4	5	7
How do you think decreasing the temperature in your work area by several degrees in cooler weather would affect your productivity?		3	5	6	1	4	5	1
How do you think decreasing the ventilation in your work area would affect your productivity?		4	3	4	5	3	0	4
How do you think including operable windows in your work area would affect your productivity?		4	0	7	4	7	4	4
How do you think decreasing the amount of daylighting in your work area would affect your productivity?		4	2	1	4	3	2	2
How do you think increasing the amount of daylighting in your work area would affect your productivity?		4	5	7	4	5	4	4
How do you think automatically turning off overhead lighting in your work area when there is sufficient daylight would affect your productivity?		4	5	4	1	1	5	4

Table 19 (Continued)

RespondentID		2434857673	2434505183	2433360907	2431206899	2427574863	2427444506	2427321634
What is your job title?	Response	Graduate student	Graduate student	Graduate student	Faculty	Faculty	Graduate student	Faculty
	Other (please specify)							
How many hours a week do you spend at MCSI?	Response	10-20	10-20	>40	>40	>40	20-30	>40
In which area of the building is your primary work area located?	Response	2nd floor MCSI wing (grad student space or dry lab)	2nd floor MCSI wing (grad student space or dry lab)	3rd floor MCSI wing (grad student space)	2nd floor MCSI wing (grad student space or dry lab)	2nd floor Benedum Hall - North offices (facing O'Hara Street)	2nd floor MCSI wing (grad student space or dry lab)	2nd floor Benedum Hall - North offices (facing O'Hara Street)
Which option best describes your work area?	Response	Open office with partitions	Open office with partitions	Open office with partitions	Private office	Private office	Open office with partitions	Private office
	Other (please specify)							
Do you have outside views from your work area while either standing or seated, including windows above eye level?	Response	No	Yes	Yes	Yes	Yes	Yes	Yes
Which direction does the window face?	Response	North (O'Hara Street)	North (O'Hara Street)	North (O'Hara Street)	East (Thackeray Street)	North (O'Hara Street)	North (O'Hara Street)	North (O'Hara Street)
Is there a corridor or hallway between your seat and the nearest window?	Response	No	No	No	No	No	No	No
In my work area, I can personally adjust or control the following. (Check all that apply):	Daylight level i.e., with window blinds or shades	x		x	x	x	x	x
	Electric light level, i.e., with a switch or dimmer	x		x			x	x
	Air supply temperature i.e., with a thermostat				x			
	Air supply volume and/or direction i.e., with an adjustable vent							
	None of the above		x					
	Other							
During warmer weather, I am satisfied with the temperature in my work area.		5	4	4	4	1	6	4
During cooler weather, I am satisfied with the temperature in my work area.		4	4	6	4	5	6	4
I am generally satisfied with the temperature in my work area.		4	4	5	4	3	6	5
During warmer weather, I believe the air is too humid in my work area.		2	3	4	5	6	2	3
During cooler weather, I believe the air is too dry in my work area.		2	3	4	5	6	2	5
I am generally satisfied with the humidity in my work area.		6	5	4	5	6	6	5
During warmer weather, I am satisfied with the air flow speed (not too drafty or too stagnant) in my work area.		6	4	5	5	6	6	5
During cooler weather, I am satisfied with the air flow speed (not too drafty or too stagnant) in my work area.	1 = Strongly disagree; 4 = Neutral; 7 = Strongly agree	6	4	5	5	5	6	5
I am generally satisfied with the air flow speed (not too drafty or too stagnant) in my work area.		6	5	5	5	5	6	5
Recalling the previous questions related to temperature, humidity, and air flow speed, I am generally satisfied with the thermal comfort in my work area.		7	5	5	4	2	6	5
I believe the air in my work area is not stuffy or stale.		6	5	6	5	5	6	6
I believe the air in my work area is clean.		6	5	6	5	5	5	6
I believe the air in my work area is generally free from odors.		4	5	6	5	2	6	5
Recalling the previous questions related to stuffiness/staleness, cleanliness and odor, I am generally satisfied with the air quality in my work area.		6	5	6	5	2	6	5
What type of lighting is provided at your work area? (Check all that apply.)	Daylighting (sunlight entering the building through windows, glass roof, or glass doors)		x	x	x	x	x	x
	Overhead lighting (lighting provided by the fixtures on the ceiling or on the walls)	x	x	x	x	x	x	x
	Task lighting (lighting provided by personal fixtures at one's work area, such as desk lights)						x	x
	Other (please specify)							
My work area is too bright.		2	3	2	3	4	2	1
My work area is too dark.		2	3	3	6	4	2	1
There is an adequate amount of daylight in my area (leave blank if none).		2	5	6	5	6	5	7
There is an adequate amount of electric light in my area.	1 = Strongly disagree; 4 = Neutral; 7 = Strongly agree	4	5	6	6	6	7	7
There is a problem with glare, reflections or contrast in my work area.		2	4	5	4	3	2	1
Recalling the previous questions related to lighting and daylighting, I am generally satisfied with the lighting quality in my work area.		6	5	6	4	5	6	7

Table 19 (Continued)

RespondentID		2434857673	2434505183	2433360907	2431206899	2427574863	2427444506	2427321634
My work area is too loud due to other people's conversations.	1 = Strongly disagree; 4 = Neutral; 7 = Strongly agree	5	4	4	7	3	2	1
My work area is too loud due to background noise other than conversations (e.g. mechanical equipment, outdoor noises).		5	3	4	7	3	2	1
My work area is too quiet.		2	3	1	1	4	3	1
There is a problem with acoustics in my work area other than generally too loud or too quiet.		2	3	1	7	4	2	1
	If you agree, please explain:				Echos, conversations, etc. -- sometimes its hard to concentrate			
Recalling the previous questions related to acoustics, I am generally satisfied with the acoustical quality in my work area.	1 = Strongly disagree; 4 = Neutral; 7 = Strongly agree	4	5	5	1	6	6	7
How does the thermal comfort (remember, this includes temperature, humidity and airspeed) in your work area affect your productivity?	1 = Strong negative effect; 4 = Neutral; 7 = Strong positive effect	5	4	4	4	3	5	3
How does the air quality (remember, this includes stuffiness/staleness, cleanliness and odors) in your work area affect your productivity?		5	4	4	5	3	4	3
How does the lighting quality (remember, this includes both daylighting and artifical - both overhead, and task-based) in your work area affect your productivity?		7	4	6	6	6	6	4
How does the outdoor view, or lack of an outdoor view, in your work area affect your productivity?		7	4	6	7	7	4	4
How does the acoustical quality or noise level in your work area affect your productivity?		7	4	5	7	6	4	4
Recalling the previous questions related to indoor environmental quality (including thermal comfort, air quality, lighting and acoustics), how does the overall indoor environmental quality in your work area affect your productivity?		7	4	5	6	3	4	4
How do you think increasing the temperature in your work area by several degrees in warmer weather would affect your productivity?	1 = Strong negative effect; 4 = Neutral; 7 = Strong positive effect; 0 = I don't know	0	5	3	4	7	3	4
How do you think decreasing the temperature in your work area by several degrees in cooler weather would affect your productivity?		0	2	3	4	2	4	3
How do you think decreasing the ventilation in your work area would affect your productivity?		3	3	0	4	4	3	3
How do you think including operable windows in your work area would affect your productivity?		6	5	6	4	4	5	7
How do you think decreasing the amount of daylighting in your work area would affect your productivity?		3	1	2	6	3		1
How do you think increasing the amount of daylighting in your work area would affect your productivity?		6	7	6	6	4	5	4
How do you think automatically turning off overhead lighting in your work area when there is sufficient daylight would affect your productivity?		7	5	4	5	4	5	4

Table 19 (Continued)

RespondentID		2427240007	2427136288	2427076875	2427012322	2426972792	2426438141	2426408347
What is your job title?	Response	Staff	Graduate student	Graduate student	Graduate student	Staff	Graduate student	Faculty
	Other (please specify)							
How many hours a week do you spend at MCSI?	Response	>40	30-40	>40	>40	20-30	>40	>40
In which area of the building is your primary work area located?	Response	2nd floor MCSI wing (grad student space or dry lab)	2nd floor MCSI wing (grad student space or dry lab)	2nd floor MCSI wing (grad student space or dry lab)	3rd floor MCSI wing (grad student space)	First floor MCSI wing (Mascaro suite)	2nd floor MCSI wing (grad student space or dry lab)	2nd floor MCSI wing (grad student space or dry lab)
Which option best describes your work area?	Response		Open office with partitions	Open office with partitions	Open office with partitions	Private office	Open office with partitions	Private office
	Other (please specify)							
Do you have outside views from your work area while either standing or seated, including windows above eye level?	Response	Yes	Yes	Yes	Yes	No	Yes	Yes
Which direction does the window face?	Response	North (O'Hara Street)	North (O'Hara Street)	North (O'Hara Street)	North (O'Hara Street)		North (O'Hara Street)	East (Thackeray Street)
Is there a corridor or hallway between your seat and the nearest window?	Response	Yes	No	No	No	Yes	Yes	No
In my work area, I can personally adjust or control the following. (Check all that apply):	Daylight level i.e., with window blinds or shades	x		x	x		x	x
	Electric light level, i.e., with a switch or dimmer	x		x	x		x	x
	Air supply temperature i.e., with a thermostat							
	Air supply volume and/or direction i.e., with an adjustable vent							x
	None of the above		x					
	Other							
During warmer weather, I am satisfied with the temperature in my work area.		1	4	6	3		3	6
During cooler weather, I am satisfied with the temperature in my work area.		1	2	3	1		5	2
I am generally satisfied with the temperature in my work area.		1	3	3	1		4	5
During warmer weather, I believe the air is too humid in my work area.		4	4	2	3		1	2
During cooler weather, I believe the air is too dry in my work area.		6	3	5	3		1	2
I am generally satisfied with the humidity in my work area.		6	3	5	5		7	5
During warmer weather, I am satisfied with the air flow speed (not too drafty or too stagnant) in my work area.		1	3	6	5		6	5
During cooler weather, I am satisfied with the air flow speed (not too drafty or too stagnant) in my work area.	1 = Strongly disagree; 4 = Neutral; 7 = Strongly agree	1	3	6	5		6	5
I am generally satisfied with the air flow speed (not too drafty or too stagnant) in my work area.		1		6	5		6	5
Recalling the previous questions related to temperature, humidity, and air flow speed, I am generally satisfied with the thermal comfort in my work area.		1	3	4	2		5	4
I believe the air in my work area is not stuffy or stale.		4	3	6	7		6	6
I believe the air in my work area is clean.		4	4	6	7		6	4
I believe the air in my work area is generally free from odors.		1	4	6	7		7	5
Recalling the previous questions related to stuffiness/staleness, cleanliness and odor, I am generally satisfied with the air quality in my work area.		1	4	6	7		6	5
What type of lighting is provided at your work area? (Check all that apply.)	Daylighting (sunlight entering the building through windows, glass roof, or glass doors)	x	x	x	x		x	
	Overhead lighting (lighting provided by the fixtures on the ceiling or on the walls)	x	x	x	x		x	
	Task lighting (lighting provided by personal fixtures at one's work area, such as desk lights)	x						
	Other (please specify)							
My work area is too bright.		7	6	4	1		2	2
My work area is too dark.		2	2	4	1		2	2
There is an adequate amount of daylight in my area (leave blank if none).		4	5	3	7		6	6
There is an adequate amount of electric light in my area.	1 = Strongly disagree; 4 = Neutral; 7 = Strongly agree	4	7	6	7		6	6
There is a problem with glare, reflections or contrast in my work area.		1	7	3	1		2	2
Recalling the previous questions related to lighting and daylighting, I am generally satisfied with the lighting quality in my work area.		6	2	4	7		6	6

Table 19 (Continued)

RespondentID		2427240007	2427136288	2427076875	2427012322	2426972792	2426438141	2426408347
My work area is too loud due to other people's conversations.	1 = Strongly disagree; 4 = Neutral; 7 = Strongly agree	5	4	3	4		5	2
My work area is too loud due to background noise other than conversations (e.g. mechanical equipment, outdoor noises).		7	4	2	1		5	2
My work area is too quiet.		1	4	3	1		2	2
There is a problem with acoustics in my work area other than generally too loud or too quiet.		6	4	2	1		2	2
	If you agree, please explain:	constant noise from air duct that supply the whole floor MCSI and Benedum; poor workmanship (sound insulation) of the duct itself plus gaps and unsealed duct joints						
Recalling the previous questions related to acoustics, I am generally satisfied with the acoustical quality in my work area.	1 = Strongly disagree; 4 = Neutral; 7 = Strongly agree	1	4	5	6		5	6
How does the thermal comfort (remember, this includes temperature, humidity and airspeed) in your work area affect your productivity?	1 = Strong negative effect; 4 = Neutral; 7 = Strong positive effect	1	6	4	3		6	3
How does the air quality (remember, this includes stuffiness/staleness, cleanliness and odors) in your work area affect your productivity?		2	6	5	6		6	4
How does the lighting quality (remember, this includes both daylighting and artifical - both overhead, and task-based) in your work area affect your productivity?		5	7	4	6		7	4
How does the outdoor view, or lack of an outdoor view, in your work area affect your productivity?		4	7	3	6		7	5
How does the acoustical quality or noise level in your work area affect your productivity?		1	4	5	4		3	4
Recalling the previous questions related to indoor environmental quality (including thermal comfort, air quality, lighting and acoustics), how does the overall indoor environmental quality in your work area affect your productivity?		1	6	5	5		6	4
How do you think increasing the temperature in your work area by several degrees in warmer weather would affect your productivity?	1 = Strong negative effect; 4 = Neutral; 7 = Strong positive effect; 0 = I don't know	3	7	5	7		7	2
How do you think decreasing the temperature in your work area by several degrees in cooler weather would affect your productivity?		5	7	1	1		2	2
How do you think decreasing the ventilation in your work area would affect your productivity?		0	6	3	3		0	3
How do you think including operable windows in your work area would affect your productivity?		4	4	5	4		7	4
How do you think decreasing the amount of daylighting in your work area would affect your productivity?		0	7	1	1		1	4
How do you think increasing the amount of daylighting in your work area would affect your productivity?		0	7	7	6		7	4
How do you think automatically turning off overhead lighting in your work area when there is sufficient daylight would affect your productivity?		4	5	6	4		2	4

Table 19 (Continued)

RespondentID		2425689242	2425258234	2425246112	2425204363	2425191480	2425175758	2425022099
What is your job title?	Response	Undergraduate student		Graduate student	Graduate student	Graduate student	Graduate student	Graduate student
	Other (please specify)		research associate					
How many hours a week do you spend at MCSI?	Response	10-20	>40	30-40	30-40	20-30	30-40	30-40
In which area of the building is your primary work area located?	Response	3rd floor MCSI wing (grad student space)	3rd floor MCSI wing (grad student space)	3rd floor MCSI wing (grad student space)	3rd floor MCSI wing (grad student space)	3rd floor MCSI wing (grad student space)	3rd floor MCSI wing (grad student space)	2nd floor Benedum Hall - Wet Lab
Which option best describes your work area?	Response	Open office with partitions	Open office with partitions	Open office with partitions	Open office with partitions	Open office with partitions	Open office with partitions	Other (please specify)
	Other (please specify)							Open laboratory space
Do you have outside views from your work area while either standing or seated, including windows above eye level?	Response	Yes	Yes	Yes	Yes	No	Yes	No
Which direction does the window face?	Response	North (O'Hara Street)	North (O'Hara Street)	North (O'Hara Street)	North (O'Hara Street)		North (O'Hara Street)	
Is there a corridor or hallway between your seat and the nearest window?	Response	No	Yes	No	No	No	No	No
In my work area, I can personally adjust or control the following. (Check all that apply):	Daylight level i.e., with window blinds or shades		x	x	x		x	x
	Electric light level, i.e., with a switch or dimmer	x		x	x	x		
	Air supply temperature i.e., with a thermostat							
	Air supply volume and/or direction i.e., with an adjustable vent							
	None of the above							
	Other							
During warmer weather, I am satisfied with the temperature in my work area.		2	6	5	3	5	4	1
During cooler weather, I am satisfied with the temperature in my work area.		2	5	6	3	5	3	5
I am generally satisfied with the temperature in my work area.		2	6	6	4	5	3	3
During warmer weather, I believe the air is too humid in my work area.		3	3	1	3	2	2	4
During cooler weather, I believe the air is too dry in my work area.		3	6	2	3	2	2	2
I am generally satisfied with the humidity in my work area.		5	3	6	3	6	6	4
During warmer weather, I am satisfied with the air flow speed (not too drafty or too stagnant) in my work area.		5	5	6	5	4	3	5
During cooler weather, I am satisfied with the air flow speed (not too drafty or too stagnant) in my work area.	1 = Strongly disagree; 4 = Neutral; 7 = Strongly agree	5	5	6	6	4	3	5
I am generally satisfied with the air flow speed (not too drafty or too stagnant) in my work area.		5	5	6	6	4	3	5
Recalling the previous questions related to temperature, humidity, and air flow speed, I am generally satisfied with the thermal comfort in my work area.		3	6	7	4	5	3	3
I believe the air in my work area is not stuffy or stale.		6	6	7	5	5	6	6
I believe the air in my work area is clean.		6	6	7	6	5	6	5
I believe the air in my work area is generally free from odors.		6	6	7	5	5	6	5
Recalling the previous questions related to stuffiness/staleness, cleanliness and odor, I am generally satisfied with the air quality in my work area.		6	6	7	5	5	6	5
What type of lighting is provided at your work area? (Check all that apply.)	Daylighting (sunlight entering the building through windows, glass roof, or glass doors)	x	x	x	x	x	x	
	Overhead lighting (lighting provided by the fixtures on the ceiling or on the walls)	x	x	x	x	x	x	x
	Task lighting (lighting provided by personal fixtures at one's work area, such as desk lights)	x				x		
	Other (please specify)							
My work area is too bright.		2	5	3	2	1	2	3
My work area is too dark.		3	3	3	2	4	2	5
There is an adequate amount of daylight in my area (leave blank if none).		5	6	7	6	2	6	5
There is an adequate amount of electric light in my area.	1 = Strongly disagree; 4 = Neutral; 7 = Strongly agree	5	5	7	6	6	6	5
There is a problem with glare, reflections or contrast in my work area.		1	7	3	3	5	6	1
Recalling the previous questions related to lighting and daylighting, I am generally satisfied with the lighting quality in my work area.		5	5	7	6	3	6	4

Table 19 (Continued)

RespondentID		2425689242	2425258234	2425246112	2425204363	2425191480	2425175758	2425022099
My work area is too loud due to other people's conversations.	1 = Strongly disagree; 4 = Neutral; 7 = Strongly agree	3	7	3	3	2	3	3
My work area is too loud due to background noise other than conversations (e.g. mechanical equipment, outdoor noises).		3	5	4	6	2	6	3
My work area is too quiet.		3	2	1	6	5	2	2
There is a problem with acoustics in my work area other than generally too loud or too quiet.		3	4	1	2	2	2	3
	If you agree, please explain:							
Recalling the previous questions related to acoustics, I am generally satisfied with the acoustical quality in my work area.	1 = Strongly disagree; 4 = Neutral; 7 = Strongly agree	6	4	6	5	5	2	5
How does the thermal comfort (remember, this includes temperature, humidity and airspeed) in your work area affect your productivity?	1 = Strong negative effect; 4 = Neutral; 7 = Strong positive effect	3	5	4	3	3	3	2
How does the air quality (remember, this includes stuffiness/staleness, cleanliness and odors) in your work area affect your productivity?		5	6	4	5	5	6	4
How does the lighting quality (remember, this includes both daylighting and artifical - both overhead, and task-based) in your work area affect your productivity?		5	6	6	7	2	6	4
How does the outdoor view, or lack of an outdoor view, in your work area affect your productivity?		5	4	6	7	2	5	5
How does the acoustical quality or noise level in your work area affect your productivity?		4	4	4	3	4	5	5
Recalling the previous questions related to indoor environmental quality (including thermal comfort, air quality, lighting and acoustics), how does the overall indoor environmental quality in your work area affect your productivity?		4	5	5	5	3	4	4
How do you think increasing the temperature in your work area by several degrees in warmer weather would affect your productivity?	1 = Strong negative effect; 4 = Neutral; 7 = Strong positive effect; 0 = I don't know	6	3	4	6	3	4	1
How do you think decreasing the temperature in your work area by several degrees in cooler weather would affect your productivity?		1	5	4	2	1	2	1
How do you think decreasing the ventilation in your work area would affect your productivity?		4	4	5	3	4	5	1
How do you think including operable windows in your work area would affect your productivity?		4		4	5	4	6	1
How do you think decreasing the amount of daylighting in your work area would affect your productivity?		3	3	2	3	2	2	1
How do you think increasing the amount of daylighting in your work area would affect your productivity?		4	3	3	4	7	5	5
How do you think automatically turning off overhead lighting in your work area when there is sufficient daylight would affect your productivity?		3	4	4	4	0	4	4

Table 19 (Continued)

RespondentID		2424969194	2424967816	2424902461	2424885322	2424821753	2424790460	2424784869
What is your job title?	Response	Graduate student	Postdoctoral researcher	Graduate student	Faculty	Graduate student	Faculty	Faculty
	Other (please specify)							
How many hours a week do you spend at MCSI?	Response	30-40	>40	20-30	>40	20-30	>40	>40
In which area of the building is your primary work area located?	Response	2nd floor Benedum Hall - Wet Lab	3rd floor MCSI wing (grad student space)	3rd floor MCSI wing (grad student space)	3rd floor MCSI wing (grad student space)	2nd floor MCSI wing (grad student space or dry lab)	2nd floor Benedum Hall - East offices (facing plaza & Thackeray Street)	First floor MCSI wing (Mascaro suite)
Which option best describes your work area?	Response	Open office with partitions	Open office with partitions	Open office with partitions	Open office with partitions	Open office with partitions	Private office	Private office
	Other (please specify)							
Do you have outside views from your work area while either standing or seated, including windows above eye level?	Response	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Which direction does the window face?	Response	South (Fifth Avenue)	North (O'Hara Street)	North (O'Hara Street)	East (Thackeray Street)	North (O'Hara Street)	East (Thackeray Street)	North (O'Hara Street)
Is there a corridor or hallway between your seat and the nearest window?	Response	No	No	No	Yes	No	No	No
In my work area, I can personally adjust or control the following. (Check all that apply):	Daylight level i.e., with window blinds or shades		x	x		x	x	x
	Electric light level, i.e., with a switch or dimmer		x	x		x		x
	Air supply temperature i.e., with a thermostat		x		x			x
	Air supply volume and/or direction i.e., with an adjustable vent							
	None of the above	x						
	Other							
During warmer weather, I am satisfied with the temperature in my work area.		4	5	7	2	3	3	6
During cooler weather, I am satisfied with the temperature in my work area.		4	5	7	4	2	1	5
I am generally satisfied with the temperature in my work area.		4	5	7	3	2	2	6
During warmer weather, I believe the air is too humid in my work area.		2	3	7	4	1	4	2
During cooler weather, I believe the air is too dry in my work area.		3	5	7	4	5	4	6
I am generally satisfied with the humidity in my work area.		4	4		4	6	4	4
During warmer weather, I am satisfied with the air flow speed (not too drafty or too stagnant) in my work area.		4	5	7	2	7	4	6
During cooler weather, I am satisfied with the air flow speed (not too drafty or too stagnant) in my work area.	1 = Strongly disagree; 4 = Neutral; 7 = Strongly agree	4	5	7	2	6	4	6
I am generally satisfied with the air flow speed (not too drafty or too stagnant) in my work area.		4	5	7	2	6	4	6
Recalling the previous questions related to temperature, humidity, and air flow speed, I am generally satisfied with the thermal comfort in my work area.		4	5	7	3	3	2	6
I believe the air in my work area is not stuffy or stale.		4	6	7	4	7	4	6
I believe the air in my work area is clean.		4	6	7	4	7	3	6
I believe the air in my work area is generally free from odors.		6	6	7	4	7	3	6
Recalling the previous questions related to stuffiness/staleness, cleanliness and odor, I am generally satisfied with the air quality in my work area.		5	6	7	4	7	4	6
What type of lighting is provided at your work area? (Check all that apply.)	Daylighting (sunlight entering the building through windows, glass roof, or glass doors)		x	x		x		x
	Overhead lighting (lighting provided by the fixtures on the ceiling or on the walls)	x	x	x	x	x	x	x
	Task lighting (lighting provided by personal fixtures at one's work area, such as desk lights)				x		x	
	Other (please specify)							
My work area is too bright.		4	2	1	4	1	4	2
My work area is too dark.		4	2	1	4	1	2	2
There is an adequate amount of daylight in my area (leave blank if none).		4	7	7	4	5	2	6
There is an adequate amount of electric light in my area.	1 = Strongly disagree; 4 = Neutral; 7 = Strongly agree	5	6	7	4	7	6	6
There is a problem with glare, reflections or contrast in my work area.		3	5	5	4	4	1	2
Recalling the previous questions related to lighting and daylighting, I am generally satisfied with the lighting quality in my work area.		5	6	7	4	5	4	6

Table 19 (Continued)

RespondentID		2424969194	2424967816	2424902461	2424885322	2424821753	2424790460	2424784869
My work area is too loud due to other people's conversations.	1 = Strongly disagree; 4 = Neutral; 7 = Strongly agree	6	5	5	4	2	7	5
My work area is too loud due to background noise other than conversations (e.g. mechanical equipment, outdoor noises).		6	5	1	7	6	5	5
My work area is too quiet.		1	1	1	1	1	1	2
There is a problem with acoustics in my work area other than generally too loud or too quiet.		4	1	2	4	1	7	2
	If you agree, please explain:						too many hard reflective surfaces - entire area echoes	
Recalling the previous questions related to acoustics, I am generally satisfied with the acoustical quality in my work area.	1 = Strongly disagree; 4 = Neutral; 7 = Strongly agree	1	3	6	1	3	1	4
How does the thermal comfort (remember, this includes temperature, humidity and airspeed) in your work area affect your productivity?	1 = Strong negative effect; 4 = Neutral; 7 = Strong positive effect	4	4	6	4	3	4	4
How does the air quality (remember, this includes stuffiness/staleness, cleanliness and odors) in your work area affect your productivity?		4	5	6	4	4	4	4
How does the lighting quality (remember, this includes both daylighting and artifical - both overhead, and task-based) in your work area affect your productivity?		4	5	7	4	4	4	5
How does the outdoor view, or lack of an outdoor view, in your work area affect your productivity?		2	7	6	4	2	2	5
How does the acoustical quality or noise level in your work area affect your productivity?		1	4	2	1	3	2	3
Recalling the previous questions related to indoor environmental quality (including thermal comfort, air quality, lighting and acoustics), how does the overall indoor environmental quality in your work area affect your productivity?		3	5	6	2	3	3	4
How do you think increasing the temperature in your work area by several degrees in warmer weather would affect your productivity?	1 = Strong negative effect; 4 = Neutral; 7 = Strong positive effect; 0 = I don't know	5	4	4	7	6	5	2
How do you think decreasing the temperature in your work area by several degrees in cooler weather would affect your productivity?		2	4	1	1	2	1	4
How do you think decreasing the ventilation in your work area would affect your productivity?		4	4	0	2	0	3	3
How do you think including operable windows in your work area would affect your productivity?		6	6	5	4	6	5	7
How do you think decreasing the amount of daylighting in your work area would affect your productivity?		4	2	1	2	2	1	3
How do you think increasing the amount of daylighting in your work area would affect your productivity?		4	6	4	5	5	5	6
How do you think automatically turning off overhead lighting in your work area when there is sufficient daylight would affect your productivity?		4	6	4	1	4	0	4

Table 20 - Post-occupancy open-ended questions and responses

Question	Number of responses	Response text
Do you have any other suggestions for improving the MCSI building? If so, what are they?	23	Dimming light switches or automated dimming. Lower air flow rate (?) for less noisy air flow. Warmer temperatures in warm months, usually I am to cold in the office during warm months. During cold months, I am not too warm. I am sometimes still cold, but can add clothing and drink hot beverages. Also, modifying workspace orientation to use daylighting but reduce glare my be helpful.
		Noise reduction, better thermal control.
		N/A
		It is typically too cold most of the year, though it has been slightly better lately. There is constant white noise from possibly air vents that can be bothersome at times. It may be nice if we were allowed to dim the lights.
		The cubicles on the right side of the 3rd floor grad space often need electric lighting even though there is enough day lighting present. Theres a wide mismatch between day lighting present in cubicles by the window and those not by the window
		The timer on the motion sensor lighting is wayyy too short. It's very annoying to have to get up everyday when I'm working at my desk and put the lights back on.
		Auto light shut off in corridors and esp bathrooms is dangerous. In offices it is annoying to wave my arms around every 5 minutes. Sound is horrendous. Smells from Basement food court (burnt bagels) every morning makes me nauseous.
		Probably make it more scenic. As in put some plants around the building. Looking at concrete doesn't increase productivity for sure.
		The sensors on the automatic bathroom fixtures seem to be using more water than previous hand fixtures (ie. the toilet flushes multiple times for a single person's use)
		1. I would prefer to have a control over over my temperature directly in my office. (It is typically very cold in the summer.) 2. The odor of the cooking food from the kitchen downstairs is often way too strong and offensive (especially in the mornings). I often get severe headaches from the strong odors --It does impact my productivity.
		The kitchen on the basement that dumps strong odour and smoke of burning food. There is no ventilation on the kitchen area, so the second floor smell really bad for hours per day. Temperature difference between office (appr 70F), corridor (appr 60F) and bathroom (sometime 80F) do not create healthy environment. My place do not have temperature control, so I'm at mercy other's lab dwellers.
		Ventilation seems to be fine. I don't mind the room being a bit warmer and "normal" in the summer and a bit "cooler" than normal in the winter, but the problem I have is that the floor heating next to the window doesn't seem to be adequate, so in (very) cold weather the ventilation heating does not compensate for the heat loss through the windows, and the room is cold. Otherwise I'm happy with the conditions and control that i have in the room (the adjustable vent is nice to have).
		label the switches for the ceiling lights.
		It often feels too cold in the summer, when people are dressed for warmer weather anyway.
		I think having better food preparation and storage areas would improve user eating habits.
		More individual thermostat, lighting and, if possible, window control. Less fan noise and drafts.
		Turn the temperature up during cooler months. The lighting timing is fine (automatics) - although the lights themselves burn out a lot. I'm not sure if that is the type of light or the contractor used.
		Too noisy
		better noise insulation between external classroom area and office space
		Improve operation of HVAC system. Check if the level of noise in the office areas are within the safety limits established by OSHA.
		Provide more non-sky outside views in 2nd floor dry lab workspaces. Reduce vent noise in same area ceiling, which sounds like an rain storm at times.
		Too many to list - many aspects of the design have proven to be a dismal failure; not least of which is the net loss of space used to support the school missions when the intent of the renovation scheme was to increase space.
		I wish I could open the windows.
Do you have any suggestions for improving this survey? If so, what are they?	8	It didn't take 30 minutes, that was somewhat misleading to me, so the updated communication was helpful and encouraged me to participate knowing 15-20minutes was a more manageable expectation.
		N/A
		Discuss cleanliness, elevator malfunctions, bathrooms, water fountains, staircases, open spaces.
		The MCSI building has a conference rooms at each floor that are not included in survey
		Would be interesting to see correlation between how green occupants are (their knowledge about green buildings or how important they think energy use is) and how they respond to certain questions
		suggestions for common areas for leftover food, cutlery, etc; students in this area are very good about re-distributing, but collection of give-aways has become high with graduating students.
		You should ask what the occupants of the building think of those who designed the building. My opinion of them is strongly negative. The building might be friendly to environment but it is unfriendly, almost hostile to the occupants.
		There were no questions regarding raising the temperature in the winter (ie. problem with building being too cold in winter).

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