

University of Alberta

**Integrating Occupational Indoor Air Quality with Building Information
Modeling (BIM)**

by

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Abstract

The occupational indoor air quality (IAQ) during construction plays a major role in workers' health and safety as construction activities frequently generate airborne pollutants. Exposure to dusts, fumes, fibres and volatile organic compounds (VOCs) can cause health issues such as lung cancer, asthma and silicosis. The occupational exposure limits for hazardous airborne pollutants in the workplace is legislated by the Alberta Occupational Health and Safety Code. This thesis proposes a methodology to predict the occupational indoor air quality during construction activities utilizing Building Information Modeling (BIM). The single zone mass balance model was used to determine the indoor pollutant concentration; the model was integrated with BIM to calculate the air pollutant concentration during construction activities. This method allows the stakeholders to determine the indoor air quality before actual construction work. A case study demonstrates the proposed methodology during a drywall sanding activity to verify its effectiveness.

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Chapter 1: Introduction

1.1 Research Motivation

Research on occupational health and safety has become a demanding field for the construction industry. In 2007, around \$214 million capital was spent on the construction sector and in May 2010 approximately 469,200 people were employed in the construction industry (Statistics Canada, 2011). Maintaining safe and healthy work environment is important for the sustainability of the construction industry, while being challenging due to its diverse and dynamic nature (DOSH, 2011). Although there has been ongoing concern about worker safety and reducing accidents and deaths, the chemical hazards and potential long-term health effects of worker related exposure still need more attention (Pritchard, 2009; Methner et al., 2000). Exposure to dusts, fumes, fibres and volatile organic compounds (VOCs) can cause diseases such as lung cancer, asthma and silicosis (DOSH, 2011). According to the 2009 Workplace Health and Safety Data Analysis, occupational disease in 2009 was 44.5% of the total fatalities in Alberta, which is the highest in the last 10 years (Work Safe Alberta, 2009). In 2008, the fatal injuries within the construction industry were 8.7 out of 100,000 workers and non-fatal injuries were 2443 out of 100,000 workers (LABORSTA Internet, 2008). However, there is no data that addresses the occupational diseases within the construction industry. Therefore, there is a need for research into occupational health hazards to address these issues such as incorporate the occupational indoor air quality with construction management tools.

Currently in the United States, the National Institute for Occupational Safety and Health (NIOSH) and Occupational Safety and Health Administration (OSHA) have set recommended exposure limits (REL) and permissible exposure limit (PEL), respectfully, for the most common chemical substances during occupational exposure (NIOSH, 2009). The Government of Alberta also has an Occupational Health and Safety Code which sets the limit for hazardous air pollutants (Government of Alberta, 2009).

The advancement of computer modeling technology can significantly contribute to the field of occupational health and safety research such as the use of Building Information Modeling (BIM) technology. BIM has been identified as a useful technology for the architecture, engineering and construction (AEC) industry in recent years. This intelligent 3D model allows end users to make precise estimation of cost and schedule, share information among the stakeholders, and perform simulation within the 3D model (Kymmell, 2008). BIM is a technology that allows the construction manager to perform realistic simulation of construction work for planning purposes and improves the productivity of the construction industry. Currently, the concept of intelligent objects in the 3D model is mostly used for cost estimation and scheduling (Cyon, 2003). Recently, BIM was used to estimate the CO₂ footprint during single family house construction (Mah et al., 2010).

This thesis presents a methodology to quantify and assess the occupational indoor air quality (IAQ) during construction using BIM. The developed methodology incorporates the occupational indoor air quality parameter such as emission rate

and air exchange rate into the building elements within BIM. BIM incorporates a mathematical model that calculates the air pollutant concentration that can be compared with occupational exposure limits (OELs). By performing analysis on the occupational indoor air quality, the project managers can schedule activities according to what is best for the worker's exposure. Incorporating occupational air quality assessment into BIM will increase its value in the AEC industry and will help keep a healthy and safe working environment.

The proposed methodology was implemented in a case study where thoracic dust particle (PM_{10}) concentration was measured during drywall sanding activity using a personal environmental monitor. From the samples, the emission rate was quantified, and using Graphisoft's VICO Constructor and Estimator, the pollutant concentration was automatically calculated by incorporating the source emission rate and air exchange rate into the BIM model.

1.2 Research Objectives

The objective of this research is to develop a methodology that incorporates occupational indoor air quality into Building Information Modeling (BIM). To achieve this objective the following processes were followed.

1. Understand the effect of occupational health hazards on the workers during construction activities.
2. Develop a methodology to predict occupational indoor air quality during construction work to help workers select appropriate protective equipment and help managers to schedule work based on the indoor air quality.

3. Implement the proposed methodology using BIM technology.

1.3 Thesis Organization

Chapter 2 (Literature Review) reviews state-of-the-art literature on occupational health hazards, indoor air quality, and BIM. Chapter 3 (Proposed Methodology) presents the proposed methodology of incorporating the occupational indoor air quality into BIM. Chapter 4 (Case Study Implementation) discusses the implementation of the proposed methodology. Drywall sanding was taken as a case study and PM₁₀ concentration was predicted using BIM. Chapter 5 (Potential Application) discusses some potential applications of the proposed methodology in construction industry. Chapter 6 (Conclusion) summarizes the research and discusses its contributions, limitations, and scope for future research.

Chapter 2: Literature Review

2.1 Background and Current Practice

Every year a significant number of construction workers experience health-related issues such as back pain, lung cancer, asthma and hearing problems and also fatal injuries (LABORSTA Internet, 2008). There are health risk factors in construction work such as dynamic environments, unskilled workers, multiple contractors and subcontractors, simultaneous activities, and exposure to hazardous substances from nearby activities (DOSH, 2011). Because of multiple contractors, it makes more difficult to monitor and regulate health issues at the construction site. Indoor construction activities such as cement mixing, wood cutting, carpeting, painting, drywall sanding and insulating generate airborne pollutants that cause occupational diseases. Brick masons are exposed to cement particles, drywall sanders are exposed to dust containing silica, wood cutting produces wood dust, carpet layers are exposed to glue vapour and concrete and brick cutting activities generate dusts around workers' vicinity (DOSH, 2011). These activities take place in an indoor environment that decreases the occupational indoor air quality. Also, because construction activities often occur simultaneously, workers may be exposed to airborne pollutants caused by multiple activities. Figure 2.1 shows some construction activities that generate air pollutants.



Figure 2.1: Air pollutants generated from construction activities- (a) blowing concrete dust with compressed air; (b) drywall sanding; (c) brick cutting; (d) painting; (e) concrete cutting; (f) insulating fibres (DOSH, 2011)

Airborne particles can penetrate the human body by inhalation, absorption through the skin, and accidental swallowing. Respiratory protection is recommended during such activities. Work Safe Alberta provides an employer's guide to select appropriate respiratory protection system (Work Safe Alberta, 2009). According to Alberta's Health and Safety regulations, employers are required to take appropriate measures, such as engineering and administrative control, to keep the air pollutants at a controlled level. If respiratory protective equipment is used, the employers must identify the type of air pollutant and the concentration level to select the appropriate respiratory mask (Work Safe Alberta, 2009). However, in most cases, construction workers seldom use respiratory protection (Methner et al., 2000).

The NIOSH certified N95 respiratory mask shown in Figure 2.2 is the most commonly used respiratory protective equipment in construction work. "N" stands for 'not resistant to oil' and "95" refers to 95% filter efficiency (Public Health Agency of Canada, 2003).



Figure 2.2: Most commonly used respiratory protective mask- N95 respirator

2.2 Regulations on Occupational Health and Safety

In the 2009 Occupational Health and Safety Act, the Government of Alberta set occupational exposure limits (OELs) for hazardous airborne pollutants. Most hazardous substances have 8-hour exposure limits, which means the average concentration of that substance in an 8-hour working shift must be below the occupational exposure limit. There are also ceiling values for some more toxic substances and at any point of time their concentration must be below the ceiling value. According to the Occupational Health and Safety Code, employers must conduct a hazard assessment before work begins. The employers are responsible for keeping the harmful substance concentration as low as possible, so as not to exceed the substance OEL. If any worker is overexposed to a harmful substance, steps must be taken immediately to prevent further exposure to that substance. The employers must also inform the affected worker about the identity of the harmful substance, the concentration, duration of exposure, toxicological properties and potential health effects. A mechanical ventilation system should be provided if the concentration of the airborne contaminant exceeds or is likely to exceed the OEL (Government of Alberta, 2009).

2.3 Literature on Occupational Health Hazards

The Division of Occupational Safety and Health (DOSH) in the US published a study called Health Hazards in Construction in May 2011. DOSH categorized health hazards in construction into four categories: (1) Chemical hazards, (2) Physical hazards, (3) Biological hazards, and (4) Ergonomic hazards (DOSH,

2011). According to the study, silica, asbestos, lead, welding fumes, carbon monoxide, cadmium, and cutting oil mists are some of the most common chemical hazards on a construction site. These chemicals can be found in the form of Particulate Matter (PM) such as dust, fumes, fibres, liquid, gases, and vapour. These can enter the human body through inhalation, ingestion, and absorption by skin. Two types of health effects can occur from the exposure to chemical hazards: acute and chronic health effects. Acute health effects occur immediately or a short time after the exposure. This category includes headaches, collapse, or death due to high concentration of carbon monoxide. Chronic health effects develop slowly over time, and may take 15 – 20 years or more to show any symptoms. Usually, exposure to the chemicals for a prolonged period of time causes chronic health effects such as lung cancer, and silicosis (DOSH, 2011).

Health Canada defines airborne particulate matter (PM) as a mixture of chemically and physically diverse substances (Health Canada, 1987). The size of suspended particulate matter is defined by the aerodynamic diameter. For airborne PM it ranges from 0.005 to 100 μm . The US Environmental Protection Agency and other air pollution regulatory bodies categorize the PM into $\text{PM}_{2.5}$ and PM_{10} . Particles smaller than 2.5 μm are categorized as $\text{PM}_{2.5}$ and particles smaller than 10 μm are categorized as PM_{10} (Environmental Protection Agency, 1996). According to Health Canada the particles from 0.1 to 10 μm in aerodynamic diameter are the main concern for indoor air quality and human health.

Valavanidis et al. (2008) described the health hazards from particulate matter. The most common health effects from exposure are eye irritation, asthma, respiratory infections and excess mortality among elderly people. Research has suggested that PM also has adverse health effects at lower concentrations. Pope and Dockery (2006) elaborated on the health effects of fine particulate pollution. They state that fine particles $PM_{2.5}$ have the most adverse health effects on human body. Fine particles have a higher possibility of being more harmful as they can contain various chemicals on their surfaces and can go deep inside the lung alveoli. The thoracic PM_{10} particles can penetrate the thoracic region of the human body and can create negative health effects. Russell and Brunekreef (2009) suggested that PM is one of the prime factors for cardiovascular and respiratory-based health effects, both acute and chronic. In North America and Europe, the regulatory bodies mainly focus on the $PM_{2.5}$ particles, although it is not clear that particles up to $10\text{ }\mu\text{m}$ are less harmful.

The degree of health risk also depends on the extent and the nature of the exposure (Health Canada, 2007). Exposure to highly concentrated pollutants will cause greater harm to the human body, and the chemical composition of pollutants also plays a vital role. Some pollutants cause temporary eye or lung irritation, whereas other pollutants can cause long-term effects such as cardiovascular diseases.

Becker (2000) reported on the pilot studies in Columbus, Ohio and Denver, Colorado by NIOSH. The objective of the studies was to develop a methodology for the identification and quantification of the chemical and physical hazards in

construction. One of the main steps in the developed methodology was onsite sampling, and subsequent identification, of the pollutants during activities.

Methner et al. (2000) assessed the hazards associated with new residential construction using a task-based exposure assessment method (T-BEAM). The potential health hazard related to new residential construction was identified based on trades and their associated tasks and the air pollutant exposure during the tasks. Excavation, concrete work, carpentry, masonry, insulation, drywall, painting, and flooring were investigated by collecting air pollutant samples during the work to measure exposure levels. The research discovered that sanding of drywall joint compounds, insulation installation, lacquering, and soldering tasks were associated with overexposure. Workers used respiratory protection only during drywall sanding. The authors further discovered that most contractors and subcontractors were not as aware of the health hazard associated with noise and chemical exposures. They concluded that in single-family home construction the workers are overexposed to chemical agents when performing tasks.

NIOSH evaluated workers' exposures during drywall sanding activity in the Health Hazard Evaluation Report 94-0078-2660, 1997 (NIOSH, 1997). Samples were collected during sanding activity at an office building in Washington, D C. and at an apartment building in Buffalo, New York, and the concentration of total and respirable dust particles was measured. NIOSH RELs and OSHA PELs were used as the evaluation criteria. The results showed that total dust generated from sanding exceeded the exposure limit more often than the respirable dust. Eight samples out of 9 exceeded the OSHA PEL of 15 mg/m^3 for total dust, but only

two samples out of 13 exceeded the OSHA PEL of 5 mg/m³ for respirable dust. Samples were also analyzed for the presence of crystalline silica. Two of 6 samples from Washington D.C. and 15 of 22 samples from New York had respirable silica (as quartz). One of the samples exceeded the NIOSH REL of 0.05 mg/m³. The report also mentioned that dust generated from drywall sanding was termed as Particulates, Not Otherwise Classified (p.n.o.c.) based on the assumption that it did not contain any substance such as silica, talc, etc. If crystalline silica is present in the dust, the OSHA PEL would not be appropriate as the dust may affect the lungs. Long-term health effects due to exposure to drywall sanding dust are unknown.

Research was conducted to establish a protocol for characterizing contaminants during construction activities (Nguyen, 2001). A sampling protocol was developed for particulate concentration for several activities including drywall sanding. The contaminant emissions during drywall sanding were estimated by measuring concentration of Total Suspended Particles' (TSP) and Respirable Suspended Particles' (RSP) from the samples along with total volatile organic compounds (TVOCs). Drywall dust samples were collected from two sites in Ottawa, Canada during sanding activity. The contaminant emission rate was calculated from the measured concentration using a steady state mass balance model. The emission rates were 64.6 and 154 mg/m²/hr for the two TSP samples and 2.1 mg/m²/hr for both RSP samples.

Young-Corbett and Nussbaum (2009) performed a laboratory study to measure the dust control effectiveness of four different drywall sanding tools. These four

tools were: (1) ventilated sander, (2) pole sander, (3) block sander, and (4) wet sponge sander. Drywall dust was measured during sanding for each type of tool using two DUSTTRAK Sidepak AM510 Personal Aerosol Monitors. There was no ventilation during the sanding task and the duration of the measurement was equal to the sanding duration. Samples were taken for thoracic and respirable particles. In this study, the particles with an aerodynamic diameter less than 10 microns were classified as thoracic dust and less than 4 microns as respirable dust. The mean concentration of respirable dust for ventilated sander was 0.54 mg/m^3 , for pole sander was 1.93 mg/m^3 , block sander was 4.65 mg/m^3 and for wet sponge sander was 1.85 mg/m^3 . The mean concentration of thoracic dust for ventilated sander was 0.96 mg/m^3 , for pole sander was 3.13 mg/m^3 , block sander was 6.31 mg/m^3 and for wet sponge sander was 3.35 mg/m^3 . The results showed that a ventilated sander reduces respirable dust by 88% and thoracic dust by 85% more than a block sander. A pole sander reduces respirable dust by 58% and thoracic dust by 50% more than a block sander. And a wet sponge sander reduces respirable dust by 60% and thoracic dust by 47% more than a block sander.

Verma et al. (2003) studied the chemical exposures among construction workers in Ontario, Canada in 2000. The objectives of the study were a literature review on current chemical exposure assessments and performing air sampling during construction works. The task-based exposure assessment method (T-BEAM) was used for the exposure assessment. Air sampling equipment was attached to the workers to collect the air samples. The authors found that the Ontario construction workers were exposed to hazardous chemical substances during their tasks. The

laborers were exposed to respirable dust and respirable silica during concrete grinding, tearing out structures, and concentration of respirable dust varied from 0.56 to 34.3 mg/m³. The concentration of respirable silica ranged from 0.10 to 0.15 mg/m³. Masons were exposed to respirable dust and respirable silica during stone chipping and clean up and. The respirable dust concentration ranged from 0.61 – 1.84 mg/m³. Painters were exposed to respirable dust and total dust during cement mixing, paint mixing, and spraying paint. The respirable dust concentration ranged from 0.07 – 2.9 mg/m³ and total dust concentration ranged from 0.06 - 848 mg/m³. The most common pollutants were wood dust, abrasive blasting dust, gypsum and alkaline dusts, silicates, diesel exhaust, and welding fumes. Also, some limitations of the T-BEAM were observed: due to the short sampling duration, it was often difficult to obtain detectable concentrations of the chemical contaminants.

2.4 Health Hazard Assessment for Airborne Pollutants

The effect of airborne pollutants on the human body largely depends on the particle size and chemical composition. The most common classifications for hazardous airborne dust particles are inhalable, thoracic and respirable. Inhalable particles are less than 100 microns in diameter and can enter the body through inhalation as deep as the nose and mouth region. Thoracic dusts pass through the nose and throat and can deposit anywhere within lung airways and the gas exchange region. Respirable dust can penetrate into the gas exchange region of the lungs.

Particle size is categorized based on a 50% cut point at a specific aerodynamic diameter (e.g. 2.5 μm or 10 μm) (Pope and Dockery, 2006). Particles that are less than 10 μm are considered to be thoracic dust, and particles less than 2.5 μm are considered to be respirable (Kumar, 2008; Valavanidis et al., 2008; Environmental Protection Agency, 1996). In some studies, particles less than 4 μm were considered to be respirable particles (Nguyen, 2001; Young-Corbett and Nussbaum, 2009). Recent studies have shown that thoracic and respirable dusts are the most health hazardous because they can reach the lungs and gas exchange region of the human body. Figure 2.3 shows different regions of a human respiratory system based on how deep particulate matters (PM) can enter the body.

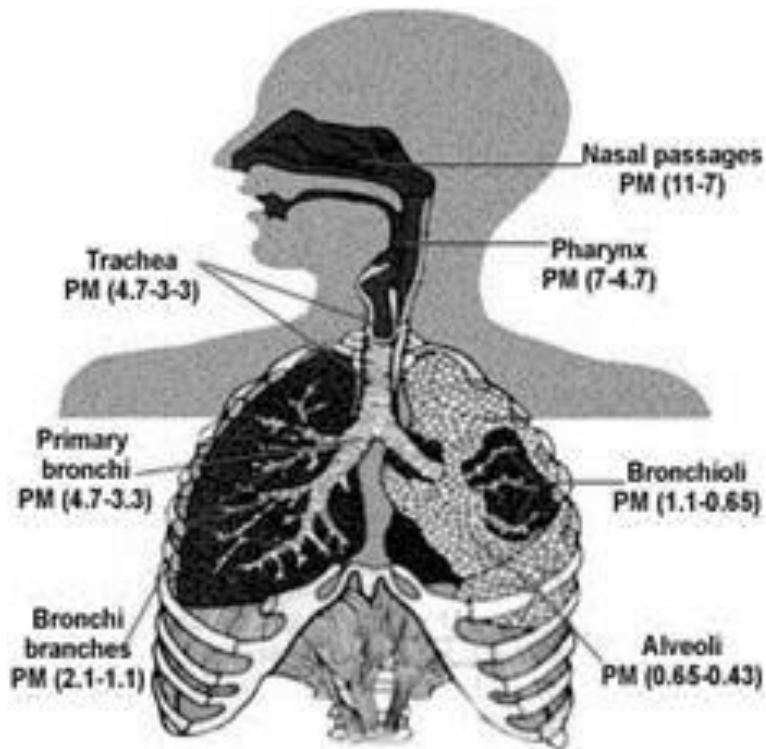


Figure 2.3 Human respiratory system (Kumar, 2008)

The air pollutant concentration within workers' vicinity is dependent on the emission rate of the pollutants from hazardous activities and the ventilation rate of the working area. The emission rate depends on the type and volume of activity, and the ventilation rate depends on the air exchange rate, which depends on the building envelope system. Several other factors, such as the types of tools and number of workers in the area, affect the occupational indoor air quality during activities. Figure 2.4 shows the major factors that affect indoor air quality and human health.

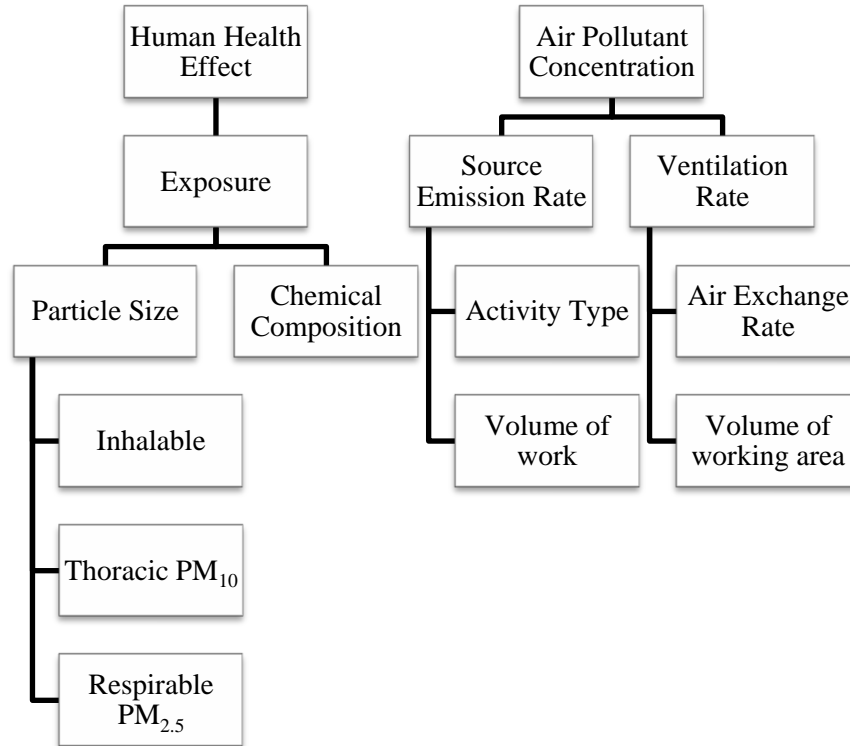


Figure 2.4 Factors affecting the indoor air quality and human health

To summarize, the key factors that affects the IAQ during construction activities are: 1) activity type and volume of work; 2) source emission rate; 3) air exchange rate; and 4) volume of working area. These factors determine the pollutant concentration during an activity. The extent of the human exposure depends on the particle size and chemical composition.

2.5 Literature on IAQ

Bai et al. (2005) studied the emission of ammonia from indoor concrete walls and assessed human exposure. The authors investigated the influence of temperature, relative humidity, and air exchange rate on the emission of ammonia by using a small environmental chamber to simulate a room. Two similar field experiments were performed in a residential apartment building. The recorded ammonia

concentration values and data on human health effects were used to calculate and evaluate the exposure to ammonia during the summer and winter using a scenario evaluation approach. An assumption was made that the chamber was in a steady state condition. Ventilating experiments were carried out in the undecorated, airtight room in the apartment building. The ammonia concentration was monitored for different air exchange rates. The average ammonia concentration in a case room during summer was 3.55 mg/m^3 in airtight condition and 0.745 mg/m^3 in ventilating condition. In winter the ammonia concentration for the same room was 2.27 mg/m^3 in airtight condition and 0.355 mg/m^3 in ventilating condition. Using the mass balance model the emission rates were calculated for various levels of air exchange rate. One of the conclusions made by the authors was that ventilating or improving the air exchange rate would significantly improve the indoor air quality.

Hodgson et al. (2000) carried out research on the concentration and emission rates of total and selected VOCs, including formaldehyde in newly manufactured and site-built houses. Also, the authors identified the sources of specific VOCs and substituted them to reduce the VOC concentration. Four manufactured and seven site-built houses in the US were selected for the study. The air sampling was performed during periods when ventilation rates were relatively constant and near a steady-state condition. It ranged from 0.14 to 0.78 hr^{-1} . The ventilation rate was identified as one of the dominant factors of indoor air quality. It serves as the primary mechanism for the removal of gaseous contaminants indoors. New construction houses have a tighter building envelope system, which lead to lower

ventilation rates. This improves energy efficiency, but decreases indoor air quality by lowering the air exchange rate. The VOC emission rates were calculated using a mass balance model, assuming steady state conditions and perfectly mixed air. Emission rate of Formaldehyde was calculated as $29 \mu\text{gm}^{-2}\text{hr}^{-1}$, Hexanal was $212 \mu\text{gm}^{-2}\text{hr}^{-1}$, Heptanal was $11 \mu\text{gm}^{-2}\text{hr}^{-1}$ and so on. Losses of VOCs due to factors other than ventilation were ignored as the model does not consider other factors.

2.6 Implementation of Mass Balance Model to Calculate Emission Rate

The Lawrence Berkeley National Laboratory (LBL) carried out a study on the chemically specific emission factors of imported drywall from China (LBL, 2009; Maddalena et al., 2010). The samples were collected in small test chambers in a steady state condition. After the sample collection, a single zone mass balance model was used to calculate the emission rate. Perfectly mixed air was assumed in the chamber. No mechanical ventilation was present and indoor air was replaced by natural ventilation. The air exchange rate was 0.15 h^{-1} . The emission rate varied from 6.1 to $52.9 \mu\text{g}/\text{m}^2/\text{hr}$ for 17 drywall samples. Kerr (1993) used a similar mass balanced model to calculate the chemical emissions during the re-carpeting of a Canadian office building. With air exchange rate of 11.9 hr^{-1} and TVOC concentration of $8.7 \text{ mg}/\text{m}^3$, the emission rate was obtained as $104 \text{ mg}/\text{m}^2/\text{hr}$ for the re-carpeting process. Nguyen (2001) used a mass balance model to calculate the emission rate of total and respirable dust during drywall sanding activity and the emission rates were 64.6 and $154 \text{ mg}/\text{m}^2/\text{hr}$ for the two TSP samples and $2.1 \text{ mg}/\text{m}^2/\text{hr}$ for both RSP samples. Scheff et al. (2000) used a mass balance model to transform measured concentrations into emission rates in a

study of indoor air quality in a middle school. Emission rates varied from 23 to 472 mg/hr for total particles and 11.4 – 71 mg/hr for respirable particles.

2.7 Determinants of Air Exchange Rate in Residential Buildings

Johnson et al. (2004) carried out a pilot study on a single-family test house to determine the key factors affecting the air exchange rate (AER). Sixty-six air exchange rates were collected which varied from 0.36 to 15.8 h⁻¹. When all exterior doors and windows were closed, the AER varied from 0.36 to 2.29 h⁻¹, and when all doors and windows were opened, it varied from 0.50 to 15.8 h⁻¹. The authors found from the test data that AER increases with the number of open windows and doors and is also affected by temperature and wind speed. Wallace et al. (2002) did a one-year study to document the change in AER due to temperature, wind, use of fans, and window opening, and developed a database of the distribution of AER. The mean AER was 0.65 h⁻¹. The authors also addressed that recent houses are built more tightly, resulting in a lower air exchange rate. The determining factor for AER was found to be the window openings, while the wind speed and direction had little effect.

2.8 Building Information Modeling

The advancement of computer technology and 3D modeling software has opened a range of opportunities to the construction industry through the utilization of Building Information Modeling (BIM) (Mah et al., 2010). The concept of BIM has been incorporated into Autodesk software since 2002 (ASHRAE, 2009). It is an innovative new modeling approach for the Architecture, Design and the

Construction industry (Nguyen et al., 2010). According to Fauerbach, BIM is a technology which shares an intelligent and computable 3D data sets among all project participants (Sah and Cory, 2009). National BIM Standards (NBIMS) has defined BIM as “the virtual representation of the physical and functional characteristics of a facility from inception onward. As such, it serves as a shared information repository for collaboration throughout a facility’s lifecycle.” Graphical elements, such as drawings and non-graphical elements, such as cost, schedule, and environmental impact, can all be shared within the BIM and changes in any data need to be made only once (Cyon, 2003). This results in fewer communication problems between project participants and higher efficiency. The main feature of BIM is its knowledge database and intelligent objects that can be used to quantify the project cost, schedule, CO₂ footprint, and other information (Sah and Cory, 2009).

2.9 Application of BIM in Construction

Nguyen et al. (2010) developed a methodology to evaluate sustainability for architectural designs which incorporate BIM. The framework used the LEED (Leadership in Energy and Environmental Design) green building rating system to evaluate the sustainability, and BIM technology to extract supporting data and information from the model to perform the evaluation. The proposed methodology included inputs such as 3D model, which are analyzed based on criteria, such as standards and guidelines. Finally, the framework provides output, such as the magnitude of the sustainability assessment. The authors implemented the proposed methodology on a hotel project using Autodesk Revit 2010. The

sustainability indicator (LEED criteria) was created and stored as a parameter in BIM. VB.Net was also used to collect information required for the LEED assessment. The system then computed the project's maximum possible points regarding LEED ratings.

Mah et al. (2010) quantified the CO₂ footprint in residential construction using BIM. The authors collected information on the source of CO₂ emission in a construction site. The construction process was divided into seventeen distinct stages and the CO₂ emission for each stage was measured. A repository was created for CO₂ emission and was linked with parametric objects in BIM. The BIM sent the objects' quantity takeoffs to an intelligent repository and calculated the emission for every object of the model, which depended on the activities related to the object. The BIM allowed rapid calculation of the CO₂ footprint for different construction processes, e.g., onsite stick-built or panelized construction, and various house sizes.

Roorda and Lui (2008) presented the use of BIM on the renovation of the Edmonton Art Gallery. Autodesk Revit was used to implement BIM. The authors addressed several obstacles regarding the implementation of BIM in a complex project such as the Art Gallery. These included the hosting of the master building information model, software limitations regarding modeling complex geometry and conflict detection, and file sharing problems. However BIM helped to detect conflict between systems, e.g., conflict between structural and mechanical systems. It also helped to monitor any changes within the model.

2.10 Benefits of BIM Technology

Azhar et al. (2008) reviewed studies on BIM benefits, risks, and future challenges, and also presented a case study to demonstrate the cost and time savings associated with BIM usage on a project. The authors pointed to the main benefits of BIM as better design, better project control as cost estimation and scheduling become faster and more accurate, better customer service, and easier sharing of information. Based on 32 BIM projects, the Stanford University Center for Integrated Facilities Engineering (CIFE) showed that BIM can reduce project time by 7%, increase cost accuracy by 3%, reduce the cost estimation time by 80%, and eliminate unbudgeted changes up to 40% (Azhar et al. 2008). The case study was performed with data provided by Holder Construction Company, Atlanta, Georgia. BIM was used in architectural and structural design and MEP systems during the design and construction phase. The analysis illustrated that BIM saved approximately \$200,392 and 1143 labour hours. Khemlani (2007) performed a survey to identify what AEC professional is desired in BIM. The key issues included the production of documents as a replacement the drafting application, smart objects and object library, and industry foundation classes (IFC) compatibility. Figure 2.5 shows different components of a building information model.

construction, BIM was used for maintenance and repair purposes, and punch list administration.

Summary

There has been ample research on occupational health and safety, indoor air quality and BIM. The single zone mass balance model has been used extensively in studying indoor air quality to quantify emission rates. However, there has been no initiative to use the concept of BIM in the field of occupational health and safety. This thesis integrates the occupational indoor air quality into BIM and uses the concept of intelligent objects to incorporate the occupational health hazard into BIM.

Chapter 3: Proposed Methodology

3.1 Introduction

This chapter summarizes the proposed methodology which provides the basic framework to quantify occupational indoor air quality during construction activities and incorporate the occupational indoor air quality assessment into BIM.

3.2 Proposed Methodology

The proposed methodology to incorporate occupational indoor air quality with BIM, as illustrated in Figure 3.1, consists of input parameters, system main process, criteria, and outputs. The system main process generates outputs based on the criteria and input parameters. The system main process is built on three pillars: 1) Development of the methodology to quantify and assess the occupational indoor air quality during construction activities; 2) Quantification of the mass balance model parameters by performing onsite air pollutant sampling; and 3) Integration of occupational indoor air quality assessment into the Building Information Model (BIM).

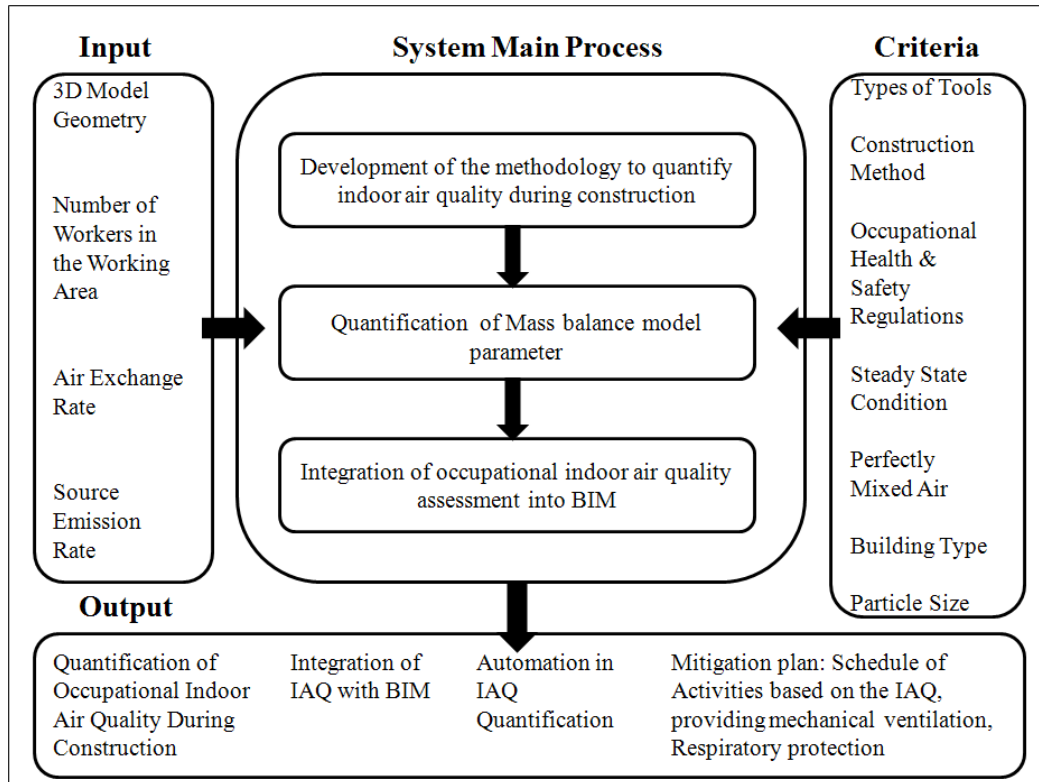


Figure 3.1 Proposed methodology

The input parameters include a 3D model which provides the geometry, source emission rate, number of workers in the working area and air exchange rate of the building envelope. The output of the proposed methodology includes: quantification and assessment of occupational indoor air quality during construction, integration of IAQ with BIM, automation in indoor air quality quantification and mitigation plan such as scheduling of activities based on pollutant concentration. The output of the proposed system must satisfy criteria, including the types of tools; construction method, such as stick-built or modular construction; occupational health and safety regulations; the steady state condition and perfectly mixed air in the indoor area; and type of building, e.g. industrial, commercial, residential, and air pollutant type such as VOCs, PM₁₀, PM_{2.5}.

3.2.1 Quantification and Assessment of Occupational IAQ

As illustrated in Figure 3.2, quantification of the occupational indoor air quality starts with the selection of the construction activity. This activity is monitored to identify the airborne air pollutant that is generated. After the identification of the airborne pollutant, the concentration of that pollutant during the activity will be predicted using the mass balance model.

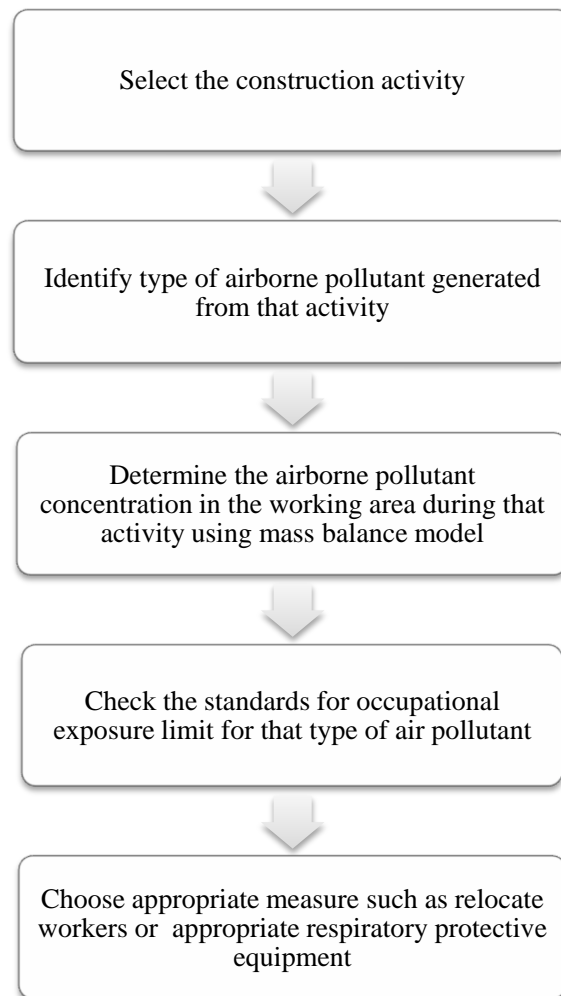


Figure 3.2: Quantification and assessment process for occupational indoor air quality

The airborne pollutant emission rate during activity, air exchange rate of the working area, room volume, and volume of the activity will be the input parameters in the mass balance model. The predicted pollutant concentration will then be compared to standards, such as occupational exposure limit or permissible exposure limit. Depending on the result, mitigation measures can be taken. Appropriate respiratory protective equipment can be selected based on the pollutant concentration (Work Safe Alberta; 2009). Research has shown that indoor air quality can also be improved by providing better ventilation systems (Hodgson et al., 2000).

3.2.2 Mass Balance Model

The pollutant concentration in typical indoor air depends mainly on factors such as the source emission rate, air exchange rate, ventilation type, building type, and season (Salonen et al., 2009). The single zone mass balance model can be used to quantify the emission rate of the source during construction activities. If the pollutant concentration during an activity is known, along with the surface area of the source, volume of the room and air exchange rate, the source emission rate can be quantified satisfying Equation (3.1).

$$ER = C \times AER \times (V/S) \text{ ----- (3.1)}$$

Where,

ER = Emission rate (mg/m²/hr)

C = Concentration of air pollutant (mg/m³)

AER = Air Exchange Rate (1/hr)

S = Surface Area of the building object that generate pollutants (m^2)

V = Volume of the area where the activity takes place (m^3)

There are two criteria that have to be satisfied for this model: steady state condition and perfectly mixed air. This model does not consider the settling effect of the pollutant with time. The concentration of the pollutants was measured close to the source during the activities in order to minimize the settling effect. Also, larger particles settle more quickly while smaller particles remain in the air for longer periods of time. However, the main focus of this study is to determine the occupational exposure to the smaller particles such as thoracic, respirable particles, as these are more harmful to the human body and remain in the air for a longer period of time.

3.2.3 Mass Balance Model Parameter Quantification

The source emission rate is one of the key determining parameters in pollutant concentration. The emission rate quantification process is described in Figure 3.3.

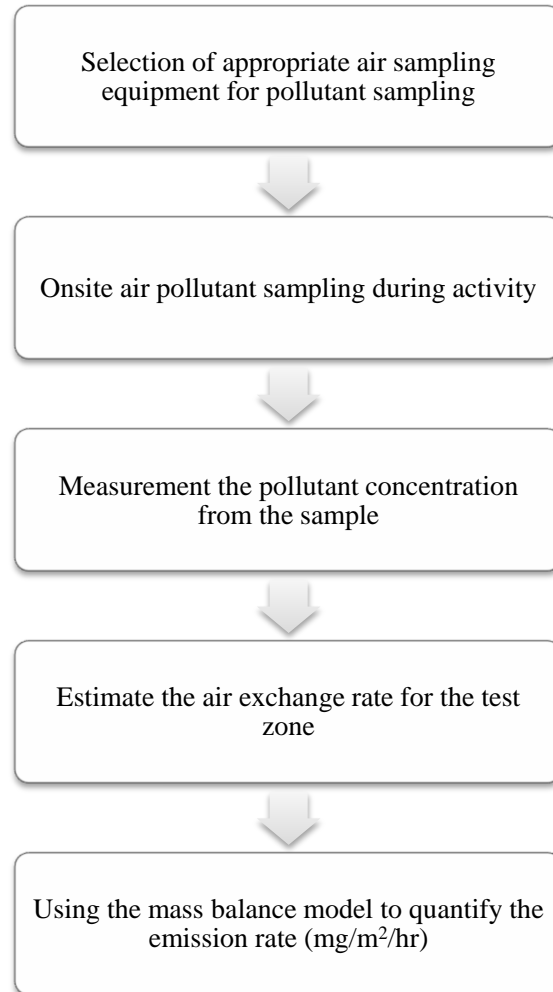


Figure 3.3: Flowchart to quantify the emission rate

The task-based exposure assessment method (T-BEAM) is followed for the quantification of the air pollutant emission rate. First, the appropriate sampling equipment was selected to collect air pollutant samples during activities. The sampling equipment was chosen to represent the workers' exposure to hazardous

particulates as accurately as possible. The air pollutants were collected on a filter paper during construction activities. After sampling, the filter paper was weighted to measure the concentration of the pollutants. Then the air exchange rate was estimated for the test zone depending on the building type and time of the year when the test was performed. From this data, and the mass balance model, the emission rate of that air pollutant for that activity was quantified for the number of workers working in the test zone. The emission rate value was normalized for one worker based on the assumption that pollutant emission rate becomes double for two workers working on the activity in that area. This process can be applied to measure the emission rate of different types of air pollutants such as thoracic or respirable particles, or VOCs generated during various construction activities.

3.2.4 Integration of Occupational IAQ Assessment into BIM

BIM has become a useful technology in the AEC industry for data sharing and the automation of the estimation process. The model contains information about cost, and schedule which are assigned to building elements. These model elements are called intelligent objects as they are used for cost estimation and information sharing among the stakeholders. The occupational indoor air quality assessment follows the same process and allows the 3D model to generate pollutant concentration during any activity in a working area.

The mass balance model (Equation 3.1) uses mathematical formula which is used to link the occupational indoor air quality assessment to the BIM model. In cost estimating, the unit price of building material, labour and equipment are

integrated with the associated building elements; the BIM model calculates the total cost of the project by extracting the necessary geometry from the 3D model. To incorporate IAQ into BIM, the source emission rate of the airborne pollutant and air exchange rate will be used similarly to the unit cost rate to calculate the air pollutant concentration during construction activities.

Equation (3.1) is divided into two parts to calculate the total emission rate per hour and the ventilation rate of the working area, satisfying Equation (3.2) and Equation (3.3) respectively.

$$TER = ER \times S \times N \text{ ----- (3.2)}$$

$$VR = AER \times V \text{ ----- (3.3)}$$

Where,

TER = Total Emission rate of airborne pollutants per hour (mg/hr)

ER = Emission rate for one worker working in the area (mg/m²/hr)

S = Surface Area of the building object that generates pollutants (m²)

N = Number of workers in the working area

VR = Ventilation Rate (m³/hr)

AER = Air Exchange Rate (1/hr)

V = Volume of the area where the activity takes place (m³)

Number of workers in the working area is incorporated into Equation (3.2), as emission rate will increase with more workers working on the activity in the area. The source emission rate will be linked to the model element, and the BIM will extract the surface area of the activity from the 3D model and calculate the total

emissions per hour for the airborne pollutant during that activity satisfying Equation (3.2). Similarly, the working area's air exchange rate will be linked to the model element, and the BIM will extract the room volume from the 3D model and calculate the ventilation rate during the activity satisfying Eq. (3.3). From the total emission rate per hour and ventilation rate, the air pollutant concentration will be calculated satisfying Equation (3.4).

$$C = \text{TER} / \text{VR} \text{ ----- (3.4)}$$

Where,

C = Concentration of air pollutant (mg/m³)

TER = Total Emission rate of airborne pollutant per hour (mg/hr)

VR = Ventilation Rate (m³/hr)

Figure 3.4 illustrates the process of calculating the pollutant concentration using BIM.

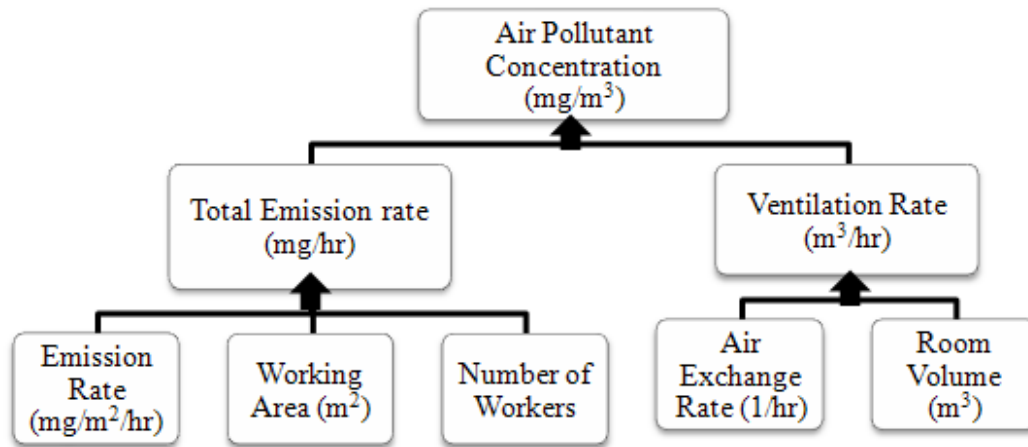


Figure 3.4: Process of calculating air pollutant concentration using BIM

The air pollutant concentration during the construction activities needs to be calculated separately based on different working areas. For example, the air pollutant concentration for Room#1 and Room#2 during Activity X should be calculated separately. This is one of the basic differences between cost estimation and indoor air quality assessment. In cost estimation, the costs per building element are added to estimate the total project cost, while during indoor air quality assessment the airborne pollutant concentration will be calculated for each working zone during the activities based on the assumption that there is negligible exchange of pollutant between the working zones. Using this framework, the concentration levels of various airborne pollutants, such as $PM_{2.5}$, PM_{10} and VOCs can be determined during construction based on their emission rates.

3.2.5 Output of the BIM Model

The BIM model will predict the air pollutant concentration during construction activities using the mass balance model and the 3D model. Construction managers can vary the number of workers in a particular area or lower the production rate if the pollutant concentration exceeds the permissible limit as it will also reduce the pollutant emission rate. If more than one activity takes place at the same time in an area and both generate air pollutants, based on the pollutant concentration determined by the model, these activities can be scheduled in a way that the pollutant concentration stays within the permissible limit.

Summary

The proposed methodology quantifies and assesses the occupational indoor air quality during construction activities and incorporates the assessment into BIM using the emission rate of the pollutants from the construction activities. The emission rate quantification process is designed based on the task-based exposure assessment method (T-BEAM). The mass balance model is used as a mathematical model to link the emission rate and ventilation rate parameters into BIM. The framework uses different input parameters within certain criteria and gives the output of air pollutant concentration in compliance with the occupational health and safety regulations.

Chapter 4: Case Study Implementation

4.1 Introduction

This chapter describes the case study implementation of the proposed methodology. The case study focuses on the drywall sanding process of a single-family house, the emission rate quantification process of the thoracic (PM₁₀) dust generated from drywall sanding, and the linking of the thoracic dust emission rate and ventilation rate into the Building Information Model using VICO Constructor and Estimator software.

4.2 Drywall Sanding in Construction

The sanding of drywall joint compounds has been identified as a health hazardous activity in the building construction process (Nguyen, 2001; NIOSH, 1997; Young, 2007). The process of drywall construction includes the placement of drywall board, taping and mudding, sanding of the joint compounds, and painting (Young, 2007). The joints between the drywall board panels are taped and mudded using the joint compound. The joint compound contains crystallize silica and the sanding of joint compounds produces inhalable, thoracic and respirable dust particles. Several research studies have discovered that the concentration of the dust generated from sanding activities is above the permissible exposure limit set by OSHA (Nguyen, 2001; NIOSH, 1997; Young-Corbett et al., 2009; Methner, 2000).

4.3 Emission Rate Quantification

The quantification process of the air pollutant emission rate involves sampling onsite air pollutants and measuring the pollutant concentration using the mass balance model equation. The sampling and quantification process includes selecting the appropriate sampling device which captures the workers' exposure to the airborne pollutant during construction work. In this case study, the Personal Environmental Monitor (PEM) was used to collect thoracic (PM₁₀) dust particles during drywall sanding. The emission rate of the thoracic dust was quantified from the measured concentration using the mass balance model equation. The detailed sampling and quantification process is described in the following sections.

4.3.1 Equipment Selection and Setups

The PEM was used as the sampling device. There are different types of PEM devices for PM_{2.5} and PM₁₀ sampling. Each type of device has a different flow rate requirement. Figure 4.1 shows the PEM device used in the sampling of thoracic PM₁₀ dust particles.



Figure 4.1: PEM device for PM₁₀ sampling (Manufacturer: MSP Corporation)

The sampling device consists of three major parts: nozzle cap, impactation ring assembly, and base. The cap has round nozzles through which the air enters the sampler. The impactation ring assembly provides the impactation surface and also serves as a clamping ring for the after-filter. The base supports the after filter. A schematic diagram of the sampler is shown in Figure 4.2.

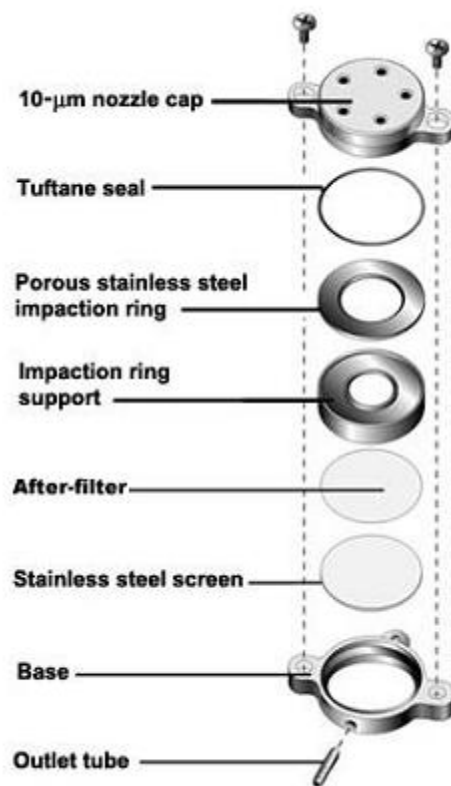


Figure 4.2: Schematic diagram of personal environmental monitor (PEM) (SKC Inc.)

When aerosol particles pass through the nozzle cap, the particles above the 50% cut-point of either 2.5 or 10 μm in aerodynamic diameter are collected on the impaction ring. The smaller particles, i.e. below 50% cut-point, pass through the impactor and are collected on a 37-mm after-filter. The filter can be analyzed gravimetrically for particle mass, or chemically for specific chemical compounds to determine personal exposure. A portable pump was attached to the sampling device to create the necessary airflow through the PEM.

The main principle of the PEM's operation is inertial separation of airborne particles using an impactor. Particle-laden air travels into the sampler through the nozzles, and due to inertia, the larger particles cross the airstreams, impact, and

are retained on the impaction ring. The smaller particles pass through and are collected on the after-filter. Oil or grease is applied to the impaction ring's surface to prevent the particles from bouncing off. As drywall sanding releases large particles, grease was applied instead of oil on the impaction ring's surface to affix the particles. Before every sampling, the impaction ring was cleaned with cyclohexane solvent and re-greased. For the PEM, a 37 mm PTFE (Polytetrafluoroethylene) filter is specified. A 37-mm Type A/E Glass Fiber Filter was used for the sampling. The nominal pore size of the filter paper was 1 μm . The empty filters were dried in a desiccator for 24 hours and then weighted on a microbalance. Gloves and forceps were used during the handling of the filter papers. A petri slide is used for storing and transporting the filter papers.

The GilAir-5 Air Sampling Pump (Figure 4.3) provided the required airflow through the PEM. The portable pump is battery operated, capable of generating a flow rate up to 5 lpm (litres per minute). Each PEM device has a specified pump flow rate based on the PM_{10} or $\text{PM}_{2.5}$ cut point. The PEM used in the sampling had the required flow rate of 4 lpm. A digital timer is integrated with the pump to record the sampling time.

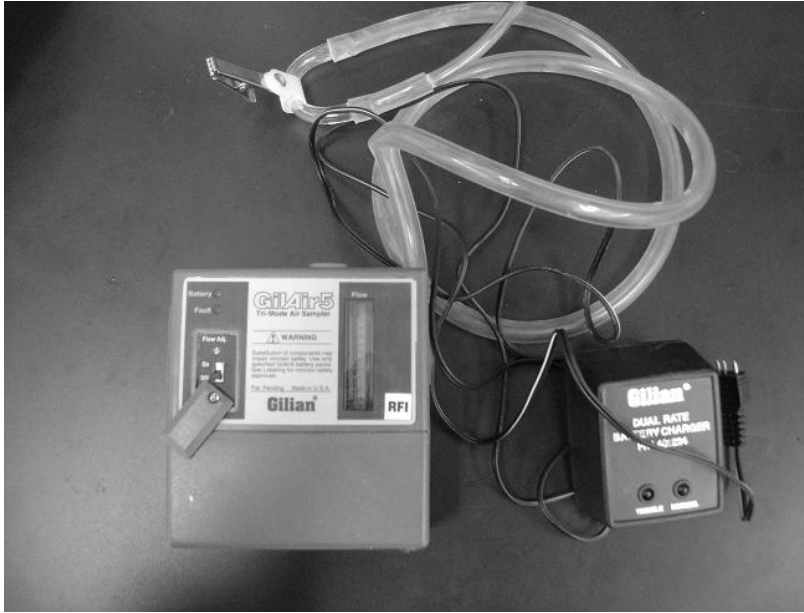


Figure 4.3: GilAir-5 air sampling pump

4.3.2 Description of the Sampling Site

The sampling was performed in a two story, single-family home with a basement in Edmonton, Alberta, Canada. Four samples of thoracic dust particles were collected during drywall sanding in four rooms on the second floor of the house. The floor plan of the second level is shown in Figure 4.4.

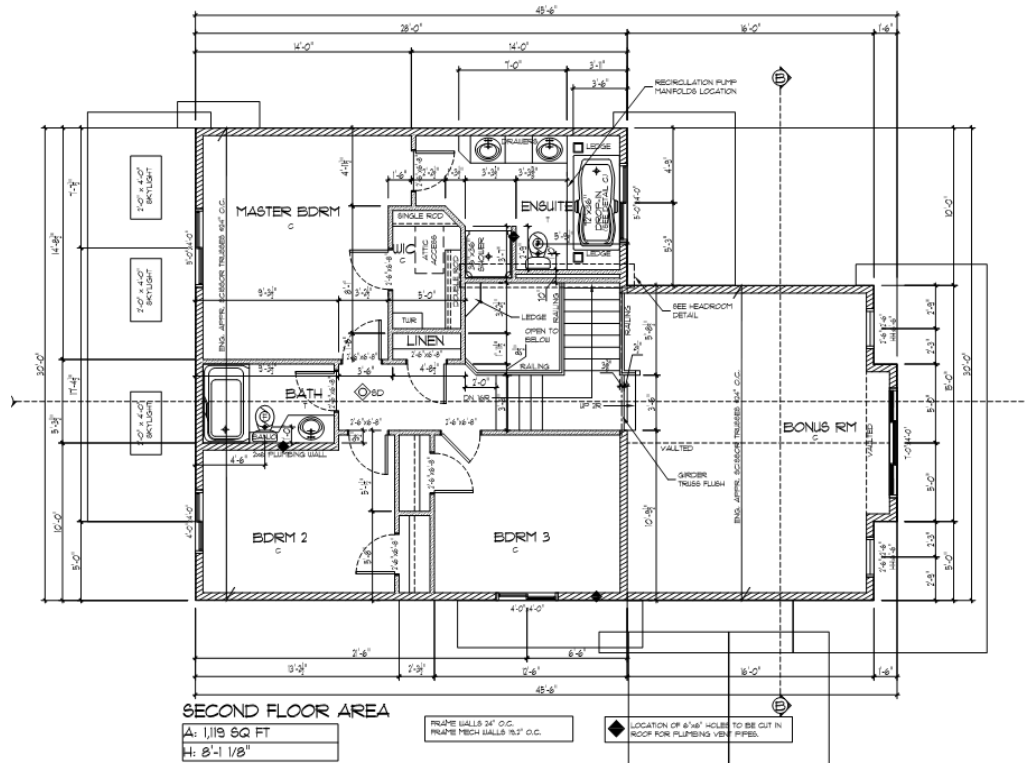


Figure 4.4: Floor plan of the test house (Courtesy of Landmark Group of Builders Inc.)

The drywall area of the two bedrooms was 32 m² and 35 m². The bonus room had the largest drywall area of 76.45 m². The master bedroom, including the attached bath, had a total of 47 m² of drywall area. The height of the second floor was 2.46 m. The measurements were calculated using the floor plan and sections of the house. The sampling was carried out in January, 2011. Due to extreme winter weather, all the exterior windows and doors were closed. There was no mechanical ventilation system during the sampling.

4.3.3 Air Pollutant Sampling

The Personal Environmental Monitors were attached to the workers' shirts, and the pumps were attached to the waists, as shown in Figure 4.5.



Figure 4.5: Air pollutant sampling using personal environmental monitor (PEM) during drywall sanding

Two workers sanded simultaneously using the block sanders. The workers stayed close to the wall and were exposed to more air pollutant while sanding with the block sanding tool compared to the pole sander. The PEM device was attached to only one worker at a time. The sanding duration of the bonus room was 64 minutes. The sanding duration of bedroom#3 was 20 minutes and bedroom#2 was 28 minutes. The master bedroom and attached bath took 109 minutes to complete. One sample was taken during each of these four sanding sessions. The PEM device was cleaned thoroughly with cyclohexene solvent and dried before each

sampling. The filter papers were kept separately in a plastic container. The pump flow rate was maintained at 4 lpm, as required for the PM₁₀ sampling.

4.3.4 Concentration Measurement

After collecting the samples, the filter papers were again dried for 24 hours in a desiccator. Then the sampled filter papers were weighted in a microbalance. The pollutant concentration was measured using the pollutant weight from the filter paper, flow rate of the pump, and duration of the sampling. The PM₁₀ concentration was calculated satisfying Equation (4.1).

$$C = \frac{PW}{FR \times T} \times 1000 \text{ --- (4.1)}$$

Where,

C = Concentration of PM₁₀ particles (mg/m³)

PW = PM₁₀ particles weight (mg)

FR = Flow rate (lpm)

T = Sampling duration (minute)

1000 = Conversion factor

Table 4.1 summarizes the PM₁₀ dust concentration for the four test rooms. The concentration ranged from 31 to 46 mg/m³.

Table 4.1: Measured PM₁₀ concentration for the four test rooms

Room	Filter (Empty) wt. (mg)	Sample + filter wt. (mg)	Sample wt. PM ₁₀ (mg)	Pump Flow Rate (lpm)	Duration (min)	Concentration (mg/m ³)
Bonus Room	69.9	79.1	9.28	4	64	36.2
Bedroom 2	70.8	75.9	5.19	4	28	46.3
Bedroom 3	70.7	73.3	2.55	4	20	31.8
Master Bedroom	69.9	88.7	18.8	4	109	43.2

4.3.5 Emission Rate Calculation

The emission rate for PM₁₀ dust pollutants was calculated for each room using the single zone mass balance model equation. The drywall sanding area and room volume for each room was measured from the drawing, and the air exchange rate was estimated from previous studies on single family houses. Based on recent studies, the air exchange rate was selected to be 0.5 hr⁻¹ during drywall sanding, considering that all the exterior windows were closed due to extreme cold weather (Johnson et al., 2004; Wallace et al., 2002). The emission rate (ER) was calculated satisfying Equation (4.2).

$$ER = C \times AER \times (V/S) \text{ ----- (4.2)}$$

Where,

ER = Emission rate (mg/m²/hr)

C = Concentration of air pollutant (mg/m³)

AER = Air Exchange Rate (1/hr)

S = Surface Area of the building object that generate pollutants (m^2)

V = Volume of the area where the activity takes place (m^3)

The concentration data used in Equation (4.2) represented the dust concentration as two workers sanded simultaneously in every room. This is why Equation (4.2) gave the emission rate for the two workers sanding in the rooms. To obtain the emission rate for one worker sanding in each room, the emission rate calculated for each room was divided by the number of workers which is two.

Table 4.2 summarizes the calculated emission rates for each room for one worker. During the sanding of all rooms with the exception of Bedroom#3, the emission rate of thoracic dust was similar.

Table 4.2: Emission rate of PM_{10} during drywall sanding for different rooms

Room	Concentration (mg/m^3)	Air Exchange Rate (hr^{-1})	Drywall Sanding Area (m^2)	Room Volume (m^3)	Emission Rate – two workers (mg/m^2hr)	Emission Rate – one worker (mg/m^2hr)
Bonus Room	36.2	0.50	47.19	73.34	28.1	14.1
Bedroom 2	46.3	0.50	31.94	30.26	22.0	10.9
Bedroom 3	31.8	0.50	35.01	30.90	14.0	7.0
Master Bedroom	43.2	0.50	76.45	79.22	22.4	11.2

This emission rate was incorporated in the BIM to perform the occupational indoor quality assessment. As the main purpose of this study was to establish a methodology to incorporate occupational indoor air quality into the BIM, the emission rate was quantified with only four sample data of thoracic dust.

4.4 Integration with the BIM

The proposed methodology for incorporating occupational indoor air quality assessment into BIM is tool-independent and applicable to different software. Constructor is a parametric CAD modeling software that uses ArchiCAD 9 as its user interface (Bazjanac, 2005). Estimator is the cost estimating software that can be integrated with Constructor. Constructor provides the model geometry and Estimator calculates the cost using a common database (Bazjanac, 2005). The proposed methodology was implemented using the ‘recipe’ feature of the software. Using the mass balance model (Equation 3.1) the emission rate recipe and ventilation rate recipe were created, and the emission rate of thoracic dust during drywall sanding and the air exchange rate of the single-family house were stored in the database. Estimator calculated the total emission rate per object for a specified working area and also the ventilation rate using Constructor 2008. From this information, the PM_{10} dust concentration was calculated during drywall sanding for different rooms.

4.4.1 3D Model Development

A 3D model was developed for a single-family house using Constructor 2008. The model was created using the object library provided by the software. Figure 4.6 shows the 3D model in Constructor 2008.

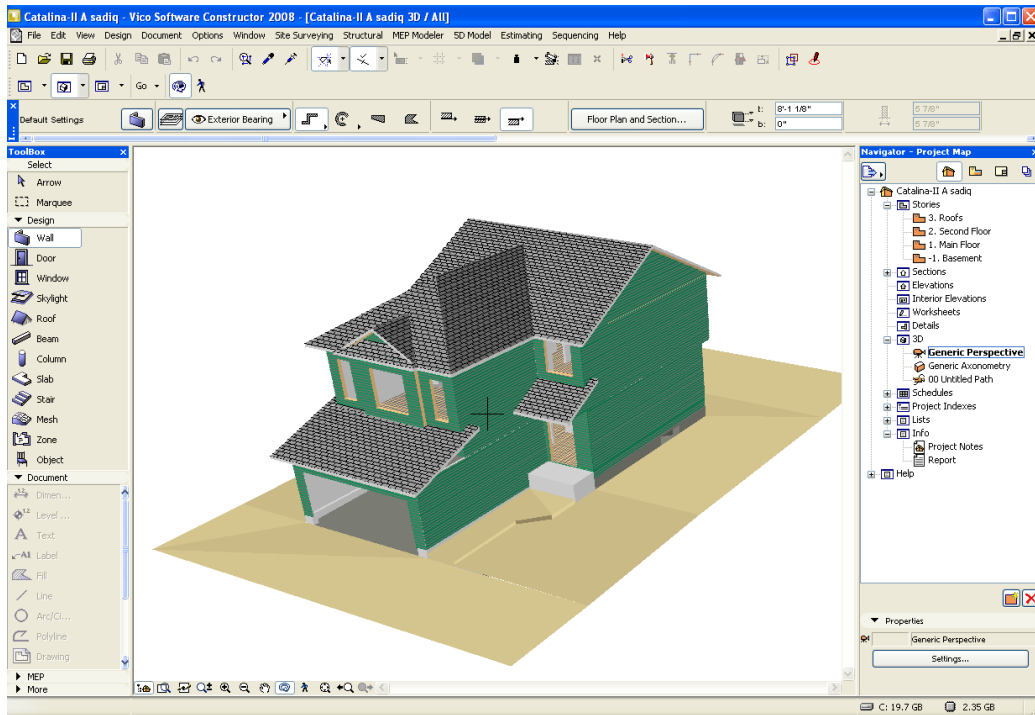


Figure 4.6: 3D Model of single-family house in Constructor 2008

The model had exterior and interior wall elements, a roof element, and floor element among others. The emission rate recipe was assigned to the wall element to calculate the total emission rate for an assigned wall and a ventilation rate recipe was assigned to the floor element to calculate the ventilation rate of any particular room.

4.4.2. Concept of Recipe, Method, and Resource

The Constructor and Estimator software have implemented the BIM technology to estimate the cost of construction projects. The unit cost associated with labour, material, and equipment is linked with the building elements using the concept of recipe, method and resource. In Constructor, the building elements are called recipes. These recipes are related to one or more activities. These activities are

called methods. Each method requires resources such as crew, material, or equipment. These resources are the cost unit. The cost per unit for each resource can be assigned for particular methods which will give the total cost for that recipe in the model. Figure 4.7 shows the breakdown of a column recipe into the method and resource levels.

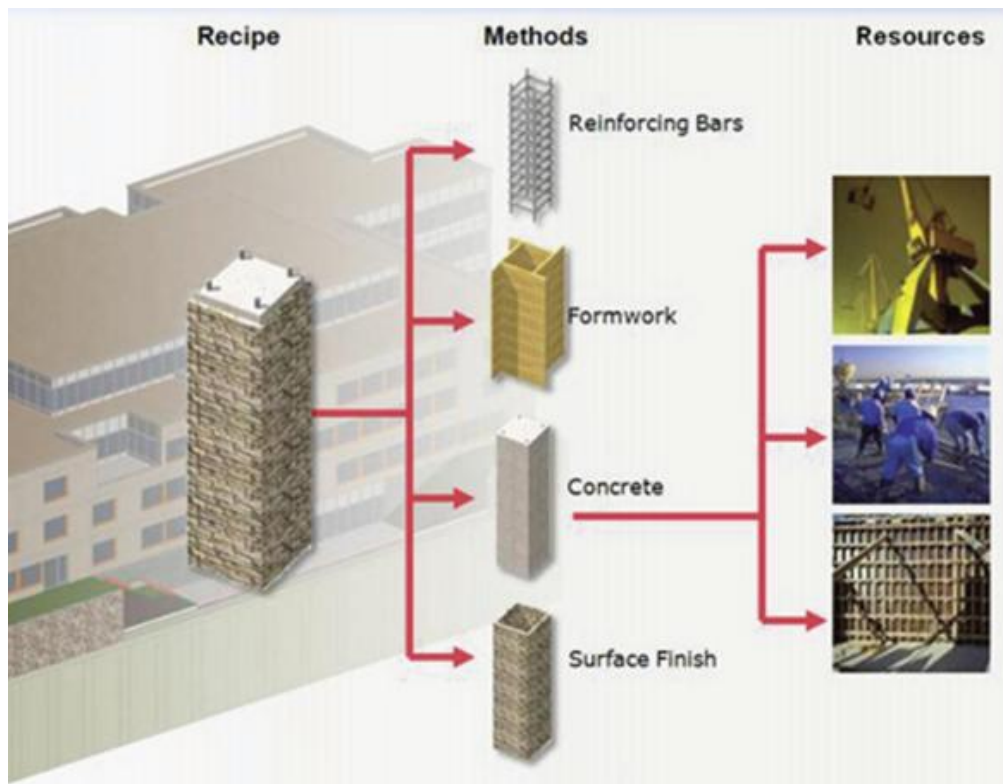


Figure 4.7: Recipe, method, and resource breakdown for a column

The column recipe represents the column as one of the building elements. Four methods are needed to complete for construction of a column – reinforcing bars, formwork, concrete, and surface finish. Each of this method requires resources such as labour, material, and equipment. To calculate the cost associated with the column, the unit rate for each resource is stored under the column recipe. Using the unit cost for the resources, the BIM can calculate the total cost for each

activity and then the cost for the column. The information flows from resource to recipe to calculate the total cost of the recipe. Each recipe also has a 'Data Quantity Type' (DQT) that defines which geometry is needed from the 3D model to calculate that recipe's cost. Examples of DQT are volume, net surface area, and gross surface area.

The same concept of recipe, method, and resource has been used to integrate the occupational indoor air quality assessment into BIM. The mass balance model was used to calculate the pollutant concentration using BIM. The main parameters of the mass balance model, the emission rate and air exchange rate, were assigned to the model elements following the same hierarchy of recipe, method, and resource to make the model elements intelligent. The recipes are the building elements such as wall, beam, or floor. However, the recipes are different for each type of building element depending on the working area, such as a room. For example, for the wall element, there is one recipe for Master Bedroom Wall, one recipe for Living Room Wall, and so on. The method is the activities that generate air pollutants. And finally the resource is the type of pollutant such as PM_{10} , $PM_{2.5}$, or VOCs. The emission rate of these pollutants was assigned in the resource level. The model calculated the total pollutant emissions per hour for each room recipe by obtaining the geometry of that element from the 3D model. The process of assigning emission rates to each model element is shown in Figure 4.8.

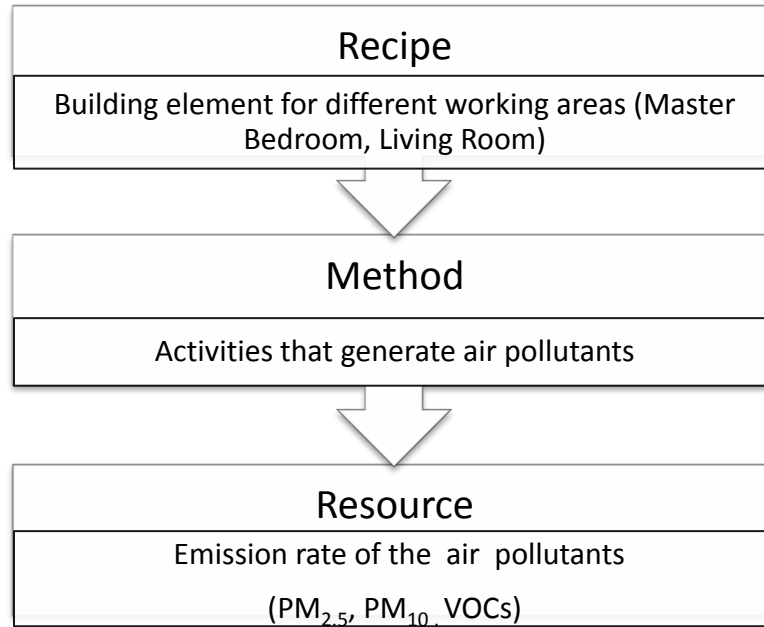


Figure 4.8: Process of assigning emission rate into the model element

The air exchange rate was similarly assigned to the floor area in order to calculate the ventilation rate of the working area or room. The air exchange rate was assigned in the resource level, and the ventilation rate for each working area was calculated by extracting the volume of the room from the 3D model for each recipe. From the total emission rate per hour and the ventilation rate, the air pollutant concentration was measured for each working area.

The recipe, method, and resource hierarchy is developed for drywall sanding of the wall element in the Constructor and Estimator. For the wall an element emission rate recipe was created. Under this emission rate recipe, which represents the wall element, the sanding activity was selected as the method. Under this method the thoracic dust pollutant was selected as the resource. The emission rate of the thoracic dust was put into this resource. Figure 4.9 shows the breakdown of the emission rate recipe for the drywall sanding activity.



Figure 4.9: Recipe, method, and resource for drywall

4.4.3 Emission Rate Calculation

The emission rate recipe calculated the total emission rate per hour for the air pollutant during the activity, satisfying Equation (3.2). In Estimator, five emission rate recipes were created for five different rooms on the 2nd floor of the single-family house. These recipes calculated the total emission rate of thoracic dust (PM₁₀) per hour during drywall sanding. The unit system for this recipe was defined as mg/hr. 'Net surface area' was selected as the data quantity type. All building objects in Constructor have specific data quantity types. The type determines the data to be extracted from the 3D model to the Estimator database. To calculate the total emission rate per hour for a wall, the net surface area was needed. Figure 4.10 shows the emission rate recipes created in Estimator 2009.

Recipes

(all)

Recipes of the selected Classification item 1 (5)

Classification & Code	Recipe Name	Quantity	Unit	mg/hr/u...	mg/hr	Determining quantity type
2G.3 2G.3.4D_1	Emission Rate MST BDRM	44.43	m2	10.75	477.66	Net_Surface_Area
2G.3 2G.3.4D_3	Emission Rate BDRM 2	34.31	m2	10.75	368.82	Net_Surface_Area
2G.3 2G.3.4D_4	Emission Rate BDRM 3	32.49	m2	10.75	349.26	Net_Surface_Area
2G.3 2G.3.4D_5	Emission Rate BONUS RM	45.72	m2	10.75	491.53	Net_Surface_Area
2G.3 2G.3.4D_6	Emission Rate ENSUITE	29.93	m2	10.75	321.69	Net_Surface_Area

Methods of the selected Recipe 1 (1)

Work Type, Method, Version	Method Name	Quantity	Unit	Consump...	Unit	mg/hr/u...	mg/hr	Proportional to Data
2G.0501 0	Sanding	44.43	m2	1.00	m2/m2	10.75	477.66	Net_Surface_Area

Resources of the selected Method (1)

Cost T...	Resource Name	Quantity	Unit	Consu...	Waste	Coefficient	Unit	mg/hr/u...	mg/hr	RT2
3 54...	Thoracic Dust PM10	44.43	m2	1.00	1.00	1.00	m2/m2	10.75	477.66	

Figure 4.10: Emission rate recipe in Estimator 2009

Under each recipe a method was created and named “Sanding.” Under this method a resource was created and named “Thoracic Dust PM₁₀.” The emission rate of the thoracic dust was put under the resource to replace the cost rate. The emission rate was selected as 10.75 mg/m²/hr for one worker sanding in the rooms which was chosen from the field sampling done in the first part of this case study. Number of worker was also incorporated in the model as a coefficient to obtain the total emission rate during sanding activity if more than one worker sanded the drywall simultaneously in the room.

In Constructor 2008, the wall elements of the rooms were assigned to the associated emission rate recipe. For example as shown in Figure 4.11, the wall elements of the master bedroom were selected and assigned to the Master Bedroom emission rate recipe.

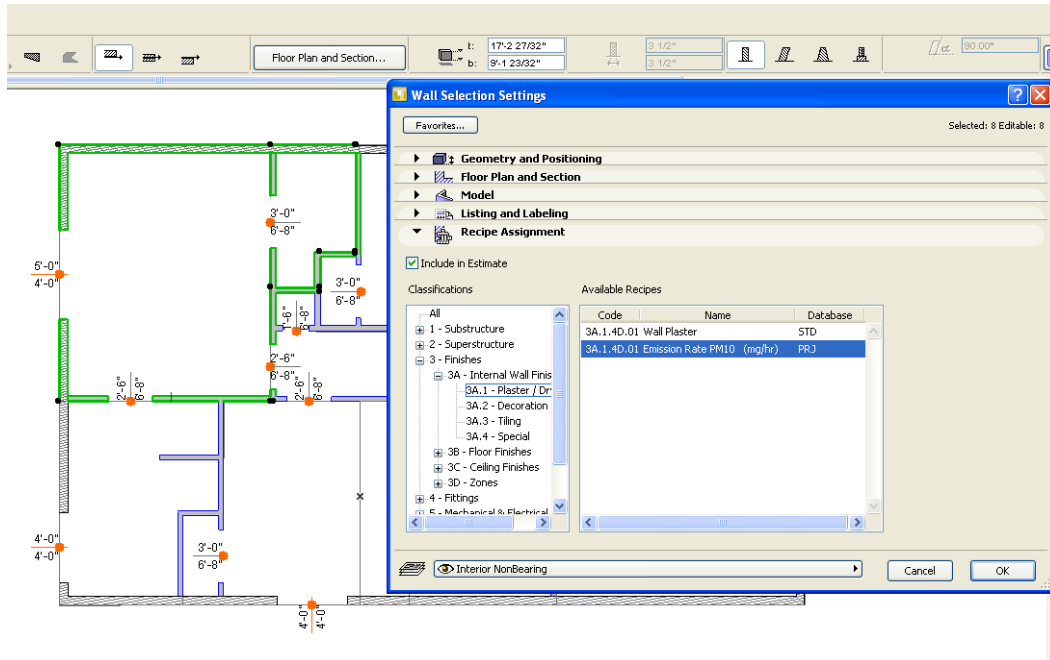


Figure 4.11: Emission rate recipe assignment to the master bedroom wall

From the emission rate information, the Estimator 2009 calculated the total emission rate per hour for every room by extracting the net surface area from the model geometry through Constructor. Figure 4.12 shows the calculated emission per hour in mg/hr for one worker sanding in each room based on Equation (3.2).

Vico Estimator 2009 - Indoor Air Quality Assessment						
Project Edit Recipe Resource Show Window Help						
Costs Tender Cost Tracking						
Structures and Quantities Recipes Methods Resources						
Recipes						
(all)						
Recipes of the selected Classification item						
(all)	Classification & Code	Recipe Name	Quantity	Unit	mg/hr/u...	mg/hr
2 Superstructure	2G.3 2G.3.4D_1	Emission Rate MST BDRM	44.43	m2	10.75	477.66
	2G.3 2G.3.4D_3	Emission Rate BDRM 2	34.31	m2	10.75	368.82
	2G.3 2G.3.4D_4	Emission Rate BDRM 3	32.49	m2	10.75	349.26
	2G.3 2G.3.4D_5	Emission Rate BONUS RM	45.72	m2	10.75	491.53
	2G.3 2G.3.4D_6	Emission Rate ENSUITE	29.93	m2	10.75	321.69

Figure 4.12: Total emission rate per hour (mg/hr) for each recipe

Figure 4.13 shows the emission per hour in each room if two workers sanded in the working area simultaneously.

Vico Estimator 2009 - Indoor Air Quality Assessment

Project Edit Recipe Resource Show Window Help

Costs | Tender | Cost Tracking |

Structures and Quantities | Recipes | Methods | Resources |

Recipes

(all)

2 Superstructure

Classification & Code

Recipe Name

Quantity

Unit

mg/hr/u...

mg/hr

Determining quantity type

2G.3 2G.3.4D._1

Emission Rate MST BDRM

44.43

m2

21.50

955.33

Net_Surface_Area

2G.3 2G.3.4D._3

Emission Rate BDRM 2

34.31

m2

21.50

737.64

Net_Surface_Area

2G.3 2G.3.4D._4

Emission Rate BDRM 3

32.49

m2

21.50

698.52

Net_Surface_Area

2G.3 2G.3.4D._5

Emission Rate BONUS RM

45.72

m2

21.50

983.06

Net_Surface_Area

2G.3 2G.3.4D._6

Emission Rate ENSUITE

29.93

m2

21.50

643.39

Net_Surface_Area

Methods of the selected Recipe

Work Type, Method, Version

Method Name

Quantity

Unit

Consump...

Unit

mg/hr/u...

mg/hr

Proportionz

2G.2G.0501 0

Sanding

44.43

m2

1.00

m2/m2

21.50

955.33

Net_Surfac

Resources of the selected Method

Cost T...

Resource Name

Quantity

Unit

Consu...

Waste

Coefficient

Unit

mg/hr/u...

mg/hr

3 S4...

Thoracic Dust PM10

88.87

m2

1.00

1.00

2.00

m2/m2

10.75

955.33

Figure 4.13: Total emission rate per hour (mg/hr) for two workers working in each room

4.4.4 Ventilation Rate Calculation

The ventilation rate recipe calculated the ventilation rate of the working area satisfying Eq. (3.3). Ventilation rate recipes were created for five different rooms. The ventilation rate recipe was assigned to the floor element of the model. Under the recipe, a method was created named “floor area.” Under this method, a resource was created named “room volume.” The air exchange rate was put into the resource to calculate the ventilation rate of the room. The air exchange rate was chosen as 0.50 hr^{-1} based on previous studies on AER for single-family

house. In the resource level, the height of the room is put as the coefficient. The unit system for the ventilation rate recipe was defined as m^3/hr . The data quantity type was selected as the “Gross Surface Area.” The ventilation rate recipe was assigned to the floor element of the associated room in Constructor. Figure 4.14 shows the ventilation rate recipe assignment to the floor element.

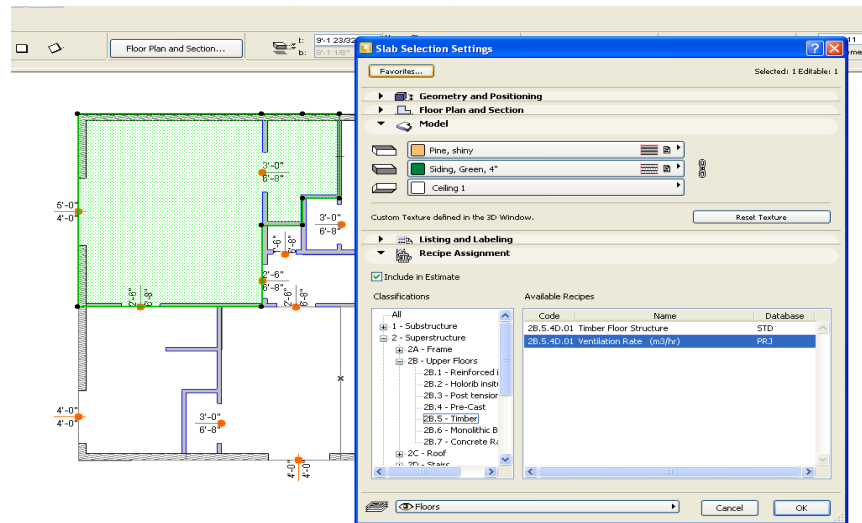


Figure 4.14: Ventilation rate recipe assignment into the floor element in Constructor 2009

The Constructor sent the floor area of the recipe to the Estimator which multiplied the floor area with the coefficient to calculate the room volume. Finally, using the air exchange rate information from the recipe, it calculated the ventilation rate for each recipe, satisfying Equation (3.3). Figure 4.15 shows the calculated ventilation rate for each recipe.

Project - Air Exchange Rate(template-based)

Project Edit Recipe Resource Show Window Help

Costs Tender Cost Tracking

Structures and Quantities Recipes Methods Resources

Recipes

(all)

2 Superstructure

Recipes of the selected Classification item

Classification & Code	Recipe Name	Quantity	Unit	m3/hr/unit	m3/hr	Determining quantity type
2B.5.2B.5.4D_3	Ventilation Rate ENSUITE	8.92	Gro...	m2	1.23	10.92 Gross_Surface_Area
2B.5.2B.5.4D_2	Ventilation Rate BDRM 3	11.47	Gro...	m2	1.23	14.05 Gross_Surface_Area
2B.5.2B.5.4D_1	Ventilation Rate BDRM 2	12.39	Gro...	m2	1.23	15.18 Gross_Surface_Area
2B.5.2B.5.4D.01	Ventilation Rate MST BDRM	19.62	Gro...	m2	1.23	24.04 Gross_Surface_Area
2B.5.2B.5.4D_4	Ventilation Rate BONUS RM	25.13	Gro...	m2	1.53	38.32 Gross_Surface_Area

Methods of the selected Recipe

Work Type, Method, V...	Method Name	Co...	Quantity	Unit	Consum...	Unit	m3/hr/unit	m3/hr	Proportional to Data	Library
2B.2B.2201.0	Floor Area		8.92	m2	1.00	m2/m2	1.23	10.92	Gross_Surface_Area	METHOD

Resources of the selected Method

Cost Type	Resource Name	Quantity	Unit	Consumption	Waste	Coefficient	Unit	m3/hr/u...	m3/hr	RT2
3 S4D004	Room Volume	21.85	Sum	1.00	1.00	2.45	Sum/...	0.50	10.92	

Figure 4.15: Ventilation rate for each room calculated in Estimator 2009

4.4.5 Air Pollutant Concentration Calculation

From Estimator 2009, the total emission rate per hour and the ventilation rate of each room were exported to an Excel spreadsheet. The PM₁₀ thoracic air pollutant concentrations for all five rooms during the sanding activity were calculated satisfying Equation (3.4). Table 4.3 shows the air pollutant concentrations for the five rooms when only one worker sanded in every room.

Table 4.3: PM₁₀ concentration for different rooms during drywall sanding with one worker

Room	Total Emission rate per hour (mg/hr)	Ventilation Rate (m ³ /hr)	PM ₁₀ dust concentration (mg/m ³)
BDRM 2	368.82	15.18	24.30
BDRM 3	349.26	14.05	24.86
ENSUITE	321.69	10.92	29.46
BONUS RM	491.53	38.32	12.83
MST BDRM	477.66	24.04	19.87

4.5 Assigning Workers in a Working Area Based on IAQ

BIM model gave PM₁₀ concentration during drywall sanding for different amount of workers sanding in each room. Table 4.4 shows the PM₁₀ concentrations in each room for one and two workers sanding.

Table 4.4: PM₁₀ concentration during drywall sanding with one and two workers

Room	PM ₁₀ dust concentration (mg/m ³) for one worker	PM ₁₀ dust concentration (mg/m ³) for two workers
BDRM 2	24.30	48.59
BDRM 3	24.86	49.72
ENSUITE	29.46	58.92
BONUS RM	12.83	25.65
MST BDRM	19.87	39.74

Based on the pollutant concentration, construction manager can assign more or less workers to the activity so that the concentration level always stays within a level that is not harmful for the workers health.

4.6 Effects of Different Types of Tools in IAQ

The effect of different types of tools in IAQ can also be determined from the BIM model. The emission rate of thoracic dust particles is calculated for block sanding tool. Young-Corbett and Nussbaum (2009) developed a relationship between different types of sanding tools in terms of thoracic and respirable dust particles emission during drywall sanding. The effect of tools can be added as a parameter in the BIM model to generate emission for different tools. Figure 4.16 shows the PM₁₀ dust emission in each room for one worker sanding with a pole sanding tool.

Vico Estimator 2009 - Indoor Air Quality Assessment

Project Edit Recipe Resource Show Window Help

Costs | Tender | Cost Tracking |

Structures and Quantities | Recipes | Methods | Resources |

ReCi(all)

Recipes of the selected Classification item

1 (5)

(all)	Classification & Code	Recipe Name	Quantity	Unit	mg/hr/u...	mg/hr	Determin
+ 2 S	2G.3 2G.3.4D_1	Emission Rate MST BDRM	44.43	m2	5.38	238.83	Net_Surf
	2G.3 2G.3.4D_3	Emission Rate BDRM 2	34.31	m2	5.38	184.41	Net_Surf
	2G.3 2G.3.4D_4	Emission Rate BDRM 3	32.49	m2	5.38	174.63	Net_Surf
	2G.3 2G.3.4D_5	Emission Rate BONUS RM	45.72	m2	5.38	245.77	Net_Surf
	2G.3 2G.3.4D_6	Emission Rate ENSUITE	29.93	m2	5.38	160.85	Net_Surf

Methods of the selected Recipe

1 (1)

Work Type, Method, Version	Method Name	Quantity	Unit	Consump...	Unit	mg/hr/u...	mg/l
2G 2G.0501 0	Sanding	44.43	m2	1.00	m2/m2	5.38	238.83

Resources of the selected Method

1 (1)

Cost T...	Resource Name	Quantity	Unit	Consu...	Waste	Coefficient	Unit	mg/hr/u...
3 S4...	Thoracic Dust PM10	22.22	m2	0.50	1.00	1.00	m2/m2	10.75

Figure 4.16: PM₁₀ emission for one worker sanding with a pole sanding tool

A tool type coefficient has been added for pole sanding tool in the model to calculate the emission. The coefficient for pole sanding tool is selected as 0.50 from the Young-Corbett and Nussbaum (2009) study.

4.7 Sensitivity Analysis

A sensitivity analysis was performed to see the effect of changing emission rate and air exchange rate on the pollutant concentration. Excel's data table feature was used to perform the analysis. The emission rate was varied from 12.05 to 48.2 mg/m²/hr and the air exchange rate was varied from 0.25 to 1.00 hr⁻¹ by an increment of 10% for two different room sizes. Table 4.5 presents the pollutant concentration in BDRM2 for different emission and air exchange rates. The emission rate was varied from 12.05 to 48.2 mg/m²/hr, and the air exchange rate was varied from 0.25 to 1 hr⁻¹. The pollutant concentration varied from 13.47 to 215.45 mg/m³.

Table 4.5: Sensitivity analysis for BDRM 2 – pollutant concentration for different emission and air exchange rates

		Emission Rate (mg/m2/hr)															
		12.05	14.46	16.87	19.28	21.69	24.1	26.51	28.92	31.33	33.74	36.15	38.56	40.97	43.38	45.79	48.2
Air Exchange Rate (1/hr)	0.25	53.86	64.63	75.41	86.18	96.95	107.72	118.50	129.27	140.04	150.81	161.59	172.36	183.13	193.90	204.68	215.45
	0.3	44.89	53.86	62.84	71.82	80.79	89.77	98.75	107.72	116.70	125.68	134.66	143.63	152.61	161.59	170.56	179.54
	0.35	38.47	46.17	53.86	61.56	69.25	76.95	84.64	92.34	100.03	107.72	115.42	123.11	130.81	138.50	146.20	153.89
	0.4	33.66	40.40	47.13	53.86	60.60	67.33	74.06	80.79	87.53	94.26	100.99	107.72	114.46	121.19	127.92	134.66
	0.45	29.92	35.91	41.89	47.88	53.86	59.85	65.83	71.82	77.80	83.79	89.77	95.76	101.74	107.72	113.71	119.69
	0.5	26.93	32.32	37.70	43.09	48.48	53.86	59.25	64.63	70.02	75.41	80.79	86.18	91.57	96.95	102.34	107.72
	0.55	24.48	29.38	34.28	39.17	44.07	48.97	53.86	58.76	63.66	68.55	73.45	78.35	83.24	88.14	93.03	97.93
	0.6	22.44	26.93	31.42	35.91	40.40	44.89	49.37	53.86	58.35	62.84	67.33	71.82	76.30	80.79	85.28	89.77
	0.6	22.44	26.93	31.42	35.91	40.40	44.89	49.37	53.86	58.35	62.84	67.33	71.82	76.30	80.79	85.28	89.77
	0.65	20.72	24.86	29.00	33.15	37.29	41.43	45.58	49.72	53.86	58.01	62.15	66.29	70.44	74.58	78.72	82.87
	0.7	19.24	23.08	26.93	30.78	34.63	38.47	42.32	46.17	50.02	53.86	57.71	61.56	65.40	69.25	73.10	76.95
	0.75	17.95	21.54	25.14	28.73	32.32	35.91	39.50	43.09	46.68	50.27	53.86	57.45	61.04	64.63	68.23	71.82
	0.8	16.83	20.20	23.56	26.93	30.30	33.66	37.03	40.40	43.76	47.13	50.50	53.86	57.23	60.60	63.96	67.33
	0.85	15.84	19.01	22.18	25.35	28.52	31.68	34.85	38.02	41.19	44.36	47.53	50.69	53.86	57.03	60.20	63.37
	0.9	14.96	17.95	20.95	23.94	26.93	29.92	32.92	35.91	38.90	41.89	44.89	47.88	50.87	53.86	56.85	59.85
	0.95	14.17	17.01	19.84	22.68	25.51	28.35	31.18	34.02	36.85	39.69	42.52	45.36	48.19	51.03	53.86	56.70
	1	13.47	16.16	18.85	21.54	24.24	26.93	29.62	32.32	35.01	37.70	40.40	43.09	45.78	48.48	51.17	53.86

Figure 4.17 shows the effects of emission and air exchange rates on the indoor air quality.

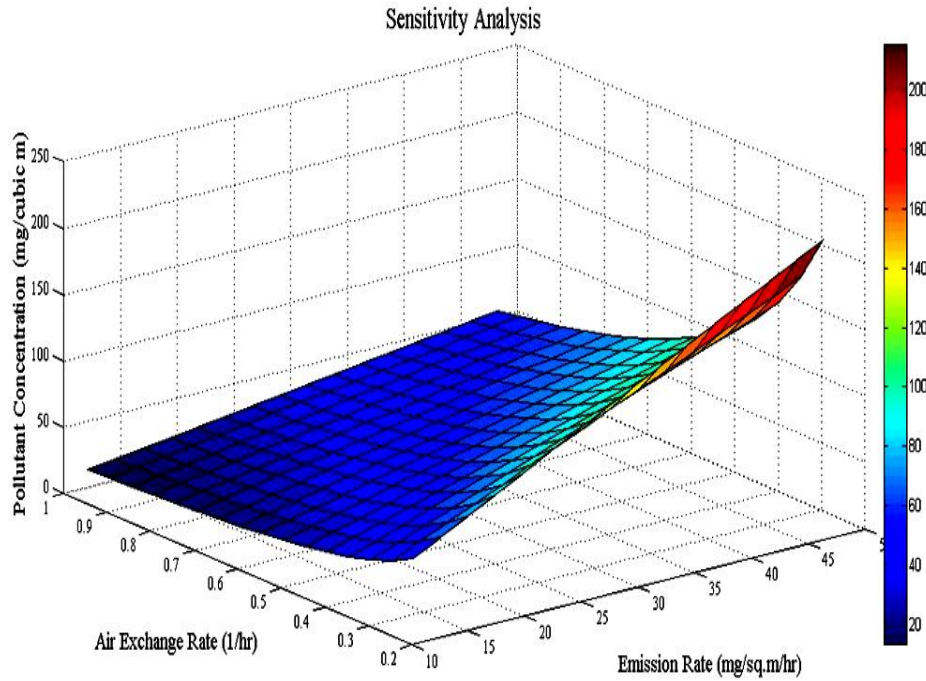


Figure 4.17: Sensitivity analysis: pollutant concentration in BDRM 2

Similar analysis was performed for another room's data, the BONUS RM. The emission rate and air exchange rate data were varied within the same margin to generate the pollutant concentration data. Table 4.6 presents the pollutant concentration in the BONUS RM for different emission and air exchange rates. The pollutant concentration varied from 7.24 to 115.81 mg/m³.

Table 4.6: Sensitivity analysis for BDRM 2 – pollutant concentration for different emission and air exchange rates

		Emission Rate (mg/m2/hr)																
		12.05	14.46	16.87	19.28	21.69	24.1	26.51	28.92	31.33	33.74	36.15	38.56	40.97	43.38	45.79	48.2	
Air Exchange Rate (1/hr)	0.25	28.95	34.74	40.53	46.32	52.11	57.90	63.69	69.49	75.28	81.07	86.86	92.65	98.44	104.23	110.02	115.81	
	0.3	24.13	28.95	33.78	38.60	43.43	48.25	53.08	57.90	62.73	67.56	72.38	77.21	82.03	86.86	91.68	96.51	
	0.35	20.68	24.82	28.95	33.09	37.22	41.36	45.50	49.63	53.77	57.90	62.04	66.18	70.31	74.45	78.58	82.72	
	0.4	18.10	21.71	25.33	28.95	32.57	36.19	39.81	43.43	47.05	50.67	54.29	57.90	61.52	65.14	68.76	72.38	
	0.45	16.08	19.30	22.52	25.74	28.95	32.17	35.39	38.60	41.82	45.04	48.25	51.47	54.69	57.90	61.12	64.34	
	0.5	14.48	17.37	20.27	23.16	26.06	28.95	31.85	34.74	37.64	40.53	43.43	46.32	49.22	52.11	55.01	57.90	
	0.55	13.16	15.79	18.42	21.06	23.69	26.32	28.95	31.58	34.22	36.85	39.48	42.11	44.74	47.38	50.01	52.64	
	0.6	12.06	14.48	16.89	19.30	21.71	24.13	26.54	28.95	31.36	33.78	36.19	38.60	41.02	43.43	45.84	48.25	
	0.6	12.06	14.48	16.89	19.30	21.71	24.13	26.54	28.95	31.36	33.78	36.19	38.60	41.02	43.43	45.84	48.25	
	0.65	11.14	13.36	15.59	17.82	20.04	22.27	24.50	26.73	28.95	31.18	33.41	35.63	37.86	40.09	42.31	44.54	
	0.7	10.34	12.41	14.48	16.54	18.61	20.68	22.75	24.82	26.88	28.95	31.02	33.09	35.16	37.22	39.29	41.36	
	0.75	9.65	11.58	13.51	15.44	17.37	19.30	21.23	23.16	25.09	27.02	28.95	30.88	32.81	34.74	36.67	38.60	
	0.8	9.05	10.86	12.67	14.48	16.29	18.10	19.90	21.71	23.52	25.33	27.14	28.95	30.76	32.57	34.38	36.19	
	0.85	8.52	10.22	11.92	13.62	15.33	17.03	18.73	20.44	22.14	23.84	25.55	27.25	28.95	30.66	32.36	34.06	
	0.9	8.04	9.65	11.26	12.87	14.48	16.08	17.69	19.30	20.91	22.52	24.13	25.74	27.34	28.95	30.56	32.17	
	0.95	7.62	9.14	10.67	12.19	13.71	15.24	16.76	18.29	19.81	21.33	22.86	24.38	25.90	27.43	28.95	30.48	
	1	7.24	8.69	10.13	11.58	13.03	14.48	15.92	17.37	18.82	20.27	21.71	23.16	24.61	26.06	27.50	28.95	

Figure 4.18 shows the changing effects of emission and air exchange rates on the indoor air quality.

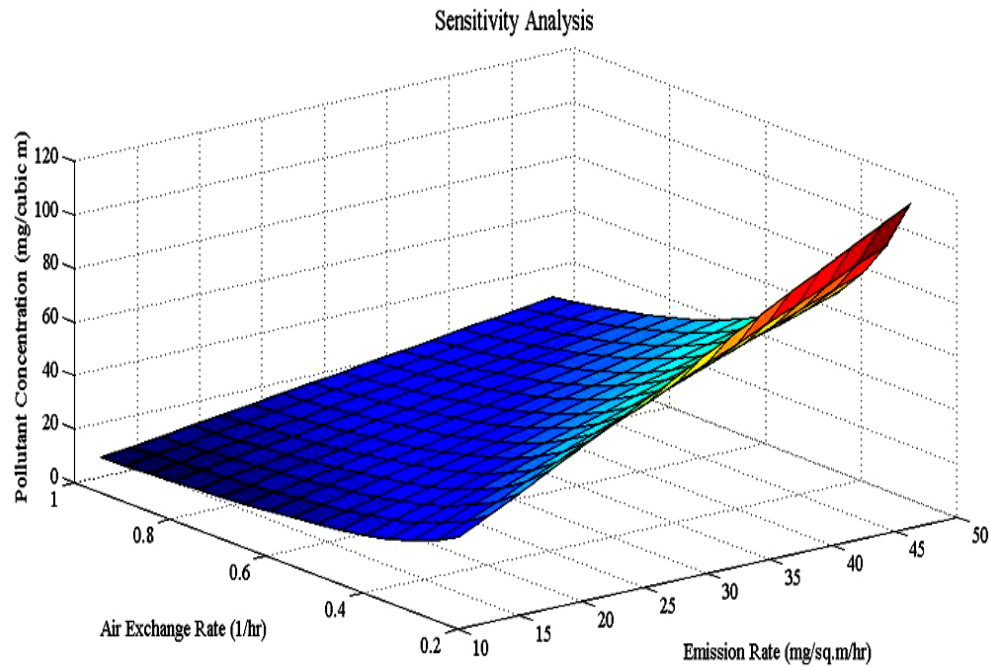


Figure 4.18: Sensitivity analysis: pollutant concentration in BONUS RM

Fig. 4.15 and Fig. 4.16 showed that air pollutant concentration is sensitive to both the emission rate and air exchange rate. However, the air pollutant concentration varied within a larger range for the smaller room size. For the BONUS RM (room volume: 76.89 m³) pollutant concentration ranged from approximately 7 to 115 mg/m³, and for BDRM2 (room volume: 30.48 m³) it ranged from approximately 13 to 215 mg/m³. This result illustrated that pollutant concentration becomes more sensitive to emission rate and air exchange rate for a smaller space.

To understand how sensitive the air pollutant concentration is to AER for different emission rates, two graphs were plotted for BDRM2 and BONUS RM as shown in Figure 4.19. The figures show that air pollutant concentration becomes more sensitive to AER as the source emission rate becomes higher. For example, when the emission rate was 12.05 mg/m²/hr the air pollutant concentration in BDRM2 varied from 13 to 58 mg/m³ for different AERs. And when the emission rate was 48.2 mg/m²/hr the air pollutant concentration varied from 53 to 213 mg/m³. The data from the larger room size illustrated a similar phenomenon. However, for the larger room, the air pollutant concentration ranged within a narrower range, and for that the effect of the emission rate is also small compared to the smaller room.

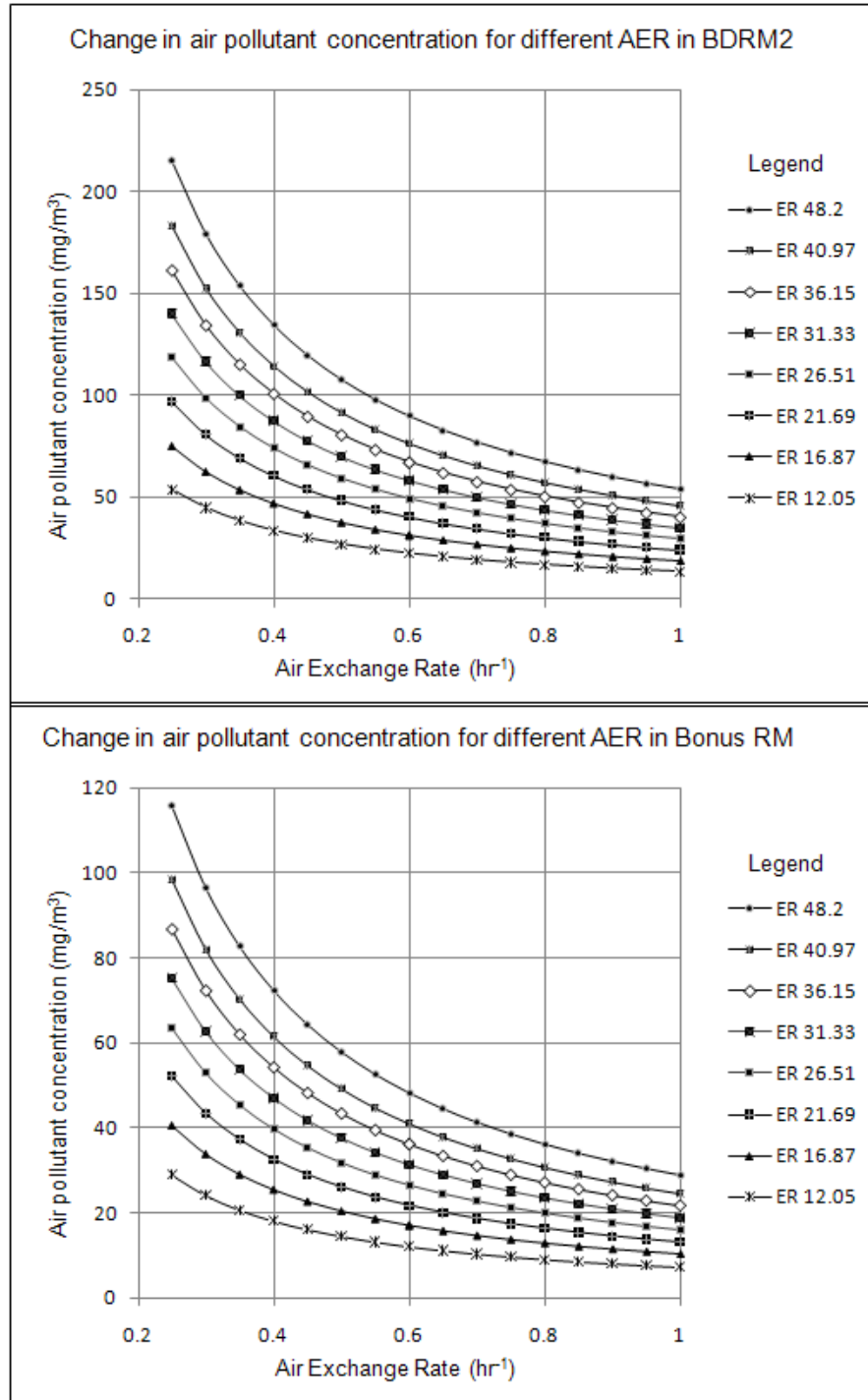


Figure 4.19: Air pollutant concentration changes for different emission rates and AERs

Summary

The proposed methodology was implemented on drywall sanding in 4 rooms in a single-family home. The emission rate was quantified using a Personal Environmental Monitor for drywall sanding, and occupational indoor air quality assessment was incorporated into BIM using Graphisoft's VICO Constructor and Estimator software. This methodology can also be implemented with other hazardous construction activities such as carpeting, painting, or wood framing and the emission rate can be quantified and incorporated into BIM to predict the indoor pollutant concentration before the actual work.

Chapter 5: Potential Application

5.1 Introduction

Project cost and duration are the two main concerns for construction project managers. Researchers have developed different techniques to estimate the project cost and duration at any given time during the planning or construction stage, such as the earned value method (EVM). Building Information Modeling (BIM) has been used in the AEC industry to estimate project cost and duration more accurately using advanced CAD softwares. The proposed methodology gives project stakeholders a new parameter to determine the air pollutant concentration during construction activities. The BIM model can be used to calculate the indoor air pollutant concentration as well as the total emission rate per hour for different activities within different areas on the construction site.

The Earned Value Method (EVM) is used extensively to evaluate, analyze and forecast project cost and duration (Byung-Cheol, K. and Reinschmidt, K. F., 2010). EVM uses three performance variables – the budgeted cost for work performed (earned value), actual cost, and the budgeted cost for work scheduled (planned value). Project performance, where the project stands in terms of cost and schedule, can be measured using these variables. The ratio of the actual cost of the project at any point and the budgeted cost until that point is called the cost performance index (CPI). Similarly, the ratio of the planned value and earned value at the current stage of the project is the schedule performance index (SPI). These two indexes forecast the total cost and duration of the project. As shown in

Figure 5.1, at any time (t) of the project, PV (t), AC (t), and EV (t) refers to the planned value, actual cost and earned value at time 't' respectively. Equation (5.1) and (5.1) show the CPI and SPI at any time t.

$$CPI = AC(t)/PV(t) \quad \text{-----} (5.1)$$

$$SPI = PV(t)/EV(t) \quad \text{-----} (5.2)$$

Using CPI and SPI, estimated cost at completion (EAC), and budgeted at completion (BAC) can be estimated using Equation (5.3). Cost overrun and schedule delays can also be identified at any time during the project.

$$EAC(t) = BAC(t) / CPI \quad \text{-----} (5.3)$$

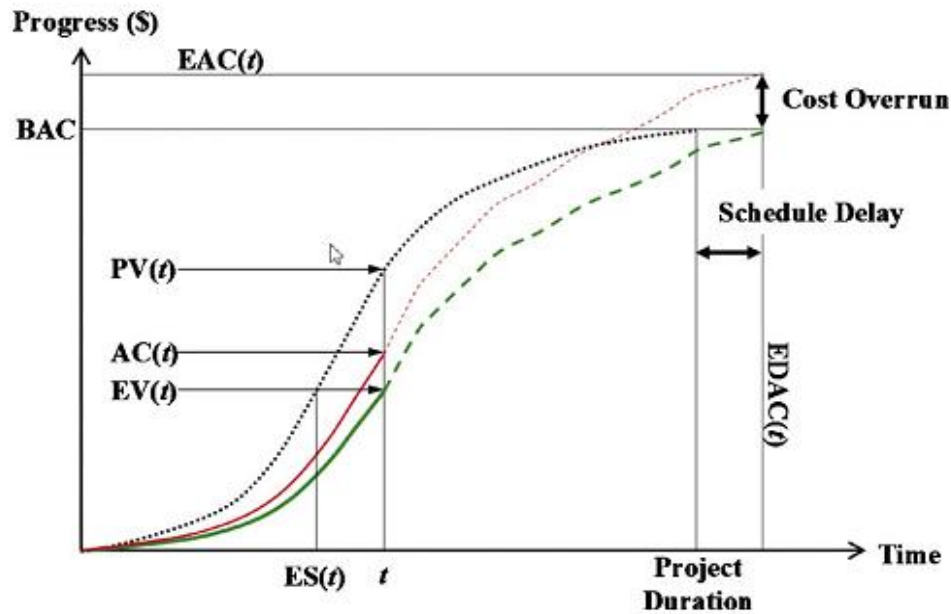


Figure 5.1: EVM metrics (Byung-Cheol, K. and Reinschmidt, K. F., 2010)

The EVM concept can be applied to air quality assessment by replacing the cost with the total emission rate of airborne pollutants such as PM₁₀, PM_{2.5}, and VOCs; the cumulative total emission rate of airborne pollutants can be determined as the

project progresses. This monitoring will identify the construction stage which generates the most airborne pollutants. The total emission rate of different air pollutants can be compared, to see the predicted effect of better work practices and work tools that generate less air pollutants on the total emissions. The air pollutant concentration during construction activities in different work areas also indicates which working areas contain high level of air pollutants, and which mitigation measures, such as increased ventilation, can be implemented. Figure 5.2 shows the actual cumulative pollutant emission with time and the estimated emission.

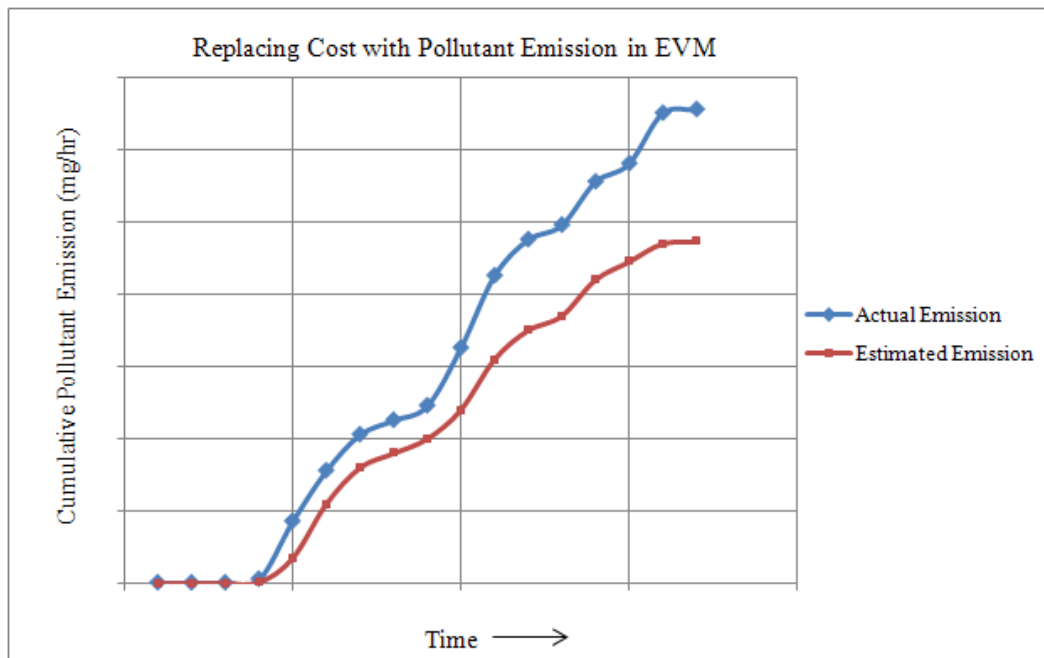


Figure 5.2: Replacing cost with pollutant emission in EVM

Similar to CPI, an emission index (EI) can be calculated at any given time of the project using Equation (5.4).

$$EI(t) = APE(t) / EPE(t) \text{ ----- (5.4)}$$

Where,

EI(t) = Emission index at time t

APE(t) = Actual pollutant emission at time t

EPE(t) = Estimated Pollutant emission at time t

5.2 Scheduling based on Pollutant Concentration

Construction activities can be scheduled based on the level of pollutant concentration using the proposed methodology. To calculate the pollutant concentration automatically with Estimator software, it is assumed that the ventilation rate is constant in a floor. The inverse of the ventilation rate is added into the 3D model elements as a coefficient, and the pollutant concentration is calculated satisfying Equation (5.5).

$$C = \text{TER} * \text{VC} \text{ ----- (5.5)}$$

Where,

C = Pollutant concentration (mg/m³)

TER = Total emission rate (mg/hr)

VC = Ventilation coefficient (hr/m³)

Figure 5.3 shows the framework for scheduling construction activities based on pollutant concentration.

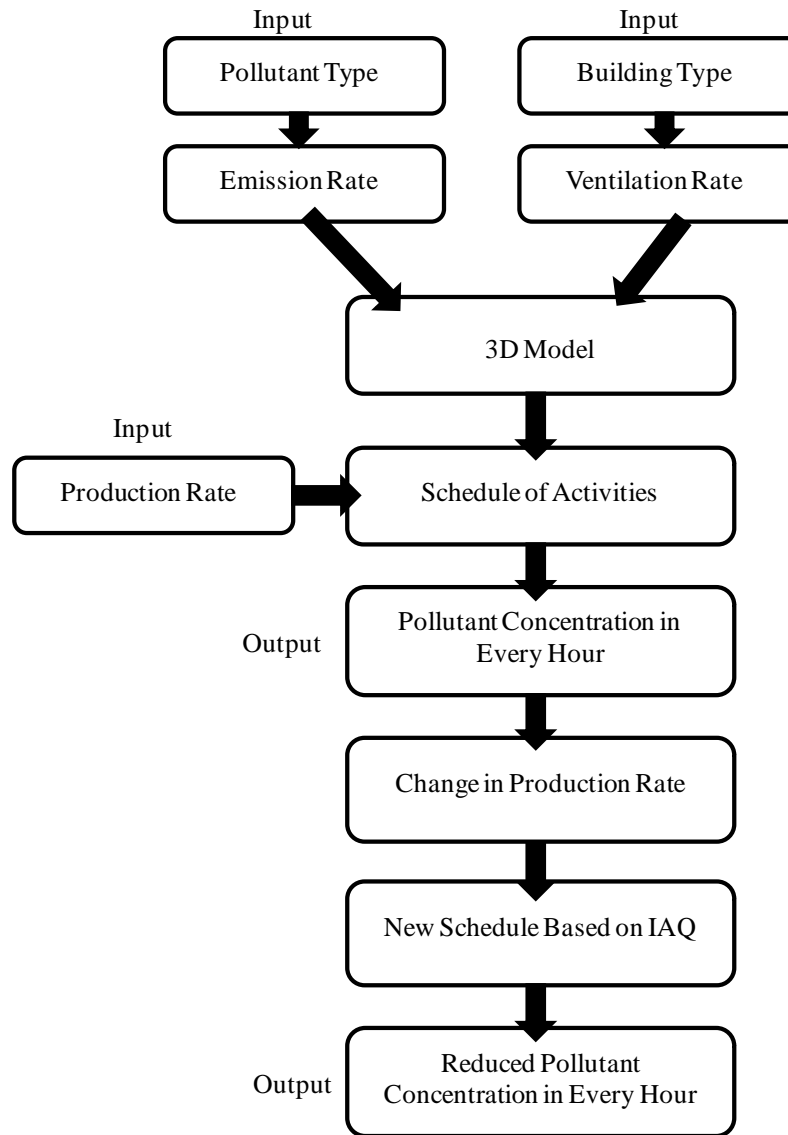


Figure 5.3: Framework for scheduling based on IAQ using BIM

Based on pollutant and building type, the source emission rate and ventilation rate are incorporated into the 3D model elements. From the production rate of the activities, the schedule of activities can be developed from the 3D model and the pollutant concentration for every hour can be calculated from the schedule based on the emission and ventilation rate. Based on the concentration, the production

rate of the activities can be lowered and a new schedule of activities can be developed.

Figure 5.4 shows the calculated pollutant concentration for PM₁₀ during drywall sanding using Estimator 2009. This concentration data is linked with scheduling software Control 2009 to schedule the sanding activity based on the concentration level.

The screenshot shows the Vico Estimator 2009 - Indoor Air Quality Assessment software interface. The main window displays a table of pollutant concentrations for PM₁₀ during drywall sanding. The table is organized into three sections: Recipes of the selected Classification item, Methods of the selected Recipe, and Resources of the selected Method.

Recipes of the selected Classification item									
Classification & Co...	Recipe Name	Quantity	Unit	mg/m3/...	mg/m3	Determining quantity type			
2G.3 2G.3.4D_1	Emission Rate MST BDRM	43.93	m2	0.54	23.62	Net_Surface_Area			
2G.3 2G.3.4D_6	Emission Rate ENSUITE	29.80	m2	0.54	16.02	Net_Surface_Area			
2G.3 2G.3.4D_5	Emission Rate BONUS RM	45.72	m2	0.54	24.58	Net_Surface_Area			
2G.3 2G.3.4D_4	Emission Rate BDRM 3	33.05	m2	0.54	17.77	Net_Surface_Area			
2G.3 2G.3.4D_3	Emission Rate BDRM 2	34.06	m2	0.54	18.31	Net_Surface_Area			

Methods of the selected Recipe									
Work Type, Method...	Method Name	Quantity	Unit	Consump...	Unit	mg/m3/...	mg/m3	Proportional to Data	Library
2G.0501 0	Sanding	43.93	m2	1.00	m2/m2	0.54	23.62	Net_Surface_Area	METHOD

Resources of the selected Method									
Cost Type	Resource Name	Quantity	Unit	Consum...	Waste	Coefficient	Unit	mg/m3/...	mg/m3
1 LPLA001	Sanding Crew	2.20	m2	1.00	1.00	0.05	m2/m2	10.75	23.62

Figure 5.4: PM₁₀ concentration during drywall sanding using Estimator 2009

Figure 5.5 shows the gantt chart in Control 2009 for drywall sanding activity with the PM₁₀ concentration for each room. There are five rooms that are scheduled for the sanding.

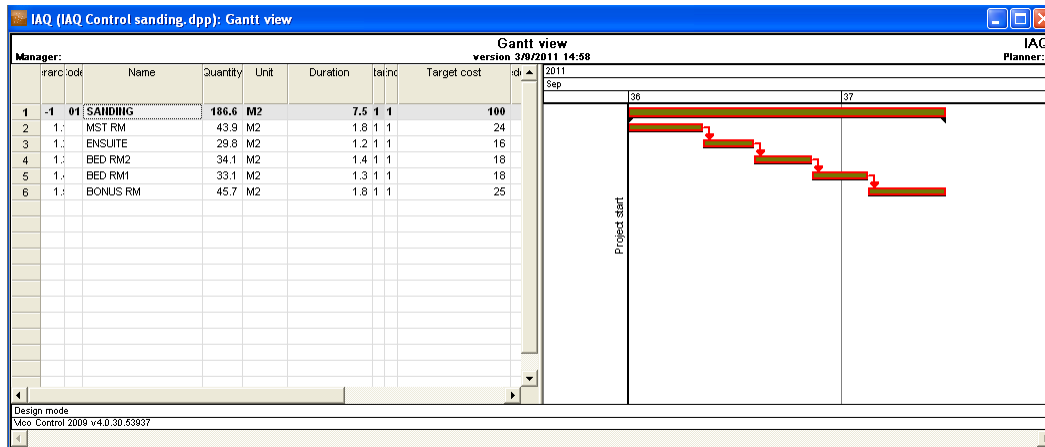


Figure 5.5: Gantt chart for drywall sanding in Control 2009

Instead of the target cost, the software provides the PM_{10} concentration in mg/m^3 during the sanding of each room. An hourly pollutant concentration histogram is shown in Figure 5.6.

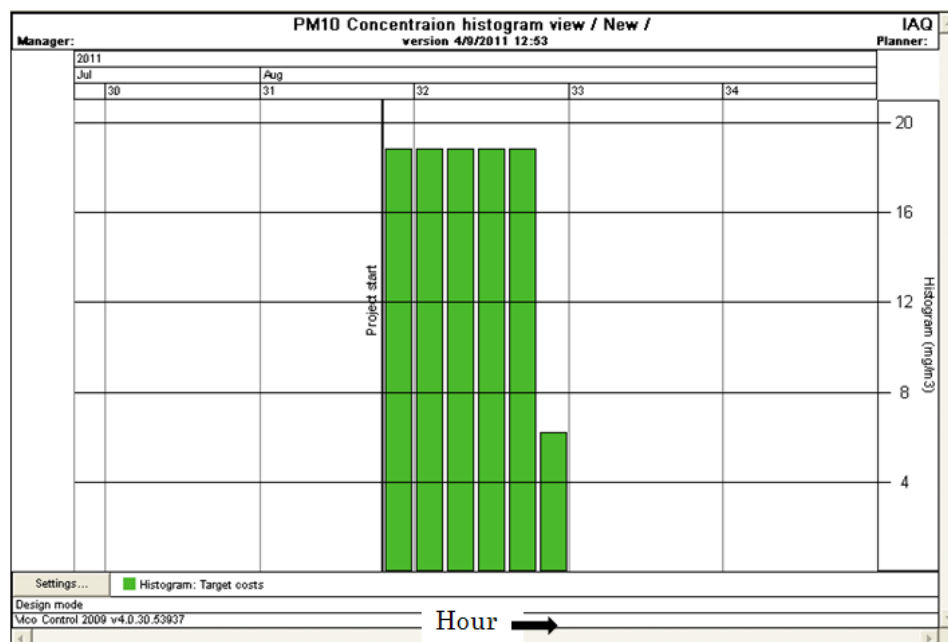


Figure 5.6: PM_{10} concentration histogram

From Figure 5.6, the pollutant concentration is near 20 mg/m^3 when the production rate of sanding is $35 \text{ m}^2/\text{hr}$. The production rate can be reduced to $18 \text{ m}^2/\text{hr}$ in the scheduling software and the pollutant concentration decreases in every hour. Figure 5.7 shows the PM_{10} concentration histogram for a production rate of $18 \text{ m}^2/\text{hr}$. The concentration in every hour during sanding is reduced to below 10 mg/m^3 .

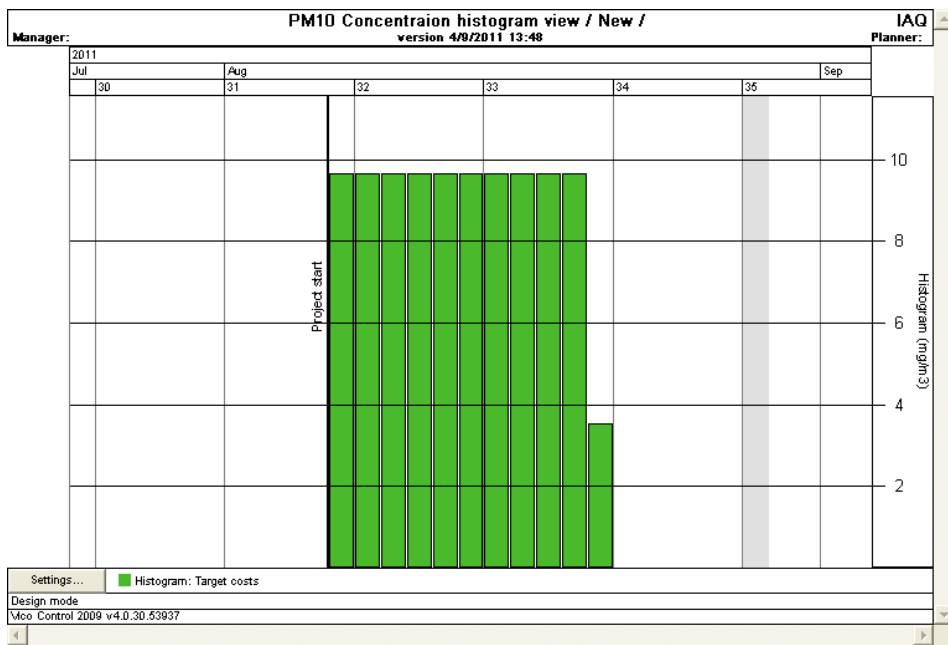


Figure 5.7: PM_{10} concentration histogram for reduced production rate

This scheduling technique can be applied to other indoor activities such as painting, carpeting and for different types of pollutants, such as $\text{PM}_{2.5}$ and VOCs.

5.3 Minimizing Pollutant Concentration using Heuristic Approach

If multiple activities take place in a confined area, the pollutant concentration can be lowered by applying a heuristic approach. If the pollutant concentration is more than the allowable limit, some of the activities can be shifted to lower the pollutant concentration level. The scheduling of the activities based on the heuristic approach is demonstrated using the example in Figure 5.8.

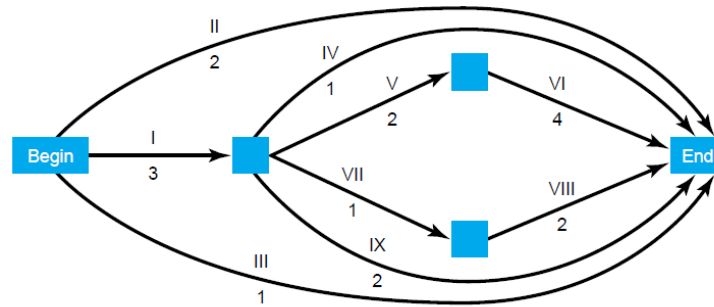


Figure 5.8: Activity-on-arrow (AOA) diagram (Moore and Weatherford, 2001)

From the activity-on-arrow (AOA) diagram, the total duration of the project is 9 hours. The critical activities are identified as activity I, V and VI. Figure 5.9 shows the relationship between the activities. Activity V is dependent on activity I and activity VI is dependent on activity V. As all three activities are critical, none of them can be delayed to reduce the pollutant concentration. Activity II, III, IV, VII, VIII and IX can be shifted within their float. Float is the maximum amount of time an activity can be delayed without delaying the whole project duration (Moore and Weatherford, 2001)

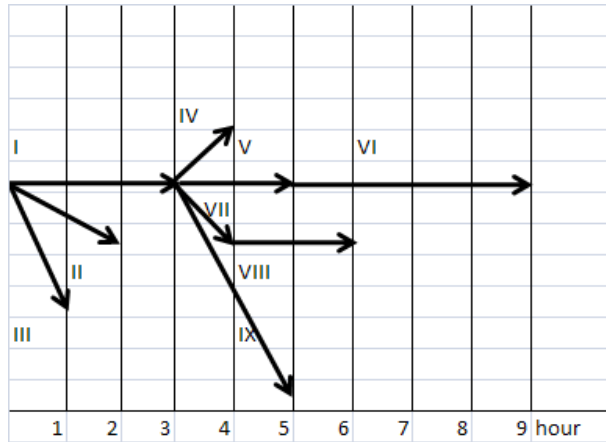


Figure 5.9: Critical activities and non-critical activities

The time required for each activity and the pollutant concentration from the activities in every hour are shown in Table 5.1. Please note that all of the values are assumed.

Table 5.1: Duration and the pollutant emission from the activities

Activity	Time required to complete (hour)	Pollutant concentration from the activity in every hour (mg/m^3)
I	3	60
II	2	30
III	1	30
IV	1	30
V	2	60
VI	4	50
VII	1	30
VIII	2	40
IX	2	30

A histogram is developed in Figure 5.10 to observe the pollutant concentration for each hour. In the heuristic approach, the non-critical activities are rescheduled to “reduce the peaks” and “raise the valleys.” In order to apply the heuristic approach, the following algorithm is followed.

1. Identify the time where the maximum concentration occurs: ‘m’ amount of concentration in the hour ‘t’.
2. Set a new upper concentration limit of (m-10) every hour. In the heuristic approach, the peaks are reduced one step at a time.
3. Shift the first activity that violates the new concentration limit to satisfy the constraint. After shifting the activities that violate the limit, one identifies the new point that has the maximum concentration and follows the same peak-reducing procedure until the current concentration is no longer reduced by shifting activities.

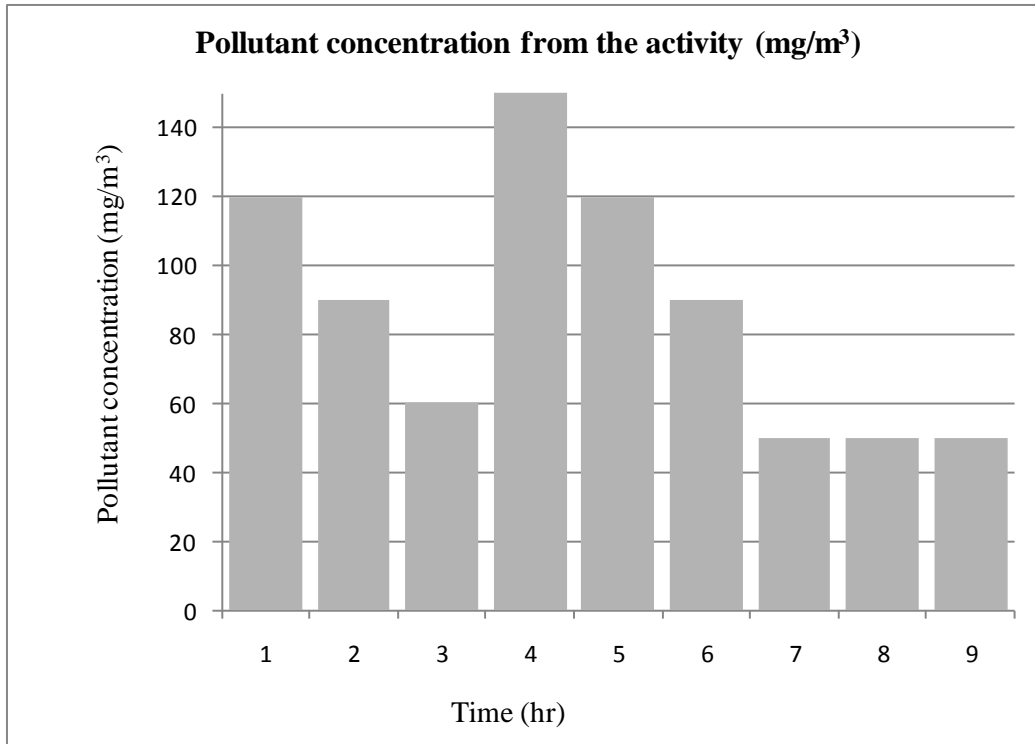
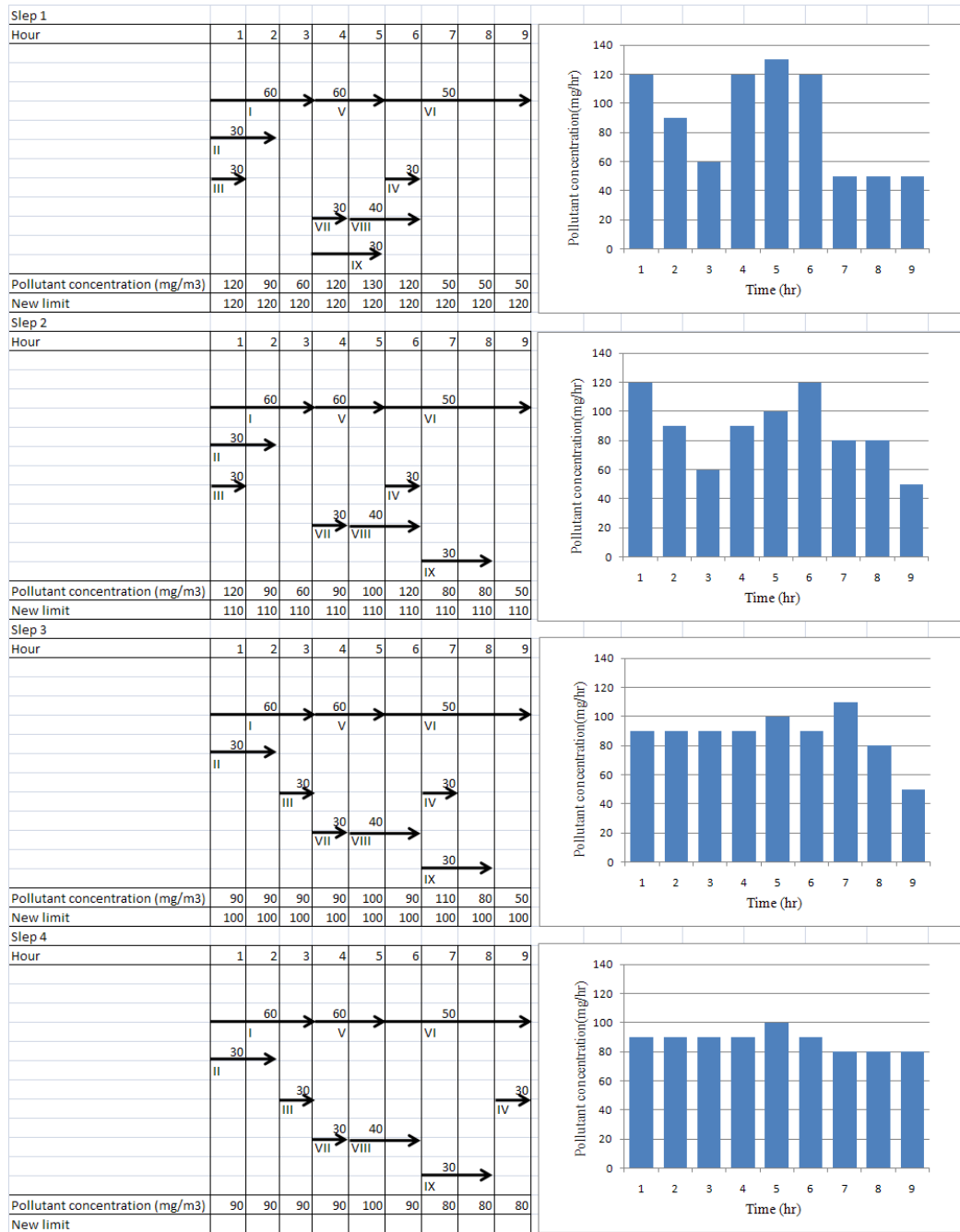


Figure 5.10: Pollutant concentration in every hour (current schedule)

Figure 5.11 shows the activity durations and their associated pollutant concentrations for every hour. Initially, the maximum concentration is identified as 150 mg/m^3 in hour 4. The new limit is set as $(150-10)$ or 140 mg/hr . Activity IV is shifted from hour 4 to hour 6 which reduces the peak in hour 4 to 120 mg/hr . The new peak is found to be 130 mg/hr in hour 5. The new limit is set as $(130-20)$ or 110 mg/hr . Activity IX is shifted from hour 4 to hour 7. This shift reduces the peak to 120 mg/hr . The new limit is set as 110 mg/hr .



Summary

Along with cost and schedule, indoor air pollutant concentration and emissions are useful performance indicators in the construction industry with respect to health hazards for workers. Although, there are currently insufficient data on total airborne pollutant emission for different activities, this methodology provides a potential means to predict the health hazards in construction work once sufficient data becomes available.

Chapter 6: Conclusion

6.1 General Conclusion

This thesis presents a methodology for incorporating occupational indoor air quality into Building Information Modeling (BIM) and implements this methodology in a case study. The key factors influencing the occupational indoor air quality during construction activities were identified, and a quantification process for the source emission rate was designed based on the task-based exposure assessment method (T-BEAM). Using the single zone mass balance model, calculation of pollutant concentration was automated through the utilization of BIM. Drywall sanding in the construction of a single-family house was chosen as a case study and the proposed methodology was implemented. The emission rate of thoracic dust particles (PM_{10}) was quantified by taking dust samples using a Personal Environmental Monitor (PEM) during drywall sanding. In Graphisoft's VICO Constructor and Estimator, the PM_{10} dust concentration during the sanding activity was calculated automatically by creating an emission rate recipe and ventilation rate recipe. The pollutant concentration in each room was calculated from these two recipes.

This methodology added a new dimension for the Building Information Modeling in terms of occupational health hazards. It helps construction managers calculate the pollutant concentration based on number of workers working in the area using BIM before actual construction. The activities can be scheduled based on the pollutant concentration level in every hour and the production rate can be varied

to keep the concentration level within the permissible limit. The construction industry will most benefit from this framework as it focuses on the occupational indoor air quality assessment during construction activities. The regulatory boards can also use this as a tool to monitor the pollutant concentration during hazardous activities, then compare the results with permissible exposure limits. The methodology can also raise awareness within the construction industry about the increasing health hazards to workers which have been relatively neglected.

6.2 Research Contribution

This research has contributed to the field of occupational health hazard assessment in the construction industry through the utilization of the Building Information Modeling. The engineering contributions of this research are summarized as follows:

- Quantification and assessment of occupational indoor air quality during construction activities.
- Utilizing BIM for the purpose of occupational health hazard assessment.
- Automation of the quantification process of airborne pollutant concentration.
- Providing the successful implementation of the proposed methodology.
- Scheduling of the construction activities based on indoor air quality as a mitigation plan.

6.3 Limitations of the Proposed Method

The limitations of this research are presented as follows:

- The mass balance model used in the quantification of the emission rates does not consider the settling effect of the pollutants with time.
- Ideal mixing of air is assumed in the work area.
- Emission rate is calculated based on limited number of measurements.
- The proposed methodology does not automatically calculate the pollutant concentration within the BIM when the ventilation rate is considered different in each working area
- The ventilation rate is assumed constant in a floor in order to calculate the pollutant concentration automatically with BIM.

6.4 Recommendations for Future Studies

The developed methodology can be a foundation for future studies on occupational health hazards and utilization of Building Information Modeling in various fields of construction such as the following:

- Incorporating more parameters in the assessment of the occupational health hazard during construction, such as season, tools or workers' age.
- Measuring the effect of occupational health hazards on construction productivity.
- Establishing guideline for best practice in construction.

- Completing a sensitivity analysis to investigate the influence of the model input parameters.

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