International Energy Agency, EBC Annex 68

Indoor Air Quality Design and Control in Low-Energy Residential Buildings Subtask 2: Pollutant loads in residential buildings (Common exercises)

Energy in Buildings and Communities Technology Collaboration Programme

October 2020

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Preface

The International Energy Agency

The International Energy Agency (IEA) was established in 1974 within the framework of the Organisation for Economic Co-operation and Development (OECD) to implement an international energy programme. A basic aim of the IEA is to foster international co-operation among the 30 IEA participating countries and to increase energy security through energy research, development and demonstration in the fields of technologies for energy efficiency and renewable energy sources.

The IEA Energy in Buildings and Communities Programme

The IEA co-ordinates international energy research and development (R&D) activities through a comprehensive portfolio of Technology Collaboration Programmes. The mission of the IEA Energy in Buildings and Communities (IEA EBC) Technology Collaboration Programme is to develop and facilitate the integration of technologies and processes for energy efficiency and conservation into healthy, low emission, and sustainable buildings and communities, through innovation and research. (Until March 2013, the IEA EBC Programme was known as the IEA Energy Conservation in Buildings and Community Systems Programme, ECBCS.)

The R&D strategies of the IEA EBC Programme are derived from research drivers, national programmes within IEA countries, and the IEA Future Buildings Forum Think Tank Workshops. These R&D strategies aim to exploit technological opportunities to save energy in the buildings sector, and to remove technical obstacles to market penetration of new energy efficient technologies. The R&D strategies apply to residential, commercial, office buildings and community systems, and will impact the building industry in five areas of focus for R&D activities:

- Integrated planning and building design
- Building energy systems
- Building envelope
- Community scale methods
- Real building energy use

The Executive Committee

Overall control of the IEA EBC Programme is maintained by an Executive Committee, which not only monitors existing projects, but also identifies new strategic areas in which collaborative efforts may be beneficial. As the Programme is based on a contract with the IEA, the projects are legally established as Annexes to the IEA EBC Implementing Agreement. At the present time, the following projects have been initiated by the IEA EBC Executive Committee, with completed projects identified by (*) and joint projects with the IEA Solar Heating and Cooling Technology Collaboration Programme by (☼):

Annex 1: Load Energy Determination of Buildings (*)
Annex 2: Ekistics and Advanced Community Energy Systems (*)
Annex 3: Energy Conservation in Residential Buildings (*)
Annex 4: Glasgow Commercial Building Monitoring (*)
Annex 5: Air Infiltration and Ventilation Centre
Annex 6: Energy Systems and Design of Communities (*)
Annex 7: Local Government Energy Planning (*)
Annex 8: Inhabitants Behaviour with Regard to Ventilation (*)
Annex 9: Minimum Ventilation Rates (*)
Annex 10: Building HVAC System Simulation (*)
Annex 11: Energy Auditing (*)
Annex 12: Windows and Fenestration (*)
Annex 13: Energy Management in Hospitals (*)
Annex 14: Condensation and Energy (*)
Annex 15: Energy Efficiency in Schools (*)
Annex 16: BEMS 1- User Interfaces and System Integration (*)
Annex 17: BEMS 2- Evaluation and Emulation Techniques (*)
Annex 18: Demand Controlled Ventilation Systems (*)

Annex 19: Low Slope Roof Systems (*)
Annex 20: Air Flow Patterns within Buildings (*)
Annex 21: Thermal Modelling (*)
Annex 22: Energy Efficient Communities (*)
Annex 23: Multi Zone Air Flow Modelling (COMIS) (*)
Annex 24: Heat, Air and Moisture Transfer in Envelopes (*)
Annex 25: Real time HVAC Simulation (*)
Annex 26: Energy Efficient Ventilation of Large Enclosures (*)
Annex 27: Evaluation and Demonstration of Domestic Ventilation Systems (*)
Annex 28: Low Energy Cooling Systems (*)
Annex 29: ☼ Daylight in Buildings (*)
Annex 30: Bringing Simulation to Application (*)
Annex 31: Energy-Related Environmental Impact of Buildings (*)
Annex 32: Integral Building Envelope Performance Assessment (*)
Annex 33: Advanced Local Energy Planning (*)
Annex 34: Computer-Aided Evaluation of HVAC System Performance (*)
Annex 35: Design of Energy Efficient Hybrid Ventilation (HYBVENT) (*)
Annex 36: Retrofitting of Educational Buildings (*)
Annex 37: Low Exergy Systems for Heating and Cooling of Buildings (LowEx) (*)
Annex 38: ☼ Solar Sustainable Housing (*)
Annex 39: High Performance Insulation Systems (*)
Annex 40: Building Commissioning to Improve Energy Performance (*)
Annex 41: Whole Building Heat, Air and Moisture Response (MOIST-ENG) (*)
Annex 42: The Simulation of Building-Integrated Fuel Cell and Other Cogeneration Systems (FC+COGEN-SIM) (*)
Annex 43: ☼ Testing and Validation of Building Energy Simulation Tools (*)
Annex 44: Integrating Environmentally Responsive Elements in Buildings (*)
Annex 45: Energy Efficient Electric Lighting for Buildings (*)
Annex 46: Holistic Assessment Tool-kit on Energy Efficient Retrofit Measures for Government Buildings (EnERGo) (*)
Annex 47: Cost-Effective Commissioning for Existing and Low Energy Buildings (*)
Annex 48: Heat Pumping and Reversible Air Conditioning (*)
Annex 49: Low Exergy Systems for High Performance Buildings and Communities (*)
Annex 50: Prefabricated Systems for Low Energy Renovation of Residential Buildings (*)
Annex 51: Energy Efficient Communities (*)
Annex 52: ☼ Towards Net Zero Energy Solar Buildings (*)
Annex 53: Total Energy Use in Buildings: Analysis and Evaluation Methods (*)
Annex 54: Integration of Micro-Generation and Related Energy Technologies in Buildings (*)
Annex 55: Reliability of Energy Efficient Building Retrofitting - Probability Assessment of Performance and Cost (RAP-RETRO) (*)
Annex 56: Cost Effective Energy and CO2 Emissions Optimization in Building Renovation (*)
Annex 57: Evaluation of Embodied Energy and CO2 Equivalent Emissions for Building Construction (*)
Annex 58: Reliable Building Energy Performance Characterisation Based on Full Scale Dynamic Measurements (*)
Annex 59: High Temperature Cooling and Low Temperature Heating in Buildings (*)
Annex 60: New Generation Computational Tools for Building and Community Energy Systems (*)
Annex 61: Business and Technical Concepts for Deep Energy Retrofit of Public Buildings (*)
Annex 62: Ventilative Cooling (*)
Annex 63: Implementation of Energy Strategies in Communities (*)
Annex 64: LowEx Communities - Optimised Performance of Energy Supply Systems with Exergy Principles (*)

Annex 65: Long-Term Performance of Super-Insulating Materials in Building Components and Systems (*)
Annex 66: Definition and Simulation of Occupant Behavior in Buildings (*)
Annex 67: Energy Flexible Buildings
Annex 68: Indoor Air Quality Design and Control in Low Energy Residential Buildings
Annex 69: Strategy and Practice of Adaptive Thermal Comfort in Low Energy Buildings
Annex 70: Energy Epidemiology: Analysis of Real Building Energy Use at Scale

Annex 71: Building Energy Performance Assessment Based on In-situ Measurements
Annex 72: Assessing Life Cycle Related Environmental Impacts Caused by Buildings
Annex 73: Towards Net Zero Energy Resilient Public Communities
Annex 74: Competition and Living Lab Platform
Annex 75: Cost-effective Building Renovation at District Level Combining Energy Efficiency and Renewables
Annex 76: ☼ Deep Renovation of Historic Buildings Towards Lowest Possible Energy Demand and CO_2 Emissions
Annex 77: ☼ Integrated Solutions for Daylight and Electric Lighting
Annex 78: Supplementing Ventilation with Gas-phase Air Cleaning, Implementation and Energy Implications
Annex 79: Occupant -Centric Building Design and Operation
Annex 80: Resilient Cooling
Annex 81: Data-Driven Smart Buildings

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Working Group - Indicators of Energy Efficiency in Cold Climate Buildings (*)
Working Group - Annex 36 Extension: The Energy Concept Adviser (*)
Working Group - HVAC Energy Calculation Methodologies for Non-residential Buildings
Working Group - Cities and Communities
Working Group - Building Energy Codes
Working Group - International Building Materials Database

Executive Summary

The objective of the present work was to develop Common exercises to help readers better understand and practice the theory that define a reference house with the local climate, methods, and techniques to evaluate and predict energy efficiency and indoor air quality in the buildings with the changing environment conditions which have been developed in Subtask 2 of Annex 68. The report includes three Common exercises. CE1: A procedure for the definition of reference buildings for estimating the pollution loads, IAQ and energy analysis for different countries/climates. CE2: A method and procedure of using a full-scale chamber to evaluate the effects of emission sources and sinks, ventilation and air cleaning on IAQ. CE3: Development of a procedure for estimating the parameters of mechanistic emission source models from chamber testing data. They are corresponding to Chapters 2, 3 and 5 in the final report of Subtask 2, respectively. Finally, the solutions for CE1 are presented in the Appendices of the report. The readers with appropriate research facilities are encouraged to use the procedures described in CE2 and CE3.

CONTENTS

1 Common exercise I: Definition of a Reference House for Determining the Baseline IAQ and Energy Consumption Conditions

1.1 Objectives

1) Develop a procedure for defining a standard reference to represent a typical design and operation condition for the local climate and practice as the baseline for evaluating IAQ and energy efficiency strategies;

2) Compare the baseline conditions of IAQ and Energy consumption of different countries/regions.

1.2 Scope

Define layout and building materials of the reference house; Specify local climate conditions; Define the schedules of equipment and occupancies; Define the pollution loads; Simulate energy consumption and IAQ of reference house.

To determine IAQ pollution load, we have a variety of methods for estimating pollutant emissions from building materials.

To determine the emission factors (EF) for the materials used in the house as constant pollutant loads, we used in the Northeast region of U.S. reference house:

1. Threshold concentration limits, material quantity and ventilation rate of the residential scenario defined in the CDPH Standard Method v1.2 with the assumption that each material should contribute no more than 1/n of the total pollution load for a given compound.
2. Threshold EF limits in emission standards for low-emission materials (e.g., -the maximum EFs defined in the Green Label Plus Emission Criteria for carpet).
3. Measured material EFs from standard testing at a specified time point (e.g., EFs at 14 day in NRC chamber test database).

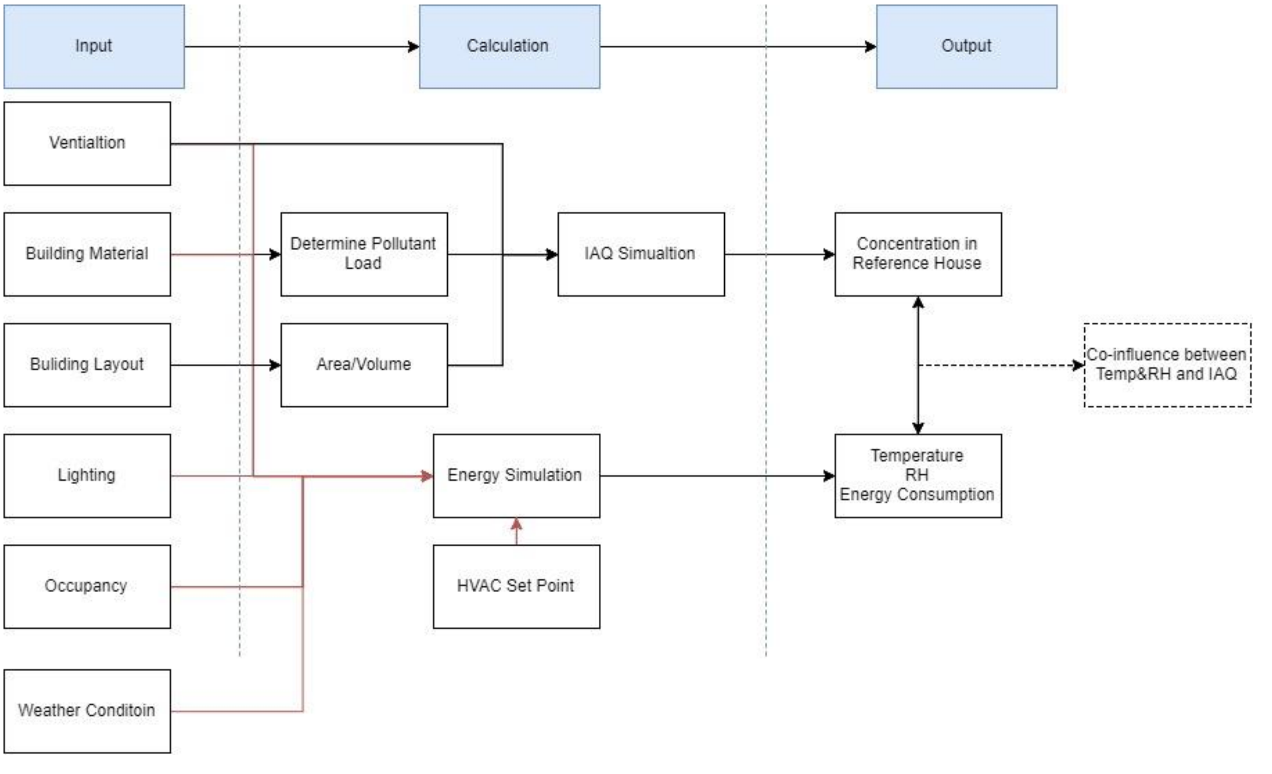
To simulate time-dependent pollutant loads, we used: -

4. Empirical model representation of material emission test data: EF(t).
5. Mechanistic model (diffusion model) representation of material emission test data (need additional work to complete).

For the purpose of this common exercise, different countries/regions should specify the maximum allowable emission factors for the materials defined in their respective reference houses/apartment based on their local or national standards. If any material or concentration limit standard is absent in a certain region, they can refer to a proper standard or research in another region. Annex 68 ST1 summarized the concentration threshold standards in the world and defined the target compounds for the Annex 68 researches.

1.3 Case definition

The following diagram outlines the steps needed to analyze the impact of temperature and relative humidity on IAQ in low-energy residential buildings. The current common exercise is limited to the definition of the reference house and the simulation of the baseline IAQ and energy consumption conditions. In other words, each country/region should define its own reference house for the case, and then perform the simulation. The following section provides an example based on the U.S. Northeast region reference house.



Please refer to the report and presentation for Definition of a Reference Residential Building Prototype for Evaluating IAQ and Energy Efficiency Strategies (see appendix A).

Case studies of different countries are presented in Appendix C - G.

2 Common Exercise 2: Full-scale chamber/room scale case exercise

2.1 Objectives

Recent wide attention to the value and importance of IAQ requires that environmental engineers and students perform adequate evaluation of human exposure and risk management for indoor environments with a cocktail of indoor pollutants. How to determine the VOC emission characteristics for indoor environments rapidly and conveniently is an important but difficulty problem. Emission modeling and evaluation software can help these professionals analyze the exposure impacts of pollutant sources, sinks, ventilation and air cleaning in given environments. The modeling studies still rely on experimental chamber test. A reliable, fewer uncertainty factors test procedure of full-scale / room-scale chamber has been studied in the furniture or building materials labeling schemes (BIFMA,2007, ASTM D5157-97, 2003, ASTM D6670-01,2007, AgBB,2010, CDPH, 2010). The current exercise defined three cases of the chamber test which are also the modeling tasks. The modeling studies will evaluate the possibilities and limitations of applying models or simulation methods to full-scale chamber test. Through the current exercise, these professionals will be equipped with the abovementioned quality and skills.

2.2 Scope

In the following three areas of application, modeling tasks will be exercised based on actual pollution measurements collected in a full-scale chamber with sources, ventilation and air cleaning:

(1) Emission source only;

(2) Emission source with filtration;

(3) Sources and sinks.

2.3 Case definition

For each case, the actual emission measurements are given in a txt form.

Case 1. Emission source only: Particleboard initial emission test (see appendix B)

- Full-scale stainless steel chamber (4.87_7 m long × 3.65_8 m wide × 3.04_8 m high) is used;
- The total effective volume including the chamber room and the ductwork is 57.12 m^3;
- Particleboard pieces with an emission area of 2.24 m^2 is put in the chamber;
- Formaldehyde emission (HCHO) is well-mixed and traced from the beginning of the test by PTR-MS;
- The chamber leakage level (the only ventilation for this case) is 0.036 ACH measured by SF_6;
- The fully-developed steady-state formaldehyde concentration level is around 154 ppb.

<u>With the given information and measurements, model the initial concentration trend of formaldehyde emitted from the particleboards</u> (Tip: Double exponential decay emission model will be better fitted than a constant emission source model).

Case 2. Emission source with filtration: Particleboard emission test with filtration in a full-scale chamber (Refer to Slides 2-3)

- Please refer to Slide 3 for model inputs and chamber conditions;
- The volume and the leakage level are the same as Case 1;

- The emission area of particleboards is 1.60 m^2;
- The steady-state concentration of HCHO is around 110 ppb right before the filter operation;
- After spending enough time to make the emission fully developed, an air filter is deployed at Time Zero to abate the formaldehyde emission from the particleboards. The filtration efficiency is measured over time and described in Slide 3;
- The airflow rate passing through the filter is 12.5 cfm.

With the given information and measurements, try to model the concentration trend of formaldehyde with an air filter in operation.

Case 3. Sources and sinks: Furnished office emission test with filtration in a full-scale chamber (See Slides 4-6)

- Please refer to Slide 5 for model inputs and chamber conditions;
- The volume and the leakage level are the same as Case 1;
- The emissions are from four types of office materials, including gypsum wallboards, oak-style vinyl tiles, textured ceiling tiles, and a wooden office desk;
- At Time Zero, an air filter is deployed, and the filtration efficiency is measured over time as described in Slide 5 (Note: The filter efficiency can be changed under different temperature, humidity and other pollutant loading conditions);
- For this case, the filter starts its operation before the emission reaches its steady-state level fully developed;
- The HCHO concentration level at Time Zero is around 58.7 ppb.
- The airflow rate through the filter is 12.5 cfm.

With the given information and measurements, try to do your best in best modeling the concentration trend of formaldehyde emitted from furnished multiple office-materials with several sink sources and an air filter in operation (Note: Please focus on the upper trend of the HCHO measurements only; the lower line is related to the downstream concentration of the filter system).

Example/Expected Results:

Please refer to the attached slides for expected results when simulated with modeling software; Appendix B Slide 1 for Case 1, Slide 2 for Case 2, and Slide 6 for Case 3.

Reference:

AgBB, 2010. Health-related evaluation procedure for volatile organic compounds emissions (VOC and SVOC) from building products. German Standard.

ASTM D5157-97, 2003. Standard Guide for Statistical Evaluation of Indoor Air Quality Models. American Standard for Testing and Materials.

ASTM D6670-01, 2007. Standard Practice for Full-scale Chamber Determination of Volatile Organic Emissions from Indoor Materials/Products American Standard for Testing and Materials

BIFMA M7.1, 2007. Standard Test Method for Determining VOC Emissions from Office Furniture Systems, Components and Seating. The Business and Institutional Furniture Manufacture Association

CDPH, 2010. Standard Method for the Testing and Evaluation of Volatile Organic Chemical Emissions from Indoor Sources using Environmental Chambers. Version1.1. California Department of Public Health

3 Common Exercise 3: Development of a Procedure for Estimating the Parameters of Mechanistic Emission Source Models from Chamber Testing Data

In order to evaluate the impacts of volatile organic compounds (VOCs) emissions from building materials on the indoor pollution load and indoor air quality beyond the standard chamber test conditions and test period, mechanistic emission source models have been developed in the past. However, very limited data are available for the required model parameters including the initial concentration (C_{m0}), in-material diffusion coefficient (D_m), partition coefficient (K_{ma}), and convective mass transfer coefficient (k_m). The objective of the current study is to develop a procedure for estimating the model parameters by using gas-phase VOCs concentration data from standard small chamber emission tests and explore the feasibility of using the estimated parameters in the mechanistic diffusion model to analyze and predict the long-term emissions from building materials and their impact on indoor air quality. In the procedure, we use the measured data to estimate initial values of the model parameters and then refine the estimates by multivariate regression analysis of the measured data. To verify the procedure and estimate its uncertainty, simulated chamber test data were generated by adding 10% "experimental uncertainties" on the theoretical curve from the analytical solution to a mechanistic emission model. Then the procedure was used to estimate the model parameters from these data and determine how well the estimates converged to the original parameter values used for the data generation. Results indicated that estimates converged to the original parameter values used for the data generation and the error of estimated parameters D_m, C_{m0} and K_{ma} were within ±10%, ±23%, and ±25% of the true values, respectively The procedure was further demonstrated by applying it to estimate the model parameters from real chamber test data. Wide application of the procedure would result in a database of mechanistic source model parameters for assessing the impact of VOC emissions on indoor pollution load, an essential input data for evaluating the effectiveness of various IAQ design and control strategies.

3.1 Introduction

Indoor air quality (IAQ) plays an important role in human health because people typically spend 80-90% of their time indoors, and many pollutants such as volatile organic compounds (VOCs) have higher concentrations indoor than outdoors due to indoor emission sources. In order to evaluate the effects of VOCs emissions from building materials, a physical mechanistic model was developed by Little and Hodgson (1994) assuming equilibrium condition at the air-material interface and Fick's diffusion inside the material. They derived the analytical solution neglecting the convective mass transfer resistance across the air boundary layer over the material surface. Since the model only considers the internal diffusion and ignore the surface convection process, it may overestimate the concentration in the air at early-stage of the material emissions. Huang and Haghighat (2002) considered the convective mass transfer resistance and obtained an analytical solution to the resulting model by neglecting the concentration in the air because of its low value relative to the concentration in the material, and used this method to study the long-term emission. Zhang and Xu (2003) presented an improved mass transfer model without neglecting the concentration in the air, which involved an analytical solution of the one-dimensional diffusion equation given in the model of Huang and Haghighat (2002). However, the concentration in the material and the mass balance equation in the air of Xu and Zhang's model (2003) must be solved simultaneously by the finite difference technique. Yang et al. (2001) developed a numerical simulation model for dry building materials, which can be used for more complex boundary conditions in general. Deng and Kim (2004) successfully derived the analytical solution to the model without neglecting the convective mass transfer resistance across the boundary layer. The model in theory can be used to evaluate and predict the emissions of VOCs from dry building materials beyond the standard chamber test condition and test period. However, very limited data are available for the required model parameters including the initial concentration (C_{m0}), in-material diffusion coefficient (D_m), partition coefficient (K_{ma}), and convective mass transfer coefficient (k_m).

Little and Hodgson (1994) performed a series of emission test for four kinds of carpets. Their experimental data were used for verifying the mathematical model and analytical solution that did not consider the convective mass transfer in the boundary layer. Bodalal et al. (1999) developed experimental method and implemented it to measure directly the D_m and K_{ma}. They tested three types of VOCs through typical dry materials (carpet, plywood, particleboard, vinyl floor, gypsum board, sub-floor tile and OSB). The correlation for predicting D_m and K_{ma} based on molecular weight and vapor pressure were developed for each product and type of VOCs. These correlations were later verified and improved by Zhang et al. (2003) in the sorption and desorption experiments. Xu et al. (2011) implemented a Dual-chamber test that can measure D_m and K_{ma} directly. Xu's data were used for developing and verifying the method that can predict D_m and K_{ma} based on the similarity between water vapor and VOC transport in porous media. A total of 94 sets of data with measured D_m and K_{ma} were found in the previous studies (Appendix 1). The measured D_m ranged across four orders of magnitudes from 1E-14 to 1E-8 m^2/s and K_{ma} ranged from 1 to 450,000, depending on the Media (materials)-Environment (T and RH)-Species (VOCs) combinations (Figure 1a and 1b).

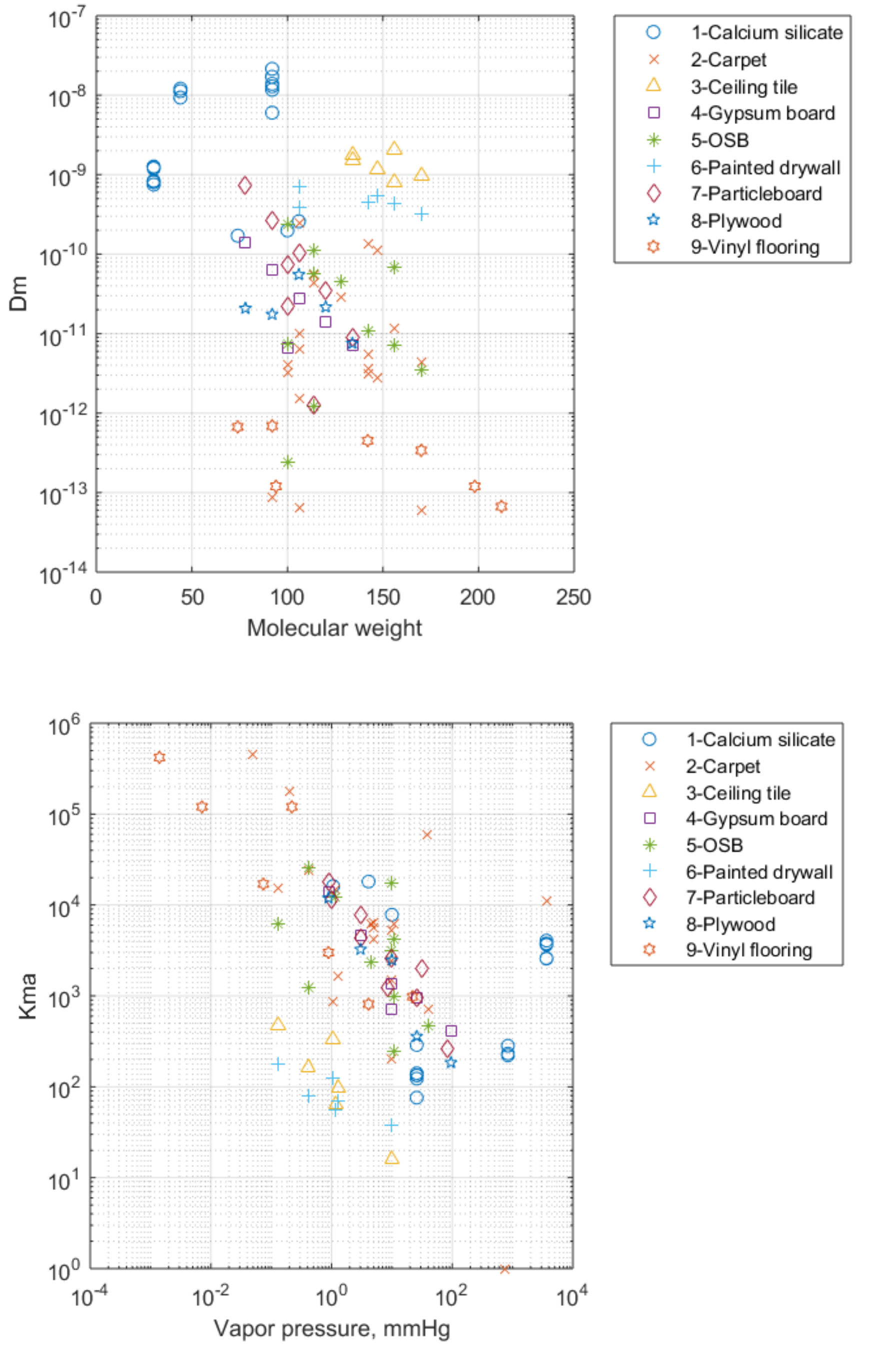


Figure 1 Summary of D_m (top) and K_{ma} (bottom) values from the literature

Although many VOC emission test data have been collected over the last two decades using small-scale chambers, majority of these data have not been used to estimate the parameters of the mechanistic models due to the lack of reliable procedure. Yang et al. (2001) developed a procedure to obtain D_m, K_{ma} and C_{m0}. Only D_m was obtained by curve fitting between the normalized experiment data and numerical solution of standard emission chamber test in Yang's procedure. K_{ma} was pre-determined by the correlation of K_{ma} and vapor pressure from Bodalal's work (Bodalal 1999). C_{m0} was calculated by correcting the initial value with the ratio between the measured peak concentration and that predicted by the model with the estimated D_m and K_{ma}. The accuracy of this correction method, however, is very sensitive to the error of the peak value measured and predicted. He et al. (He and Yang 2005; He et al. 2005) developed a non-linear regression procedure to obtain D_m, K_{ma} and C_{m0} based on chamber emission test data and tested the performance of the method. In their procedure, Little's model (Little et al. 1994) was used which ignores the effect of convective mass transfer through the boundary layer. Xiong et al. (2011, 2012, 2013) developed a method to estimate D_m and k_m by linear regression of the analytical solution of the sorption process in an air-tight chamber and wet coating material emission process. The K_{ma} and C_m was determined by the mass conservation of VOC inside of the chamber and the definition of $K_{ma}= C_m/C_{a,equ}$. Zhou et al. (2018) designed an experiment to obtain K_{ma} and C_{m0} by linear regression of equilibrium state gas phase concentrations under several cycles of air-tight and ventilated conditions. The experimental method can reduce the test period to 48 hours. That is a much shorter time than many of the standard chamber test periods, but the emission process involved in Zhou et al.'s test (Zhou et al. 2018) is presumably in a thin layer below the surface. In the present study a procedure for estimating the model parameters of dry building materials with known accuracy is developed by using gas-phase VOCs concentration data from standard small chamber emission tests. Its adoption for data analysis will result in a database of mechanistic model parameters for evaluating the impact of material emissions on indoor pollution load and IAQ. .

3.2 Method and Procedure

3.3 Mathematical model

A schematic of emission test of a dry material in a ventilated chamber is shown in Fig.2. Assuming that (1) the material is homogenous with a uniform initial concentration; (2) The diffusion process is one dimensional in the material; (3) The pollutant in the chamber air is perfectly mixed; and (4) the interactions between different VOCs are negligible; the in-material diffusion process for a VOC of interest can be described by Eqs.1 - 6:

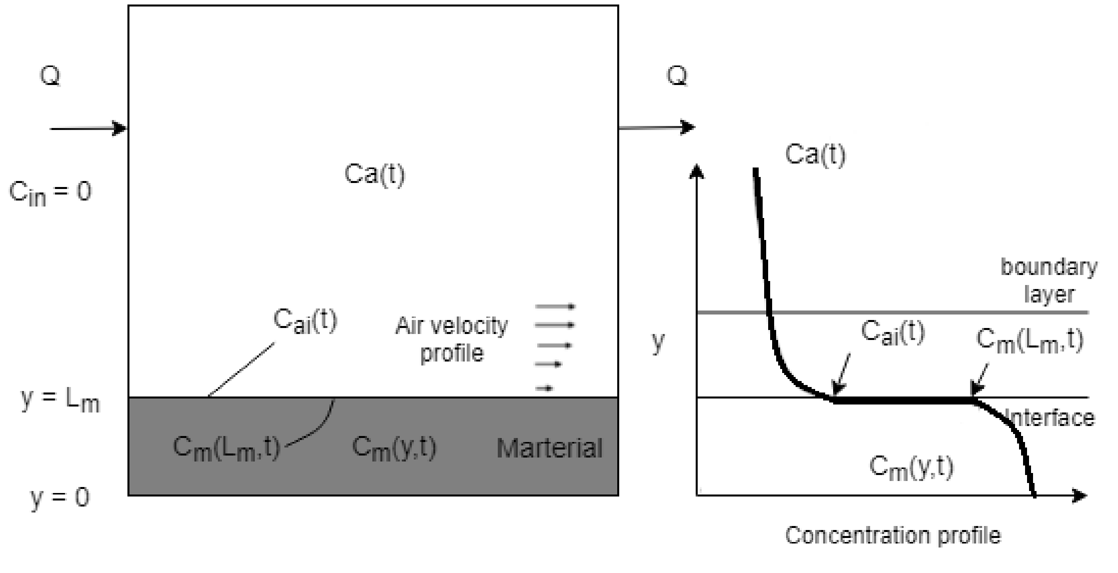


Figure 2 Schematic representation of VOCs emission in a chamber

In-material diffusion process:

$$\frac{\partial C_m}{\partial t} = D_m \frac{\partial^2 C_m}{\partial y^2} \qquad \text{Eq.1}$$

Where,

C_m is the concentration of the VOC in the material, µg/m^3;

D_m is the diffusion coefficient of the VOC in the material and is assumed to be constant, m^2/s;

t is the elapsed time, s;

y is the vertical coordinate from the bottom to the top surface of the material.

The initial condition of Eq.1 is given as follows:

$$C_m(y,0) = C_{m0}\,, \qquad 0 \le y \le L_m \qquad \text{Eq.2}$$

Where,

C_{m0} is the initial concentration of the VOC in the material, µg/m^3;

L_m is the thickness of the material, m.

The boundary conditions of Eq.1 are:

$$\frac{\partial C_m}{\partial y} = 0\,, \qquad at\ y = 0 \qquad \text{Eq.3}$$

$$-D_m \frac{\partial C_m}{\partial y} \ = \ k_m \left(\frac{C_m}{K_{ma}} - C_a\right), \qquad at\ y = L_m \qquad \text{Eq.4}$$

Where,

C_a is the concentration of VOC in the chamber air, µg/m^3;

K_{ma} is the partition coefficient;

k_m is the convective mass transfer coefficient of VOC through the top surface, m/s.

For the concentration in the chamber air, the governing equation can be represented as:

$$V \cdot \frac{dC_a}{dt} = \ -QC_a - AD_m \cdot \frac{\partial C_m}{\partial x} \qquad \text{Eq.5}$$

Initial condition:

$$C_a = 0\,, \qquad at\ t = 0 \qquad \text{Eq.6}$$

Where,

V is the volume of the chamber, m^3;

A is the top surface area of the material, m^2;

Q is the air flow rate, m^3/s.

3.4 Analytical solution

Deng and Kim (2004) derived an analytical solution based to the above diffusion model as follows:

Concentration in the material:

$$C_m(y,t) = 2C_{m0}\sum_{n=1}^{\infty}\frac{\alpha - q_n^2}{A_n}\cdot\cos\left(\frac{y}{L_m}q_n\right)e^{-D_m L_m^2 q_n^2 t} \quad \text{Eq.7}$$

Concentration in the gas-phase:

$$C_a(t) = 2C_{m0}\beta\sum_{n=1}^{\infty}\left(\frac{q_n \sin q_n}{A_n}\right)e^{-D_m L_m^2 q_n^2 t} \quad \text{Eq.8}$$

With

$$\begin{aligned} A_n = {} & [K_{ma}\beta + (\alpha - q_n)K_{ma}Bi_m^{-1} + 2]q_n^2 \cos q_n \\ & + q_n \sin q_n[K_{ma}\beta + (\alpha - 3q_n^2)K_{ma}Bi_m^{-1} + \alpha - q_n^2] \end{aligned} \quad \text{Eq.9}$$

$$Bi_m = k_m L_m / D_m \quad \text{Eq.10}$$

$$\alpha = N{L_m}^2 / D_m \quad \text{Eq.11}$$

$$\beta = L \cdot L_m \quad \text{Eq.12}$$

Where,

Bi_m is termed as the Biot number for mass transfer, which represents the ratio of in-material to on-surface mass transfer resistance;

α is the dimensionless air exchange rate, which shows the ratio of dilution rate in the chamber air to the in-material diffusion rate;

L is loading ratio, area of material / volume of chamber;

β is the ratio of the volume of chamber to the volume of the material;

The q_n are the positive roots of:

$$q_n \tan q_n = \frac{\alpha - q_n^2}{K_{ma}\beta + (\alpha - q_n^2)K_{ma}Bi_m^{-1}} \quad \text{Eq.13}$$

3.5 Approach to the determination of the model parameters

The present model has four key parameters: k_m, K_{ma}, D_m, and C_{m0}. The latter three will be determined by the regression analysis procedure developed in this study. Due to the consistent flow patterns in the standard chamber test condition, the k_m can be pre-determined as part of the chamber characterization measurements. For example, the k_m of the two small scale environmental chambers used to establish the material emission database (MEDB-IAQ) at the National Research Council Canada (NRC) were measured to be 1.0 and 1.5 m/h, respectively (Zhang et al. 1999). Some empirical relations were also adopted for the gas-phase mass transfer coefficient (Huang and Haghighat 2002). For laminar flow, there exists (White, 1988)

$$\mathrm{Sh} = 0.644 Sc^{1/3} Re^{1/2} \qquad \text{Eq.14}$$

Where,

Sh is Sherwood number ($\mathrm{Sh} = \frac{k_m}{Dm/Lm}$);

Sc is Schmidt number ($\mathrm{Sc} = \frac{\upsilon}{Dm}$), υ is the kinematic viscosity, m^2/s

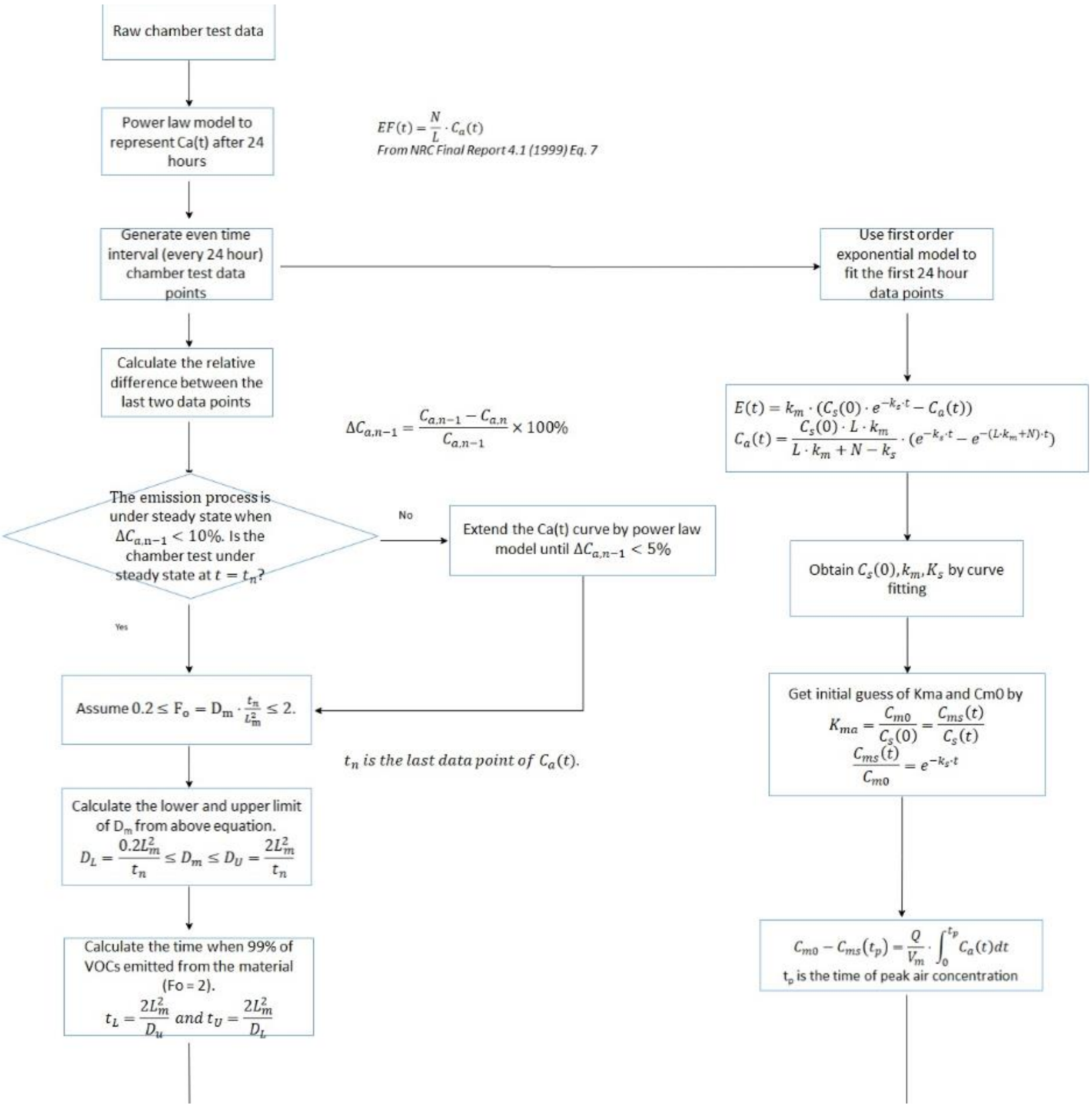
Re is Reynolds number ($\mathrm{Re} = \frac{v \cdot l}{\upsilon}$), v is the velocity of the fluid, m/s, l is the characteristic dimension, m.

Therefore, the gas-phase mass transfer coefficient (k_m) for the small chamber test can be estimated independently. When the mechanistic model is applied to a full-scale environmental condition, the mass transfer coefficient for the full-scale condition should be used together with the K_{ma}, D_m, and C_{m0} determined by the small-scale chamber test data. Such an approach was verified in the study of material emissions from "wet" coating materials where the VOC emission rate was more sensitive to k_m than dry materials (Zhang et al. 1999).

The remaining three key parameters (C_{m0}, D_m and K_{ma}) need to be obtained from the emission test data. From Deng's analytical solution of gas-phase concentration (Eq.8), C_{m0} did not affect the shape of concentration curve ($C_a(t)$), even though it affected the magnitude of $C_a(t)$. So, we used the normalized curve that $\overline{C_a(t)} = \frac{C_a(t)}{C_{a,avg}}$ to estimate D_m and K_{ma} firstly. Logically, the maximum measured concentration ($C_{a,\ max,data}$) could be used to normalize the concentration data, but due to measurement error, the uncertainty in the measured maximum concentration could distort the shape of the curve (e.g., where the maximum concentration actually occurs, and the overall decay of the concentration as the source is depleted). To minimize such distortion, we used the average concentration over the test period ($C_{a,avg}$) to normalize the measured concentrations in the chamber. The C_{m0} can be expressed as $C_{m0} = \frac{total\ emitted\ mass}{material\ volume}$ by the definition of C_{m0}. The total mass emitted from the material is obtained by integrating the $C_a(t)$ curve from t = 0 to t = ∞. The details will be discussed in the next section

3.5.1 Procedure for the determination of the model parameters

We first provide an overview of the procedure, and then discuss the key issues involved in the procedure. As shown in Figure 3, the chamber data (with t>24 h) are first pre-processed by curve fitting with a power law model, which is then used to generate the data with the same "sampling" time interval. The initial guesses of the three key parameters are obtained from the generated data. The generated data are then normalized by the average concentration throughout the test period. Then the regression analysis with global minimum algorithm is performed on the normalized data, which is followed by the re-calculation of the C_{m0}. If the results of D_m and K_{ma} are in the range of K_{ma} dominated state (i.e., D_m is so large that there is abundant VOC mass on the surface that the in-material diffusion resistance is inconsequential comparing to the convective mass transfer resistance over the surface), the upper limit of D_m (the procedure to obtain the upper limit of D_m will be discussed later) were accepted as the final estimation of D_m as the conservative estimate.



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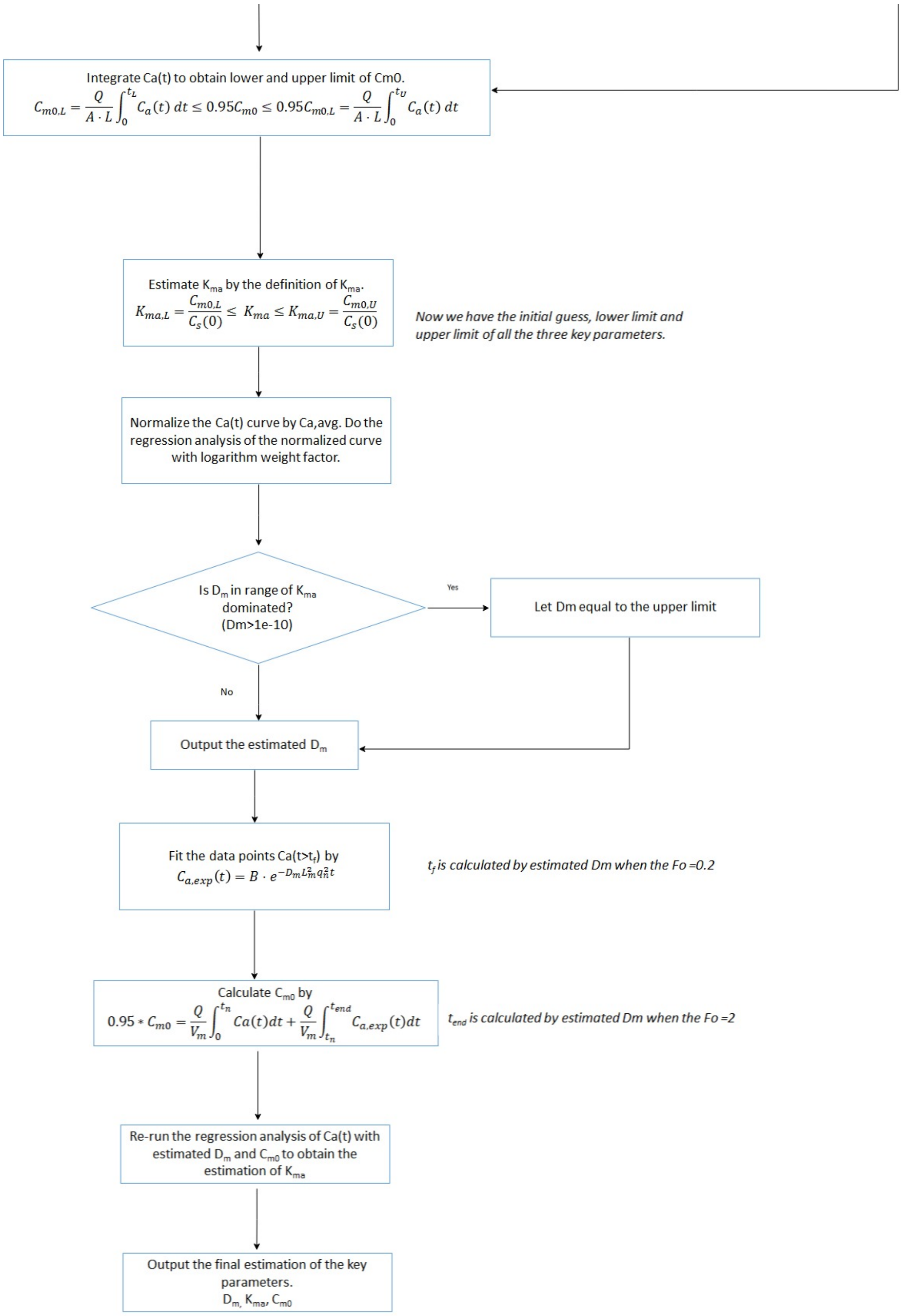


Figure 3 Flow diagram of the regression analysis procedure

3.5.1.1 Regeneration of data with even time interval

Due to the different test conditions, the real chamber test data from different labs or previous studies may have different sampling time intervals. In order to implement the procedure consistently and minimize the effect of sampling interval on the regression results, we adopted an even sampling approach in which the raw chamber data were first fitted with a power-law model, and then "sampled" in an equal interval to generate the data for the regression analysis. The power-law model was found to represent well the data after first 24 hours to 96 hours for several dry building materials, as verified by Zhang et al. (1999). We tested the power-law model for the particleboard test (PB6) from NRC's chamber test whose test period was as long as 840 hours to verify the power law model under long-term emission test (Figure 4).

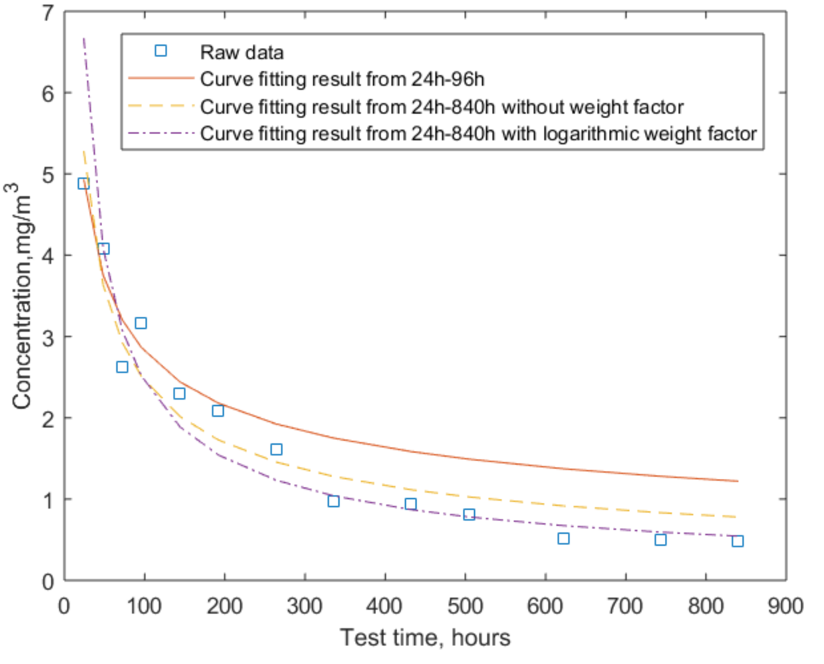


Figure 4 Power law model of PB6

From the results, use 24-96 hours data point to do the power law curve fitting gives the same trend, but over-estimates the long-term concentration. If the entire test data is used to do the power law model curve fitting, power law model gives a good behavior of concentration but still slightly over-estimates the long-term concentration due to the higher concentration or emission factor at initial period. So finally, logarithm weight factor is used to increase the weight of long-term concentrations. The power law model obtained by the logarithm weight factor represents the raw data very well, but overestimate the concentration at initial period. In the real chamber test, more samples are collected at the beginning of the test. So the long-term prediction is more important for even "sampling" time and hence logarithm weight factor is adopted in the procedure.

3.5.1.2 Effect of Chamber Test Period (Elapsed Time)

Based on the literature review, chamber test period (i.e., the elapsed time) varied from 96 to 840 hours in the previous studies. A reference emissoin test with 840 hours of experimental data for a particlebpard obtained by NRC was used to examine the effect of the elasped time on the regression results. In this reference emission test, VOC concentrations were measred at t=94, 120, 168, 240, 336, 504, 672 and 840 hours (Figure 5). The data were well represented by Deng's analytical solution with the parameters: D_m=7.65 × 10^{-11} m^2/s and K_{ma} = 3289 for toluene (note that the volume of the small-chamber is 50 L, the air change rate is 1 ACH, the loading ratio is 0.729, the thickness of the material is 0.0159 m, k_m is 1/3600 m/s). We use the Deng's analytical solution to generate simulated concentration data with the same "sampling" time as the real chamber test. And a "sampling" interval of 24 hours data points are generated by power law curve fitting as discussed previously, which were then used to test the effects of the test period (i.e., the simulated test peiord or elapsted time). As shown in Figure 5, the relative error in estimating the three parameters deceases with the increase of the simulated test period. A test period of 96 h and 120 h would give 1.5-2 times estimation of D_m due to not enough data to capture the behavior. A test period of longer than 240 h (10 days) test would reduce the relative error to be less than 1%.

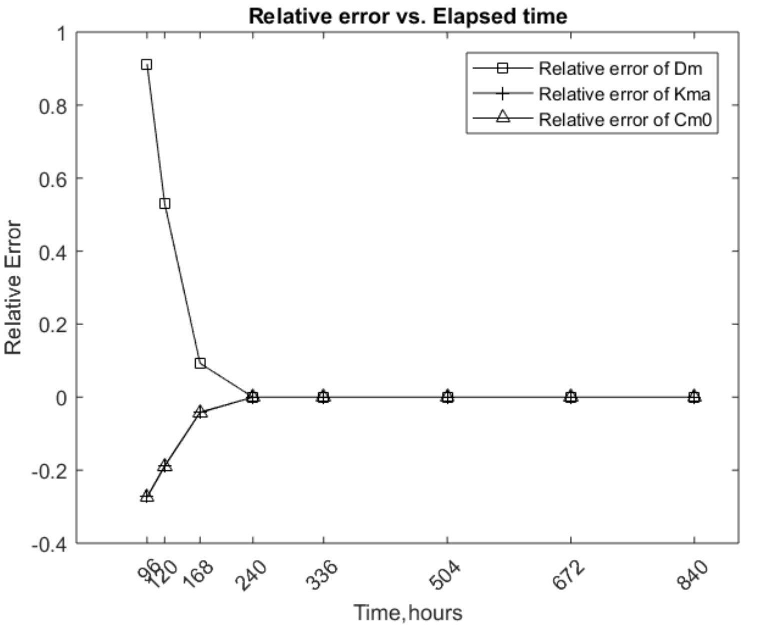


Figure 5 Relative error of key parameters vs. time

3.5.1.3 Weight Factor

In this study, the regression analysis results without applying a weight factor and two different strategies of applying a weight factor have been compared. As implied by the power law model, a logarithmic scale would enhance the impact of long-term data points. Relative weight factor approach (i.e., using the relative deviation as oppose to the absolute deviation between the predicted and the measured data) would give more even weight for each data point. For the PB6 case, all the three weight factor strategies resulted in the same values for the model parameters when no uncertainties were imposed on the data (D_m = 7.56E-11, K_{ma}=3.29E+03 and C_{m0}=5.28E+07).

The regression results obtained by the different weight factors showed no significant difference, even when the ratio between the peak and lowest concentrations was about 10 times. If the mean value of concentration is used as reference value to normalize the curve, the number of data points with the concentrations lower than the mean value (i.e., during the later slow decay period when the level of concentration does not change quickly) is more than that with the concentrations higher than the mean value during the initial period if the elapsed time is longer than 10 days. The mean value is only two times of the lowest value, which also means most of the data points are during the slow decay period, which is an indication of the internal diffusion-controlled process that the mechanistic model intents capture.

For 99+% of the cases with 10% imposed uncertainties in the simulated test data, the different weight factor methods also gave similar regression results. However, for a little less than 1% of the cases, the 10% imposed experimental uncertainty gave much underestimated (less than 1% of given true value) D_m when no weight factor was applied. For these cases, increasing the weight factor for the slow decay period improved the estimation for long-term behavior. In Figure 7 and Figure 6, the x-axil shows the number of all the data points (lower number means earlier data point). As comparing between the two figures, the residuals decrease with the x-axil, which means the logarithm weight factor method matches the slow decay period better than the early period.

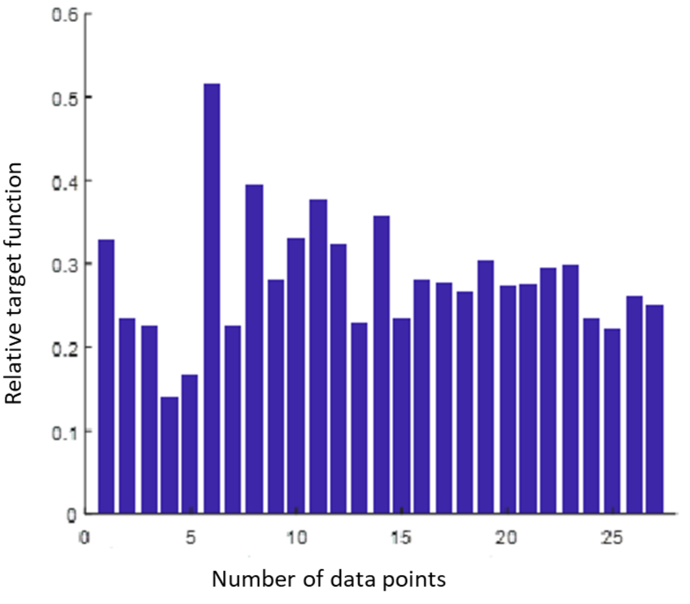


Figure 6 Residuals (target function) distribution for one of the extreme cases

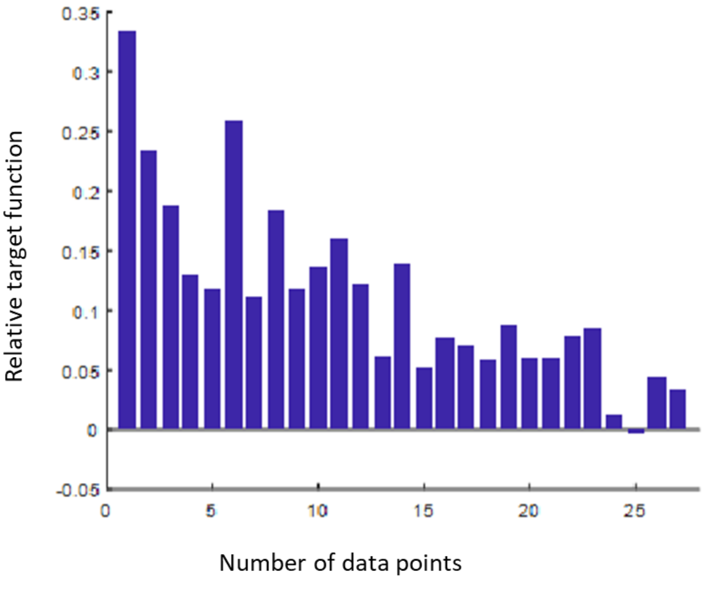


Figure 7 Residuals (target function) distribution for one of the extreme case with logarithm weight factor

So, the logarithm weight factor is finally adopted in the regression analysis procedure since the logarithm weight factor can reduce the underestimation of D_m in the extreme cases (<1%) while provide good estimate of D_m in the 99+% cases.

3.5.1.4 Effects of Initial Guesses of Model Parameters

3.5.1.4.1 Proper initial guesses of the model parameters are necessary to avoid unrealistic regression results and improve the convergence of the regression analysis to the correct model parameters.

3.5.1.4.2 Initial guess of D_m

To obtain the initial guess of D_m, we applied the correlation between the emission rate and the four dimensionless parameters (α, βK_{ma}, Fo, Bi_m/K_{ma}) derived by Qian et al. (2007). The mass-transfer Fourier number ($\mathrm{Fo} = \frac{D_m \cdot t}{{L_m}^2}$), representing the ratio between the emission time and the time-scale of the in-material diffusion process (i.e., a dimensionless time with the in-material diffusion time scale as the reference), could be used to divide the total emission period into three stages: (1) $0 \leq F_o < 0.01$, a peak period or initial period (evaporation-controlled emission period); (2) $0.01 \leq F_o < 0.2$, a transition period; (3) $0.2 \leq F_o \leq 2$, a quasi-steady-state period (i.e., the slow decay period, internal diffusion-controlled emission period). The emission process was approximately complete (over 99% of VOCs is emitted from the material) when Fo = 2.0 with Bi_m/K_{ma} in the range of 20-700 as shown by Qian et al. (2007). All the cases from literature showed that 95% of VOCs emitted from the material when Fo = 2 with Bi_m/K_{ma} in the range of 6.13 – 8189. The range covered all the chamber test cases except Xu's (2011) tests and acetaldehyde of Carpet 3 from John Little (1994). From Little's (1994) research, they didn't have the data of air concentration in the storage bag of Carpet 3. Therefore, they could not calculate K_{ma} independently as Carpet 1 and 4 which created one more freedom when they estimated the parameters D_m and K_{ma}. The acetaldehyde of Carpet 3 gives the lowest K_{ma} (K_{ma} = 1) from the literatures. All of Xu's tests of calcium silicate were with Bi_m/K_{ma} range from 1.07-2.87. Xu used dual-chamber test to measure the value of D_m and Kma, which was different between emission test and sorption test. Since this study is primary used in standard chamber test, we will do some further study about Xu's case in the future. Now, we can accept that Fo = 2 can be considered as at least 95% of VOCs has already emitted from the dry materials with Bi_m/K_{ma} ranged from 6.13-8189.

For a standard chamber test there is no simple criteria to determine whether an emission process reaches the quasi-steady state or the concentration is too low to be detected. We compared the relative difference among the last few data points and used 10% relative difference that was equal to the empirical uncertainty in small standard chamber test as the criteria. We also compared the change of slope of the concentration profile. When the change of slope is below 10%, the tests from literature are considered to reach the quasi-steady state ($0.2 \leq F_o \leq 2$). If the air concentration profile matches either of the above criteria, we can assume the emission process reaches the quasi-steady state. i.e.,

$$0.2 \leq \; F_o(t_n) \leq 2 \qquad \text{Eq.15}$$

Where, t_n is the time of the last data point.

The lower and upper limit of D_m can be solved by Eq.15, and the results are shown as Eq.16.

$$D_{m,L} = \frac{0.2L_m^2}{t_n} \leq D_m \leq D_{m,U} = \frac{2L_m^2}{t_n} \qquad \text{Eq.16}$$

Where, $D_{m,L}$ is the lower limit of D_m

$D_{m,U}$ is the uuper limit of D_m

3.5.1.4.3 Lower and upper limit of C_{m0}

The lower limit of C_{m0} can be determined by integrating the gas-phase concentration from initial time to the end time of the test. The calculation is shown as Eq.17.

$$C_{m0,L} = \frac{Q}{V_m} \cdot \int_0^{t_n} C_a(t)dt \qquad \text{Eq.17}$$

The upper limit of C_{m0} has the relationship with the lower limit of D_m. The lower limit of D_m means the in-material diffusion resistance is large that only a small ratio of VOCs is emitted from the material during the test period. When Fo =2, the maximum possible terminate time can be calculated with the criteria that over 95% of VOCs is emitted.

$$F_o(t_U) = 2 = D_{m,L} \cdot \frac{t_U}{L_m^2} = \frac{0.2L_m^2}{t_n} \cdot \frac{t_U}{L_m^2} \qquad \text{Eq.18}$$

Where,

t_U is the maximum possible time when 95% of VOCs is emitted.

From Eq.18, we have $t_U = 10t_n$. So, the upper limit of C_{m0} can be solved by Eq.19, in which the air concentration between t_n and t_U are extrapolated with the power-law model that is used to represent the test data for t>24 h.

$$C_{m0,U} = \frac{Q}{V_m} \cdot \left(\int_0^{t_n} C_a(t)dt + \int_{t_n}^{t_U} C_a(t)dt\right) \qquad \text{Eq.19}$$

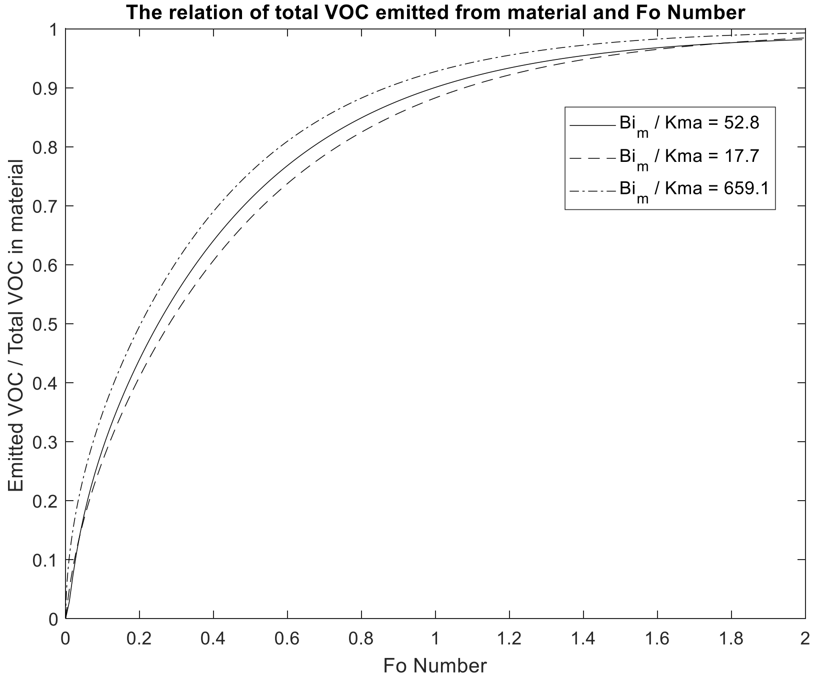


Figure 8 Ratio of VOC mass emitted to total emitable from the material versus Fo Number

3.5.1.4.4 Initial guess of K_{ma} and C_{m0}

For the nonlinear regression analysis, the initial guess of K_{ma} is not important for single solution problems but sensitive to multi-solution problems. The single or multiple solutions of parameters will be discussed later. The initial guess of C_{m0} can be assumed as an arbitrary value for this procedure due to the normalized concentration curve. This study also developed a conservative way to determine the initial guesses of these two parameters assuming a first order decay emission rate during the initial emission period (first 24 hours), adopting the approach used in establishing a semi-empirical emission model for wet coating materials (Zhang et al. 1999):

$$E(t) = k_m(C_s(0) \cdot e^{-K_s \cdot t} - C_a(t)) \qquad \text{Eq.20}$$

Where,

Cs—Concentration on the emitting surface

k_m---convective mass transfer coefficient, m/h

k_s—first-order constant for the VOC concentration on the surface, 1/h

The model result calculated by governing equation (Eq.5) is in the following equation for $C_a(t)$ in the chamber.

$$C_a(t) = \frac{C_s(0) \cdot L \cdot k_m}{L \cdot k_m + N - k_s} \cdot (e^{-k_s \cdot t} - e^{-(L \cdot k_m + N) \cdot t}) \qquad \text{Eq.21}$$

C_s (0), k_m and K_s can be determined by non-linear regression analysis from the gas-phase concentration test data of first 24 hours for use in Eq.21. From the definition of K_{ma}, K_{ma} can be expressed as $K_{ma} = \frac{C_{m0}}{C_s(0)}$. Integrating the emission factor E(t) with Eq.20 from initial time point to the time when gas-phase concentration reaches the peak value can obtain the mass of VOC (ΔM) emitted during this period. Assuming an equilibrium condition between the solid material and gas-phase concentration at the peak value of the concentration of chamber air, K_{ma} can be expressed as $K_{ma} = \frac{C_{m0} - \frac{\Delta M}{Vm}}{Ca_{t-peak}}$. The initial guesses of K_{ma} and C_{m0} were calculated from the above two equations of K_{ma} and C_{m0}.

3.5.1.5 Local Minimum or Global Minimum

3.5.1.5.1 Sensitivity Analysis

To better interpret the experimental results analyzed by the diffusion model, a sensitivity study of the diffusion model is considered and its results presented here. The simulated cases for the sensitivity study are also created by the analytical solution for the same standard small-chamber test condition. The total elapsed time is 672 hours (28 days) which is the common elapsed time in Europe emission test for most dry building materials (ISO,2011). Based on the range from the data above, seven sets of diffusion and partition coefficient levels are selected as shown in Table 2.

Table 2

Sensitivity study with seven sets of parameter values

D_m	1.00E-14	1.00E-13	1.00E-12	1.00E-11	1.00E-10	1.00E-09	1.00E-08
K_{ma}	100	1,000	5,000	10,000	50,000	100,000	1,000,000

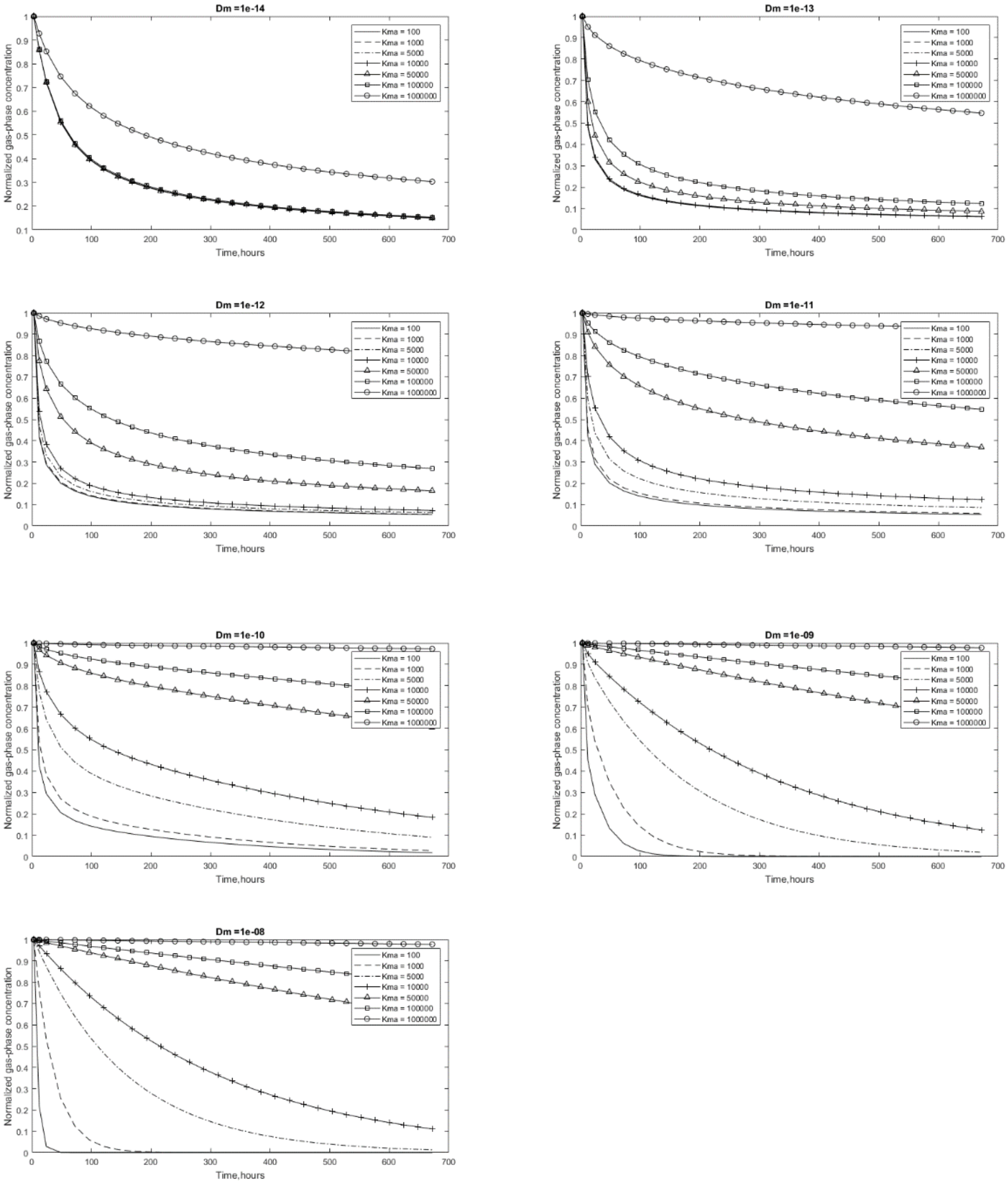


Figure 9 Sensitivity study of effect of K_{ma} under different levels of D_m

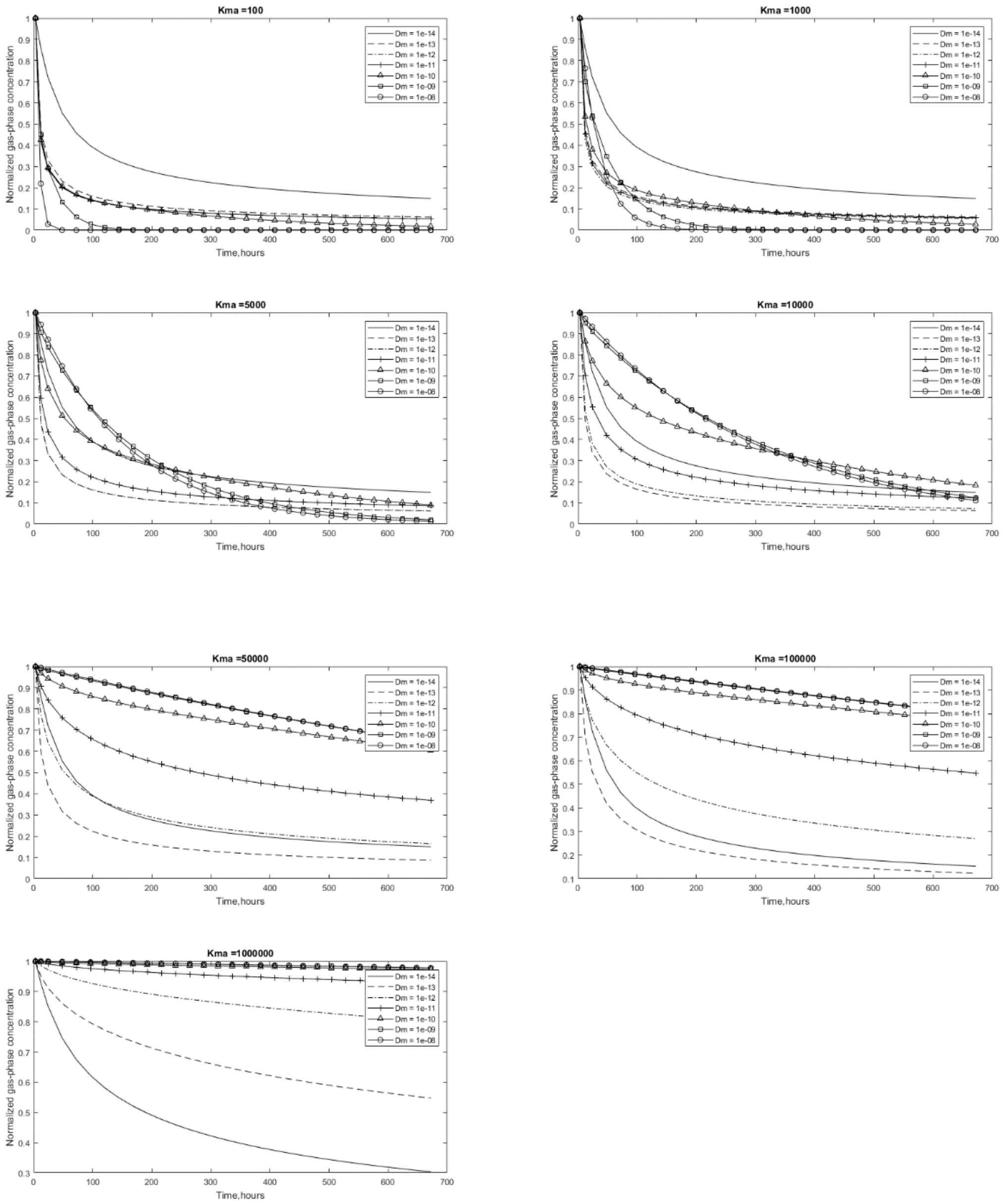


Figure 10 Sensitivity study of effect of D_m under different levels of K_{ma}

The overall rate of emission rate is dominated by internal diffusion process controlled by D_m and surface emission process controlled by k_m and K_{ma}. According to the sensitivity study, as shown in figure 9 and 10, when the value of D_m is over 1 x 10 $^{-9}$ m^2/s, surface emission process is the rate controlling process. As a result, D_m cannot be obtained from the nonlinear regression process since D_m = 1 x 10^{-9} m^2/s and D_m = 1 x 10^{-8} m^2/s may not be distinguished from the concentration curve under any value of K_{ma}. When the K_{ma} = 100, D_m in the order from 1.0E-13 to 1.0E-11 may not be distinguished from the concentration curve. In theory, the diffusion coefficient D_m discussed above is applied with the assumption that the material is homogeneous, and the diffusion is driven by the total concentration (i.e., sorbed phase plus free gas phase VOCs) gradient in the material. However, many building materials are better represented as a porous media in which the VOC diffusion is driven by the free gas phase concentration gradient in the pore air with the pore diffusion coefficient, Dp, as the calcium silicate, the effective diffusion coefficient D_e is the diffusion coefficient with gas-phase concentration difference as the driving force ($D_e = D_m \cdot K_{ma}$). This means even we assume that D_m and K_{ma} are independent, but there exists the relationship between D_m and K_{ma} for certain materials and compounds. If assume all the literature cases with the same k_m and L_m in the emission test, 87.3 % of the values of Bi_m/K_{ma} range from 1 to 1000. A large possibility that the case with a large D_m will have a small K_{ma}

in the real test. So, surface process controlling region can be defined when the D_m is over 1 x 10^{-10} m^2/s according to the sensitivity study.

3.5.1.5.2 Local minimum

For the method of regression analysis, least square of target function and trust-region have been applied in this study. The target function is $F(D_m, K_{ma}) = \sum\left(C_{a,estimate} - C_{a,data}\right)^2$ .The case of D_m and K_{ma} gives the minimum of the target function F means the best curve fitting result obtained from the chamber test data. The process of the kth iteration has the form:

- Check if $F(D_m^k, K_{ma}^k)$satisfies the convergence criteria.($\left|D_m^k - D_m^{k+1}\right|$ or $\left|K_{ma}^k - K_{ma}^{k+1}\right| < 1 \times 10^{-6} \cdot (D_m^k\ or\ K_{ma}^k)$ and $\left|F(D_m^k, K_{ma}^k) - F(D_m^{k+1}, K_{ma}^{k+1})\right| < 1 \times 10^{-6}$)
- If not, determine a δD_m (δK_{ma}) such that F ($D_m + \delta D_m$, K_{ma}) < F (D_m, K_{ma}) or F (D_m, $K_{ma} + \delta K_{ma}$) < F (D_m, K_{ma}). The value of target function is always decent.
- Let the new $D_m^{k+1} = D_m^k + \delta D_m\ or\ K_{ma}^k = K_{ma}^{k+1} + \delta K_{ma}$.

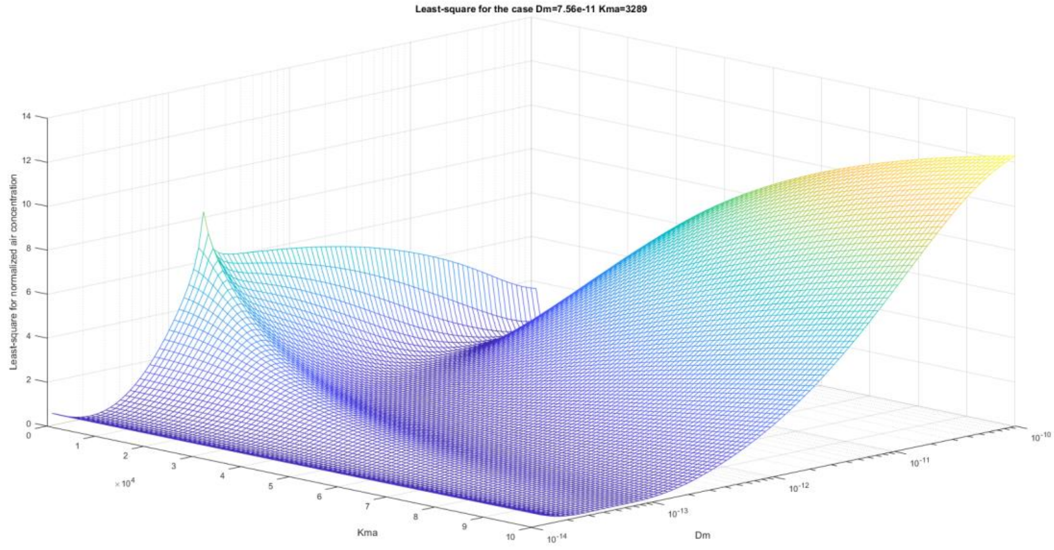
The trust region is the algorithm to determine the value of δD_m (δK_{ma}) for each iteration step. Trust region means the δD_m(δK_{ma}) of target function F(D_m, K_{ma}) in iteration is believed adequately small to apply the model:

$$\mathrm{F}(\mathrm{D_m} + \delta\mathrm{D_m}, \mathrm{K_{ma}}) = \mathrm{F}(\mathrm{D_m}, \mathrm{K_{ma}}) + \frac{\partial F}{\partial D_m}\delta D_m + \frac{1}{2}\frac{\partial^2 F}{\partial D_m^2}\delta \mathrm{D_m}$$

to estimate the function F($D_m + \delta D_m$, K_{ma}). δKma can be determined by the same way as the parameter D_m. From the structure of the iteration, this method can finally find out the minimum value of the target function or lead to a local minimum result for multiple solution problems. The key parameters of the current step are the case that matches the modified chamber test data best or one of the best for multiple solutions.

3.5.1.5.3 Global minimum

To figure out whether the target function has multiple solutions or not, the target functions for two cases with D_m in two orders difference (1×10^{-11} and 1×10^{-13}) were calculated in the entire range of D_m and K_{ma}. Fig. 11 shows the least-square of the cases of different levels of D_m with the key parameters are given as x-axis and y- axis. Both two figures show multiple solutions are existing in this kind of nonlinear regression analysis problems.



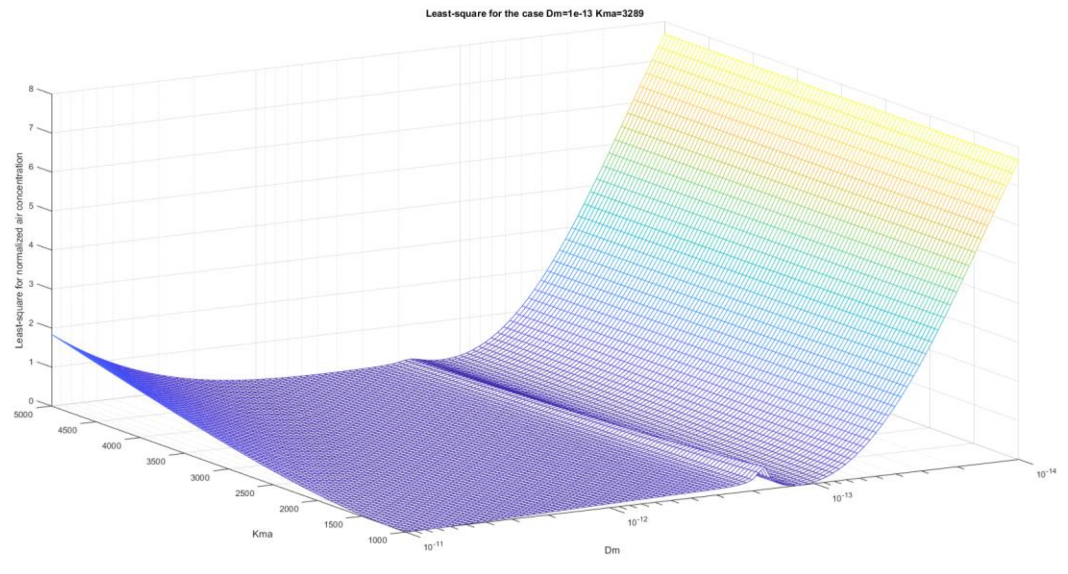


Figure 11 Two cases in local minimum region and global minimum region

Even the figure of case 1 illustrates there are multiple sets of key parameters which give the same levels of least-square value, which satisfy the convergence criteria. Because the initial guess of D_m is higher than given value. The best results have been found based on this initial guess and are always equal to the key parameters as given. But for case 2 shown in Fig 11, since the initial guess of D_m is at the left edge, local minimum method cannot overcome the hill of least-square goes up and gives the correct parameters as given. In the global minimum case, the result is sensitive to the initial guess of the key parameters. For the cases in this region, the multi-start global minimum strategy can be applied to find the global minimum.

3.5.1.5.4 Conclusion for sensitivity study

Based on the sensitivity study, when the D_m is more than 1×10^{-10} m^2/s, the net emission rate is controlled by surface resistance. In this range, K_{ma} is the parameter control the shape of the gas-phase concentration curve. That means, if we can get a good result of K_{ma} when D_m is larger than 1×10^{-10} m^2/s, this procedure captures the behavior of chamber test data very well. For any case, there are multiple solutions for least-square problems. So, the global minimum algorithm is suggested by this procedure. As we know, the local minimum can reduce the calculation load and save time. For the cases that the relative errors of the D_m and K_{ma} are more than 10%, the gas-phase concentrations in the typical test period were also very well represented with a residual less than 4%. The error of the estimated emission factor for these cases are less than 10% with the typical test period.

3.6 Verification of Procedure

3.6.1 Literature Review Case

Gas-phase concentrations of measured cases (only D_m and K_{ma}) from literature shown in Figure 1 are generated by analytical solution. 80% of D_m and 90% of K_{ma} ranged from 20% - 500% that covered most of the compounds in the materials except vinyl flooring from Cox and carpet3 from John Little. For all the out of range cases, they have very small D_m (<1E-12) and K_{ma} ranged from 810 to 450,000. The D_m of these cases converged around 1E-12 m^2/s by the global minimum algorithm with 300 multi-start points. 1E-12 m^2/s was one of the local minimum but not the global minimum of target function. 7 out of 10 of these cases could find the global minimum by increasing the multi-start points to 1000. Genetic algorithm will be tested in the future to increase the speed of convergence to global minimum.

3.6.2 Effects of Experimental Uncertainty in the Data on the Regression Results

All the previous discussion or verification of procedure are based on simulated data by analytical solution without any uncertainty of measured chamber concentration which is the ideal condition. From NRC database, the experience value of uncertainty in the standard chamber test is 10%. To test the effect of uncertainty, 100 cases of PB1 were generated by analytical solution by adding 10% uncertainty which followed the normal distribution on each data points. The results are shown in Figure 12 -14.

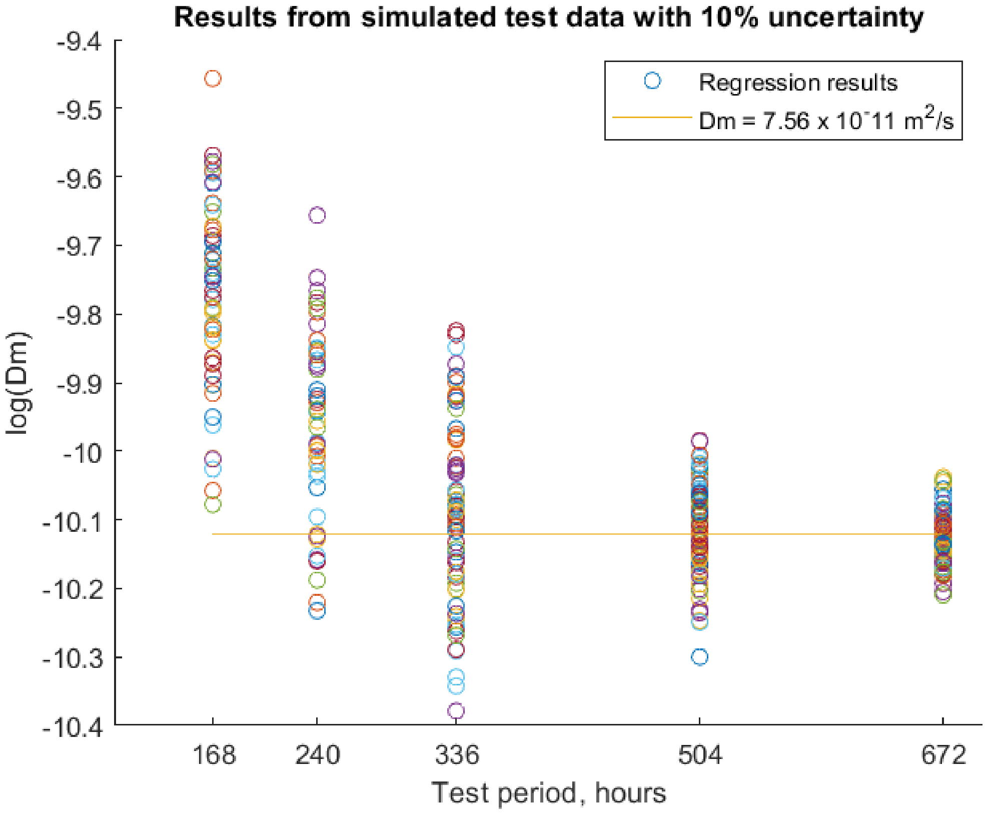


Figure 62 Results of D_m for 100 Cases with 10% uncertainty

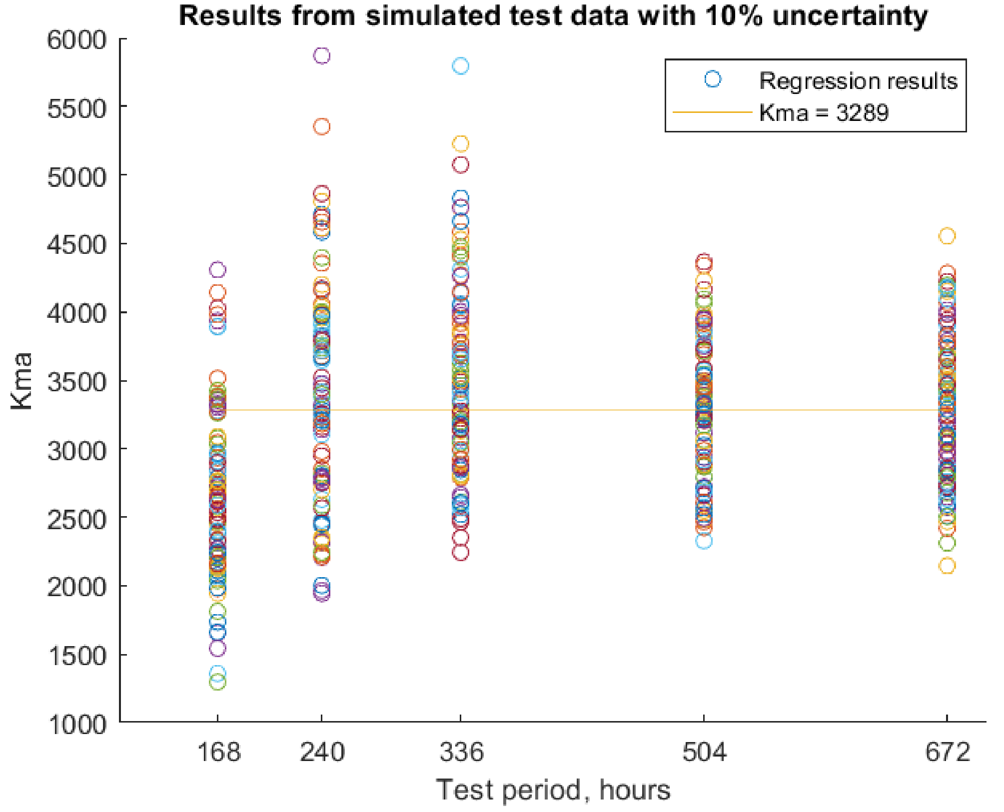


Figure 13 Results of K_{ma} for 1000 cases with 10% uncertainty

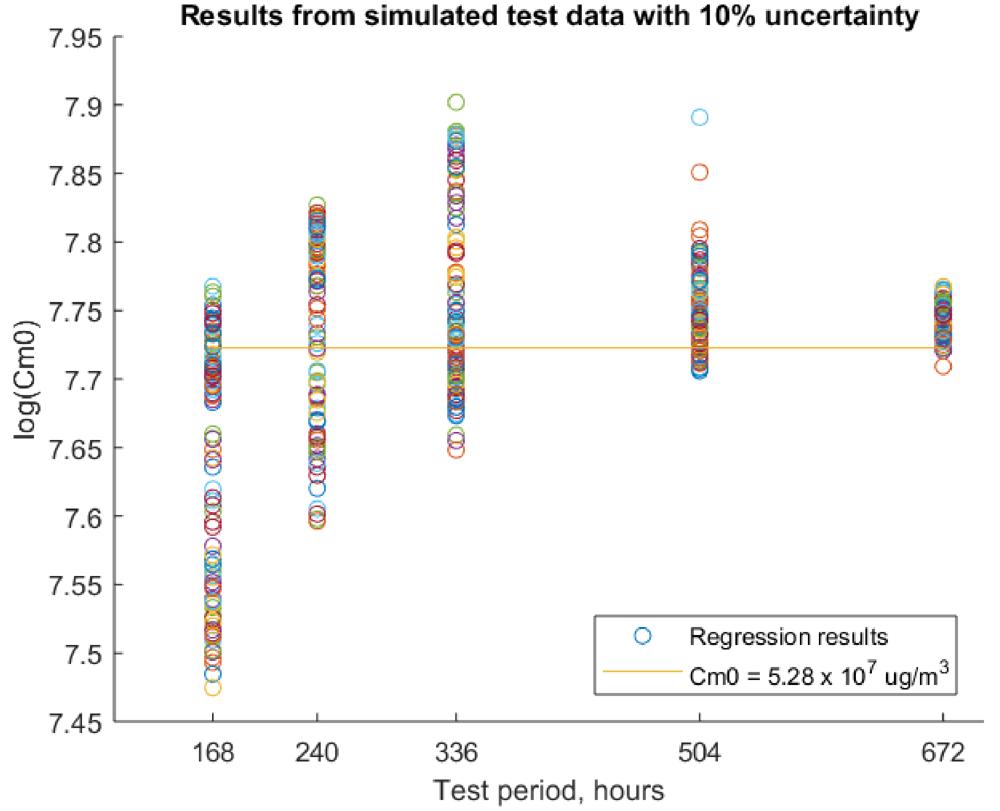


Figure 14 Results of C_{m0} for 1000 cases with 10% uncertainty

From the above figures, the uncertainty of measured data has a significant impact on the estimation of key parameters for any single case. The statistic results show that the estimated parameters can coverage to the true value with the increasing of test period. . The uncertainty has a larger impact on the early period than the slow decay period. In other words, the uncertainty has a larger impact on the shorter test period. The above figures showed the overall magnitude order of D_m had a great influence on the accuracy of estimating C_{m0} since we integrated the air concentration to obtain the value of C_{m0}. And the D_m will affect the decay speed of the air concentration curve after the last data point. Fig 15 and Table 3 show the relative errors between mean value of 100 cases and given parameters vary with test period. Based on the relative errors of the three key parameters, the prediction of D_m is higher at 168 h and 240 h, but less than 3.02% after 336 h. The prediction of K_{ma} is less than 2.36% with test period longer than 240 h. The prediction of C_{m0} is under 3.72% with the test period longer than 240 h. The standard deviation of the prediction ranged from 54.17% to 2.47% for all the three keys parameters. The procedure can give the same order prediction with test period between 168 h to 240 h and less than 1% +/- 16.01% with 672 h test. Based on the discussion in the sensitive study section, the D_m and Kma with 16% difference, the curve of concentration is hard to distinguish. So the prediction of the procedure gives the good estimation of air concentration and emission factor.

Table 3 Statistic of 100 uncertainty cases

		Average	Relative-difference	Standard deviation	Relative-Std
168 h	Dm	1.43E-10	89.14%	7.75E-11	54.17%
	Kma	2801.28	-14.83%	638.87	22.81%
	Cm0	4.28E+07	-18.99%	8.25E+06	19.28%
240 h	Dm	8.67E-11	14.68%	3.38E-11	39.03%
	Kma	3333.55	1.35%	774.30	23.23%
	Cm0	5.24E+07	-0.76%	7.86E+06	14.99%
336 h	Dm	7.79E-11	3.02%	2.57E-11	32.94%
	Kma	3366.53	2.36%	707.82	21.03%
	Cm0	5.48E+07	3.72%	8.76E+06	16.00%
504 h	Dm	7.44E-11	-1.57%	1.33E-11	17.83%
	Kma	3274.04	-0.45%	546.41	16.69%
	Cm0	5.36E+07	1.44%	3.73E+06	6.97%
672 h	Dm	7.55E-11	-0.08%	7.11E-12	9.42%

	Kma	3287.01	-0.06%	526.29	16.01%
	Cm0	5.28E+07	-0.04%	1.30E+06	2.47%

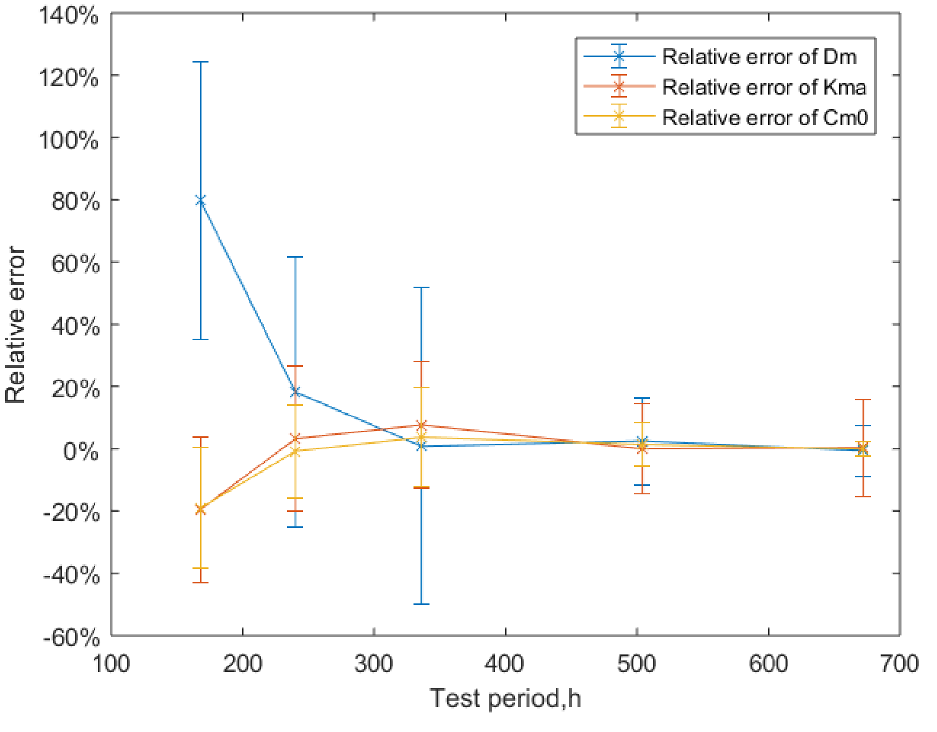


Figure 7 Relative error of the key parameters vs. time

3.7 Application of Procedure

3.7.1 NRC database

One material (particleboard ID: PB 6) was selected from the NRC database (Magee et al. 1999) to investigate the application of the procedure. Figure 15 gives the results of PB6 when implement this procedure. For PB6, when the time is longer than 336 h, this procedure gives good results to approach the test data that agree with the above uncertainty test. Using all 840 h data resulted in D_m and K_{ma} that gave the best curve fitting for the long-term prediction, but the initial concentration data points were not as well represented.

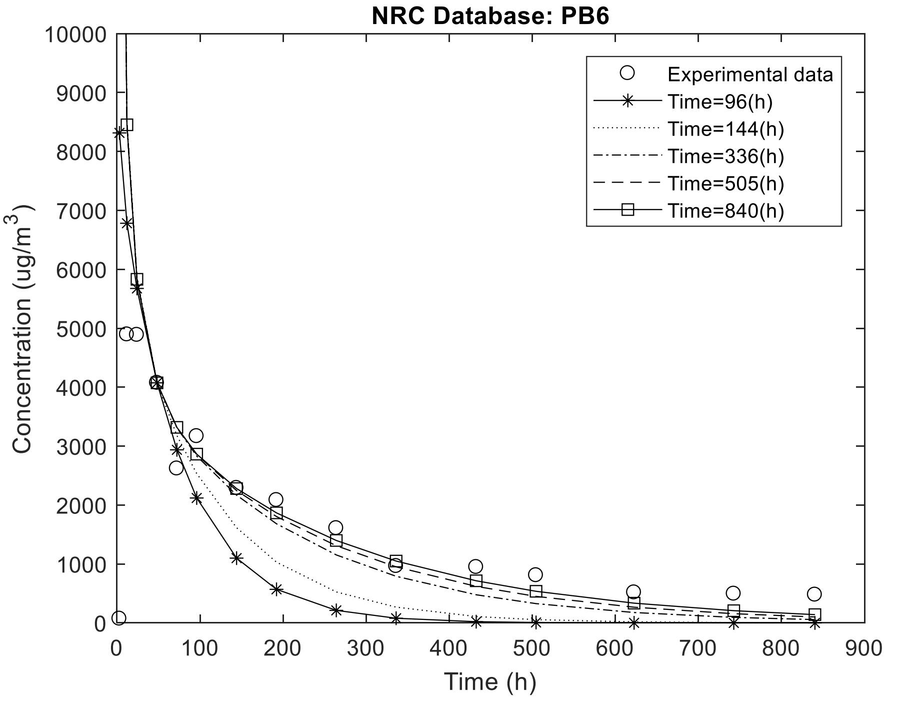


Figure 85 Gas phase concentration of PB6

3.7.2 Pandora database

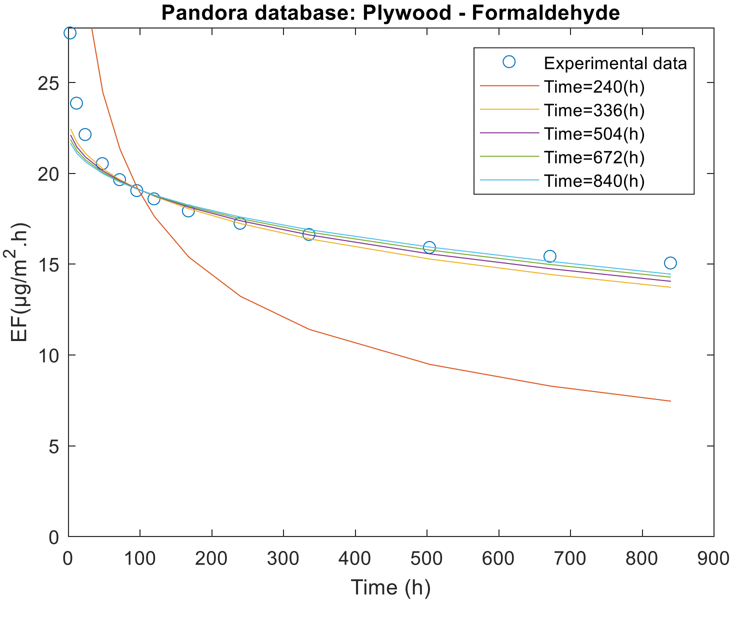


Figure 16 Emission factor curve of Pandora test

The Pandora database (Abadie, Marc and Blondeau, Patrice, 2011) has four test points in the 42 days test period (3, 28, 35, 42 days). The procedure can only give a good curve fitting with elapsed time longer than 336 hour. Due to the slope of power law model is steep at early stage, the procedure cannot predict EF(t) well before 336 hours. And too few data points cause large uncertainty of the power law curve.

3.8 Conclusion

Based on the standard chamber test and analytical solution of diffusion model, a procedure has been developed, which can obtain the key parameters of the diffusion model by multi-variance nonlinear regression analysis. The concentration curve generated by estimated key parameters shows a good agreement with the real chamber test data. The procedure was suggested using in the validated region ($1\times10^{-13} < D_m < 1\times10^{-9}$ m^2 /s, $1000 < K_{ma} < 100{,}000$). Applying the procedure to literature cases, all the regression analysis had good convergence with residual less than 4%. 67.5% of the cases had the estimation errors for D_m, C_{m0}, and K_{ma} within ±10%, ±22.7%, and ±25%, respectively. Uncertainty of measurement affects the accuracy of estimated key parameters very much, but the statistic results show good convergence to the true value when the developed procedure was applied to 100 cases. Further studies will focus on more efficient global search algorithm (e.g., genetic algorithm) in the future. The procedure also needs to be further validated by applying it to more chamber test data.

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Appendix 1 Summary Table of Literature Review Cases

Material	VOCs	K_{ma}	D_m	Reference
Calcium silicate	Formaldehyde	2574	1.20E-09	Jing Xu
Calcium silicate	Formaldehyde	2597	1.26E-09	Jing Xu
Calcium silicate	Formaldehyde	4057	7.49E-10	Jing Xu
Calcium silicate	Formaldehyde	2568	1.25E-09	Jing Xu
Calcium silicate	Formaldehyde	3775	8.37E-10	Jing Xu
Calcium silicate	Formaldehyde	3656	8.04E-10	Jing Xu
Calcium silicate	Acetaldehyde	232	1.13E-08	Jing Xu
Calcium silicate	Acetaldehyde	283	9.33E-09	Jing Xu
Calcium silicate	Acetaldehyde	221	1.21E-08	Jing Xu
Calcium silicate	Butanol	18100	1.71E-10	Jing Xu
Calcium silicate	Toluene	288	6.01E-09	Jing Xu
Calcium silicate	Toluene	133	1.29E-08	Jing Xu
Calcium silicate	Toluene	76	2.14E-08	Jing Xu
Calcium silicate	Toluene	123	1.71E-08	Jing Xu
Calcium silicate	Toluene	134	1.39E-08	Jing Xu
Calcium silicate	Toluene	141	1.17E-08	Jing Xu
Calcium silicate	Hexanal	7809	1.98E-10	Jing Xu
Calcium silicate	Benzaldehyde	16111	2.59E-10	Jing Xu
Carpet	Heptane	708.55	5.50E-11	Bodalal
Carpet	Octane	6171.31	4.31E-11	Bodalal

Material	VOCs	K_{ma}	D_m	Reference
Carpet	Nonane	6216.05	2.83E-11	Bodalal
Carpet	Decane	14617.24	5.42E-12	Bodalal
Carpet	Undecane	24255.9	2.79E-12	Bodalal
Carpet	Benzaldehyde	865	1.11E-10	Jinsong Zhang
Carpet	Ethylbenzene	204	2.43E-10	Jinsong Zhang
Carpet	1,4-dichlorobezene	1643	1.36E-10	Jinsong Zhang
Carpet	Dodecane	15345	1.18E-11	Jinsong Zhang
Carpet	Fornaldehyde	11000	3.20E-12	John Little
Carpet	Acetaldehyde	1	6.40E-12	John Little
Carpet	1,2-Propanediol	180000	6.50E-14	John Little
Carpet	Styrene	4200	4.10E-12	John Little
Carpet	Styrene	6500	3.60E-12	John Little
Carpet	Styrene	5700	3.10E-12	John Little
Carpet	Ethylbenzene	1500	1.02E-11	John Little
Carpet	Ethylbenzene	2400	4.30E-12	John Little
Carpet	Ethylbenzene	5300	1.50E-12	John Little
Carpet	4-Ethenylcyclohexene	1400	5.20E-12	John Little
Carpet	4-Ethenylcyclohexene	1700	2.10E-12	John Little
Carpet	2,2,4-Trimethylpentane	59000	6.00E-14	John Little
Carpet	2-Ethyl-1-hexanol	450000	8.80E-14	John Little

Material	VOCs	K_{ma}	D_m	Reference
Carpet	4-Phenylcyclohexene	81000	5.90E-13	John Little
Carpet	4-Phenylcyclohexene	67000	5.00E-13	John Little
Carpet	4-Phenylcyclohexene	170000	1.20E-12	John Little
Ceiling tile	Benzaldehyde	327.6	7.97E-10	Jinsong Zhang
Ceiling tile	Ethylbenzene	16	1.80E-09	Jinsong Zhang
Ceiling tile	Decane	64.1	1.50E-09	Jinsong Zhang
Ceiling tile	1,4-dichlorobezene	97	1.17E-09	Jinsong Zhang
Ceiling tile	Undecane	162.8	2.08E-09	Jinsong Zhang
Ceiling tile	Dodecane	475.6	9.62E-10	Jinsong Zhang
Gypsum board	Benzene	416	1.42E-10	Bodalal
Gypsum board	Toluene	941	6.38E-11	Bodalal
Gypsum board	Ethylbenzene	1360	2.77E-11	Bodalal
Gypsum board	Propylbenzene	4562	1.41E-11	Bodalal
Gypsum board	Butylbenzene	14031	7.05E-12	Bodalal
Gypsum board	Hexanal	708	6.51E-12	Yang
Gypsum board	Acetic Acid	2070	2.63E-11	Yang
Gypsum board	pentanal	695	2.19E-10	Yang
Gypsum board	pentanol	17800	1.88E-12	Yang
OSB	Heptane	472.47	2.34E-10	Bodalal
OSB	Octane	998.94	1.12E-10	Bodalal

Material	VOCs	K_{ma}	D_m	Reference
OSB	Nonane	2369.11	4.51E-11	Bodalal
OSB	Decane	12027.74	1.07E-11	Bodalal
OSB	Undecane	25931.86	7.24E-12	Bodalal
OSB	Hexanal	17311	2.43E-13	Yang
OSB	Hexanal	3160	7.55E-12	Yang
OSB	Octane	4244	1.23E-12	Yang
OSB	Octane	248	5.75E-11	Yang
OSB	Undecane	1250	6.92E-11	Yang
OSB	Dodecane	6250	3.45E-12	Yang
OSB	pentanal	150	7.83E-11	Yang
OSB	pentanal	373	8.16E-11	Yang
Painted drywall	Benzaldehyde	123.9	3.88E-10	Jinsong Zhang
Painted drywall	Ethylbenzene	37.5	7.14E-10	Jinsong Zhang
Painted drywall	Decane	55	4.51E-10	Jinsong Zhang
Painted drywall	1,4-dichlorobezene	70.4	5.51E-10	Jinsong Zhang
Painted drywall	Undecane	80	4.31E-10	Jinsong Zhang
Painted drywall	Dodecane	176.7	3.23E-10	Jinsong Zhang
Particle board	Benzene	266	7.33E-10	Bodalal
Particle board	Toluene	968	2.68E-10	Bodalal
Particle board	Ethylbenzene	1237	1.05E-10	Bodalal

Material	VOCs	K_{ma}	D_m	Reference
Particle board	Propylbenzene	4388	3.42E-11	Bodalal
Particle board	Butylbenzene	18042	8.97E-12	Bodalal
Particle board	Pentannal	1980	3.66E-10	Bodalal
Particle board	Hexanal	2602	7.42E-11	Bodalal
Particle board	Heptanal	7714	2.22E-11	Bodalal
Particle board	Octanal	11591	1.26E-12	Bodalal
Plywood	Benzene	184	2.08E-11	Bodalal
Plywood	Toluene	358	1.75E-11	Bodalal
Plywood	Ethylbenzene	2476	5.53E-11	Bodalal
Plywood	Propylbenzene	3249	2.16E-11	Bodalal
Plywood	Butylbenzene	11918	7.55E-12	Bodalal
Vinyl flooring	Butanol	810	6.70E-13	Cox
Vinyl flooring	Toluene	980	6.90E-13	Cox
Vinyl flooring	Phenol	120000	1.20E-13	Cox
Vinyl flooring	n-decane	3000	4.50E-13	Cox
Vinyl flooring	n-dodecane	17000	3.40E-13	Cox
Vinyl flooring	n-tetradecane	120000	1.20E-13	Cox
Vinyl flooring	n-pentadecane	420000	6.70E-14	Cox

4 Appendix A

Building Energy and Environmental Systems Laboratory (BEESL)
Department of Mechanical and Aerospace Engineering
College of Engineering and Computer Science
Syracuse University

Definition of a Reference Residential Building Prototype for
Evaluating IAQ and Energy Efficiency Strategies

By
Zhenlei Liu, Rui Zhang, Tim Stenson, and Jensen Zhang

Project Objectives

Objectives:

- In order to evaluate and compare the energy efficiency and indoor air quality of residential buildings cross different climates, a standard reference is necessary to be defined to represent a typical design and operation condition for each region.

Scopes:

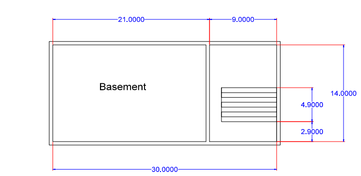
- Floor plans for a small single-family house design
- Building envelope: Materials and assemblies
- Ventilation and infiltration
- Internal and external pollution loads*
- Simulation by IAQX 1.1/EPA

2

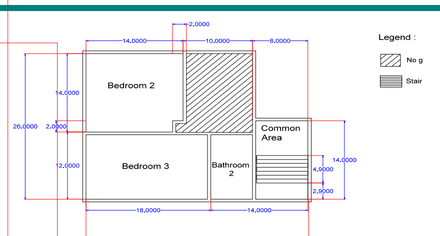
Introduction of Reference House

- The house is intended to be an medium size
  - Floor Area: 1,481 ft^2 (137.6 m^3)
  - Ceiling Height: 8 ft (2.44m)
  - Total Volume: 11,841 ft^3 (335.3 m^3)
  - 3 bedrooms
  - 2 bathrooms
  - 1 kitchen
  - 1 dining room
  - 1 family/living room
  - No garage
  - Unconditioned basement.

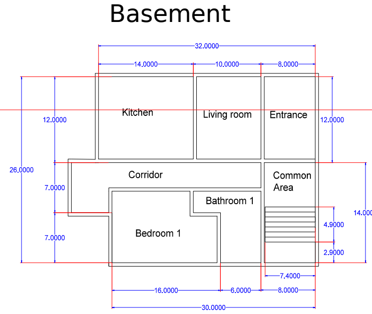
Floor Plans



Basement

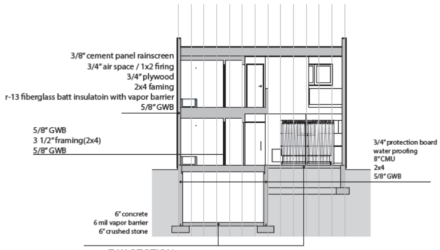


1st Floor

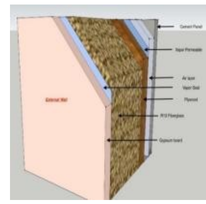


2nd Floor

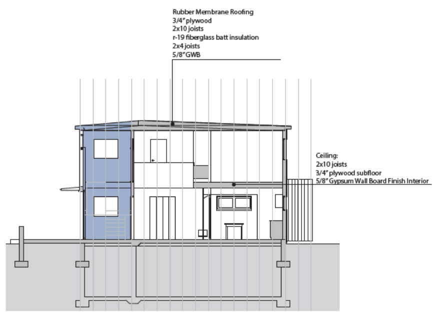
Section Drawings



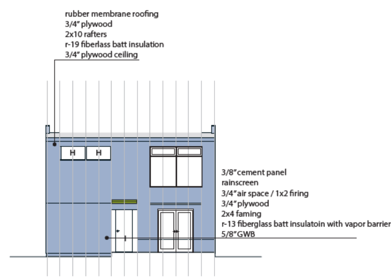
E-W SECTION @ LIVING ROOM



Sectional View of External Wall



N-S SECTION @ LIVING ROOM



SOUTH ELEVATION

Materials in the Reference House

- When we develop the energy model, we choose typical materials used in northeast region of US.
- Based on original drawing and energy model of the reference house, we can define the type and area of each building material used in the reference house.

Reference House		
Product Type	Material	Surface Area(m^2)
Internal Floor	carpet	69.10
	Hardwood	69.10
Celings	Gypsum Board	69.75
External wall	Cement Panel	92.26
	Plywood	92.26
	Fiber Glass	92.26
	Gypsum Board	92.26
Partition	Gypsum Board	126.48
	Fiber Glass	126.48
Paint		288.49
Flat Roof	Asphalt Shingles	68.45
	Roofing Felt Undarlayment	68.45
	Plywood	68.45
	Fiber Glass	68.45
	Gypsum Board or Plywood	58.03 or 10.42
Below Grade Wall	Expanded polystyrene	65.47
	Concrete masonry unit	65.47
	Fiber Glass	65.47
	Gypsum Board	65.47
Ground Floor	Cast Concrete	30.69
	Vapor Barrier	30.69
	Crushed Stone	30.69
Door	Plywood	15.81

Ventilation, Space Conditioning

- Ventilation
  - Infiltration rate: 0.22 ACH
  - Mechanical ventilation: 0.14 ACH
  - Total air change rate: 0.36 ACH

- HVAC system set point:
  - For cooling: 78 F (electricity)
  - For heating: 68 F (natural gas)

Single Zone Model

- To analyze the IAQ for reference house, we can build a single zone model:
- Single zone model was used in CDPH standard to evaluate the overall IAQ for the entire house by neglecting influence between different rooms.
  - Model parameters: Q, V, Co, R
    - N=0.36 1/h
    - V=335.3 m^3
    - Co—outside concentration (outside pollutant load)
    - R --- emission rate (inside pollutant load)
- How to determine R?
  - Constant?
     Threshold concentration limits defined for CDPH house → EF
    - Threshold emission factor limits in emission standards for low-emission materials
    - Measured material emission factor (EF) from standard testing at a specified time point
  - Vary with time?
    - Empirical model representation of material emission test data: EF(t)
    - Mechanistic model representation of material emission test data
      - a unified approach is needed
      - Be able to consider the effect of temperature and RH

Allowable Thresholds in CDPH House

- CDPH Standard Method for The Testing and Evaluation of Volatile Organic Chemical Emissions from Indoor Sources Using Environmental Chambers Version 1.1---2010 Feb, Section 01350
- Health-based standard method widely accepted in U.S. for building materials and products testing and certification.
- Maximum allowable concentrations for target VOC's.
  - The allowable concentration for each VOC compound is compared to one-half of the CRELs. (except for formaldehyde)
  - CRELs--non-cancer Chronic Reference Exposure Levels
    - CRELs are inhalation concentrations to which the general population, including sensitive individuals, may be exposed for long periods (10 years or more) without the likelihood of serious adverse systemic effects (excluding cancer).
  - Formaldehyde: The allowable limit for emissions of formaldehyde corresponds to an indoor air concentration not to exceed the full CREL of 9 µg m^3 from January 1, 2012.
  - CDPH: California Department of Public health

CAS#	Contaminants	Molecular Weight (g/mol)	Concentration Reference Level (ug/m^3)					
			Exposure	ELV[1]	Exposure	WHO	Exposure	CDPH
75-07-0	Acetaldehyde	44	Long	48	Long		Long	70
107-02-8	Acrolein	56	Long	0.35	Short	50		
80-56-8	alpha-Pinene	136	Long	200				
71-43-2	Benzene	78	Long	0.2		n.v.	Long	30
	Carben dioxide		Long	-				
50-00-0	Formaldehyde	30	Long	9	Short	100	Long	9
91-20-3	Naphthalene	128	Long	2	Long	10	Long	4.5
	Nitrogen dioxide	46	Long	20	Long	40		
	PM10	-	Long	20	Long	20		
	PM2.5	-	Long	10	Long	10		
	Radon	222	Long	200				
100-42-5	Styrene	104	Long	30	Short	260	Long	450
108-88-3	Toluene	92	Long	250	Short	260	Long	150
79-01-6	Trichloroethylene	131.4	Long	2		n.v.	Long	300
	TVOC		Long	-				
	Mold	-	Long	200				
1. ELV from Annex-68 subtask1, Exposure Limit Value								

Single-Family Residence Model --- CDPH House

- A preliminary new single-family residence model has been developed.
- It is based on the assumed dimensions of a median size new detached single-family home.
- IAQ Concentration Modeling
  - Steady state mass balance model, zero outdoor concentrations, perfect mixing, no net losses.

Definition of Residence House		CDPH House	Syracuse Reference House
Parameter	Unit of Measure	Parameter Value	Parameter Value
Floor Area	m^2	211	137.6
Ceiling Height	m	2.59	2.44
Volume	m^3	547	335.7
ACH	1/h	0.23	0.22
Air flow rate	m^3/h	127	73.86
No.Bedrooms	unit	4	3
No.Bathrooms	unit	2	2
No.Other Rooms	unit	3	3

Single-Family Residence Model --- CDPH House

- From above IAQ concentration model calculate emission factor
- $EF = \frac{Q * (C - Co)}{A}$

CDPH House									
Product Type	Area or Quantity		Area/ Unit Specific Air Flow Rate		Maximum Emission Factor				
					Toluene (Limit concentration = 150 ug/m^3)		Formaldehyde (Limit concentration = 9 ug/m^3)		
Flooring	m^2	211.00	m/h	0.602	ug/(m^2*h)	45.15	ug/(m^2*h)	2.71	
Ceiling	m^2	217.00	m/h	0.585	ug/(m^2*h)	43.88	ug/(m^2*h)	2.63	
Walls & wallcoverings	m^2	562.00	m/h	0.226	ug/(m^2*h)	16.95	ug/(m^2*h)	1.02	
Interior wallboard paint	m^2	779.00	m/h	0.163	ug/(m^2*h)	12.23	ug/(m^2*h)	0.73	
Thermal insulation	m^2	284.00	m/h	0.447	ug/(m^2*h)	33.53	ug/(m^2*h)	2.01	
Acoustic insulation	m^2	343.00	m/h	0.370	ug/(m^2*h)	27.75	ug/(m^2*h)	1.67	
Windows		19/38	m/h	3.340	ug/(m^2*h)	250.50	ug/(m^2*h)	15.03	
Exterior doors	unit/m^2	4/7.56	m/h	16.800	ug/(m^2*h)	1260.00	ug/(m^2*h)	75.60	
Interior doors	unit/m^2	12/37.2	m/h	3.410	ug/(m^2*h)	255.75	ug/(m^2*h)	15.35	
Closet doors	unit/m^2	6/44.6	m/h	2.850	ug/(m^2*h)	213.75	ug/(m^2*h)	12.83	
Kitchen Cabinets	unit	15	m^3/(h*unit)	8.470	ug/(unit*h)	635.25	ug/(unit*h)	38.12	
Other Cabinets	unit	5	m^3/(h*unit)	25.400	ug/(unit*h)	1905.00	ug/(unit*h)	114.30	

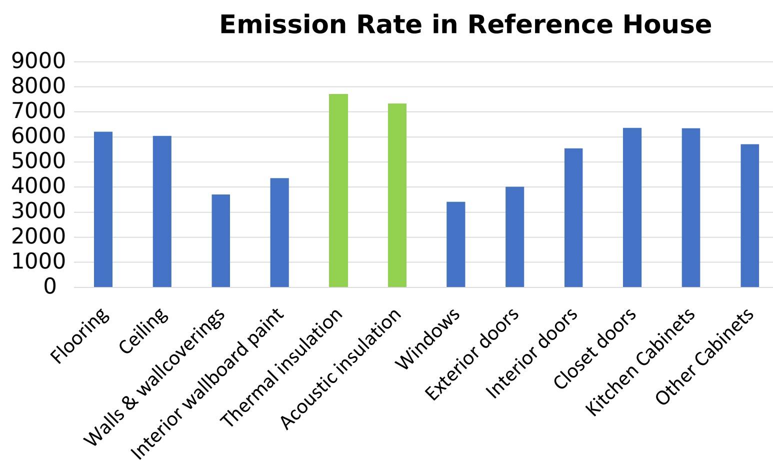
1. To ensure indoor air concentration are within allowable limits, each individual product category is capped at no more than 50% contribution to air concentration for each chemical.

Emission rates for the reference house: Toluene

No.of pollut ant source	Reference House			Emission Factor from CDPH house		Emission Rate (ug/h)	
	Product Type	Area or Quantity		Toluene		Toluene	
1	Flooring	m^2	137.60	ug/(m^2*h)	45.15	ug/h	6212.64
2	Ceiling	m^2	137.60	ug/(m^2*h)	43.88	ug/h	6037.2
3	Walls & wallcoverings	m^2	218.74	ug/(m^2*h)	16.95	ug/h	3707.643
4	Interior wallboard paint	m^2	356.34	ug/(m^2*h)	12.23	ug/h	4356.2565
5	Thermal insulation	m^2	229.86	ug/(m^2*h)	33.53	ug/h	7706.0565
6	Acoustic insulation	m^2	264.08	ug/(m^2*h)	27.75	ug/h	7328.22
7	Windows	unit/m^2	20/13.6	ug/(m^2*h)	250.50	ug/h	3406.8
8	Exterior doors	unit/m^2	3/3.18	ug/(m^2*h)	1260.00	ug/h	4006.8
9	Interior doors	unit/m^2	7/21.7	ug/(m^2*h)	255.75	ug/h	5549.775
10	Closet doors	unit/m^2	4/29.76	ug/(m^2*h)	213.75	ug/h	6361.2
11	Kitchen Cabinets	unit	10.00	ug/(unit*h)	635.25	ug/h	6352.5
12	Other Cabinets	unit	3.00	ug/(unit*h)	1905.00	ug/h	5715

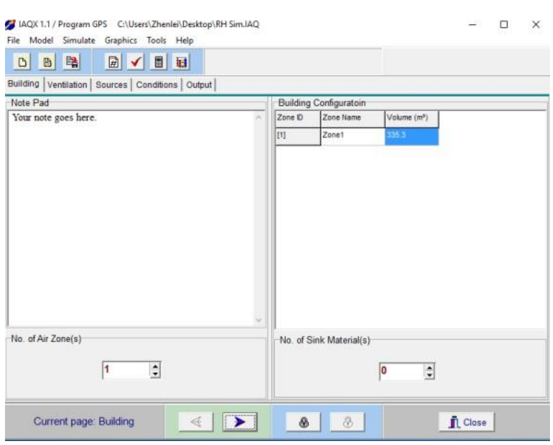
Emission Rates for the Reference House Based on the CDPH Emission Factor Threshold Values

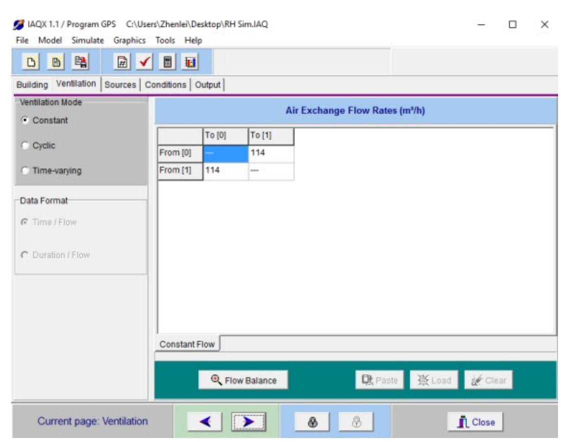
- Input max emission factor into reference house
  - Based on the EF from the CDPH house
  - Emission rate: $R_i = A_i\, EF_i$, where A_i is the quantity of the material i used in the reference house
- Two scenarios:
  - Insulation is exposed into air
    - Worst case scenario
  - Insulation is perfectly sealed in wall
    - No air infiltration/exfiltration



Simulation

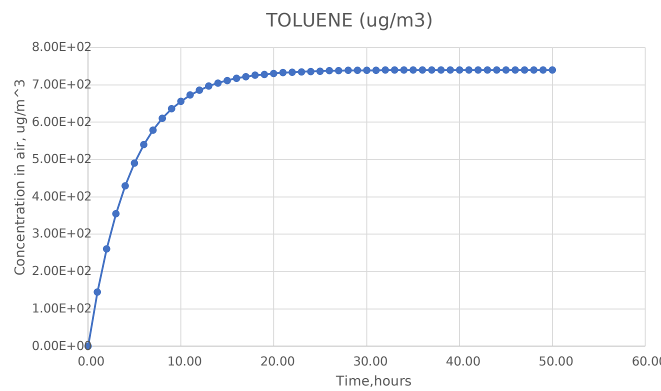
- Generate single zone model for reference house in IAQX 1.1





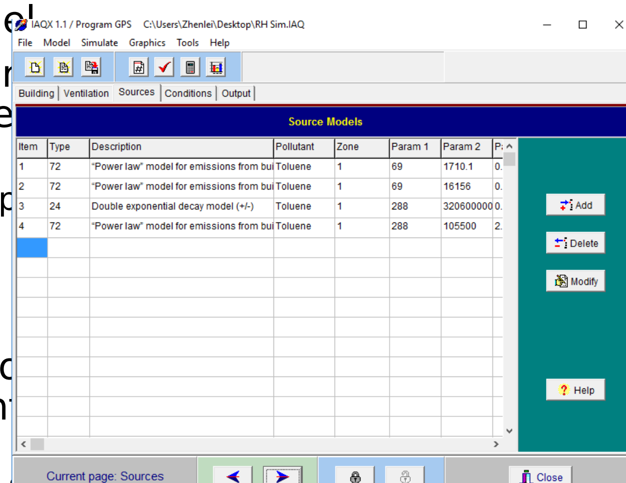
Simulation: worst case scenario (all exposed)

- Constant Emission Rate



Empirical Model & Simulation

- Source term: empirical model
- Only suitable for single layer material, so we only conside interior material.
    - Floor (half hardwood, half carp
    - Paint (ceiling, external wall, partition)
    - Door(plywood)
- Do curve fitting to obtain mo parameters from experimen data.
    - Standard chamber test result from NRC Final Report 4.1



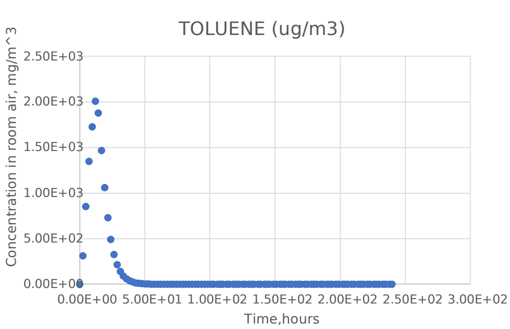
Empirical Model & Simulation

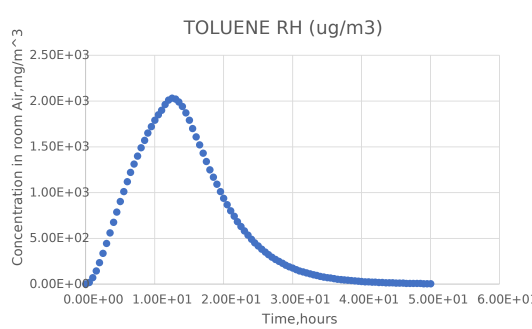
- Toluene
- Plywood and Carpet are dry materials
  - Power law model
  - $R(t) = A * a * t^{b}$ (A is source area. Unit of R is mg/(hour*m^2)
- Paint is “wet” coat material
  - Initial period(< 12 hours): exponential
  - $R(t) = A * \left(a * e^{b*t}\right)$
  - Long term period : power law model
  - $R(t) = A * a * t^{b}$

	Plywood	Carpet	Paint	
	power law	power law	exponential	power law
a	0.4432	3.7830	12820	34700
b	-0.1430	-0.4372	-0.1811	-1.8220

Empirical Model & Simulation

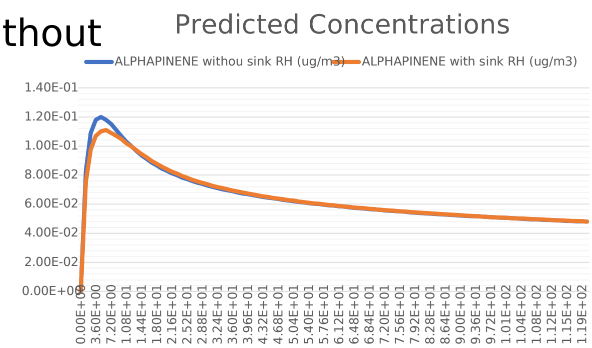
- Simulate from 0 to 240 hours
- Simulate from 0 to 50 hours





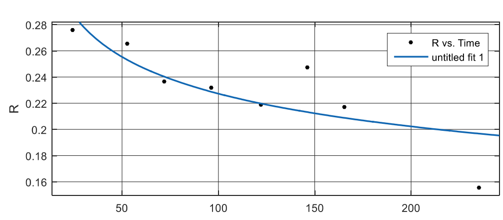
Empirical Model & Simulation—add sink for α-pinene

- Simulate α-pinene with/without sink model.
- Coefficients are from NRC reports.

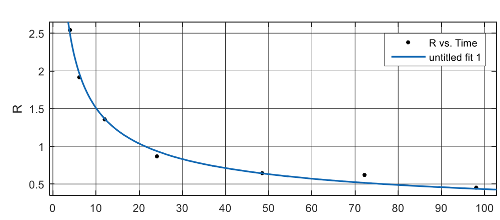


Appendix

Plywood curve fitting result

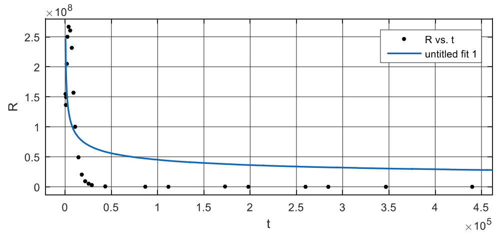


Carpet curve fitting result

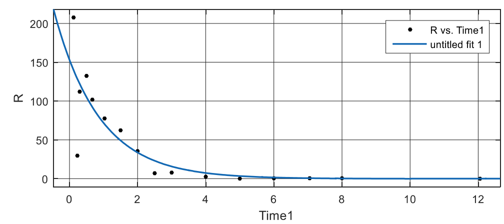


Appendix

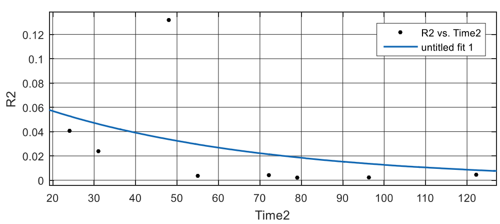
Paint curve fitting result , power law for entire period



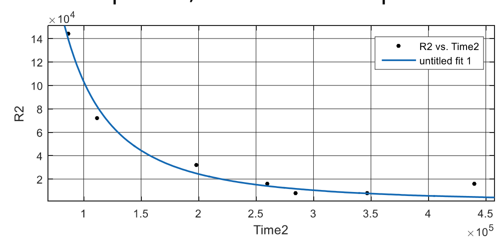
Paint curve fitting result , exponential for initial period



Paint curve fitting result , power law for long term period, with one noise point

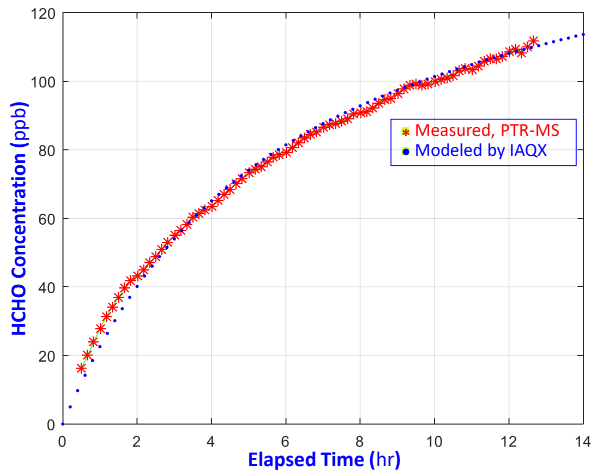


Paint curve fitting result , power law for long term period, without noise point



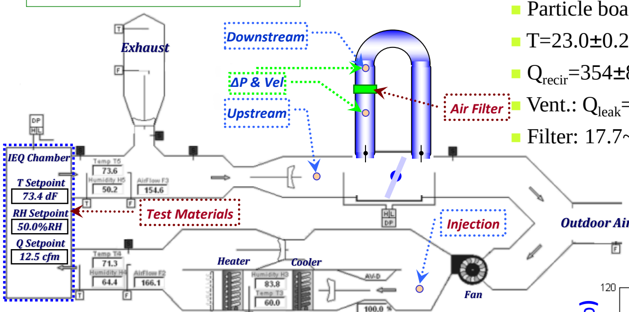
Appendix B

Case 1: Emission source only (from Particleboard test)



Case 2: Emission source w/ filtration (from Particleboard)

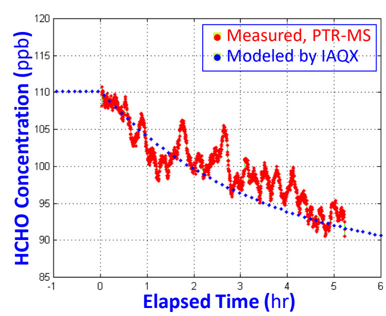
Full-scale Chamber Test



Test Conditions

- Particle boards: A=1.60 m^2, C_{steady}=110 ppb
- T=23.0±0.2˚C, RH=50.0±0.4%, V_{eff}=57.12 m^3
- Q_{recir}=354±8.5 LPM (When mixing, 5 ACH for 50-hr)
- Vent.: Q_{leak}=0.036 ACH
- Filter: 17.7~12.8% removal efficiency over time

- IEQ Chamber: low leakage, highly accurate control;
- Target Compound: Formaldehyde or HCHO;
- Enough mixing time required even with high ACH;
- Small leakage was the only ventilation in this case;
- At **Time Zero**, air cleaner was in operation;
- Time-varying efficiency was measured at 11 points.
- Modeling software can model the case.



Model Inputs and Chamber Conditions (Case 2)

- Emission Area: $A = 1.6\ m^2$
- Effective Volume: $V_{eff} = 57.12\ m^3$, including the ductwork volume
- Air cleaning efficiency over time:

  - Modeled as Stand-alone declining efficiency air cleaner;

  17.7% (at 5/60 h) → 17.3 (+0.5 h)→ 15.3 (..) → 15.4 (..) → 14.7 (..) →

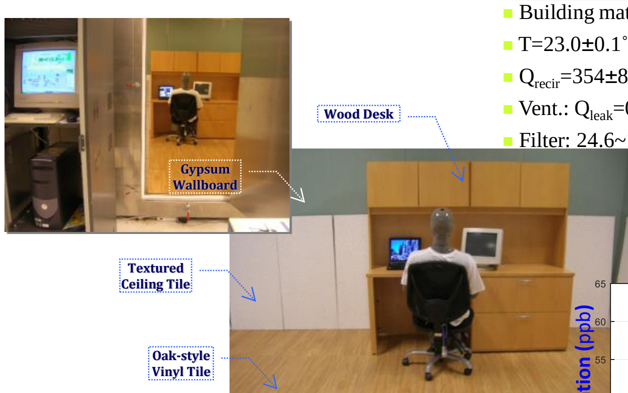
  14.4 (..) → 14.4 (..) → 13.7 (..) → 13.3 (..) → 13.1 (..) → 12.8% (5+5/60 h)

- Air change rate: $Qv = Q_{leak} = 0.036$ ACH or 2.05632 m^3/h; $Q_{cl} = 12.5$ cfm
- Temperature fluctuation in supply air: $26.2_4 \pm 0.7_7\ ^\circ C$

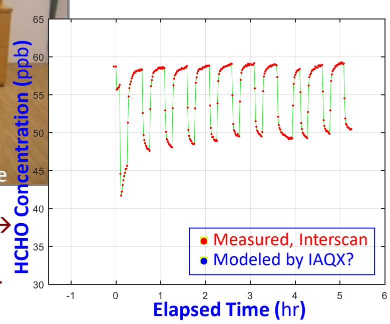
Case 3: Sources and sinks (from Furnished test)

Test Conditions

- Building materials: in a 16' x 12' x 10' h room
- T=23.0±0.1˚C, RH=50.0±0.2%, $V_{eff}=57.12\ m^3$
- $Q_{recir}=354\pm8.5$ LPM (When mixing, 5 ACH for 12-hr)
- Vent.: $Q_{leak}=0.036$ ACH
- Filter: 24.6~15.0% efficiency over time



- Small-scale chamber tests: EF, D and K from each test material ;
- Before main tests, IAQX can be used to estimate the mixing time required for actual full-scale tests, considering A, V_{eff}, Qr and Qv;
- Spending not-enough time can result in a challenging case like →
- If IAQX is successful in modeling the full-scale test, a similar method can be used to scale up lab. results for a reference house.



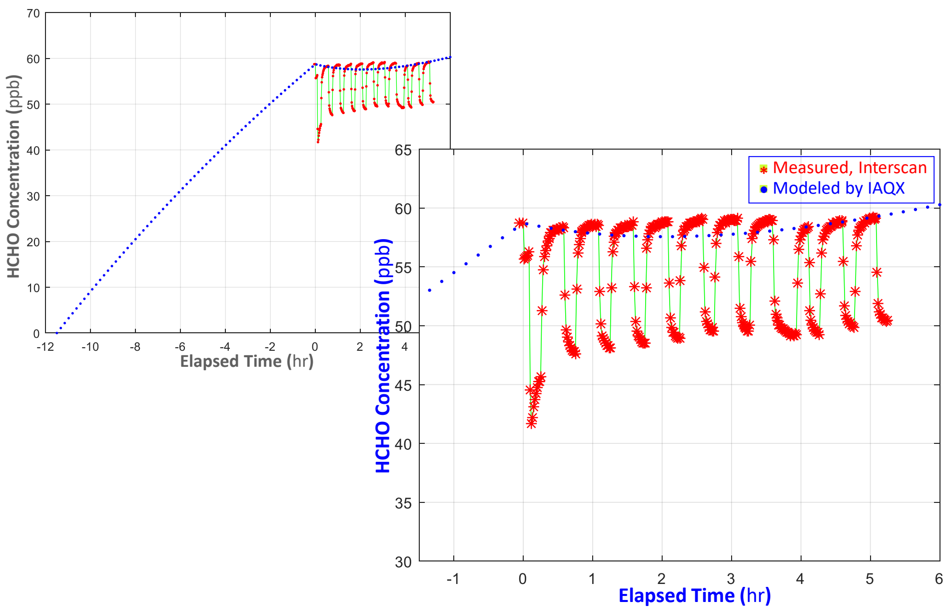
Model Inputs and Chamber Conditions (Case 3)

- Emission Area: $A = 87.70\ m^2$
- Effective Volume: $V_{eff} = 57.12\ m^3$, including the ductwork
- Air cleaning efficiency over time:

  - Can be modeled as Stand-alone declining efficiency air cleaner;

  24.6% (at 5/60 h) → 18.5 (+0.5 h)→ 18.0 (..) → 17.8 (..) → 17.1 (..) → 16.1 (..) → 15.9 (..) → 16.5 (..) → 15.1 (..) → 15.2 (..) → 15.0% (5+5/60 h)
- Air change rate: $Qv = Q_{leak} = 0.036$ ACH or $2.05632\ m^3/h$; $Q_{cl} = 12.5$ cfm

Full-scale Furnished Test - IAQX modeling



Appendix C: Case study – France

Definition of a Reference Residential Building Prototype for Evaluating IAQ and Energy Efficiency Strategies – France

Participant: Marc Abadie, University of La Rochelle, France

Content :

1 Introduction

This report presents in a first part the description of a reference house for France. This house has been defined to comply the French low-energy building regulation (RT2012). Two ventilation system options have been studied as they provide different level of air change rates: a mechanical exhaust ventilation (humidity control) and a mechanical balanced ventilation with heat recovery. The second part is dedicated to the evaluation of formaldehyde and toluene concentration levels. Two approaches have been employed: the first one is based on the indoor decorating and refurbishing materials labelling system in France and the second one uses emission rates extracted from PANDORA database. Discussion and conclusion are given at the end of the report.

2 Definition of the reference house

2.1 Description

The reference house has a 100 m^2 floor area (heated area) for a total volume of 250 m^3. It includes 4 living spaces (1 dining/living room and 3 bedrooms), 1 kitchen, 1 bathroom, 1 WC, 1 cellar and 1 garage (unheated, 37 m^2, not accounted in the 100 m^2). The location of the house is La Rochelle that is in the H2 climatic zone according to French classification (moderate in France), CFc (subpolar oceanic climate) according to Köppen classification. Figure 1 and Figure 2 present the geometry of the reference house.

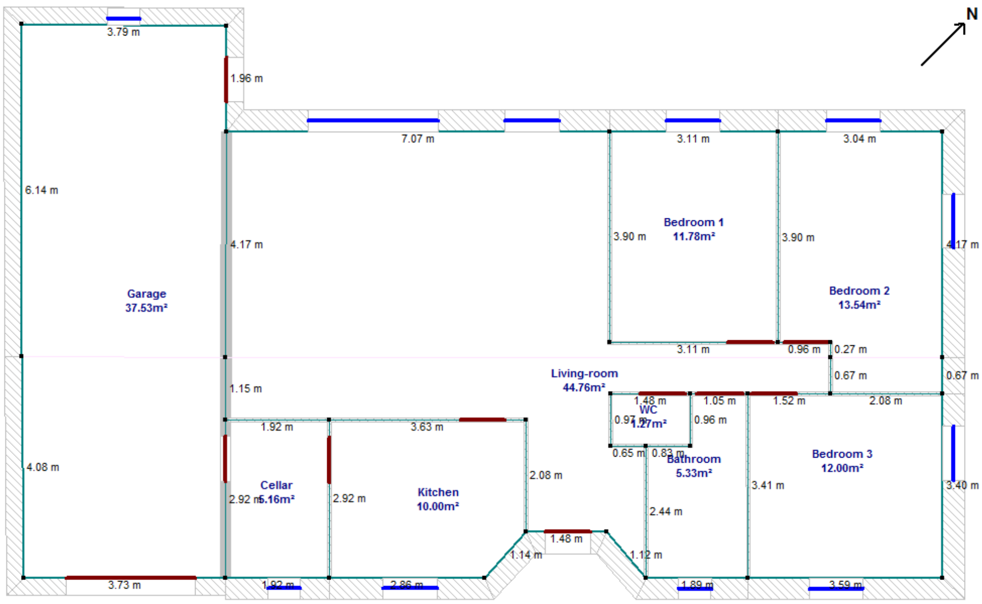


Figure 1: Floor plan of the French reference house.

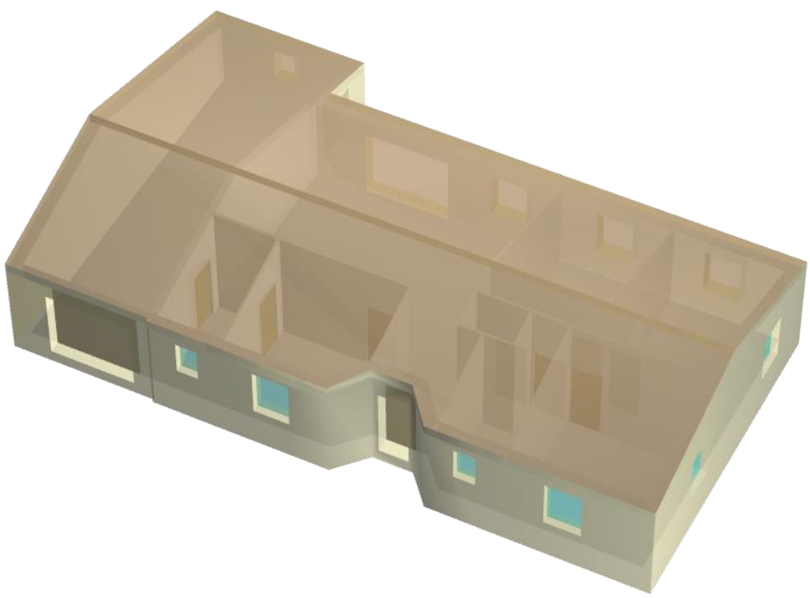


Figure 2: 3D view of the French reference house.

2.2 Building assemblies and material thermal properties

The house is made up of internal thermal insulated walls, an insulated concrete slab and ceiling (unused attic). Windows are double-glazed with Argon and low emissivity treatment. Figure 3 and

present the composition of the house envelope with building assemblies dimensions and material thermal properties.

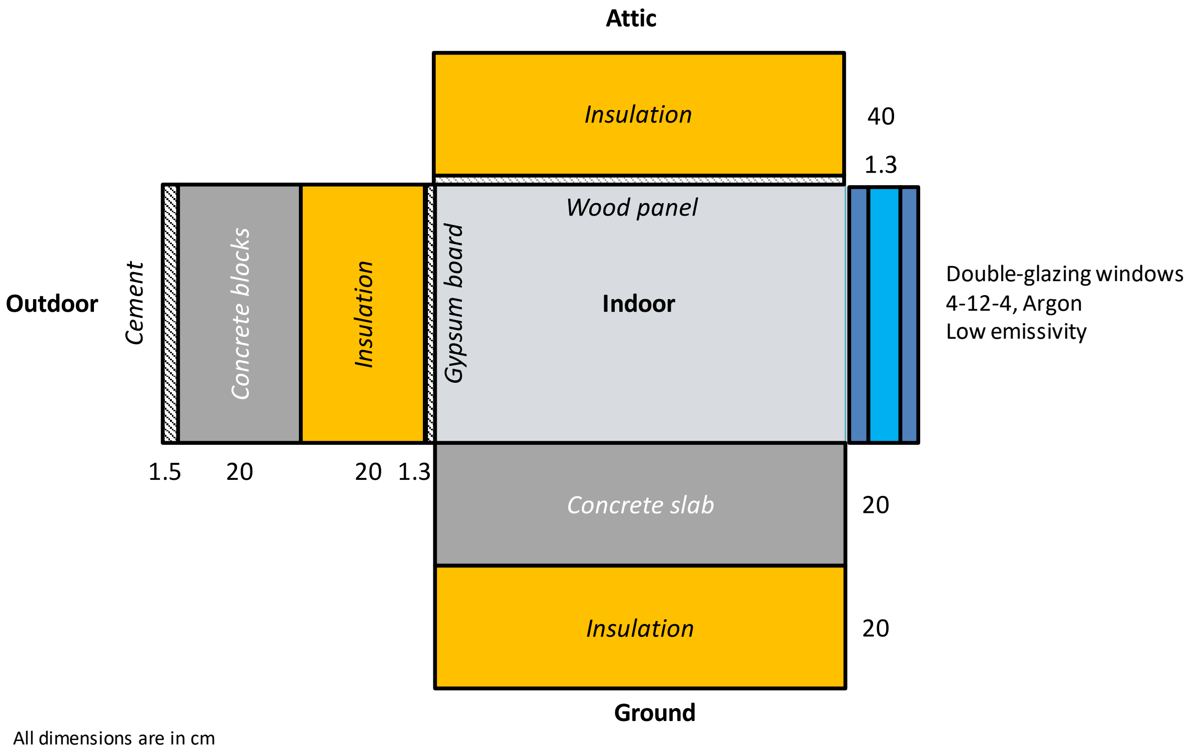


Figure 3: Composition of the house envelope.

Table 1: Building assemblies and material thermal properties.

	Building Envelope					
Assembly	Materials (exterior to interior)	Area (m^2)	Thickness (m)	Conductivity (W/(m-K))	Specific Heat*(J/(Kg-K))	Resistance((m^2*K)/W)
Flat roof with unused attic	Insulation	100	0.4	0.038	1030	10.53
	Wood panel		0.013	0.29	1600	0.04
External Wall	Cement	96.28	0.015	1.4	1000	0.01
	Concrete block		0.2		1000	0.23
	Insulation		0.2	0.035	1030	5.71
	Gypsum board		0.013	0.35	1000	0.04
Floor	Insulation	100	0.2	0.04	1030	5.00
	Concrete slab		0.2	2	1000	0.10
Exterior Door	Plywood	1.935			1600	0.67
Internal Walls	Gypsum board	111.76	0.013	0.35	1000	0.04
	Insulation		0.045	0.04	1030	1.13
	Gypsum board		0.013	0.35	1000	0.04
Name	Total Solar transmission (SHGC)	Area		Light transmission		U value
Vertical glazing	0.4	16.08		0.5		1.371

	Building Assemblies		
Assembly	Materials	Area or Quantity Unit	Value
Interior Door	Wood	7	1.935

2.3 Space heating, DHW and ventilation

Space heating generation is provided by a heat pump with a COP between 3.1 and 5.0 (with outdoor air varying from -7 to 7°C). Heat emission to the air space is handled by low-temperature radiators (mean surface temperature of 35°C, inlet-outlet temperature gradient of 5°C).

Domestic Hot Water (DHW) is also provided by a heat pump with a COP equal to 3.59 (with outdoor air of 7°C). DHW is stored in a hot water tank of 290 l (loss coefficient of 2.054 W/K).

Two ventilation systems are compared in this study: a mechanical humidity control exhaust ventilation (equivalent constant airflow: 75.9 m^3/h) and a mechanical balanced ventilation with 93% heat recovery efficiency (equivalent constant airflow: 123.1 m^3/h).

2.4 Energy consumption

2.4.1 French low-energy building regulation (RT 2012)

The RT 2012 thermal regulations (RT 2012, 2010) have strengthened requirements regarding the thermal performance of new buildings, specifically all buildings for which a building permit was applied for after 1 January 2013 (MESDE, 2014). The envelope of the building, without considering the HVAC system and other technical facilities, has to be designed such as bioclimatic needs factor Bbio Factor remains below a limit ($Bbio_{max}$). These buildings must also have a primary energy consumption below a threshold of 50 kWh_{PE}/m^2.year (Cep_{max}) on average for the 5 regulatory uses (heating, domestic hot water, lighting, cooling and auxiliary systems). Maximum permitted annual consumption of primary Energy of the building taking into account performances of HVAC system, DHW production and, if any, artificial lighting through the Cep factor. $Bbio_{max}$ and Cep_{max} are adjusted based on geographical location, altitude, building use, average surface area of the dwellings. Thermal comfort in summer is also checked and is based on the compliance with a maximum comfort calculated temperature Tic that should be below the Tic_{ref}. Complementary prescriptive requirements are envelope airtightness, window area (natural lighting), cold bridges and the use of at least one renewable energy for houses (solar PV, heating, biomass or the use of heat pumps).

The RT 2012 compliance of the reference house has been checked via a commercial software that use the generic RT 2012 calculation core. Calculations are similar to any building energy simulation software with the exceptions of some restrictions such as the use of standardized schedules for occupancy, set point temperature, ventilation airflow, lighting (1.4 W/m^2) and hot water demand. Heat loads are also unmodifiable: occupants in activity (90 W and 0.055 $kg_{water\ vapour}/h$), into sleep (63 W and 0.0385 $kg_{water\ vapour}/h$), equipment in activity (5.7 W/m^2) and during night or unoccupied period (1.1 W/m^2).

Results for the two ventilation systems are presented in Table 2. The only difference lies in the primary energy consumption that is higher for the balanced system because of the added electricity consumption caused by the two fans and the added pressure loss (heat exchanger, filters, ducts).

Table 2: RT 2012 calculation results.

	Ventilation #1 (EXHAUST)	**Ventilation #2 (BALANCED)**
Bbio	51.9 <= $Bbio_{max}$ = 61.2	51.9 <= $Bbio_{max}$ = 61.2
Cep	**42.1** <= Cep_{max} = 51.2 kWh_{PE}/m^2.year	**50.7** <= Cep_{max} = 51.2 kWh_{PE}/m^2.year
Tic	29.8°C <= Tic_{ref} = 32.5°C	29.7°C <= Tic_{ref} = 32.5°C

2.4.2 Energy Consumption

Table 3 presents the energy consumption by use. Heating energy consumption is lower for the balanced system even with higher airflow rates thanks to the heat recovery. However, as observed before, fan consumption is 4-5 times higher than the exhaust system. Figure 4 presents a comparison of the two systems. In both case, energy consumption of electrical equipment other than those for heating, DHW and ventilation is responsible of about 2/3 of the total energy consumption of the house.

Table 3: Energy Consumption.

		kWh/year	kWh/m².year	MJ/year	MJ/m².year
Heating	EXH	794	7.9	2857	29
	BAL	771	7.7	2774	28
Cooling	EXH/BAL	0	0	0	0
DHW	EXH/BAL	782	8	2815	28
Lighting	EXH/BAL	207	2	745	7
Pumps	EXH/BAL	12	0	41	0
Fans	EXH	115	1.2	414	4
	BAL	506	5.1	1822	18
Total	EXH	1886	18.9	6790	68
	BAL	2254	22.5	8114	81
+Interior Equipment	EXH/BAL	4112	41	14804	148
Total	**EXH**	**5998**	**60.0**	**21593**	**216**
	BAL	**6366**	**63.7**	**22918**	**229**

Note : the considered surface area is the heated zone area (garage excluded), final energy is provided here (not primary energy), EXH is for exhaust system, BAL is for balanced system.

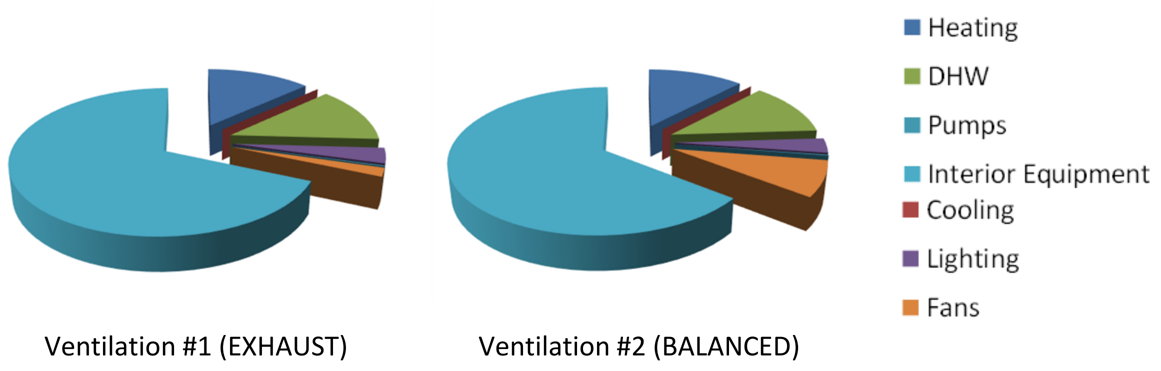


Figure 4: Energy consumption for the two ventilation systems.

2.5 Conclusion

The reference house complies the French low-energy building regulation (RT2012) with any of the chosen ventilation systems. The energy consumption, without other electrical equipment sur as fridge, washing machine, television…, is about close to 20 kWh/m².year of electricity or 52 kWh_{PE}/m^2.year.

3 Indoor Air Quality

3.1 Description

In this exercise, two approaches are compared to evaluate the concentration levels of formaldehyde and toluene in the reference house. The first one is based on the indoor decorating and refurbishing materials VOC emission labelling system used in France and the second one uses emission rates extracted from PANDORA database.

3.2 French VOC emission labelling system

The French VOC emission labelling regulation was published on 25 March 2011 with details published on 13 May 2011 regarding a mandatory labelling of construction products installed indoors, floor and wall coverings, paints and lacquers with their emission classes based on emission testing. Any covered product placed on the market has to be labelled with emission classes based on their emissions after 28 days, as tested with ISO 16000 and calculated for European reference room. This room has a volume of 30 m^3 and is ventilated with clean air at a rate of 0.5 vol/h. Indoor conditions have to be maintained during the measurement period of 28 days (T=23°C, RH=50%) in the test cell. VOC emission rates are then deduced from simple mass balance considering constant emission. Concentrations are calculated for the reference room according to the load factor given in Table 4. Pollutant concentrations are then compared to threshold limits of Table 5. The label is given considering the worst classification obtained for one pollutant. For example, using the results in bold in Table 4, the label is B (toluene's label).

Table 4: Load Factors.

	Load Factor (L = S/V) (m^2/m^3)	**Area (m^2)**
Floor	0.4	12
Ceiling	0.4	12
1 Door	0.05	1.6
1 Window	0.07	2
Wall (without window/door)	1	31.4
Sealant	0.007	0.2

Table 5: VOC limitations of indoor decorating and refurbishing materials in France (Concentration at 28th day in µg/m^3).

	C	**B**	**A**	A+
Formaldehyde	>120	<120	**<60**	<10
Acetaldehyde	>400	<400	<300	**<200**
Toluene	>600	**<600**	<450	<300
Tetrachloroethylene	>500	<500	**<350**	<250
Xylene	>400	<400	<300	**<200**
1,2,4-Trimethylbenzene	>2000	<2000	**<1500**	<1000
1,4-Dichlorobenzene	>120	<120	**<90**	<60
Ethylbenzene	>1500	<1500	**<1000**	<750
2-Butoxyethanol	>2000	<2000	<1500	**<1000**
Styrene	>500	<500	<350	**<250**
TVOC	>2000	<2000	<1500	**<1000**

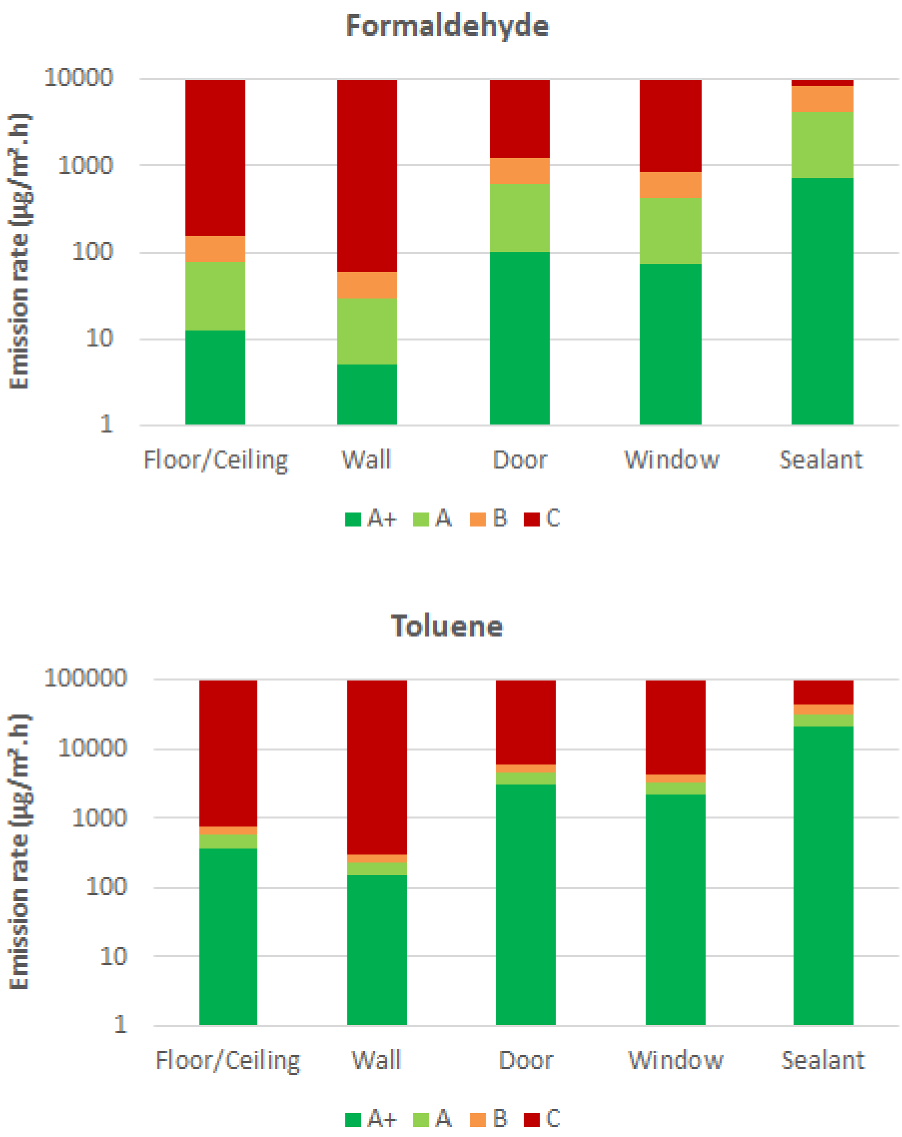


Figure 5: Relation between emission rates and use of materials according to labelling system.

It is important to understand that this labelling system depends on both the VOC emission rate and the use of the tested material (i.e. the load factor). As an illustration, Figure 5 presents this dependency for formaldehyde and toluene. **For the present common exercise, emission rates are taken as the maximal value for the A+ label according to the type of use and is multiplied by 50% as mentioned in the exercise.**

3.3 PANDORA database

PANDORA (a comPilAtioN of inDOor aiR pollutAnt emissions) database has been created to compile the available data from literature regarding the emission rates of both gaseous and particulate pollutants in a systematic way into a unique database to provide useful information for IAQ modelers (Abadie and Blondeau, 2010). The last version (2017) includes 604 indoor pollutant sources (from materials, occupant activity…) for 9003 pollutant emission rates of gaseous (8813) and particulate (190) origins. The collected emission rate data are constant, discrete (value at a specified time) and transient. For the purpose of this common exercise, we calculated statistics by considering the emission rates of formaldehyde and toluene after 28 days and for different categories such as carpeting, flooring, finishes… Figure 6 presents the results for the case of flooring/ceiling (load factor of 0.4). Label has been also added for comparison. Almost all data from PANDORA for formaldehyde are equivalent to A+ and A labels; all data for toluene lie in the A+ category. **For the common exercise, median values multiplied by 50% are chosen as emission rates to be used.**

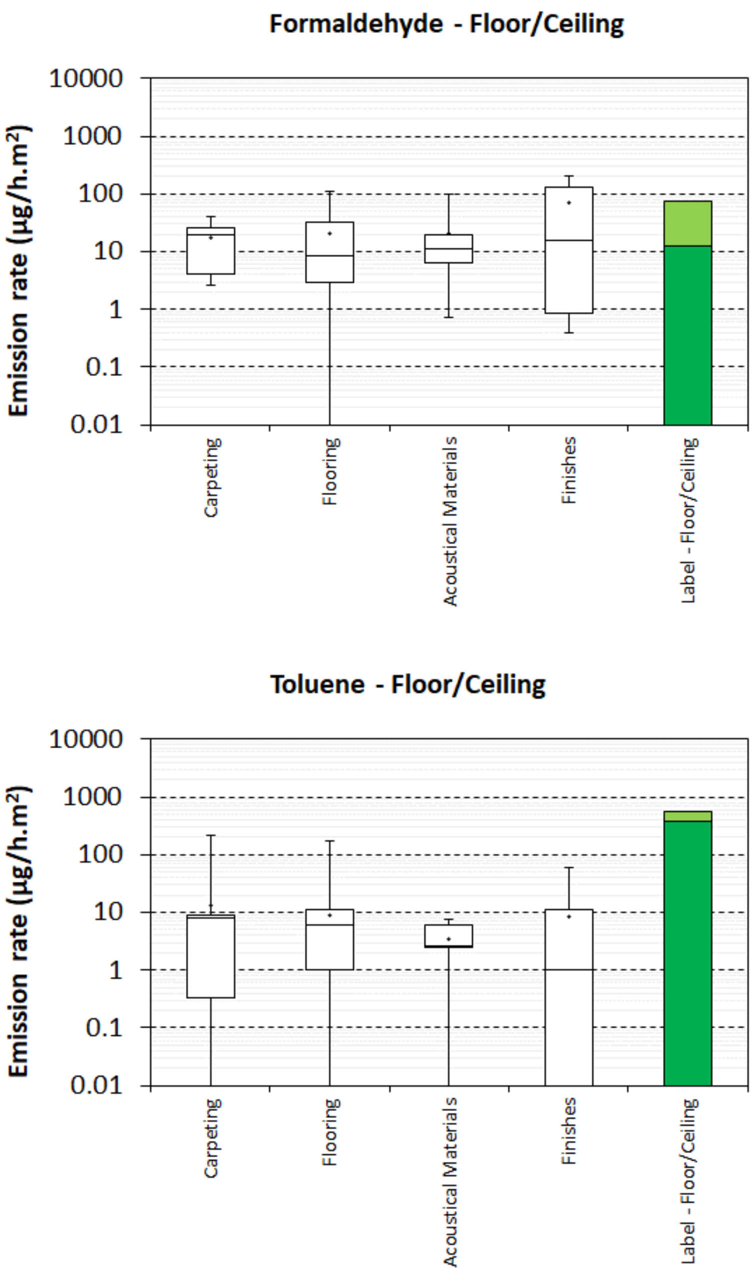


Figure 6: Emission rates from PANDORA database evaluated at t = 28 days – Example for floor and ceiling.

3.4 Results

Table 6 and Table 7 present the calculation and concentration levels obtained by the two approaches. Note that no furniture are taking into account in this common exercise.

Table 6: Concentration levels in the reference house – French VOC emission labelling system (50% A+ label).

Label A+	Area (m^2)	Nb of Face	Emission Surface (m^2)	Load Factor (m^2/m^3)	E Form. (µg/m^2.h)	E Tol. (µg/m^2.h)	E Form. (µg/h)	E Tol. (µg/h)
Flat roof with unused attic	100.0	1	100.0	0.4	6.25	188	625	18750
External Wall	96.3	1	96.3	1	2.50	75	241	7220
Floor	100.0	1	100.0	0.4	6.25	188	625	18750
Exterior Door	3.5	1	3.5	0.05	50.00	1500	173	5202
Internal Walls	84.7	2	169.5	1	2.50	75	424	12711
Vertical glazing	8.5	1	8.5	0.07	35.71	1071	304	9118
Interior Door	12.1	2	24.3	0.05	50.00	1500	1214	36414
Closet doors								
Kitchen Cabinets								
						Sum	3605	108165

	Form.	**Tol.**
ELV (µg/m^3)	**10**	**300**

Surface emission factor	**50%**

	Q (m^3/h)	ACH (/h)
Ventilation #1 (EXHAUST)	75.9	0.30
Ventilation #2 (BALANCED)	123.1	0.49

Ca (µg/m^3)	**Form.**	**Tol.**
Ventilation #1 (EXHAUST)	**47.5**	**1425.1**
Ventilation #2 (BALANCED)	**29.3**	**878.7**

Table 7: Concentration levels in the reference house – PANDORA database.

PANDORA	Area (m^2)	Nb of Face	Emission Surface (m^2)	Load Factor (m^2/m^3)	E Form. (µg/m^2.h)	E Tol. (µg/m^2.h)	E Form. (µg/h)	E Tol. (µg/h)
Flat roof with unused attic	100.0	1	100.0	0.4	4.15	3.10	415	310
External Wall	96.3	1	96.3	1	7.73	0.50	744	48
Floor	100.0	1	100.0	0.4	4.15	3.10	415	310
Exterior Door	3.5	1	3.5	0.05	7.73	0.50	27	2
Internal Walls	84.7	2	169.5	1	7.73	0.50	1309	85
Vertical glazing	8.5	1	8.5	0.07	7.73	0.50	66	4
Interior Door	12.1	2	24.3	0.05	7.73	0.50	188	12
Closet doors								
Kitchen Cabinets								
						Sum	3163	771

Median values (µg/m^2.h)	**Form.**	**Tol.**
Flooring	**8.3**	**6.2**
Finishes	**15.5**	**1.0**
	Q (m^3/h)	ACH (/h)
Ventilation #1 (EXHAUST)	75.9	0.30
Ventilation #2 (BALANCED)	123.1	0.49

Surface emission factor	**50%**

Ca (µg/m^3)	**Form.**	**Tol.**
Ventilation #1 (EXHAUST)	**41.7**	**10.2**
Ventilation #2 (BALANCED)	**25.7**	**6.3**

3.5 Discussion

Figure 7 compiles all the results for formaldehyde and toluene. Experimental data from the study of Derbez et al. in 2015 (OQAI-BPE) are also presented for comparison.

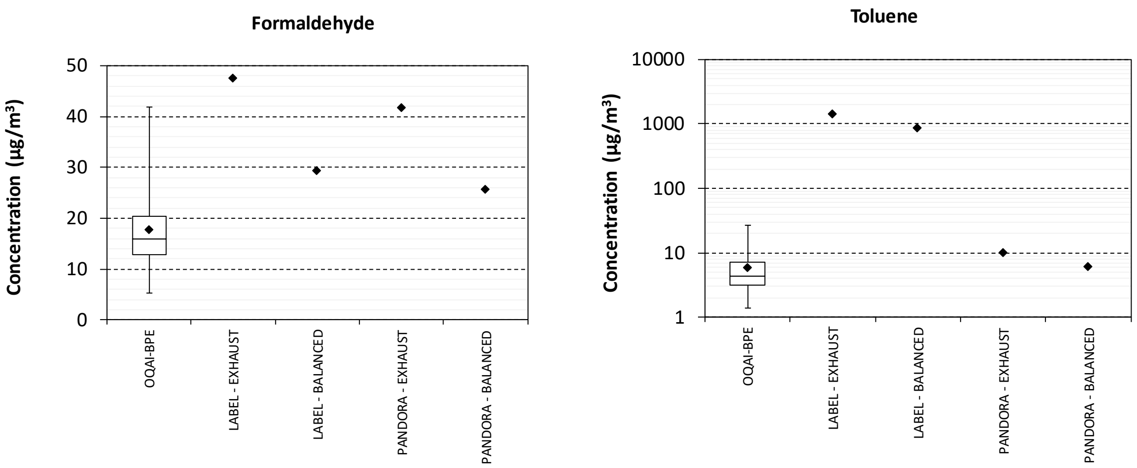


Figure 7: Comparison between the two approaches and the experimental data for low-energy buildings (OQAI-BPE).

Note that, as formaldehyde and toluene have only indoor sources here, the concentration level differences observed between the two ventilation systems are directly correlated with the airflow rate ratio.

The PANDORA based approach tends to predict slightly lower concentration of formaldehyde than the labelling system one. However, both results remain slightly higher than the OQAI-BPE measurements and, as a result, twice to three times higher than the recommended Exposure Limit Value (ELV) for long-term exposure of 10 µg/m^3.

The case of toluene shows that the labelling system approach overestimates by a factor of 100 the concentration levels measured during OQAI-BPE. On the other hand, the PANDORA based approach tends to predict slightly higher concentration than the measurement data with about the same difference than for the case of formaldehyde. In this case, the concentration level remains well below the ELV of 300 µg/m^3.

3.6 Conclusion

The two approaches rely on the same arbitrary choice i.e. the determination of a reference emission rate and the consideration that, statistically, real materials emits pollutants at only half of this constant rate. Indeed, if the real material emission rates were uniformly distributed between zero and the reference value, 50% would be the right choice to correct the calculations. However, no data from manufacturers are available to confirm or infirm this value.

It appears that the PANDORA based approach better suit for predicting the concentration levels of both studied pollutants. As the 50% value can be seen as a fitting parameter, a value of 25% would better suit for formaldehyde and toluene (values between the OPQA-BPE 25th and 75th percentiles) when using the PANDORA based approach.

4 Conclusion

This exercise shows that, as expected in the studied configuration, the mechanical balanced ventilation with heat recovery (123.1 m^3/h) provides better IAQ than the exhaust ventilation with humidity control (75.9 m^3/h) with very low energy consumption penalty.

In addition, both approaches (A+ labeling and data from PANDORA) give similar results for formaldehyde but the A+ labelling approach fails to predict the order of magnitude for toluene. The second approach should be then applied to evaluate, in an easy and fast way, the concentration levels of this two pollutant in low-energy residential buildings.

5 References:

Abadie, MO., Blondeau P. 2011. PANDORA database: A compilation of indoor air pollutant emissions. HVAC&R Research 17 (4), 602-613.

Derbez M, Wyart G, Douchin F, Lucas JP, Ramalho O, Ribéron J, Kirchner S, Mandin C. 2015. Base de référence nationale sur la qualité de l'air intérieur et le confort des occupants de bâtiments performants en énergie - Description des premiers résultats de la qualité de l'air intérieur et du confort de bâtiments d'habitation performants en énergie. Observatoire de la qualité de l'air intérieur, Report CSTB-OQAI/2015-012, 56 pages.

MESDE. National Energy Efficiency Action Plan. Report from the Directorate General for Energy and Climate Climate and Energy Efficiency Service, Ministry of Ecology, Sustainable Development and Energy, 2014, 118 p.

RT 2012. Decree No 2010-1269 of 26 October 2010 relative to the thermal characteristics and energy performance of constructions and the decree of the 26 October 2010 relative to the thermal characteristics and energy performance requirements of new buildings and new building extensions.

Appendix D: Case study – UK

Definition of a Reference Residential Building Prototype for Evaluating IAQ and Energy Efficiency Strategies – England

Participant: Esfand Burman, University College London, United Kingdom

Content:

1 Introduction

This report presents a description of a reference house for England compliant with the latest energy and ventilation requirements in the UK Building Regulations. This dwellings is used to evaluate the relation and trade-offs between energy efficiency, ventilation strategy, and indoor air quality (IAQ). The metrics used for IAQ in this exercise are formaldehyde and toluene. The ventilation strategies used are mechanical extract ventilation (MEV) and mechanical balanced ventilation with heat recovery (MVHR), the most prevalent ventilation strategies used in low-energy dwellings in the UK. As formaldehyde and toluene are not currently regulated under the UK Building Regulations, limited information is available about the corresponding emission factors of construction material. The PANDORA database was therefore used to estimate the emission factors.

2 Definition of the reference house

2.1 Description

The reference house has an 84-m² floor area (heated area) for a total volume of 210 m³. It includes five living spaces (1 dining room, 1 living room and 3 bedrooms), in addition to kitchen, bathroom, toilet, entrance hall and stairs. It is assumed that the house is located in southeast England, which is the reference location for heating degree-day analysis in the UK (2021 heating degree-days over the base temperature of 15.5 °C). It is also assumed that four occupants live in this house. Figure 1 presents the layout plans of the reference house. Floor to ceiling height in each floor is 2.5 m. The side-hinged windows are 1.0 m high and openable to a fixed position of 20 °. The reference house is defined based on the worked example provided in Approved Document Part F, means of ventilation, for ventilation sizing for dwellings (HM Government, 2013).

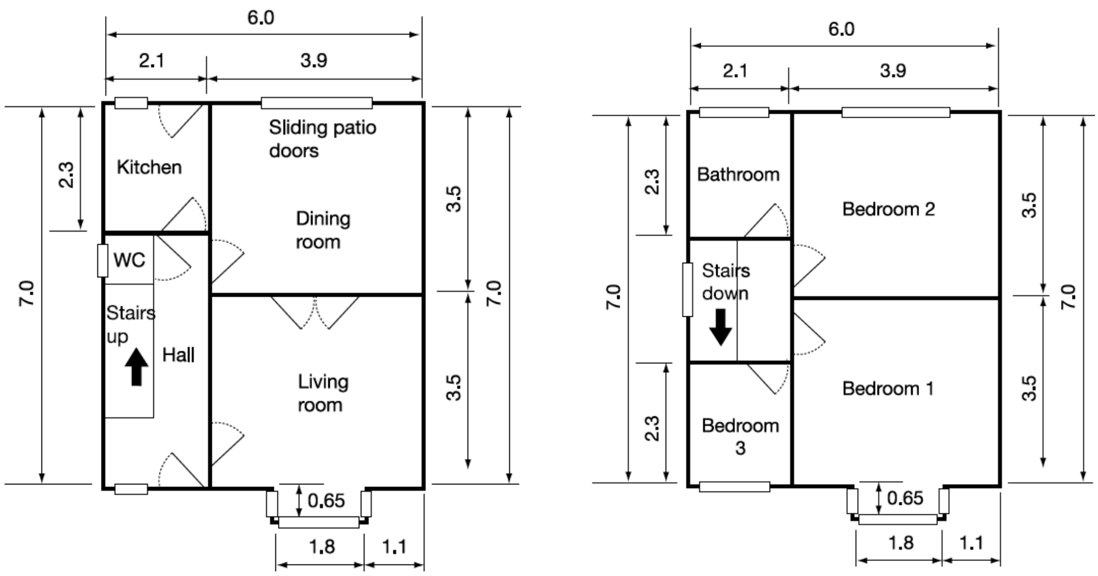


Figure 1: Layout plans for a typical semi-detached house in the UK defined as an example in Approved Document Part F (2010 edition).

2.2 Building material thermal properties

The house is made up of internal thermal insulated walls, an insulated concrete slab and ceiling (unused attic). Windows are double-glazed with Argon and low emissivity treatment. The U values selected for the house are consistent with the Notional values prescribed in Approved Document Part L1A of the UK Building Regulations (HM Government, 2016) as presented in Table 1. Other assumptions used for building fabric are as follows:

Thermal bridging y-value: 0.05 W/m²K

Air permeability: 5 m³/h.m² at 50 Pa

Thermal mass: Medium (250 kJ/m²K)

Table 1: Building fabric U values in Approved Document Part L (2016).

Thermal element	Notional U value (W/m²K)	Limiting U value (W/m²K)
External walls	0.18	0.30
Floor	0.13	0.25
Roof	0.13	0.20
Opaque door (<30% glazed area)	1.00	2.00
Windows	1.4	2.00

2.3 Space heating, DHW, ventilation and lighting

Space heating generation is provided by a gas-fired boiler with gross seasonal efficiency of 89.5% consistent with the efficiency prescribed for the notional dwelling in England. Low-temperature radiators handle heat emission to the air space.

Domestic Hot Water (DHW) is also provided by the boiler. DHW is stored in an insulated hot water tank of 150 l capacity with a standing heat loss of 1.44 kWh/day.

Two ventilation systems are compared in this study: 1) a mechanical humidity control extract ventilation (equivalent constant airflow: 90.7 m^3/h) with specific fan power of 0.4 W/l/s, and 2) a mechanical balanced ventilation with 85% heat recovery and specific fan power of 1 W/l/s (equivalent constant airflow: 104.4 m^3/h). The ventilation rate in the first scenario complies with the minimum requirements. The ventilation rate in the second scenario represents 15% enhanced ventilation.

It is assumed that low energy lighting is used throughout the dwelling.

2.4 Energy consumption

2.4.1 Regulatory context (Approved Document Part L)

The Building Regulations in the UK are devolved to the four nations of the United Kingdom. The case covered in this report represents England. Although there are slight differences between the regulations in England, Northern Ireland, Scotland and Wales, the same fundamental principles apply to all. In England, Approved Document Part L1A, a second-tier document in support of Part L of the Building Regulations, sets out detailed requirements for energy performance of new dwellings (HM Government, 2016).

According to Criterion 1 of Approved Document Part L1A, the carbon dioxide emissions associated with regulated energy use of a new dwelling should not be greater than a Target Emission Rate (TER) set out for that dwelling. TER for a new dwelling is determined by applying prescribed fabric characteristics to the geometry of the dwelling and prescribed building services efficiencies (notional values). Designers therefore have some flexibility for trade-offs between various energy efficiency measures in the actual building as long as total calculated carbon dioxide emissions are not greater than the TER.

Other requirements in Part L1A address: Target Fabric Energy Efficiency (TFEE), limits on design flexibility (maximum permissible U values and minimum efficiencies required for building services), limiting the effects of heat gains in summer (to mitigate the risk of overheating whilst improving energy efficiency), consistency between design and construction, and provision of information for energy-efficient operation of dwellings.

2.4.2 Energy consumption

Energy calculations for the Reference dwelling were carried out using the Standard Assessment Procedure (SAP) for regulatory energy calculations in England (BRE, 2012). Table 2 presents the energy consumption by use. Heating energy consumption is lower for the balanced system even with higher airflow rates thanks to the heat recovery. However, fan consumption is higher than the MEV system. Figure 2 presents a comparison of the two systems. In both case, energy consumption of electrical equipment other than those for lighting and ventilation is responsible of about 2/3 of the total electricity consumption of the house.

Table 2: Energy Consumption.

			kWh/year	kWh/m^2.year	MJ/year	MJ/m^2.year
Heating	MEV		3,444	41	12,398	147.6
	MVHR		2,688	32	9,677	115.2
Cooling	MEV/MVHR		0	0	0	0
DHW	MEV/MVHR		3,192	38	11,491	136.8
Lighting	MEV/MVHR		420	5	1,512	18
Fans & Pumps	MEV		252	3	907	10.8
	MVHR		420	5	1,512	18
Total regulated energy	MEV	Natural gas	6,636	79	23,890	284.4
		Electricity	672	8	2,419	28.8
	MVHR	Natural gas	5880	70	21,168	252
		Electricity	840	10	3,024	36
+Interior Equipment	MEV/MVHR		2,604	31	9,374	111.6
Total	**MEV**	**Natural gas**	**6,636**	**79**	**23,890**	**284.4**
		Electricity	**3,276**	**39**	**11,794**	**140.4**
	MVHR	**Natural gas**	**5,880**	**70**	**21,168**	**252**
		Electricity	**3,444**	**41**	**12,398**	**147.6**

Note: final energy is provided here (not primary energy).

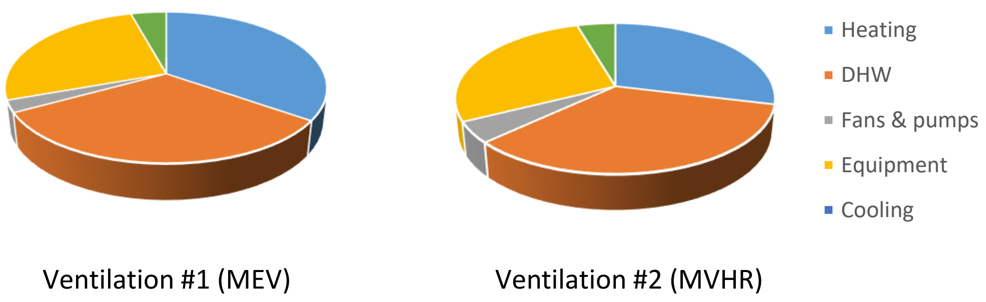


Figure 2: Energy consumption for the two ventilation systems.

2.5 Summary

The specification for the Reference house in England was chosen based on the notional values defined in the Standard Assessment Procedure used for energy calculations, except for ventilation strategy. The ventilation strategy used for the notional dwelling in SAP is currently based on natural ventilation with intermittent extract fans in wet rooms. The ventilation strategies investigated in this study were based on continuous mechanical ventilation, which is more relevant to low energy and airtight dwellings. The reference house complies with the low-energy Building Regulations in England (Part L1A 2013) with any of the chosen ventilation systems as the savings achieved in heating energy in both ventilation scenarios offset the excess in fan energy use, and the corresponding carbon dioxide emissions in both scenarios is not greater than the notional dwelling. The regulated energy consumption, without plug in equipment such as fridge, washing machine, television, etc. is 79 kWh/m²/annum gas and 8 kWh/m²/annum electricity for the MEV scenario and 70 kWh/m²/annum gas and 10 kWh/m²/annum electricity for the MVHR scenario with enhanced ventilation.

3 Indoor Air Quality

3.1 Regulatory context (Approved Document Part F)

Indoor air quality in England is covered by Approved Document Part F (HM Government, 2013). This Approved Document sets out the ventilation requirements for buildings. It is therefore predominantly focused on means of ventilation rather than setting out exposure limit values for various airborne pollutants. Performance criteria for nitrogen dioxide, carbon monoxide, and TVOC have been defined for dwellings (Table 3). No performance criteria, however, has currently been defined for specific VOCs.

Table 3: Performance-based ventilation criteria for dwellings (Approved Document Part F, 2010 edition)

Moisture	There should be no visible mould on external walls in a properly heated dwelling with typical moisture generation
Nitrogen dioxide (NO_2) exposure limit values	288 µg/m³ (150 ppb) – 1 hour average
	40 µg/m³ (20 ppb) – long term average
Carbon monoxide (CO) exposure limit values	100 mg/m³ (90 ppm) – 15 minute averaging time
	60 mg/m³ (50 ppm) – 30 minute averaging time
	30 mg/m³ (25 ppm) – 1 hour averaging time
	10 mg/m³ (10 ppm) – 8 hours averaging time
TVOC	300 µg/m³ – 8 hours averaging time
Ventilation rate	Minimum 3.5 l/s/person for control of bio-effluents for adapted individuals

According to Approved Document Part F the whole dwelling ventilation rate for the supply of air to the habitable rooms in a dwelling should be no less than what is prescribed in Table 4 whatever ventilation strategy is used. These minimum ventilation rates were used to define the airflow rate for scenario 1 (MEV). For enhanced ventilation, the ventilation rate prescribed for three bedroom dwellings in Home Quality Mark (HQM), an accreditation scheme for assessment and rating of new homes in the UK, was used.

Table 4: Whole dwelling ventilation rates (HM Government, 2013)

	Number of bedrooms in dwelling				
	1	2	3	4	5
Whole dwelling ventilation rate (L/s)	13	17	21	25	29
Notes: - In addition, the minimum ventilation rate should be not less than 0.3 L/s per m² of internal floor area. (This includes all floors, e.g. for a two-storey building add the ground and first floor areas.) - This is based on two occupants in the main bedroom and a single occupant in all other bedrooms. This should be used as the default value. If a greater level of occupancy is expected, add 4 L/s per occupant.					

3.2 PANDORA database

PANDORA (a comPilAtioN of inDOor aiR pollutAnt emissions) database has been created to compile the available data from literature regarding the emission rates of both gaseous and particulate pollutants in a systematic way into a unique database to provide useful information for IAQ modelers (Abadie & Blondeau, 2011). The last version (2017) includes 604 indoor pollutant sources (from materials, occupant activity, etc.) for 9003 pollutant emission rates of gaseous (8813) and particulate (190) origins. The collected emission rate data are constant, discrete (value at a specified time) and transient. For the purpose of this common exercise, the emission rates of formaldehyde and toluene after 28 days and for different categories such as carpeting, flooring, finishes, etc. were used. For this common exercise, median values multiplied by 50% are chosen as emission rates to be used.

3.3 Results

Table 5 presents the calculation and concentration levels obtained for formaldehyde and toluene. Note that no furniture have been taken into account in this common exercise and therefore the calculation in effect represents the as-built status.

Table 5: Estimation of concentration levels in the English reference house using PANDORA database.

PANDORA	Area (m^2)	No. of Face	Emission Surface (m^2)	Load Factor (m^2/m^3)	E Form. ($\mu g/m^2.h$)	E Tol. ($\mu g/m^2.h$)	E Form. ($\mu g/h$)	E Tol. ($\mu g/h$)
Flat roof with unused attic	84.0	1	84.0	0.40	4.15	3.10	347	260
External Wall	113.7	1	113.7	0.54	7.73	0.50	879	57
Floor	84.0	1	84.0	0.40	4.15	3.10	349	260
Exterior Door	4.4	1	4.4	0.02	7.73	0.50	34	2
Internal Walls	55.25	2	110.5	0.53	7.73	0.50	854	55
Vertical glazing	11.9	1	11.9	0.06	7.73	0.50	92	6
Interior Door	20.0	2	40	0.19	7.73	0.50	309	20
Closet doors								
Kitchen Cabinets								
						Sum	2864	660

PANDORA Median values (μg/m².h)	Form.	Tol.
Flooring	**8.3**	**6.2**
Finishes	**15.5**	**1.0**
	Q (m³/h)	ACH (/h)
Ventilation #1 (MEV)	90.7	0.43
Ventilation #2 (MVHR)	104.4	0.50

Surface emission factor	**50%**

Ca (μg/m³)	Form.	Tol.
Ventilation #1 (MEV)	**31.6**	**7.3**
Ventilation #2 (MVHR)	**27.4**	**6.3**

3.4 Discussion

Table 6 compares the concentration levels derived for formaldehyde and toluene against the key statistics obtained from Subtask 1 of IEA EBC Annex 68 representing the concentration levels reported in the literature (Salis, et al., 2017).

Table 6: VOC concentrations: ventilation scenarios considered against key statistics from IEA EBC Annex 68

VOC	Min	25th pctl.	Median	Average	75th pctl.	Max	Ventilation #1 (MEV)	Ventilation #2 (MVHR)
Formaldehyde	14.4	17.7	25.9	37.4	43	86	31.6	27.4
Toluene	5.7	7.2	11.0	16.4	17.8	45.2	7.3	6.3

As formaldehyde and toluene have only indoor sources here, the differences in concentration levels observed between the two ventilation systems are directly correlated with the airflow rate ratio. The concentration levels derived for formaldehyde in both ventilation scenarios fall between the median and average of the sample. This indicates that the emission factors reported in PANDORA database combined with the 50% correction factor yield results that are comparable to the typical/average formaldehyde concentration levels reported in the literature. The concentration levels derived for toluene are lower than the median stock. Formaldehyde and toluene are not currently regulated by the UK Building Regulations and therefore corresponding emission factors of the construction material used are not reported. However, the concentration levels calculated in Table 5 are broadly consistent with measurements of pollutants in new-built dwellings in England (Burman, et al., 2018).

The formaldehyde concentrations derived for both scenarios are higher than the best-practice exposure limit value identified in Subtask 1 of IEA EBC Annex 68 (i.e. 9 μg/m³); whereas toluene concentrations are significantly lower than the best-practice limit of 250 μg/m³ (Salis, et al., 2017).

Given the ever-increasing requirements for improving energy efficiency, it is very difficult to reduce formaldehyde levels to the best-practice exposure limit value without compromising energy performance, unless advanced source control measures are adopted and emission factors are reduced. Currently, most suppliers of material and building designers in the UK at best consider TVOC which is not necessarily a good metric to identify the risks associated with health.

BRE Digest 464 provides good practice recommendations to control VOC emissions from construction products (Yu & Crump, 2002). Low formaldehyde material such as wood-based boards classified as E1 in accordance with BS EN 13986:2004 (BSI, 2005) can be used in construction. California Air Resources Board's Phase 2 standard (CARB2) also sets out requirements for emissions from composite wood products including hardwood plywood, particleboard and medium density fiberboard (MDF). Using CARB2 compliant material can help reduce the emission sources for formaldehyde in low energy dwellings. The United States Environmental Protection Agency Formaldehyde Standards for Composite

Wood Products Act (TSCA Title VI) has also established stringent emissions requirements for composite wood products that can help reduce emission sources significantly (EPA, 2018).

It is important to reduce emission sources first and use enhanced ventilation only as a complementary measure if necessary to ensure concentration levels do not exceed the exposure limits.

The emission databases available for IAQ modelling do not necessarily represent the emission factor of the construction products currently used in the industry. It is therefore important to develop a national database that represent various building products used and updated emission factors for formaldehyde and other critical VOCs in the UK.

3.5 Summary

This study points to the significance of the following measures to improve IAQ in new dwellings in the UK:

- National regulations for critical VOCs,
- Provision of further information about VOC emission factors of the construction products used in the industry (e.g. a national database for emission factors of the material in the UK),
- Labelling and rating schemes for IAQ that go beyond metrics such as CO_2 concentrations and TVOC and address specific health related pollutants,
- Promotion of best practice for construction material, exposure limit values, and ventilation rates in the industry to strike the right balance between IAQ and energy efficiency.

4 Conclusion

This exercise shows that, as expected in the studied configuration, the mechanical enhanced ventilation with heat recovery scenario (104.4 m^3/h) provides better IAQ than the mechanical extract ventilation (90.7 m^3/h) with very low penalty in terms of electricity use associated with fans, although the heat recovery in MVHR system can actually bring benefits for heating energy.

In addition, it was demonstrated that, in the absence of national regulations and database for VOCs in the UK, the PANDORA database could help estimate the likely concentration levels of specific VOCs such as formaldehyde and toluene in low-energy dwellings. The results show that concentration of formaldehyde in new low-energy dwellings may be higher than the best-practice exposure limit value.

It is important to consider the health impact of indoor sources of pollution in addition to outdoor sources, regulate these sources, and provide best practice advice to ensure good indoor air quality is achieved in dwellings that are constructed in accordance with new energy regulations.

5 References:

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HM Government, 2016. Approved Document Part L1A: Conservation of fuel and power in new dwellings (2013 edition with 2016 amendments), London: NBS.

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Appendix E: Case study – China

Definition of a Reference Residential Building Prototype for Evaluating IAQ and Energy Efficiency Strategies –China

Participant: Chen Huang, Chanjuan Sun, University of Shanghai for Science and Technology, China

Content

1. Introduction

This report presents in a first part the description of a reference apartment for China. This apartment has been defined to meet the standard for energy efficiency of residential building in Shanghai (DGJ08-205-2015). Two ventilation systems in reference building were set as natural ventilation and mechanical ventilation. Two different level of air change rates were set in mechanical ventilation. The actual schedule of opening windows in Shanghai residential buildings was used as a reference. Indoor air pollutants (formaldehyde and benzene series) used the measured data in 149 residences in Shanghai. Simulation on building energy consumption and indoor air pollutants in this reference building were conducted by EnergyPlus. The thermal parameters, results and conclusion were given in next parts.

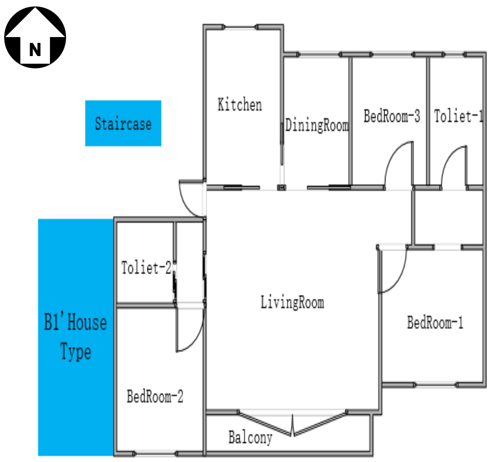
2. Definition of the reference building

2.1 Description

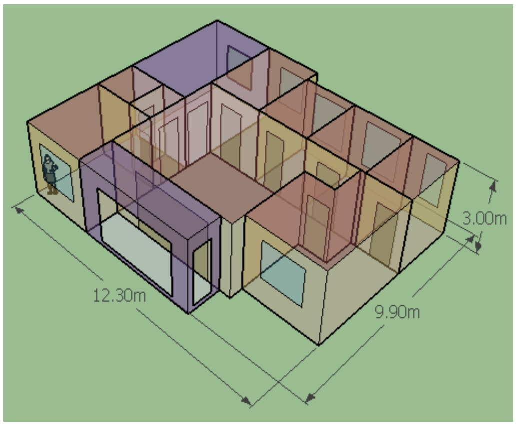
The reference building has an 87.36 m^2 floor area. The layout of this apartment was shown in table 1. It includes 4 living spaces (1 dining/living room and 3 bedrooms), 1 kitchen, 2 bathrooms and 1 restaurant. The location of the building is Shanghai that is in the hot summer and cold winter climatic zone according to the classification of design standard for energy efficiency of public buildings (GB 50189—2005). Figure 1 presents the floor plan and 3D model of this reference building.

Table 1 Room Type of Reference Building

Room type	Area (m^2)	Air condition (Yes/ No)
Bedroom 1 (master bedroom)	13.14	Yes
Bedroom 2	10.05	Yes
Bedroom 3	7.28	Yes
Living room	31.32	Yes
Restaurant	6.44	Yes
Kitchen	8.5	No
Bathroom 1	5.32	No
Bathroom 2	3.15	No



(a) Floor plan



(b) 3D model map

Figure 1: Floor plan and 3D model of the reference building in Shanghai

2.2 Building assemblies and material thermal properties

Table 2: Thermal Parameters of Building Envelope

Items	Materials (Outside To In)	Thickness (m)	Thermal conductivity(W/(m·K))	Density(Kg/ m^3)	Specific heat(J/(kg•K)
floor	Wood floor	0.012	0.17	600	2510
	C20 Fine stone concrete	0.03	0.93	1800	920
	120mm Steel reinforcement	0.12	1.74	2500	920
Outside wall	50mm Thick plasterboard sound-proof wall	0.05	0.33	1050	1050
	15 Thick gypsum mortar	0.015	0.76	1500	1050
	200 Thick sand aerated block (B06)	0.2	0.19	600	1050
Inside wall	15 Thick gypsum mortar	0.015	0.76	1500	1050
	200 Thick sand aerated block (B06)	0.2	0.19	600	1050
Roof	15 Thick gypsum mortar	0.015	0.76	1500	1050
	120mm Steel reinforcement	0.12	1.74	2500	920
Anteport	0.8mm Metallic surface	0.0008	45.28	7824	500
	Steel 0.5mm wood 25mm composite door	0.0254	0.15	608	1630

Inside door	Steel 0.5mm wood 25mm composite door	0.0254	0.15	608	1630

This reference building was in the standard floor. Its floor, ceiling and splitting wall were set to be heat insulation. Table 2 presents the composition of the house envelope with building assemblies dimensions and material thermal properties.

2.3 Space heating, cooling and ventilation

Space heating and cooling generation is provided by a split air conditioner in this reference building. Indoor control temperature and related parameters of split air conditioner are determined according to "Design Standard for Energy Efficiency of Residential Building in Hot Summer and Cold Winter Zone" (JGJ134-2010) and investigation, as seen in table 3.

Table 3: Indoor air temperature and parameters of split air condition

	Indoor control temperature	Parameter of split air conditioner
Summer	26°C	Refrigeration COP=2.8
Winter	18°C	Heating COP=1.2

Natural ventilation (opening windows) was set in reference building. Outdoor air temperature and pollutants impact residents opening windows. The duration of opening windows has further great impact on indoor air quality and building energy consumption. When outdoor air temperature was 16-28 °C and the concentration of outdoor PM2.5 was below 35μg/m^3 with nobody indoors, the air conditioner was closed and the windows were opened in reference building.

2.4 Occupants, lighting and equipment

Table 4: Personnel schedule in reference building

Rooms	Number	Workdays	Weekends
Living room	3 (changed)	18:00-22:00	11:00-22:00
Master bedroom	2 (unchanged)	22:00-07:00	
Secondary bedroom	1 (unchanged)	22:00-07:00	
Study room	1 (unchanged)	19:00-21:00	

Personnel alteration time in living	
Workdays	Weekends
/	11:00-12:00—2
/	12:00-18:00—3
18:00-20:00—	18:00-20:00—2

Kitchen	1 (unchanged)	18:00-19:00	11:00-12:00 18:00-19:00	20:00-21:00—1	20:00-21:00—1
Bathroom	1 (unchanged)	7:00-7:30；20:00-21:00		21:00-22:00-3	21:00-22:00-3

Information on occupants' number, lighting and equipment in residence in Shanghai were obtained from survey. Table 4- 6 present the detailed settings.

Table 5: Power and runtime of indoor lighting equipment

Room	Living room	Master bedroom	Secondary bedroom	Study room	Kitchen	Bathroom
Power/W	100	60	20	20	20	15
time	18:00-22:00	22:00-23:00	22:00-23:00	19:00-21:00	18:00-19:00	20:00-21:00

Table 6: Power and runtime of indoor electric equipments

Zone	Equipment	Power	Workdays	Weekends
Living room	TV	100W	18:00-22:00	14:00-17:00,18:00-22:00
	Refrigerator	50W	24h	24h
Kitchen	Induction cooker	1200W	18:30-19:00	11:30-12:00， 18:30-19:00

2.5 Mechanical ventilation

When somebody indoors and natural ventilation was not used, mechanical ventilation was applied. Fresh air change rate confirmed by ASHRAE Standard 62.1 was used to calculate indoor fresh air volume, as seen in Equation (1).

$$V_{bz} = R_P P_Z + R_a A_Z \tag{1}$$

Herein: V_{bz} is designed fresh air volume. L/s; R_P is $L/(s \cdot person)$; P_Z is number of indoor person, R_a is required air volume per unit floor area, $L/(s \cdot m^2)$; A_Z is covered area , m^2。

Two different air change rates were set. One was calculated by the equation and another was set as 50% of designed air volume. Table 7 lists the detailed settings.

Table 7: Air volume of mechanical ventilation

	Master bedroom	Secondary bedroom	Living room
Designed fresh air volume(m^3/s)	0.008942	0.006442	0.019396
50% of designed fresh air volume(m^3/s)	0.00447	0.003221	0.009689

2.6 Energy consumption

Energy consumption in different ventilation modes were simulated by EnergyPlus with the related building parameters listed in section 2.6. The energy consumption of natural ventialation was the lowestn, and that for mechanical ventilation increased but non-significant, as seen in table 8.

Table 8: Energy consumption in different ventilation modes (kWh).

Energy consumption	Heating	Cooling	Interior Lighting	Interior Equipment	Fans	Total
Natural ventilation	353.98	289.82	195.28	2024.7	55.39	2919.17
50% Mechanical ventilation	393.69	327.06	195.28	2024.7	59.47	3000.20
100% Mechanical ventilation	435.17	324.54	195.28	2024.7	63.03	3042.73

2.7 Conclusion

Ventilation mode has an impact on building energy consumption. Based on the simulation results, there was no significant difference on energy consumption between natural ventilation and 100% mechanical ventilation. Mechanical ventilation could be an optimal choice if the condition allows.

3. Indoor Air Quality

3.1 Description

In this exercise, indoor decorating and refurbishing materials VOC emission factor was used to evaluate the concentration levels of formaldehyde and toluene in the reference building.

3.2 Emission rate of different air pollutants

Formaldehyde and benzene series were mainly considered in current reference building study. Based on field measured data of indoor pollutants in 149 residences, emission rate of indoor pollutants were obtained ($\mu g/(s \cdot m^2)$). Emission rate per floor area in living room was twice as that in bedroom, then the simulation input parameters of indoor pollutants in living room and bedroom were obtained. Using 1-st quartile (25%), 2-nd quartile (25%), 3-rd quartile (25%), 4-th quartile (100%) of emission rate as 4 cases, Energyplus was applied in simulation of this reference building and annual concentrations of indoor pollutants were obtained. Figure 2 and figure 3 show the emission rates of reference building. Table 8 and 9 list the settings on emission rate.

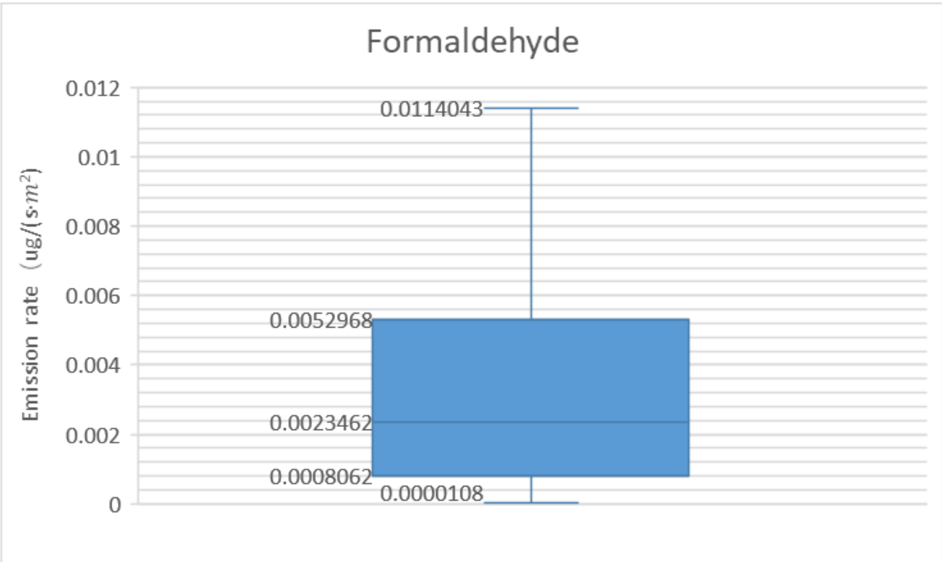


Figure 2: Emission rate of formaldehyde

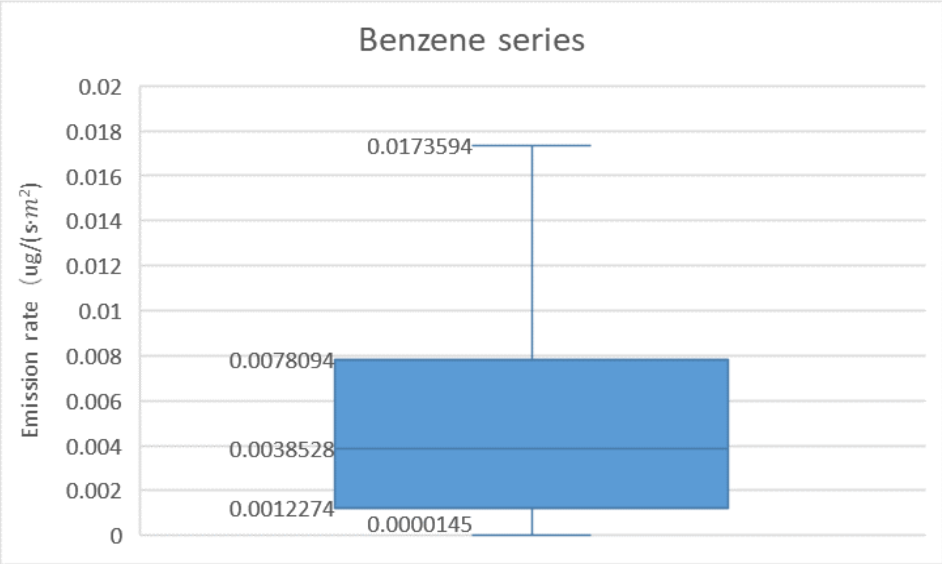


Figure 3: Emission rate of benzene series

Table 8: Emission rate of formaldehyde (μg/s)

Rooms	Case 1	Case 2	Case 3	Case 4
Bedroom 1	0.01059347	0.03082907	0.06959995	0.14985250
Bedroom 2	0.00810231	0.02357931	0.05323284	0.11461322
Bedroom 3	0.00586914	0.01708034	0.03856070	0.08302330
Living room	0.05050037	0.14696597	0.33179155	0.71436535

Table 9: Emission rate of benzene series (μg/s)

Rooms	Case 1	Case 2	Case 3	Case 4
Bedroom 1	0.01612804	0.05062579	0.10261552	0.22810252
Bedroom 2	0.01233537	0.03872064	0.07848447	0.17446197
Bedroom 3	0.00893547	0.02804838	0.05685243	0.12637643

Living room	0.07688434	0.24133939	0.48918082	1.08739282

3.3 Concentration of indoor air pollutants and energy consumption

Annual concentrations of indoor pollutants were simulated and obtained by EnergyPlus. Moreover, dissatisfied rate of indoor pollutants in different status were calculated. Average concentrations of pollutants in master bedroom and energy consumption with different ventilations status were shown in figure 4 and figure 5, while those in living room were shown in figure 6 and figure 7. The dissatisfied rates of pollutants in master bedroom and living room were showed in figure 8-11, respectively.

Mechanical ventilation could greatly decrease the concentration of indoor air pollutants, especially in case 4 (with the maximum emmision rate). The concentration of air pollutants were relatively high, even higher than limited values in standard. The dissatisfied rate was high. By using mechanical ventilation, the concentration of air pollutants decreased lower than limits in standard.

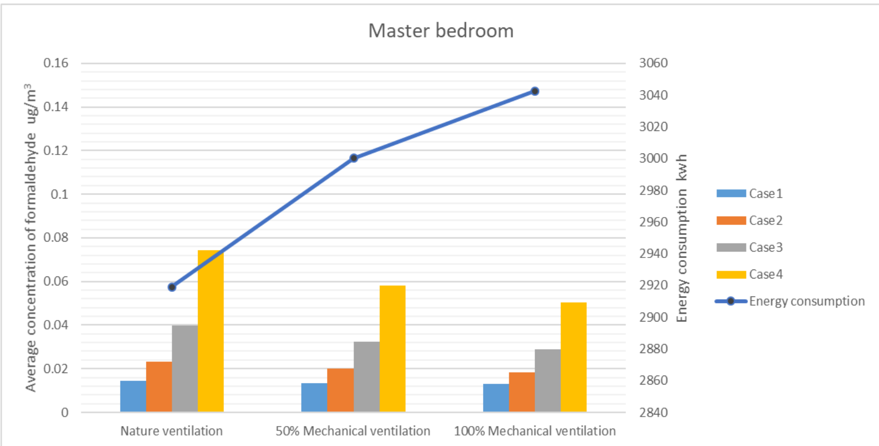


Figure 4: Average concentrations of formaldehyde and energy consumption in master bedroom

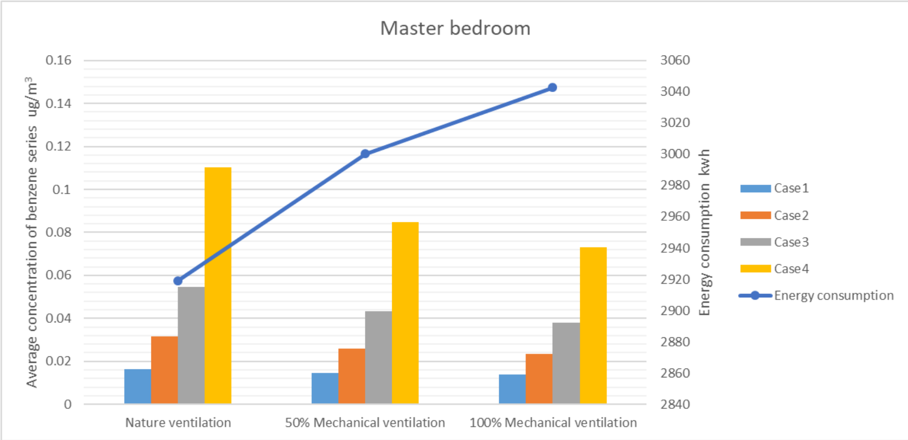


Figure 5: Average concentrations of benzene series and energy consumption in master bedroom

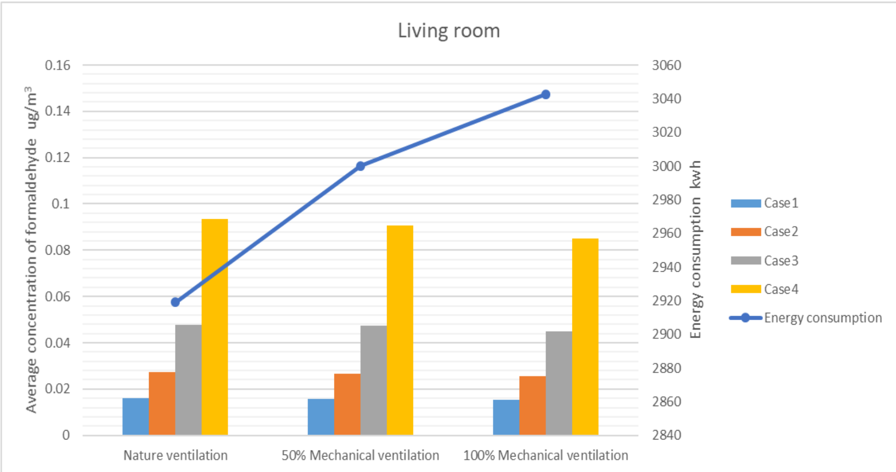


Figure 6: Average concentrations of formaldehyde and energy consumption in living bedroom

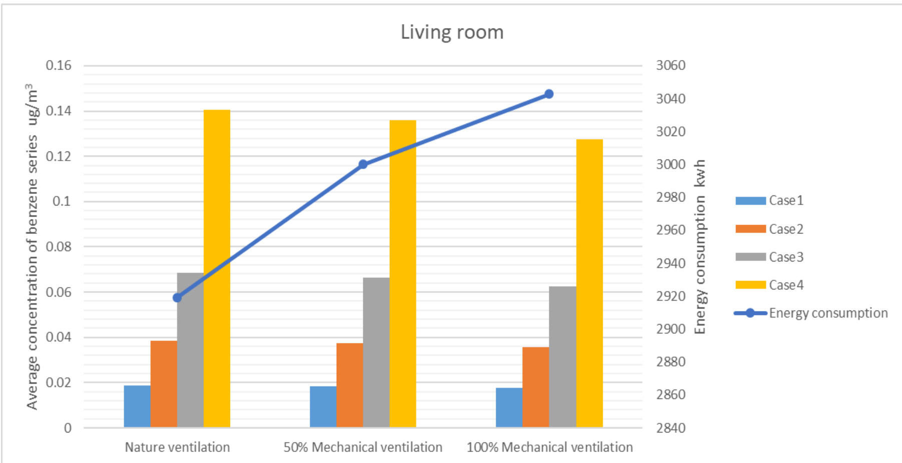


Figure 7: Average concentrations of benzene series and energy consumption in living bedroom

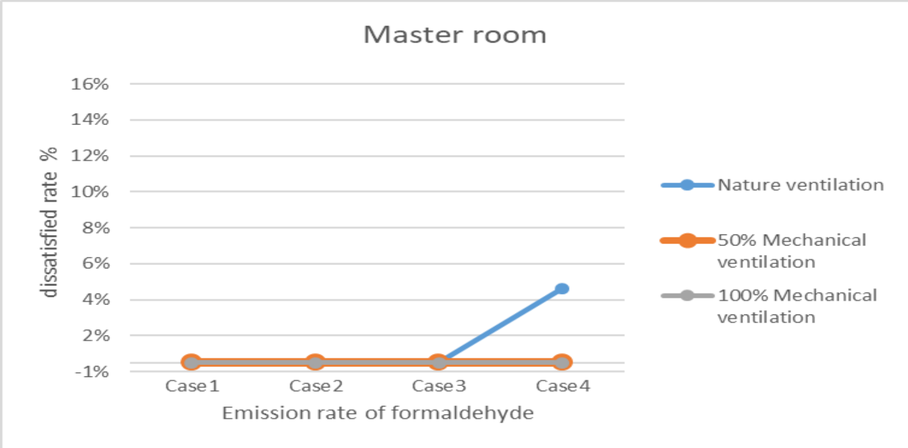


Figure 8: The dissatisfied rate of formaldehyde in master bedroom

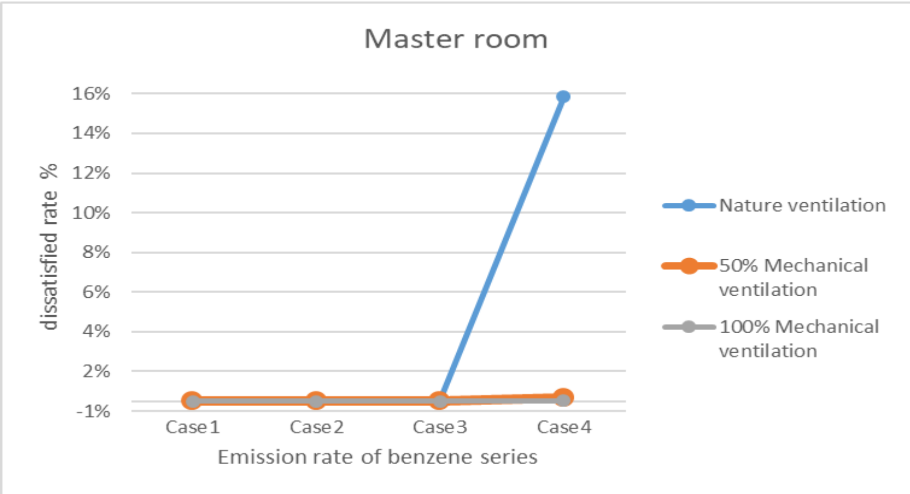


Figure 9: The dissatisfied rate of benzene series in master bedroom

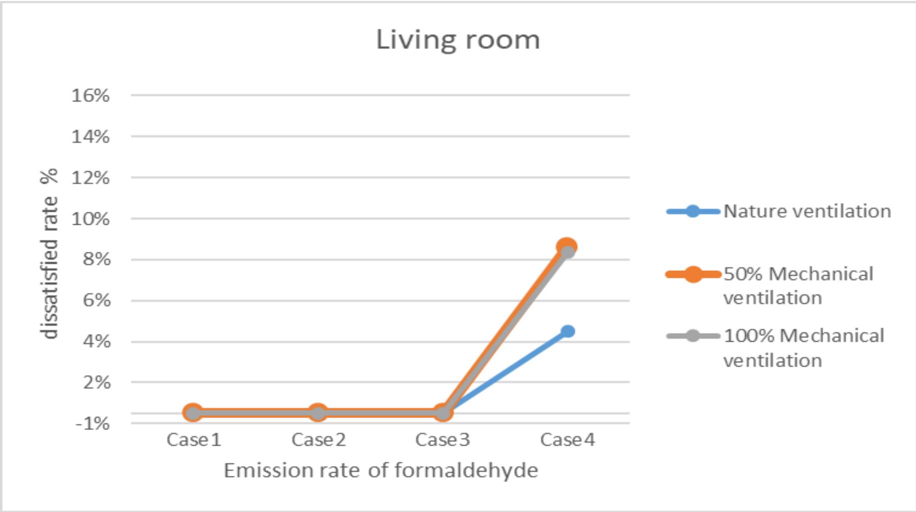


Figure 10: The dissatisfied rate of formaldehyde in living bedroom

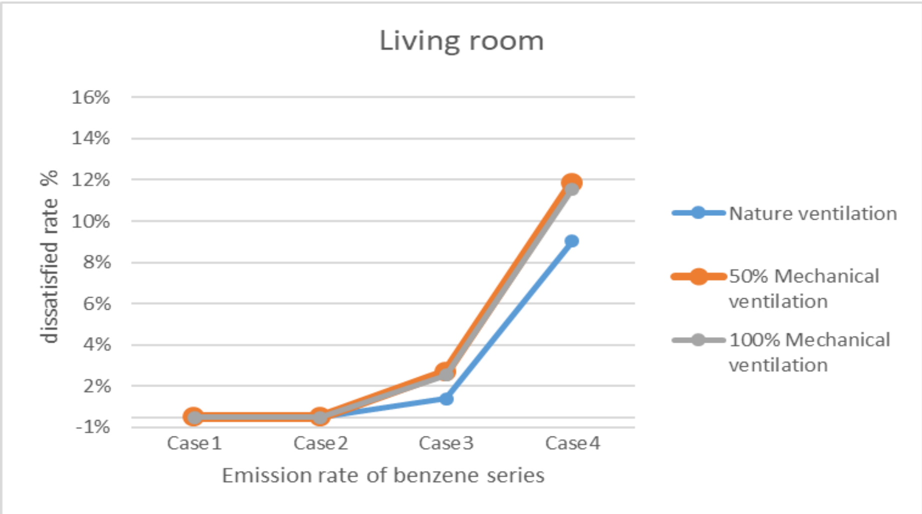


Figure 11: The dissatisfied rate of benzene series in living bedroom

3.4 Conclusion

With natural ventilation, the average concentration of indoor air pollutants were high and even exceeded limited values in standards. This brought low indoor air quality and high occupants' dissatisfied rate. However, mechanical ventilation could decrease the concentration of indoor air pollutants and provide a good indoor environment. From the simulation results, the occupants' dissatisfied rate in living room by using mechanical ventilation was higher than natural ventilation, but the average concentration of air pollutants was relatively lower and indoor air quality was higher than natural ventilation.

4. Conclusion

This exercise shows that, as expected in the studied configuration, the 100% mechanical ventilation provides better IAQ than the natural ventilation with very low energy consumption penalty.

In addition, with the quartiles increasing, the concentration of both benzene series and formaldehyde increased, accompanied by the dissatisfied rate increased. In living room, mechanical ventilation system caused higher dissatisfied rate than natural ventilation, but the opposite situation was found in mater bedroom. This is because the concentration of indoor air pollutants was higher. Moreover. Mechanical ventilation could decrease the average concentration of these air pollutants not exceeding the standard value.

5. References

Jianbing Liu and Xiangping Zhu. Analysis and study on indoor and outdoor Benzenses next to traffic trunk. North Environment. 2013, 25 (11): 71-73.

ASHRAE Standard 62.1-2007: Ventilation for Acceptable Indoor Air Quality.

GB/T 18883-2002, Indoor Air Quality Standard [S].

Appendix F: Case study – Belgium

Reference house for the IAQ and energy assessment of Demand Controlled Ventilation – Belgium

Participant: Klaas De Jonge, Ghent University, FWO, Belgium

Content

1 Introduction

In what follows, the legislation concerning IAQ and VOCs in Belgian residences and the Belgian reference house are discussed. The reference house is only used for 1 specific purpose: the assessment of DCV systems (IAQ and Energy).

2 Context

In Belgium, the legislation concerning VOC levels in the indoor environment is quite limited. There are 7 legislative mechanisms which cover ventilation system design, Indoor Air Quality (IAQ) and the relation to energy consumption and comfort.

1. System design
    a. NBN D50-001 (residential)
    b. NBN EN 13779
    c. NBN EN 15251
2. IAQ
    a. Codex for wellbeing at work
    b. IAQ decree
    c. Royal decree for Emissions from Building products
3. IAQ, Comfort and Energy
    a. EPB legislation
        » Method of equal performance

From these, only the NBN D50-001, the EPB legislation, the IAQ decree and the Royal decree for Emissions from Building products are applicable for residential buildings.

For the design of a residential ventilation system, the NBN D50-001 [1], published in 1991, is still the governing standard (some official notes were added later in 2007). The NBN D50-001 standard is applicable to new residential buildings and extensive renovations of buildings, parts of a building with a residential function or comparable spaces. It defines a nominal supply or extraction rate for all spaces generally found in a residence.

Because of the development of Demand Controlled Ventilation (DCV) systems, a way to check if a certain control strategy based on H2O and/or CO2 does ensure a sufficient IAQ (comfort) was introduced as part of the EPB legislation [2]. This method does also allow for an objective way to quantify the energy savings of such a system in the calculation of the energy level (E-level). It was in light of this method that a reference house was defined.

The third legislation which is applicable in residential buildings is the 'Binnenmilieubesluit' (translated: 'Indoor Air Quality decree' or 'IAQ-decree') of 2004 is a resolution made by the Flemish government that forces all parties involved with the building, maintenance or technical installations of a residential or public building to limit the health risk due to a bad IAQ. It proposes quality standards based on maximum concentrations of a small selection of substances in the indoor air. The legislation was updated in 2018. This decree and its maximum concentrations are not directly linked to the NBN D50-001. The enforcement of this legislation is based on measurements when issues (health or comfort) concerning IAQ are reported. Table 1 shows the recommended and intervention limit concentrations of the IAQ decree for a selection of common VOCs in the indoor environment [3].

Table 1 Recommended and maximum concentrations in the indoor air for a selection of VOCs [3].

	IAQ decree (2018)	
	Recommended concentration	Intervention limit concentration
Formaldehyde	-	100 µg/m³
Toluene	< 5000 µg/m³	14000 µg/m³
Benzene	< 2 µg/m³	10 µg/m³
Ozone	< 40 µg/m³	78 µg/m³
Acetaldehyde	< 160 µg/m³	480 µg/m³
Naphthalene	< 2 µg/m³	31 µg/m³
Nitrogen Dioxide	< 20 µg/m³	40 µg/m³
2-ethylhexanol	< 100 µg/m³	810 µg/m³
C4-C11-aldehydes	< 650 µg/m³	1600 µg/m³
C9-C14-alkanes	< 250 µg/m³	490 µg/m³
TVOC	< 300 µg/m³	1000 µg/m³

The last legislation is the 'Koninklijk besluit tot vaststelling van de drempelniveaus voor de emissies naar het binnenmilieu van bouwproducten voor bepaalde beoogde gebruiken'. (translated: Royal Decree for the limitation of emissions to the indoor environment from building products for certain usage) [4]. This legislation is in this text referred to as 'Royal decree for Emissions from Building products'. This legislation prohibits the production of building materials with high emission rates if the material is meant to be used in spaces where people reside for long periods of time.

The testing should be done according to the European CEN/TS 16516 standard. After careful standardized sampling of the material, the sample is placed in a small test chamber of steel or glass. Temperature, humidity and air change rates are kept constant and after 28 days, an air sample is taken and tested. Because of margins in the procedure and specifications of the test chamber and to ensure fair competition, the results are recalculated to match the standard 'European reference room' [5] . The limit values from Royal decree for Emissions from Building products are the maximum concentrations of a certain contaminant that may occur in the European reference room after 28 days.

Table 2 is the translation of the table found in the royal decree for emissions from building products and shows the maximum values in the reference room for different substances or categories of substances.

Table 2 - table from royal decree for emissions from building products showing the maximum values in the reference room for seven substances or categories of substances (translated from Dutch) [4].

<table>
<tr><th>Characteristic</th><th>Obtained according to</th><th>Limit after 28 days</th></tr>
<tr><td>R
The R-value is the sum of all ratios Ri for all VOCs with a known LCI-value (lowest concentration of interest).
De ratio Ri is de ratio of the measured concentration in the test room of a certain VOC and the corresponding LCI-value of this VOC.</td><td>The concentrations of the individual VOCs are obtained following the CEN/TS 16516 standard (Construction products – Assessment of emissions of regulated dangerous substances from construction products – Determination of emissions into indoor air.)</td><td>≤ 1 µg/m³</td></tr>
<tr><td>The total concentration of VOC (TVOC)</td><td rowspan="6">The LCI-value are those from the harmonised list prepared by the Joint Research Centre of the European Commission (DG JRC) (Report No 29).

For substances without a known LCI-value, the notified LDI-value of the AgBB is used from the date the products is put into the market.

Sampling and preparation must be done according to ISO16000-11, CEN/TS 16516 and all relevant additions in CEN product standards.</td><td>≤ 1 000 µg/m³</td></tr>
<tr><td>The total concentration of semi volatile organic compounds (TSVOC)</td><td>≤ 100 µg/m³</td></tr>
<tr><td>CMR substances category 1A and 1B as mentioned in Art. 36(1)(c) of (EG) nr. 1272/2008 of the European parliament, the council of 16.Dec.2008.</td><td>≤ 1 µg/m³</td></tr>
<tr><td>Acetaldehyde (EINECS 200-836-8; CAS 75-07-0)</td><td>≤ 200 µg/m³</td></tr>
<tr><td>Toluene (EINECS 203-625-9; CAS 108-88-3)</td><td>≤ 300 µg/m³</td></tr>
<tr><td>Formaldehyde (EINECS 200-001-8; CAS 50-00-0)</td><td>≤ 100 µg/m³</td></tr>
</table>

Although the principle and application feels adequately comprehensive, the legislation does only limit VOC emission from materials for use as a flooring material. There is no reason mentioned why walls or ceilings are not considered.

3 Definition of reference house

As mentioned in the previous section, the reference house was developed to asses DCV system controls. The method has been developed and fine-tuned by several authors [6], [7]. The method uses CONTAM, a free contaminant and airflow simulations software developed by NIST, to simulate a series of pre-defined cases and scenarios [8]. Analysis of all these results allow to compare the DCV controlled system with the standard, continuous airflow systems as defined in the NBN D50-001. The method follows the 'principle of equal performance': if the DCV system results in an equal or better IAQ than one of the reference systems and while doing so does not lead to more ventilation heat losses, the system is allowed to enter the market.

The method is therefore often referred to as: 'method of equal performance'.

3.1 Description

The floorplan of the test reference house was adopted from the EL²EP-project [9]. In this study, different reference dwellings where defined for different types of living (terraced house, classic detached house, architectural detached house, semi-detached house and an apartment). Each type represents the statistically average building of his kind for a family of four people.

The building used in this method of equal performance is the 'detached house' and is shown in Figure 1 and Figure 2. It is a 2 storey house with on the ground floor: a living room with open connection to the kitchen, toilet, entrance/hallway and a service room. On the first floor: 2 children's bedrooms, 1 master bedroom and the bathroom.

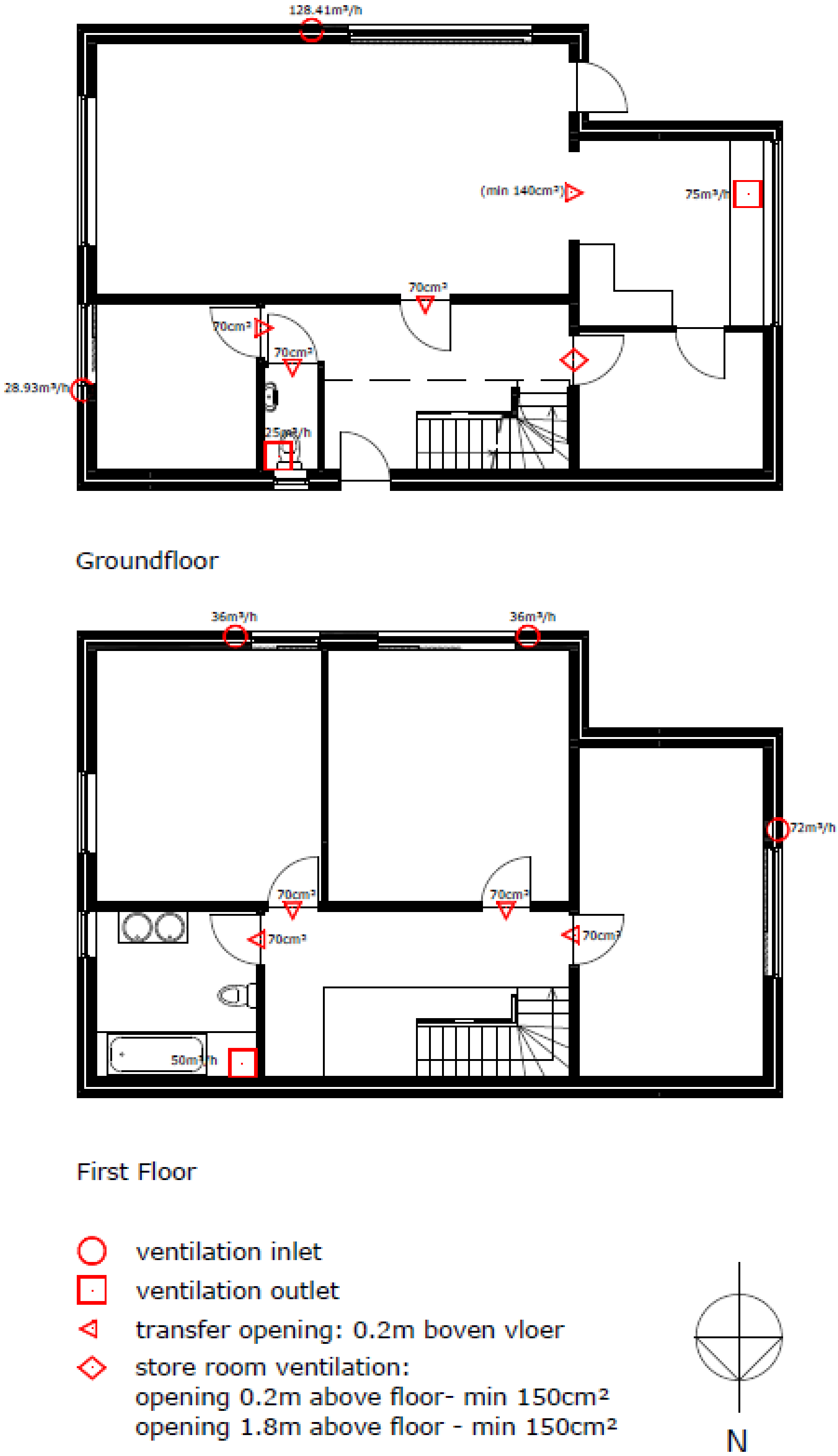


Figure 1 Floor plan of reference house with indication of ventilation system components and nominal airflow rates [6].

Figure 2 Elevations of the reference house for major orientations [6].

3.2 Building assemblies and material thermal properties

As CONTAM does not allow for thermal calculations without co-simulation, the indoor temperature is defined as 18°C, constantly. Because of this decision, is was not necessary to define a certain wall construction. As the focus of this report are new, low-energy buildings, the wall assemblies and window types of the original 'detached house' from the EL^{2}EP-project where updated according to the minimum requirements in Flanders for 2018. Figure 3 and Table 3 present the composition of the house envelope with building assemblies dimensions and material thermal properties. Because of the application of this reference house, the assessment of DCV systems, no heating system is defined.

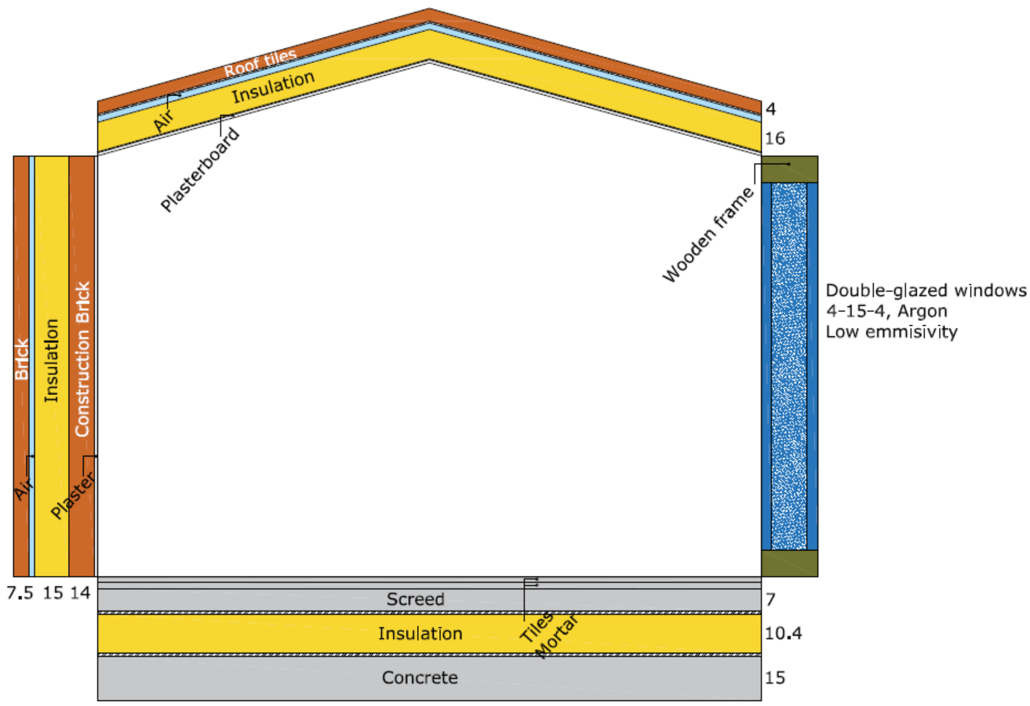


Figure 3: Composition of the house envelope.

Table 3: Building assemblies and material thermal properties.

Building Envelope						
Assembly	Materials (exterior to interior)	Area (m^2)	Thickness(m)	Conductivity (W/(m-K))	Specific Heat*(J/(Kg-K))	Resistance((m^2*K)/W)
External wall	Brick (facade brick)	182.89	0.09	0.75	840	0.12
	Air gap (ventilated)	182.89	0.03	-	1000	0.17
	Insulation	182.89	0.149	0.041	1030	0.00
	Brick (construction brick)	182.89	0.14	0.54	840	0.26
	Plaster	182.89	0.01	0.52	1000	0.02
Tilted Roof	Roof tiles (and wooden roof tile carrier structure)	63.38	0.04	-	-	-
	Membrane (Fibre cement)	63.38	0.004	0.5	1650	0.01
	Air gap	63.38	0.15	-	1000	0.16
	Mineral wool	63.38	0.161	0.041	840	0.00
	Membrane	63.38	-	-	-	-
	Plasterboard	63.38	0.01	0.2	1000	0.05
External Floor on	Reinforced concrete	92.70	0.15	1.7	1000	0.09
	Membrane	92.70	-	-	-	-

solid ground	Insulation (pressure resistant)	92.70	0.104	0.028	1400	0.00
	Membrane	92.70	-	-	-	-
	Screed (cement based)	92.70	0.07	0.37	1000	0.19
	Mortar (for tile placement)	92.70	0.01	0.93	1000	0.01
	Tiles	92.70	0.01	1.2	1000	0.01
Double pane Windows (Thermal)		26.98				$R_{window} = 0.67$
	Frame percentage	17%				$R_{glass} = 0.91$
	Glass	22.42	0.004	-	-	-
	Argon		0.015	-	-	-
	coating		-	-	-	-
	Glass		0.004	-	-	-
	Frame (Wood)	4.57	0.050	-	-	-
Exterior Door	Wooden door	3.39	0.04	0	1880	0.00
Windows	Total Solar transmission (SHGC)			Light transmission		U value
Glazing	0.7 (g-value)			-		1.1

Building Assemblies				
Assembly	Materials	Area or Quantity		Thickness(m)
		Unit	Value	
Interior Door	-	-	-	-
Closet doors	-	-	-	-
Kitchen Cabinets	-	-	-	-
Interior Floors	Floor finishing	m^2	86.05	0.01
	Product for placement	m^2	86.05	0.01
	Screed	m^2	86.05	0.07
	Membrane	m^2	86.05	-
	Bearing floor	m^2	86.05	0.15
	plaster	m^2	86.05	0.01

3.3 Ventilation system

A variation of the reference house is modelled in CONTAM for three nominal, reference systems:

- System A - Natural inlet, Natural outlet
  (Extraction flow through vertical shafts based on natural convection)
- System C - Natural inlet, Mechanical outlet
  (Extraction flow through the use of ventilators)
- System D - Mechanical inlet, Mechanical outlet
  (Supply and extraction flow through the use of ventilators)

System B (mechanical supply, natural outlet) is not considered as it is not a common system in Belgium. For every DCV which needs to be tested, a new variation of the control algorithm is defined and compared to the reference systems.

Table 4 shows the general sizing rule for ventilation system design. The nominal airflow rates are independent of the chosen reference system.

Table 4 Nominal flow according to NBN D50-001 [1].

Living room	1l/s per m² floor surface (3,6m³/hm²) with a minimum of 21l/s (75m³/h). It is not necessary to supply more than 42l/s (150m³/h).
Bedroom Study room Playroom	1l/s per m² floor surface (3,6m³/hm²) with a minimum of 7l/s (25 m³/h). It is not necessary to supply more than 10l/s (72m³/h).
Kitchen* Bathroom Laundry room Or similar 'wet spaces'	1l/s per m² floor surface (3,6m³/hm²) with a minimum of 14l/s (50 m³/h). It is not necessary to supply more than 21l/s (75m³/h).
Toilet	7 l/s (25m³/h)
Hallways, Stairs Or similar connecting spaces	1l/s per m² floor surface (3,6m³/hm²)
* For kitchens that cannot be closed off from connecting rooms, the minimal ventilation rate is 21l/s (75m³/h)	

For the openings between spaces a pressure difference of 2 Pa is assumed. Table 5 is the translated table found in the NBN D50-001 for connecting openings between spaces [1].

Table 5 Nominal air flow through connecting openings according to NBN D50-001 [1].

Living room	7 l/s (25 m³/h)	An opening between these rooms has to be at least 0.007 m² (70cm²). Bigger openings are recommended.
Bedroom Study room Playroom		
Bathroom Laundry room Or similar 'wet spaces'		
Toilet		
Kitchen	14 l/s (50 m³/h)	The sum of all openings has to be at least 0.014m² (140m²) between the kitchen and neighbouring rooms.

The nominal airflows for the reference building are defined according to NBND50-001 and are illustrated on the floor plan, Figure 1.

4 Conclusion

The legislation covering pollution to the indoor environment regarding VOCs in Belgium is quite limited. A reference house is defined for the single purpose of assessing DCV systems for IAQ (comfort) and Energy. Adding data about typical VOC emissions to the indoor environment in this method is ongoing work and will lead to a more comprehensive way to assess DCV systems (including the health effect related to VOCs).

Concerning the Royal decree for Emissions from Building products, efforts should be made to expand the legislation to include at least walls and ceilings.

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Appendix G: Case study – Estonia

Definition of a Reference Residential Building Prototype for Evaluating IAQ and Energy Efficiency Strategies – Estonia

Participant: Ülar Palmiste, Areenika Lumilaan, Tallinn University of Technology, Estonia

Content :

1 Introduction

This report presents the description of a reference house for Estonia. The second part is dedicated to the evaluation of formaldehyde and toluene concentration levels.

2 Definition of the reference house

2.1 Description

The reference house is a typical example of a medium-sized residential house in Estonia. The reference house is depicted in Figure 1 and the building characteristics are summarized in Table 1.

Figure 1. 3D view of the Estonian reference house

Table 1. Basic information of Estonian reference building

Characteristic	Unit	Value
Num of Floors (Above Grade)	unit	2
Building Aspect Ratio (Width/Depth)	ratio	1.24
Conditioned Floor Area	m^2	128.7
Total Floor Area	m^2	151.6
Ceiling Height	m	2.6
Volume	m^3	374.7
Window area	m^2	23.3 (18%)
ACH	1/h	0.52
Airflow rate	m^3/h per heated m^2	1.5
Num of Bedrooms	unit	3
Num of Bathrooms	unit	2
Num of Other Rooms	unit	4
Num of Occupancy	1 person	4

The size of the building (area) and the number of rooms were determined based on the results of the last 2011 Population and Housing Census. The reference house has a 128,7 m^2 floor area of heated rooms with a total volume of 374,7 m^3. It includes 4 living spaces (3 bedrooms, 1 living room, and 1 home office), 1 kitchen, 2 bathrooms, 1 WC, 1 sauna and 1 entrance with a wardrobe. The location of the house is Estonia that according to Köppen-Geiger climate classification can be classified as Dfb (humid continental climate with strong seasonality – severe winters, warm summers, no dry season) and by ASHRAE climate zone definitions, the Estonian climate is type 6A (cold-humid with annual heating degree days between 4000 and 5000 at base 18°C). Figure 2 and Figure 3 present the floor plans and views of the reference house.

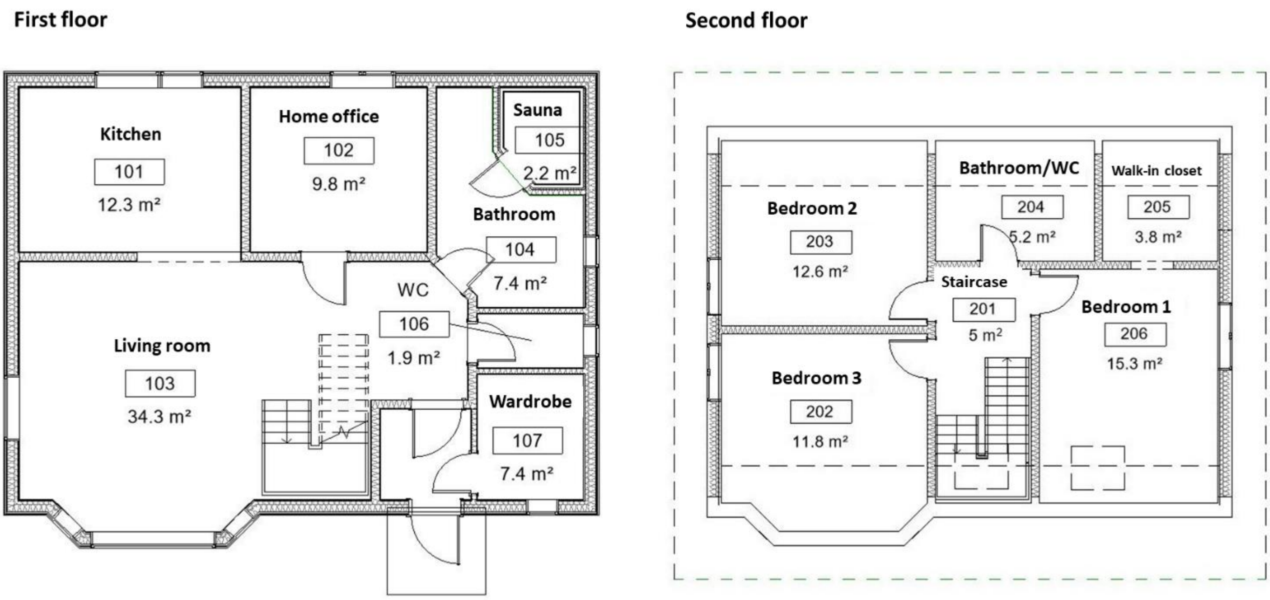

Figure 2: Floor plans of the Estonian reference house.

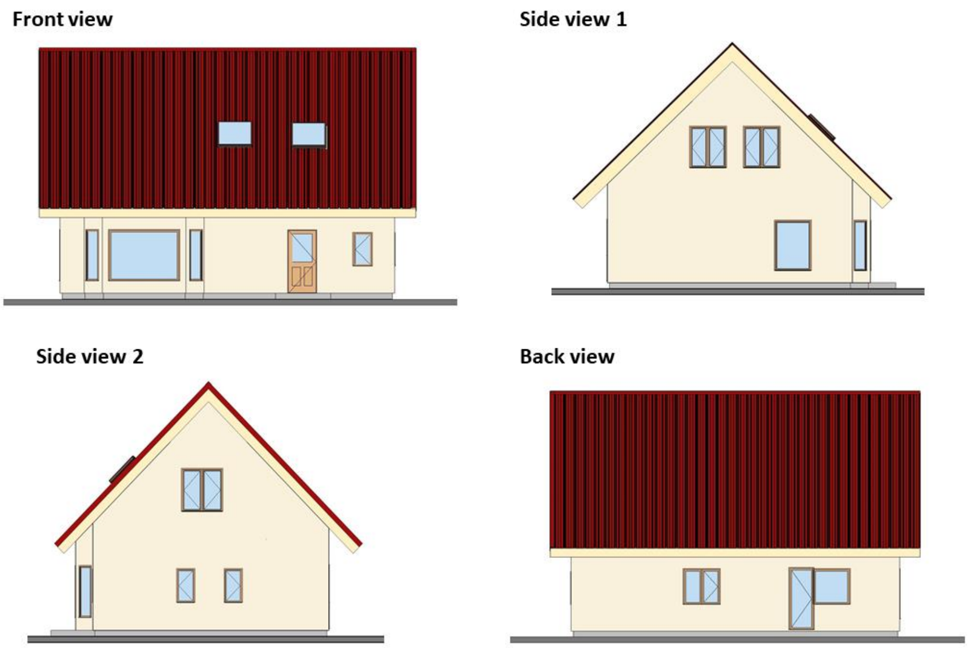

Figure 3: Views of the Estonian reference house.

2.2 Building assemblies

The reference building is a two-story timber frame prefabricated-element house with a gable roof. Figure 4 presents the cross-section view of the building assemblies.

External walls are insulated wooden frame walls covered with wooden boarding on the outside and gypsum board on the inside. Interior walls are also wooden frame walls covered with gypsum board. Mineral wool is used both as thermal insulation in the building envelope and sound insulation in the interior structures. Thermal conductivities of boundary structures are as follows: external walls U=0.16 W/(m^2·K), roof U=0.15 W/(m^2·K) and subfloor U=0.14 W/(m^2·K). The detailed summary of the thermal properties of the materials used in the building assemblies is given in Figure 5: Composition of the reference house envelope.Figure 5 and Table 2.

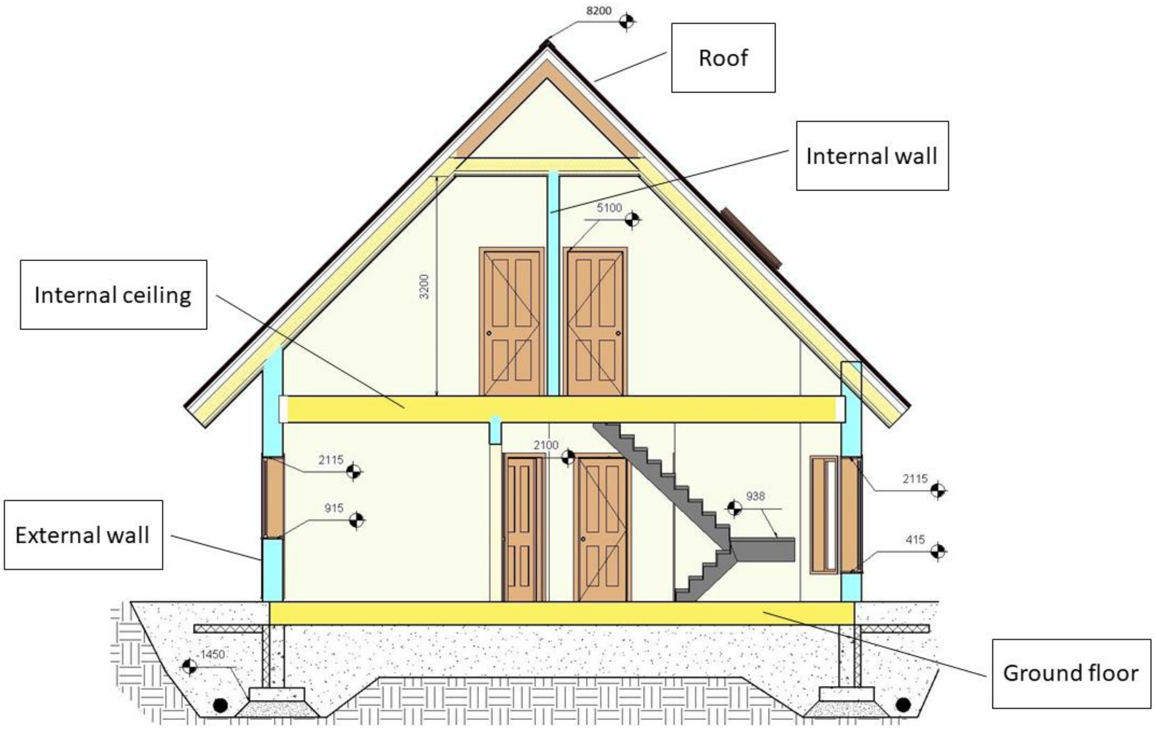

Figure 4. Cross-section view of the Estonian reference house

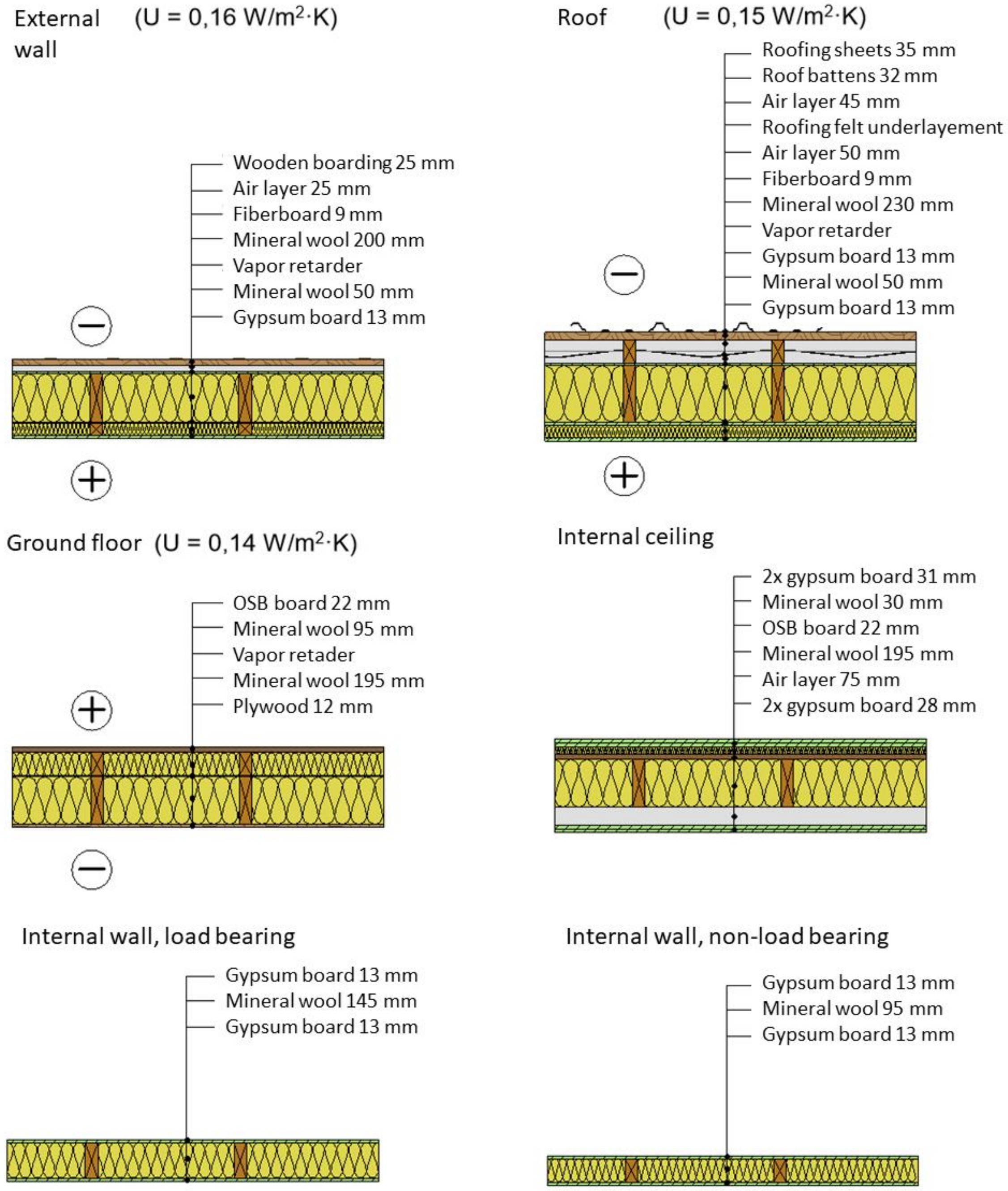

Figure 5: Composition of the reference house envelope.

Table 2: Building assemblies and material thermal properties.

Assembly	Materials (exterior to interior)	Area m^2	Thickness m	Conductivity W/(m·K)	Specific Heat J/(Kg·K)	Resistance $(m^2 \cdot K)/W$
	Building Envelope					
Gable roof (simplified for modeling purpose)	Roofing sheets	94	0.035	30	460	0.001
	Air layer		0.045	0.025	1000	1.80
	Roofing felt underlayment		0.001	0.2	1920	0.01
	Air layer		0.05	0.025	1000	2.00
	Fiberboard		0.009	0.25	900	0.04
	Mineral wool		0.23	0.036	1030	6.39
	Vapor retarder		0.0002	0.33	2200	0.001
	Gypsum board		0.013	0.25	1090	0.05
	Mineral wool		0.05	0.036	1030	1.39
	Gypsum board		0.013	0.25	1090	0.05
External Wall	Wooden boarding	118	0.025	0.13	1600	0.19
	Air layer		0.025	0.025	1000	1.00
	Fiberboard		0.009	0.032	900	0.28
	Mineral wool		0.2	0.036	1030	5.56
	Vapor retarder		0.0002	0.33	2200	0.001
	Mineral wool		0.05	0.036	1030	1.39
	Gypsum board		0.013	0.25	1090	0.05
Exterior door	Wooden door	2	0.12	0.13	1600	0.92
Ground floor	Plywood	75,8	0.012	0.1	1210	0.12
	Mineral wool		0.195	0.036	1030	5.42
	Vapor retarder		0.0002	0.33	2200	0.001
	Mineral wool		0.095	0.036	1030	2.64
	OSB board		0.022	0.13	1700	0.17
Internal wall, load bearing	Gypsum board	197	0.013	0.25	1090	0.05
	Mineral wool		0.145	0.036	1030	4.03
	Gypsum board		0.013	0.25	1090	0.05
Internal wall, non-load bearing	Gypsum board	33	0.013	0.25	1090	0.05
	Mineral wool		0.095	0.036	1030	2.64
	Gypsum board		0.013	0.25	1090	0.05
Interior door	MDF board	31,2	0.04	0.15	1600	0.27
Name	Total Solar transmission (SHGC)	Area, m^2		Light transmission		U value
Vertical glazing	0.55	23,3		0.72		1.0

Most rooms have laminate parquet flooring and paint coating on interior walls and ceilings. In damp rooms, there are ceramic tiles on walls and floors. In the sauna, the walls and ceiling are covered with boards. The building has three-layered PVC windows, medium density fiber (MDF) panel interior doors, and wooden exterior door. Finishing materials are summarized in Table 3.

Table 3. Interior finishing materials

Assembly	**Material**	**Surface area, m^2**
Ceiling	Ceiling paint	161.6
	Wooden boarding	2.2
Floors	Laminate parquet	106.9
	Ceramic floor tile	39.5
Interior walls	Ceramic wall tile	62.9
	Wall paint	273.8
	Wooden boarding	13.3
Interior doors	MDF-board, painted	31.2

Glazing	Glass/PVC	23.3
Front door	Wood	2.0

2.3 Building mechanical systems

The building mechanical systems are summarized in Table 4.

The building has a central heating system with a wood-pellet boiler. The heating equipment is hydronic radiators on both floors and electric floor heating in wet rooms.

The ventilation system is mechanical supply-exhaust ventilation with heat recovery. It has an efficiency of η = 0.8 for the heat exchanger and specific fan power of *SFP*=1.8 kW/(m^3/s). Air is supplied to the bedrooms, living room and home office. Air is extracted from the kitchen, bathrooms and WC. The kitchen cooker hood is a local extraction unit that is not integrated into central mechanical ventilation and forms a separate system in which the extracted air is exhausted straight to outdoors.

Domestic hot water (DHW) is also provided by the wood-pellet boiler. DHW is stored in a hot water tank.

Table 4. Building mechanical systems

Parameter	**Unit**	**Value**
Heating		
Heating equipment type	-	Hydronic radiator
Heating fuel type	-	Wood pellets
Heating system efficiency	-	1.0
Heating setpoint	°C	21
Ventilation		
System type	-	Balanced supply-exhaust
Mechanical airflow rate	l/(s·m^2)	0.42
Infiltration	l/(s·m^2)	0.0185
Total airflow rate	l/(s·m^2)	0.4385

3 Energy performance

3.1 Energy modeling

The energy modeling is conducted according to Estonian governmental regulation No 58 «Hoone energiatõhususe arvutamise metoodika» (*The methodology for calculating the energy performance of buildings*) (Majandus- ja taristuministri määrus nr. 58, 2019). Dynamic energy simulation is conducted using simulation software IDA ICE 4.8. The energy consumption of DHW and equipment is estimated by a hand calculation conducted according to the above-referred methodology.

Thermal transmittance values (U-values):

- external wall 0.16 W/(m^2·K)
- flat roof 0.15 W/(m^2·K)
- ground floor 0.14 W/(m^2·K)
- glazing, external door 1.0 W/(m^2·K)

Thermal bridges :

- external wall – internal wall 0.1 W/(m·K)
- external wall – internal slab 0.1 W/(m·K)
- external wall – external wall 0.2 W/(m·K)

- external walls, inner corner -0.1 W/(m·K)
- external windows perimeter 0.1 W/(m·K)
- roof – external walls 0.2 W/(m·K)
- external walls – ground floor 0.3 W/(m·K)

Infiltration

- q_{50} 1.6 $m^3/(h \cdot m^2)$

Ventilation

- volume air flow rate 0.42 $l/(s \cdot m^2)$ (per heated area)

Internal heat gains

- lighting 8 W/m^2
- equipment 2.4 W/m^2
- occupants 2 W/m^2 (42.5 m^2/person)

Time schedules

- lighting 0.15 [6-10, 22-24], 0.05 [10-16], 0.2 [16-22], 0.0 [0-6]
- equipment 0.7 [7-9, 17-19], 0.6 [11-15, 22-24], 0.8 [19-22], 0.5 [9-11, 15-17, 0-7]
- occupants 0.5 [6-9, 16-19], 0.1 [9-13], 0.2 [13-16], 0.8 [19-22], 1.0 [22-6]

3.2 Minimum requirements for energy performance in Estonia

Minimum requirements for energy performance in Estonia state that the primary energy of a newly built residential house with heated area over 100 m^2 may not be over 160 $kWh/(m^2 \cdot year)$. New requirements that will come into force from January 1st, 2020 will set higher requirement of 100 $kWh/(m^2 \cdot year)$ for a house with heated area between 120-220 m^2.

3.3 Energy consumption

Energy consumption analysis was conducted with commercial building simulation software IDA Indoor Climate and Energy (IDA ICE) using the input data from the previous sections. Table 5 presents the energy consumption summary for the reference building with mechanical supply-exhaust ventilation with heat recovery.

Table 5: Reference building energy consumption

Consumer	kWh/year	$kWh/m^2 \cdot year$	MJ/year	$MJ/m^2 \cdot year$
Room heating	8890	58.6	32004	210.96
Ventilation air heating	562	3.7	2023.2	13.32
Cooling	0	0	0	0
DHW	3218	25	11584.8	90
Lighting	1063	7	3826.8	25.2
Pumps	129	1	464.4	3.6

Fans	970	6.4	3492	23.04
Total	14832	101.7	53395.2	366.12
+Interior Equipment	2713	17.9	9766.8	64.44
Total	32377	221.3	116557.2	796.7

Figure 6 provides an overview of building energy end uses proportions.

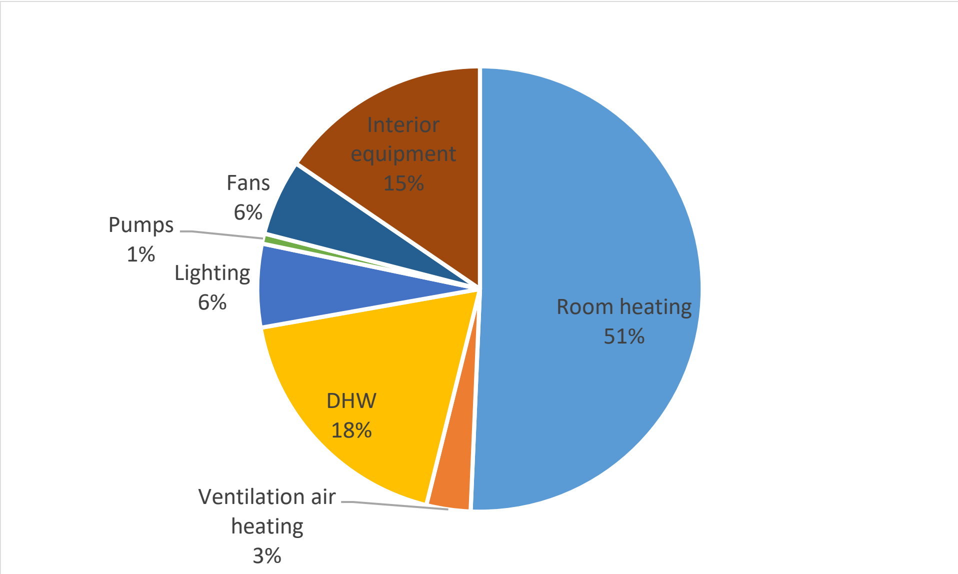

Figure 6: Reference building energy consumption by end-use

4 Indoor Air Quality

Building material emission rates and indoor air pollutant concentration levels in the Estonian reference house are evaluated using the local indoor air quality requirements and material emission factors extracted from the IA-QUEST database.

4.1 Estonian requirements for indoor air quality

The requirements for indoor air quality in residential buildings are summarized in the Estonian government working draft «Requirements for indoor environmental quality in buildings» that is expected to enter into force in 2020. In addition to requirements for IAQ, the regulation will also specify the design values for other indoor environmental quality parameters that must be followed in the building design and construction. The limit and comfort values for indoor air pollutant concentrations are summarized in Table 6.

Table 6. Concentration values for different indoor air pollutants

No	Pollutant	Limit value for indoor air, [µg/m^3]	Comfort value, [µg/m^3]
1	Carbon monoxide (CO)	7000	2000
2	Nitrogen dioxide (NO_2)	200 (1-hour average)	-

		40 (year-average)	
3	Formaldehyde (CH_2O)	100 (30-minute average)	30
		50 (year-average)	
4	Naphthalene ($C_{10}H_8$)	10	-
5	Ammonia (NH_3)	50	20
6	Styrene (C_8H_8)	40	30
7	Limonene ($C_{10}H_{16}$)	10000	1000
8	Perchloroethylene (C_2Cl_4)	250 (year-average)	-
9	Benzene (C_6H_6)	5	-
10	2-Ethylhexanol (2EH, $C_8H_{18}O$), (toluene-based)	100	10
11	2,2,4-Trimethyl-1,3-pentanediol diisobutyrate (TXIB, $C_{16}H_{30}O_4$)	-	10
12	TVOC (toluene-based calibration)[1]	400	200
13	PM10	50 (24-hour average)	-
14	PM2.5	25 (24-hour average)	-

1 - The concentration of each individual VOC that is not listed above may not be above 50 μg/m^3.

4.2 Indoor concentration modeling

Indoor air pollutant concentrations are modeled using a steady-state single-zone mass balance model which assumes constant VOC emission and building ventilation rates, zero outdoor concentrations, perfect indoor mixing, and no net losses from the air due to effects such as filtration, sorption on surfaces or chemical reactions.

Emission factor EF_A is an area-specific emission rate that shows the mass of pollutants emitted from a specific unit area of product surface per unit time. Maximum allowable emission factor $EF_{Ai,\,max}$ is calculated by the following equation:

$$EF_{Ai,\,max} = q_A \cdot C_{i,\,max} \cdot 0.5 \qquad [1]$$

where $EF_{Ai,\,max}$ is the maximum allowable emission factor [μg/(m^2·h)], q_A is area-specific air flow rate (m/h), and $C_{i,\,max}$ is limit concentration of pollutant i (μg/m^3). Each individual product category is capped at no more than 50% of the concentration limit value for each pollutant.

Area-specific air flow rate q_A is calculated by the following equation:

$$q_A = L_h / A_m \qquad [2]$$

where A_m is the area of emission surface i (m^2) and L_h is the ventilation air exchange rate (m^3/h).

Emission rate ER is calculated by the following equation:

$$ER_i = EF_{Ai} \cdot A_m \quad [3]$$

where ER is emission rate of material i (μg/h), EF_{Ai} is the emission factor of emission surface i [μg/(m³·h)], A_m is the area of emission surface i (m²).

Indoor air concentration $C_{i,\,in}$ is calculated by the following equation:

$$C_{i,\,in} = EF_{Ai} \cdot A_m / L_h = EF_{Ai} / q_A \quad [4]$$

where $C_{i,\,in}$ is the concentration of pollutant i in indoor air (μg/m³), EF_{Ai} is the emission factor of emission surface i [μg/(m³·h)], A_m is the area of emission surface i (m²), L_h is the ventilation air exchange rate (m³/h), and q_A is area-specific air flow rate (m/h).

The building emission surfaces are separated into building product categories for which the area-specific airflow rates, emission factors and emission rates can be specified or calculated. An approach by Chen et al. (Chen et al., 2014) is followed and the definitions for different product categories are provided in Table 7.

Table 7. Definitions for product category emission surfaces

Product category	Definition
Flooring	Sum of all floor area including finished basement
Ceiling	Sum of ceiling area
Walls and wall coverings	Sum of the surface area of all walls without the surface area of all openings, doors and estimated window area
Interior wallboard paint	Sum of ceiling and wall area
Thermal insulation - ceiling	Ceiling area of top floor only
Thermal insulation - wall	Sum of the exterior wall surface area without the surface area of all openings, doors and estimated window area
Thermal insulation – ground floor	Floor area of ground floor
Acoustic insulation - ceiling	Surface area of internal ceiling multiplied by two (emission in both vertical directions assumed)
Acoustic insulation – interior walls	Sum of the surface area of all walls minus that of exterior walls (application on all interior partition walls assumed)
Exterior doors	Surface area of exterior doors, including only surface exposed to the interior
Interior doors	Surface area of interior doors, including both surfaces
Windows (glazing)	Sum of window area

4.3 Maximum allowable emission factors

The maximum allowable constant emission factors are calculated using equation 1 and pollutant concentration limit values listed in Table 6.

Table 8. Maximum constant emission factors for general product types based on Estonian IEQ regulation

Product type	**Emission surface area A_m, m²**	**Area specific air flow rate q_a, m/h**	**Maximum constant emission factors $EF_{Ai,\,max}$, μg/(m²·h)**								
			Toluene	Formaldehyde	Acetaldehyde	alpha-pinene	Benzene	Naphtalene	Styrene	Trichloroethylene	TVOC
Flooring	151.6	1.51	37.81	37.81	37.81	37.81	3.78	7.56	30.25	37.81	302.51
Ceiling	163.8	1.40	35.00	35.00	35.00	35.00	3.50	7.00	28.00	35.00	279.98
Walls and wallcoverings[1]	350	0.66	16.38	16.38	16.38	16.38	1.64	3.28	13.10	16.38	131.03

Interior wallboard paint	513.8	0.45	11.16	11.16	11.16	11.16	1.12	2.23	8.93	11.16	89.26
Thermal insulation	118.3	1.94	48.46	48.46	48.46	48.46	4.85	9.69	38.77	48.46	387.66
Acoustic insulation	381.6	0.60	15.02	15.02	15.02	15.02	1.50	3.00	12.02	15.02	120.18
Windows	23.3	9.84	246.03	246.03	246.03	246.03	24.60	49.21	196.82	246.03	1968.24
Exterior doors	2	114.65	2866.3	2866.3	2866.3	2866.3	286.63	573.3	2293.0	2866.3	22930
Interior doors	31.2	7.35	183.73	183.73	183.73	183.73	18.37	36.75	146.99	183.73	1469.87
Closet doors	nd[2]	nd	-	-	-	-	-	-	-	-	-
Kitchen cabinets	nd	nd	-	-	-	-	-	-	-	-	-
Other cabinets	nd	nd	-	-	-	-	-	-	-	-	-
Limit concentration, µg/m³			50	50	50	10	5	10	40	50	400

1. Walls and wall coverings category does not include paint, which is considered separately
2. nd – not defined in the reference building

Table 9. Maximum constant emission factors for individual product types based on Estonian IEQ regulation

Product type	**Emission surface area A_m, m²**	**Area-specific air flow rate q_a, m/h**	**Maximum constant emission factors $EF_{Ai,\ max}$, µg/(m²·h)**								
			Toluene	Formaldehyde	Acetaldehyde	alpha-pinene	Benzene	Naphtalene	Styrene	Trichloroethylene	TVOC
Flooring											
Laminate parquet	106.9	2.14	53.63	53.62	53.62	53.62	5.36	10.72	42.90	53.62	429.00
Tiles	39.5	5.81	145.13	145.13	145.13	145.13	14.51	29.03	116.10	145.13	1161.01
OSB board	75.8	3.03	75.63	75.63	75.63	75.63	7.56	15.13	60.50	75.63	605.01
Ceiling											
Paint	161.6	1.42	35.47	35.47	35.47	35.47	3.55	7.09	28.38	35.47	283.79
Wooden boarding	2.2	104.23	2605.68	2605.68	2605.68	2605.68	260.57	521.14	2084.55	2605.68	20845.45
Gypsum board	94	2.44	60.98	60.98	60.98	60.98	6.10	12.20	48.79	60.98	487.87
Walls and wallcoverings											
Paint	273.8	0.84	20.94	20.94	20.94	20.94	2.09	4.19	16.75	20.94	167.49
Tiles	62.9	3.65	91.14	91.14	91.14	91.14	9.11	18.23	72.91	91.14	729.09
Wooden boarding	13.3	17.24	431.02	431.02	431.02	431.02	43.10	86.20	344.81	431.02	3448.12
Gypsum board	350	0.66	16.38	16.38	16.38	16.38	1.64	3.28	13.10	16.38	131.03
Thermal insulation											
Ceiling	94	2.44	60.98	60.98	60.98	60.98	6.10	12.20	48.79	60.98	487.87
External walls	118	1.94	48.58	48.58	48.58	48.58	4.86	9.72	38.86	48.58	388.64
Ground floor	75.8	3.03	75.63	75.63	75.63	75.63	7.56	15.13	60.50	75.63	605.01
Acoustic insulation											
Ceiling	75.8	3.03	75.63	75.63	75.63	75.63	7.56	15.13	60.50	75.63	605.01
Interior walls	230	1.00	24.92	24.92	24.92	24.92	2.49	4.98	19.94	24.92	199.39
Windows	23.3	9.84	246.03	246.03	246.03	246.03	24.60	49.21	196.82	246.03	1968.24
Interior doors	31.2	7.35	183.73	183.73	183.73	183.73	18.37	36.75	146.99	183.73	1469.87
Exterior doors	2	114.65	2866.25	2866.25	2866.25	2866.25	286.63	573.25	2293.00	2866.3	22930.0
Closet doors	nd[1]	nd	-	-	-	-	-	-	-	-	-
Kitchen cabinets	nd	nd	-	-	-	-	-	-	-	-	-
Other cabinets	nd	nd	-	-	-	-	-	-	-	-	-
Limit concentration, µg/m³			50	50	50	10	5	10	40	50	400

1. nd – not defined in the reference house

4.4 IA-Quest database

IA-Quest (Indoor Air Quality Emission Simulation Tool) is an open access indoor air quality prediction software developed by The National Research Council Canada (NRC). IA-Quest provides a database of materials and their measured emissions and predicts the emission of volatile organic compounds from building materials and furnishings. The experimental conditions for emission factor determination were the following: temperature 23°C, relative humidity 50%.

Emission factors for thermal and acoustic insulation and structural wallboard are only considered for worst-case scenarios in which air leakage from internal materials is assumed.

Table 10 presents the experimental emission factors for indoor contaminants listed in Salis et al. (Cony Renaud Salis, Abadie, Wargocki, & Rode, 2017). The nominal emission factor stands for emission factor measured 24 hours after a material specimen was placed in the test chamber, and emission factor at 96th hour is predicted based on the emission model, for which the measured emission factors were used. Ceramic tiles and glazing are not on the list because they are not emission sources. Emission factors for thermal and acoustic insulation and structural wallboard are only considered for worst-case scenarios in which air leakage from internal materials is assumed.

Table 10. Building material emission factors (EF) from IA-Quest database

Material	Pollutant	Measured EF at 24 h, µg/(m²·h)	Modeled EF at 96 h, µg/(m²·h)
Softwood (wooden boarding in ceiling and walls in the sauna ; exterior door)	α-pinene	2323	1499
	Benzene	1.290	0.574
	Toluene	3.450	1.463
	TVOC	4526	2608.6
Water-based latex paint (ceilings and interior walls)	Benzene	26.73	3.67
	TVOC	55287	15189.3
Laminate parquet / foam underlayment / OSB board (flooring)	Acetaldehyde	4.794	4.667
	α-pinene	7.941	1.606
	Benzene	1.676	0.178
	Formaldehyde	1.318	1.295
	Styrene	0.0567	0.00986
	Toluene	1.055	0.211
	TVOC	491.54	228.6
Mineral wool[1] (thermal and acoustic insulation)	Toluene	0.13	-
	Formaldehyde	1.1	0.35
	Acetaldehyde	0.019	0.074
	TVOC	4.3	0.57
Gypsum board (wallboard)	Toluene	0.1795	0.519
	α-pinene	57.77	42.77
	Benzene	0.298	0.259
	Trichloroethylene	0.598	0.345
	TVOC	96.78	53.24
MDF-board (interior doors)	Acetaldehyde	89.920	42.884
	α-pinene	0.097	0.079
	Benzene	1.110	0.569
	Formaldehyde	441.59	605.87
	Toluene	2.104	0.828
	TVOC	165.90	160.7

1 – emission factor data for mineral wool (fiberglass) are from (Alevantis, 2003)

4.5 Pollutant emission rates

Emission rates calculated based on maximum emission factors and modeled emission factors at 96th hour are presented in Table 11 and Table 12, respectively. For calculating resulting indoor air concentration two simple scenarios can be considered: (1) worst-case scenario with insulation materials exposed to indoor air, (2) insulation layers perfectly sealed.

Table 11. Emission rates based on the maximum emission factors for the general product types in Estonian reference house

Product type	**Emission surface area, m²**	**Area-specific air flow rate qa, m/h**	**Emission rate, µg/h**							
			Toluene	Formaldehyde	α-pinene	Benzene	Styrene	Acetaldehyde	Trichloroethylene	TVOC
Flooring	151.6	1.51	5733	5733	5733	573	4586	5733	5733	45860
Ceiling	163.8	1.40	5733	5733	5733	573	4586	5733	5733	45860
Walls and wallcoverings	350	0.66	5733	5733	5733	573	4586	5733	5733	45860
Interior wallboard paint	513.8	0.45	5733	5733	5733	573	4586	5733	5733	45860
Thermal insulation	118.3	1.94	5733	5733	5733	573	4586	5733	5733	45860
Acoustic insulation	381.6	0.60	5733	5733	5733	573	4586	5733	5733	45860
Windows	23.3	9.84	5733	5733	5733	573	4586	5733	5733	45860
Exterior doors	2	114.65	5733	5733	5733	573	4586	5733	5733	45860
Interior doors	31.2	7.35	5733	5733	5733	573	4586	5733	5733	45860

Table 12. Emission rates based on the IA-QUEST material emission factors for the general product types in Estonian reference house

Product type	**Emission surface area, m²**	**Area-specific air flow rate qa, m/h**	**Emission rate, µg/h**							
			Toluene	Formaldehyde	α-pinene	Benzene	Styrene	Acetaldehyde	Trichloroethylene	TVOC
Flooring	151.6	1.51	22.56	138.44	171.68	19.04	1.05	498.90	-	24437
Ceiling	163.8	1.40	52.00	-	7318.18	25.61	-	-	32.43	10743
Walls and wallcoverings	350	0.66	201.11	-	34906.20	98.28	-	-	120.75	53328
Interior wallboard paint	513.8	0.45	-	-	-	1597.92	-	-	-	6613421
Thermal insulation[1]	118.3	1.94	-	100.73	-	-	-	21.30	-	164.05
Acoustic insulation[1]	381.6	0.60	-	107.03	-	-	-	22.63	-	174.31
Windows	23.3	9.84	-	-	-	-	-	-	-	
Exterior doors	2	114.65	25.83	18903.14	2.46	17.75	-	1337.98	-	5013.84
Interior doors	31.2	7.35	2.93	-	2998.00	1.15	-	-		5217.20

1 - Emission factor data for mineral wool (fiberglass) are from (Alevantis, 2003)

Table 13. Emission rates based on the IA-QUEST material emission factors for the individual product types in Estonian reference house

Product type	Emission surface area, m^2	Area-specific airflow rate qa, m/h	Emission rate, µg/h							
			Toluene	Formaldehyde	α-pinene	Benzene	Styrene	Acetaldehyde	Trichloroethylene	TVOC
Flooring										
Laminate parquet / underlayment /OSB-board	106.9	2.14	22.56	138.44	171.68	19.04	1.05	498.90	-	24437.34
Tiles	39.5	5.81	-	-	-	-	-	-	-	-
Ceiling										
Paint	161.6	1.42	-	-	-	593.07	-	-	-	2454591
Wooden boarding	2.2	104.23	3.22	-	3297.80	1.26	-	-	-	5738.92
Gypsum board	94	2.44	48.79	-	4020.38	24.35	-	-	32.43	5004.56
Walls and wallcoverings										
Paint	273.8	0.84	-	-	-	1004.85	-	-	-	4158830
Tiles	62.9	3.65	-	-	-	-	-	-	-	
Wooden boarding	13.3	17.24	19.46	-	19936.70	7.63	-	-	-	34694.38
Gypsum board	350	0.66	181.65	-	14969.50	90.65	-	-	120.75	18634.00
Thermal insulation										
Ceiling	94	2.44	-	32.90	-	-	-	6.96	-	53.58
External walls	118	1.94	-	41.30	-	-	-	8.73	-	67.26
Ground floor	75.8	3.03	-	26.53	-	-	-	5.61	-	43.21
Acoustic insulation										
Ceiling	75.8	3.03	-	26.53	-	-	-	5.61	-	43.21
Interior walls	230	1.00	-	80.50	-	-	-	17.02	-	131.10
Windows	23.3	9.84	-	-	-	-	-	-	-	-
Interior doors	31.2	7.35	25.83	18903.14	2.46	17.75	-	1337.98	-	5013.84
Exterior doors	2	114.65	2.93	-	2998.00	1.15	-	-	-	5217.20

1 - Emission factor data for mineral wool (fiberglass) are from (Alevantis, 2003)

4.6 Indoor concentrations

IA-QUEST, version 1.1 (Indoor Air Quality Emission Simulation Tool) software was used for time-dependent dynamic simulation of pollutant concentrations in the Estonian reference house. The resulting concentrations are depicted on a logarithmic scale in Figure 7.

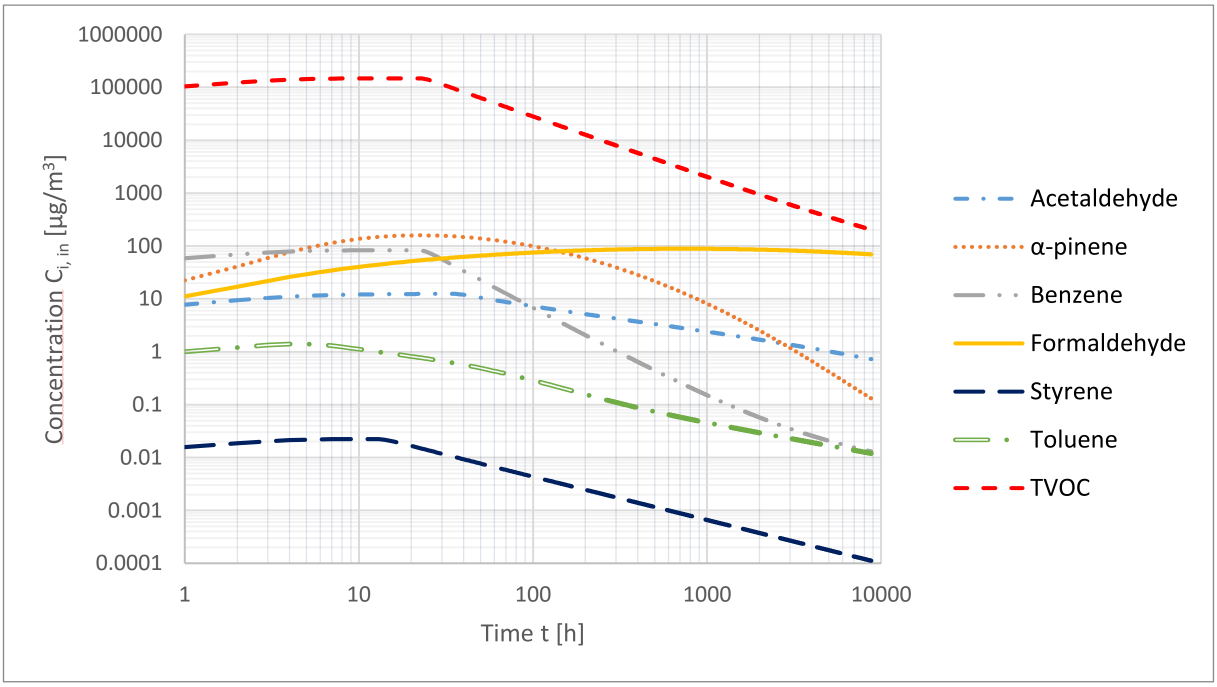

Figure 7: Indoor concentration of pollutants in the Estonian reference house

presents the estimated steady-state VOC concentrations associated with emissions from general building product types with perfectly sealed insulation layers and wallboard. Table 15 presents the worst-case indoor concentrations with insulation layers and wallboard exposed. It is important to consider that the total indoor concentration includes only emissions from building materials and not from other indoor sources like furniture, thus reference building definition can be updated in the future to also include the other sources.

Table 14. Estimated indoor concentrations from the emission of the general product types with insulation and wallboard sealed from the air

Product type	Concentration rate, µg/m³							
	Toluene	Formalde-hyde	α-pinene	Benzene	Styrene	Acetalde-hyde	Trichloro-ethylene	TVOC
Flooring	0.10	0.60	0.75	0.08	0.005	2.18	-	106.6
Ceiling	0.01	-	14.38	0.01	-	-	-	25
Walls and wallcoverings	0.08	-	86.95	0.03	-	-	-	151
Interior wallboard paint	-	-	-	6.97	-	-	-	28842
Windows	-	-	-	-	-	-	-	-
Exterior doors	0.11	82.44	0.01	0.08	-	5.84	-	21.9
Interior doors	0.01	-	13.07	0.01	-	-	-	22.8
Total indoor concentraion	**0.32**	**83.04**	**115.16**	**7.17**	**0.005**	**8.01**	**-**	**29169**
Estonian limit concentration	**50**	**50**	**50**	**5**	**40**	**50**	**50**	**400**

Table 15. Estimated indoor concentrations from the emission of the general product types with insulation and wallboard exposed into air

Product type	Concentration rate, µg/m³							
	Toluene	Formalde-hyde	α-pinene	Benzene	Styrene	Acetalde-hyde	Trichloro-ethylene	TVOC
Flooring	0.10	0.60	0.75	0.08	0.005	2.18	-	106.57
Ceiling	0.23	-	31.92	0.11	-	-	0.14	47
Walls and wallcoverings	0.88	-	152.23	0.43	-	-	0.53	233
Interior wallboard paint	-	-	-	6.97	-	-	-	28842
Thermal insulation	-	0.44	-	-	-	0.09	-	0.72
Acoustic insulation	-	0.47	-	-	-	0.10	-	0.76
Windows	-	-	-	-	-		-	-
Exterior doors	0.11	82.44	0.01	0.08	-	5.84	-	21.87
Interior doors	0.01	-	13.07	0.01	-		-	22.75
Total indoor concentration	**1.33**	**83.95**	**197.98**	**7.67**	**0.005**	**8.20**	**0.67**	**29274**
Estonian limit concentration	**50**	**50**	**50**	**5**	**40**	**50**	**50**	**400**

5 Conclusion

In this common exercise, a reference house for IAQ analysis for Estonia was defined. The reference house specification includes the geometry, building assemblies and materials, and building mechanical systems.

Emission of pollutants released to the indoor air from building materials was estimated using maximum allowable emission factors based on Estonian IEQ regulation and emission factors from the IA-QUEST database.

Steady-state estimation of pollutant emission rates and resulting indoor concentrations that are based on emission factors from short-term laboratory tests will likely overpredict indoor concentrations because the emissions are still in the unsteady state and therefore this method is a conservative approach to represent the long-term emissions in the IAQ modeling with constant emission factor.

6 References

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