Volatile Organic Compound Concentrations and Estimation of Optimal Source Strengths to Achieve a High Level of Acceptance Indoors using Multi- Zone Simulation

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SUMMARY
This study investigated the possibility of identifying chemical pollutant profiles and concentration levels that result in a high level of acceptance indoors. In addition, a multi-zone simulation tool, CONTAM, developed by the National Institute of Standards and Technology (NIST) (US), was used to estimate optimal source strengths for the pollutants of interest in a typical Finnish single family house. VTT indoor air and material emission databases were used to identify and differentiate chemical pollutant profiles and concentration levels that are measured in complaint vs. non-complaint residential buildings. The results indicate that certain volatile organic compound (VOC) profiles result in a high level of acceptance indoors. The simulation performed for a typical Finnish single family house showed that to achieve optimal total volatile organic compound (TVOC), formaldehyde, and single VOC concentration levels of less than 300 µg/m^3, 30 µg/m^3, and 10 µg/m^3 , respectively, the specific emission rate (SER) should be less than 92 µg/m^{2}h, 10 µg/m^{2}h, and 4 µg/m^{2}h respectively.

IMPLICATIONS
The study gives guidance values for indoor air concentration levels and source strengths in realistic environments, which support the efforts by builders and material producers to improve indoor air quality (IAQ).

KEYWORDS

TVOC, VOC, formaldehyde, building simulation, multi-zone model

INTRODUCTION
Poor IAQ reduces well being and comfort in buildings. In recent decades, extensive research has been done to clarify the impact of pollutants on IAQ. World Health Organization (WHO) air quality guidelines exist for major ambient air pollutants such as nitrogen dioxide and ozone as well as for a few organic pollutants, including mainly chlorinated and aromatic hydrocarbons (WHO, 2010). The International Agency of Cancer Research recently upgraded formaldehyde to Group 1–known human carcinogen (IARC, 2004). However, there is still inadequate information about health effects of other VOCs. The total amount of VOCs, or TVOC, has not been proven to correlate with symptoms (Andersson et al., 1997; Molhave, 2003). In general, IAQ is determined by the interaction of: 1.) contaminants as well as heat and moisture sources, 2.) contaminant sinks, and 3.) ventilation in a space. Consequently, there are three targets when controlling the indoor air quality: contaminant-source, heat and moisture control, and ventilation. Currently, a fairly good picture exists of what pollutant levels can be achieved with today's building practice, including the use of low-emitting materials (Jarnstrom 2007). However, since there is still a general lack of information about

the health effects of VOCs, the source control approach, e.g. limiting emissions from building materials, is used to limit exposure to these compounds.

Simulation tools have been developed for the analysis of building performance and they have been increasingly used by researchers and professionals (Crawley et al., 2005). IAQ simulation tools can be used to calculate building air change rates, to analyze ventilation strategies as well as contaminant transport, as a design tool for IAQ and smoke transport (fire), and also for contaminant source isolation (Dols 2001). Multi-zone models have two primary uses; calculating airflows and calculating pollutant concentration (gases and aerosolized particles). The CONTAM model developed by NIST in the USA is a multi-zone type. The user must supply data on airflow paths, contaminant source emission rates, contaminant removal rates, chemical reaction coefficients, filter efficiencies and occupant schedules. Parameters for source emission rates, contaminant sink and deposition rates, as well as particle filter efficiencies, need to be supplied to the model to predict the exposure to indoor air pollutants from consumer products, cooking, and combustion.

According to Statistics Finland there were 1,406,000 buildings in Finland at the end of 2007. Residential buildings made up 86% of the total building stock and the majority of these (1,074,059) are single family houses (Statistics Finland, 2009). The structure of the single family homes built today is usually timber-framed (Pientalobarometri, 2007). Natural ventilation was the most common type of ventilation employed before 1960's. After this time, mechanical exhaust ventilation was introduced and the prevalence increased to 80% in buildings built between 1960 and 1969 and to 90% in buildings built between 1970 and 1979 (Sateri et al., 1999). Today, the energy efficiency requirements favor the use of a balanced mechanical supply and exhaust air system with heat recovery in new buildings.

There are no requirements on air leakage in the Finnish building code for indoor climate and ventilation (Ministry of the Environment, 2003). However, part *C3* of the Finnish building Code (Thermal insulation in a building, Ministry of the Environment, 2002) states that the structures spanning the envelope and between rooms should be sufficiently airtight to ensure proper functioning of the air handling system. Also, the building codes for indoor climate and ventilation give maximum permissible leakage air flow rates for ventilation systems and their parts per casing surface area (Ministry of the Environment, 2003). Typical air leakage numbers in Finnish buildings are shown in Table 1 (Ministry of the Environment, 2007).

Table 1 Typical air leakage numbers (n_{50}) in Finnish buildings (Ministry of the Environment, 2007).

Air tightness	**Description**	**Typical n_{50} values (h^{-1})**
Good	Special attention has been paid to ensure the air tightness of joints during planning, realization, and supervision.	Single family houses: 1-3 Residential and commercial buildings: 0.5-1.5
Moderate	Normal practice has been taken to ensure the air tightness of joints during planning, realization, and supervision.	Single family houses: 3-5 Residential and commercial buildings: 1.5-3
Poor	No special attention has been paid to ensure the air tightness of joints during planning, realization, and supervision.	Single family houses: 5-10 Residential and commercial buildings: 3-7

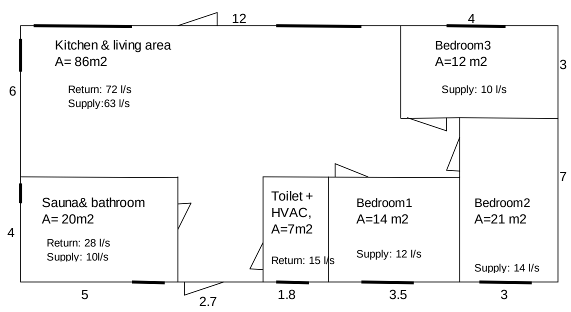
The objective of this work was to analyse existing data in the VTT indoor air and material emission databases on VOC profiles that achieve a high level of acceptance indoors. Based on the VTT database analysis, simulations within a typical Finnish single family house were performed in order to evaluate source strengths and exposures indoors using the CONTAM IAQ simulation tool.

METHODS

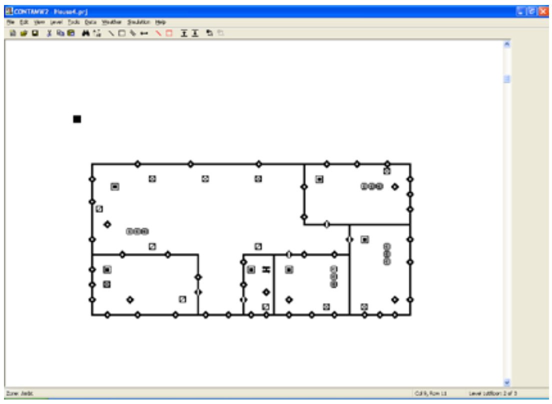
The dataset includes indoor air measurements collected from Finnish buildings between 1995 and 2004. These buildings were more than one year old at the time measurements were taken and no renovation work had been done prior to measurement. “Normal” sites were cases where no indoor air problem had been reported. 173 of these “normal” measurement sites were identified that included residential buildings (apartments, row houses, single family houses). “Problem” sites were cases where symptoms of poor health had occurred or bad odor was observed. 346 of these “problem” measurement sites were identified that included residential buildings. The average TVOC and formaldehyde concentration were calculated along with the maximum, minimum, and standard deviation. The detailed statistical analysis is presented in another publication (under preparation). The data has been collected with accredited methods, including uncertainty estimated up to ±30% for a 95% confidence interval.

Based on the VTT database analysis presented earlier, multi-zone simulations were performed using CONTAM to evaluate source strengths and exposures indoors of residential buildings. Calculated emission source strengths that achieve optimal concentrations levels are included in the data analysis section.

The simulations were performed for a typical Finnish one family house having 6 rooms, including a combined bathroom and sauna and a utility closet, as shown in Figure 1. The living area is 160 m^2, all on one level. A total air volume of 448 m^3 was used in the simulation (the room height was 2.8 m). The simulated house has mechanical ventilation with a supply and exhaust air system (slightly under pressurized). The air handling unit ran on a schedule (full airflow 7-9 a.m. and 5-7 p.m., other times half airflow). Typical air leakages were added at windows and doors, at ceiling/floor and external wall junctions, and in the floor so that the building pressurization test at n_{50}, as performed using CONTAM, had a value of about 4 h^{-1}. This value represents a house with moderate air tightness (Table 1). A crawl space and an attic with air leakages were included in the simulation model. The house was simulated as unfurnished with building materials as the only contaminant sources (Figure 1b).



a.



b.

Figure 1 Building floor plan and CONTAM model of the simulated building.

RESULTS

Optimal concentration levels for pollutants determined from the statistical analysis of the VTT database are summarised in Table 2 (the detailed analysis is presented in a publication under preparation). The TVOC and formaldehyde concentrations were analysed because the Finnish material classification (*M1*) includes target values for these compounds (FiSIAQ, 2008).

Target emission values for a *M1* product are as follows: TVOC 200 µg/m^2h and formaldehyde 50 µg/m^2h.
The concentration and profile of VOC groups differed between "normal" and "problem" buildings. In non-complaint residential buildings, the average concentrations of VOC groups were typically less than 50 µg/m^3. However, aliphatic and aromatic hydrocarbons were measured up to 400 µg/m^3 in residential buildings that received no complaints. In problem cases, however, the concentration of these VOC groups was clearly higher, up to 1000 µg/m^3 compared to sites with no complaints. Also, silyl compounds, typically in cleaning agents, were higher in "problem" homes (up to 800 µg/m^3). On the contrary, much higher terpene concentrations were measured in residential buildings that received no complaints, up to 1400 µg/m^3.

Table 2 Summary of "optimal" values for indoor pollutants in residential buildings based on VTT indoor air database analysis (VTT, 2008).

Indoor pollutant	**Concentration, µg/m^3**
Formaldehyde	< 30
TVOC	< 350 < 270 (low-emitting materials used)
VOC groups (acis, alcohol, aldehydes, esters, ketones, terpenes, glycols/glycolethers, aromatic hydrocarbons, aliphatic hydrocarbons, silyl compounds)	< 50
Single VOCs (as toluene equivalents)	< 10

Next, contaminant source strengths were evaluated for the target concentration levels presented in Table 2 using the CONTAM model of the house. Figure 2 shows the airflow simulation results of the model. The ventilation rate calculated by CONTAM was 0.92 h^{-1} (between 7-9 a.m. and 5-7 p.m.) and 0.48 h^{-1} (other times).
Bedroom 2, which had the highest concentration, was chosen as the reference room ("worst case"). The source strengths needed to achieve TVOC and formaldehyde concentration levels of < 300 µg/m^3 and < 30 µg/m^3 were calculated using the model to be 92 µg/m^2h and 10 µg/m^2h, respectively, with results shown in Figures 3-4. An SER value of less than 17 µg/m^2h was needed to achieve a concentration level of 50 µg/m^3 for VOC groups. If a concentration level of less than 10 µg/m^3 is desired, like for single VOCs, then the SER should be less than 4 µg/m^2h, as shown in Table 3.

Table 3 Summary of "optimal" values for specific emission rates (SER) in single family houses based on VTT indoor air database analysis and building simulation results.

Indoor pollutant	**SER, µg/m^2h**
Formaldehyde	< 10
TVOC	< 92
VOC groups (acis, alcohol, aldehydes, esters, ketones, terpenes, glycols/glycolethers, aromatic hydrocarbons, aliphatic hydrocarbons, silyl compounds)	< 17
Single VOCs (as toluene equivalents)	< 4

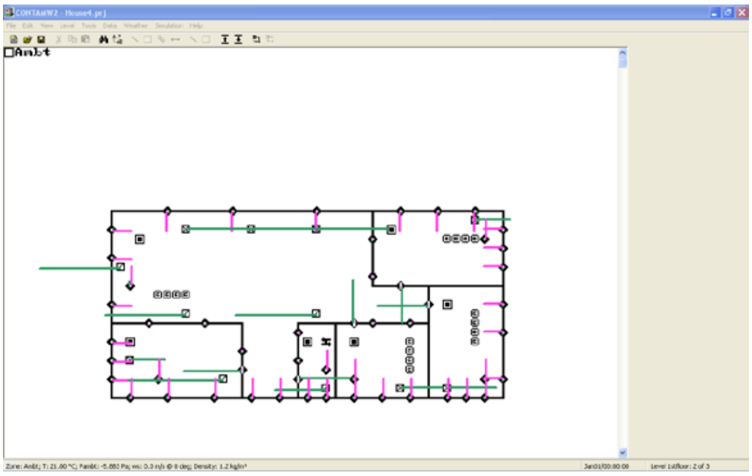


Figure 2 Airflow simulation result for the model (air flows = green lines, pressure drop = red lines).

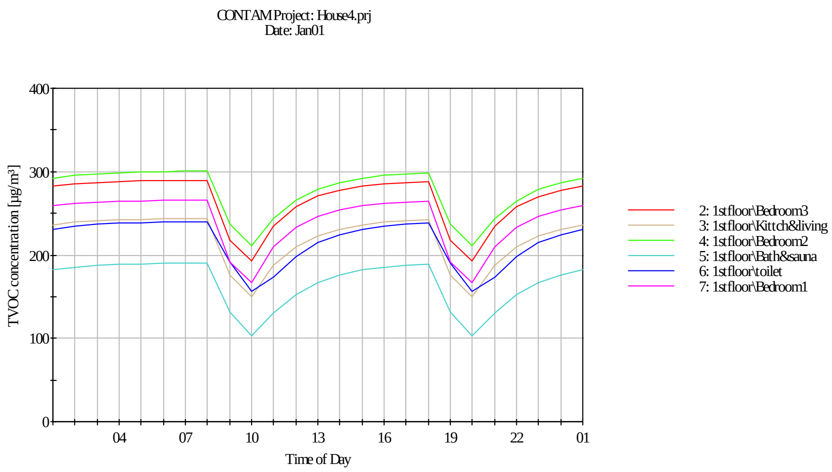


Figure 3 The TVOC concentration when the SER from surfaces is 92 µg/m^{2}h.

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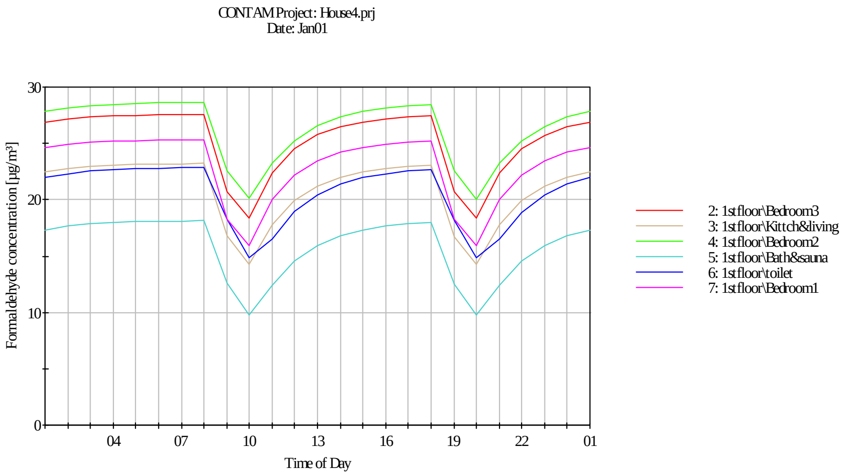

Figure 4 The formaldehyde concentration when the SER from surfaces is 10 µg/m^{2}h.

DISCUSSION AND CONCLUSIONS

Simulation tools can be used as decision making tools for designers and building engineers as well as for maintenance and service providers and officials. The simulation performed in this study showed that the *M1* target levels for surface emissions (FiSIAQ, 2008) are not sufficiently low to achieve optimal concentration levels in a typical Finnish home. The emission levels should be 20% to 45% of the current values in order to achieve the concentration levels that result in a high acceptance. In addition, the introduction of target values for VOC groups and single VOCs would be advantageous in terms of the perceived IAQ. Moreover, efforts to decrease the energy consumption in buildings, namely decreased ventilation rates, may lead to unwanted side effects that reduce indoor air quality (IAQ) and increase the risk for indoor air related health problems. Our study provides target values for IAQ and source strengths that can be used to reduce such outcomes, i.e. the result from this project supports builders and material producers working towards better products and practices by estimating the impact of materials in realistic environments.

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