IEREK PRESS
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CrossMark
http://www.press.ierek.com
ESSD
ISSN (Print: 2357-0849, online: 2357-0857)
International Journal on:
Environmental Science and Sustainable Development

DOI: 10.21625/essd.v4i2.557

Estimation of Coating Materials Contribution to the TVOCs Emissions of Wood Flooring in Indoor Environment

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Abstract

Based on the increasing concern about the exposure to volatile organic compounds (VOCs) from indoor finishing materials, industrial companies are called to meet the growing demand for more sustainable products. Recently, most designers and consumers have more environmental considerations while selecting the finishing materials. These considerations are related to the VOCs content of the finishing material itself regardless of its coating layers. Nowadays, interior wood coatings are commonly applied to large surfaces (ceilings, walls, floors) and many types of furnishing, leading to a high loading factor (surface-to-volume ratio). These coatings might contribute significantly to the VOCs emissions due to repeatedly and periodically use during maintenance, remodeling, and renovation of interior spaces.

The aim of this study is to estimate the wood coating materials contribution to the TVOCs emissions of wood product in the indoor environment to shed light on the importance of comprehensive analysis of wood material with all treatment coatings. So, a small interior space with controlled temperature, relative humidity, and air exchange rate was simulated using IA-Quest program to investigate the influence of three wood coating materials; stain, wax, and varnish which were applied to an area of natural hardwood Oak floor. The TVOCs emission data resulted from the different coated wood floor was compared with VOCs emissions caused by the natural wood floor to find out the coating material contribution in TVOCs emissions of a wood flooring material.

Keywords

Wood coating materials; volatile organic compounds; Simulation software; Finishing materials; Interior spaces

1. Introduction

There is an increasing attention concerning Indoor air quality for public health because individuals spend up to 90% of their time in the indoor environment (Bluyssen, 2009). EPA studies of human exposure to air pollutants indicate that the indoor pollutant levels may be 25 times and it maybe reaches to 100 times higher than outdoor levels (Daisey, Angell & Apte, 2003). Volatile Organic Compounds (VOCs) are considered to be the most important indoor pollutants due to continuous emissions from many sources (Bacaloni, Insogna & Zoccolillo, 2011). Finishing materials among all sources have a significant attention showing that more than 60% of VOCs emissions come from finishing materials and furnishings.

Numerous studies have shown that reducing the indoor air quality (IAQ) result from the VOCs emissions of from commonly used materials such as wood products, floor coverings, wall coverings, etc. These emissions may cause general symptoms from inhalation of fumes or vapors and skin absorption (Hussain, He, Mohamad, & Tao, 2015). The symptoms include a headache; eye, nose, or throat irritations; a dry cough; dizziness and nausea; difficulty in concentration; tiredness. The health effects differ widely as shown in (Figure 1), based on the exposure period that can be either acute term exposures (hours to days) or chronic exposures (years to a lifetime) (Bluyssen, 2009).

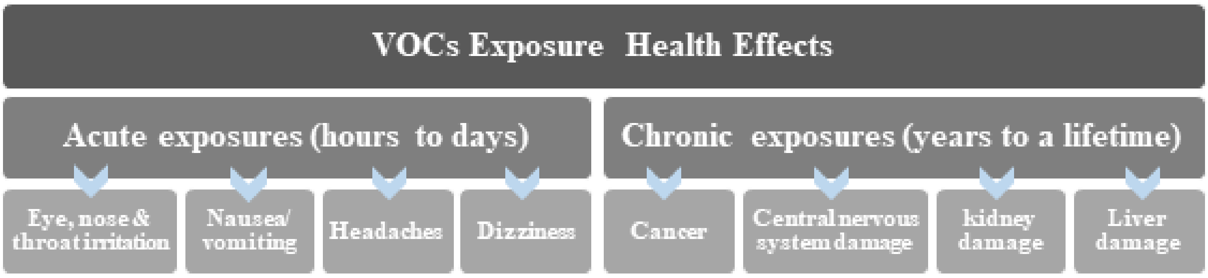

Figure 1. Common symptoms of exposure to high levels of VOCs (Bluyssen, 2009).

Generally, finishing materials appear in composite forms such as the wall assembly (paint/ gypsum board) or the floor assembly (varnish/ stain/ wood). VOC emissions floor assembly has not been theoretically examined. From the experimental studies of carpet/adhesive assembly, it has been found that the main source of VOC comes from the adhesive in the floor assembly. It has been found that adhesive in the floor assembly is the main source of VOC; the emission of the assembly displays lower delayed peak and slower decay rate in comparison with the adhesive alone (Black, Pearson & Work 1991; Low, Zhang, Plett, & Shaw, 1998). Thus, it is more important to understand multi-layer material emission characteristics in a building than single-layer one. Some multi-layer models were proposed (Bodalal, 1999), a general multi-layer emission model that can be used to simulate wet/dry, dry/dry, dry/wet material assemblies is not yet available (Haghighat & Huang, 2003).

Until now, abundant studies have been done on of VOC emissions measurement. Most of the studies use a small-scale test chamber under controlled environmental conditions. Such these measurements are very essential in order to accumulate and compile a reliable database of indoor materials. However, there is maybe a difference between both the geometry and boundary conditions in buildings and that in the test sample. Hence, the measured data from a chamber may not be entirely suitable for actual buildings. On the other hand, with the rapid progress of computer hardware and numerical algorithms, mathematical models and numerical simulations can partly overcome the disadvantage of laboratory measurements (Xu & Zhang, 2003).

This paper discusses the simulation method of predicting VOCs emissions from a multilayer material with a specific focus on the emissions from wood-based floor material. Three types of coating layers; stain, wax, and varnish were applied to the natural type of wood flooring; unfinished hardwood- Red Oak. The objective of this study is to estimate the wood coating materials contribution to the TVOCs emissions of wood product in the indoor environment to shed light on the importance of comprehensive analysis of wood material with all treatment coatings.

2. Multi-Layer Material Concept

Most finishing and furniture consist of multi-layer materials which are considered to be as sources of VOCs. These finishing materials may include both wet and dry materials such as carpeting, wallpaper, wood floor, paint, and glue. Indoor air quality is considerably affected by the VOCs emission from dry building materials, as not only the emission is a long-time process but their large surface areas are also permanently exposed to indoor air (Yang et. al, 2001).

On the other hand, the characters of VOC emissions from wet materials have a high initial emission rate and fast decay, afterwards a low emission rate and slow decay. It can be clarified by three emission stages from wet materials: evaporation dominant phase (wet material), transition phase (relatively wet), and internal diffusion controlled phase (completely dry) (Yang, Chen, Zeng, Zhang & Shaw, 2001) . For wet materials, such as glue, wood stain, VOC concentration within the materials has a very high initial, consequently (Haghighat & Huang, 2003).

Each layer in the multilayer assembly has VOCs emissions, not only from the top surface but also from the core and bottom layer. It is essential to recognize the emission characteristics of common multilayer materials to provide valuable information for the manufacturing process and to finally eliminate the VOCs released into the indoor air (Xu & Zhang, 2009). Multi-layer materials contain three composition forms: dry/dry (e.g. composite particleboard or plywood), dry/wet (e.g. vinyl floor tile+ glue+ plywood; carpet+adhesive) and wet/dry (e.g. paint + gypsum board). The material configuration and VOC emission processes are shown in (Figure 2) (Haghighat & Huang, 2003).

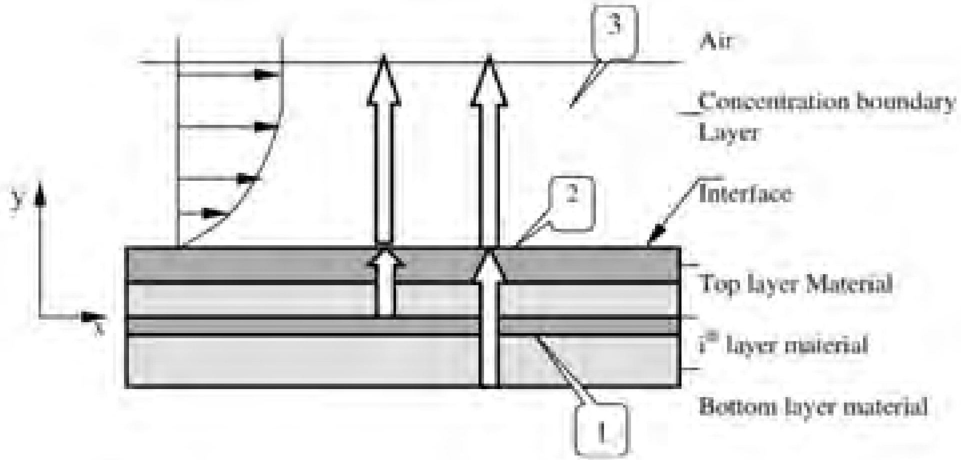

Figure 2. Physical configuration of VOC emissions from a multi-layer material. (1) Internal diffusion; (2) desorption; and (3) external convection and diffusion (Haghighat & Huang, 2003).

Most types of wood-based flooring are made of composite assembly as natural wood floor usually passes through numbers of treatment steps in the finishing process as shown in (Figure 3) (Kim, 2010). This treatment applying as a coating layer such as stain, wax, and varnish layer. Wood stains, also known as wood dyes are designed to change the color of wood while leaving the grain still visible by soaking pigment into wood fibers with a solvent and then having it set and bind to the wood. Most stains don’t offer a lot of protection to wood, so when using a stain it’s regularly a good idea to apply a protective coat of something else like a varnish or wax (Rowell, 2012).

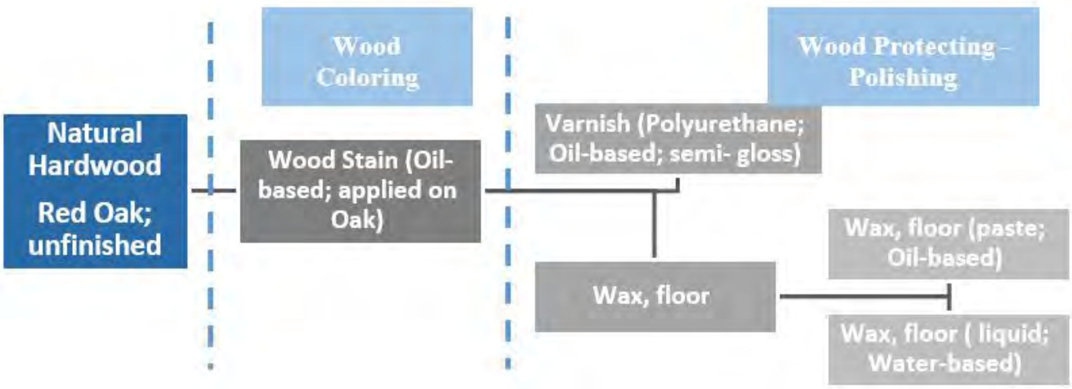

Figure 3. The wood floor finishing with different coating layer

Varnish begins as oil, but it’s cooked with a resin to produce a drying, hard, wood finish. Its main role is that of a protective coating on the surface; it doesn’t penetrate like wax does (Flexner, 1993). Waxes are derived from many types of mineral, vegetable and animal sources. As a finish, waxes don’t penetrate wood, but rather sit atop it. They will prevent it from oxidizing but don't particularly enhance the wood. (Shupe, Lebow & Ring, 2008). Applying all these three types of coatings aren't be essential for each wood finishing process as each type of wood floor has its required treatment steps.

3. Case Study Procedure

This paper established a simulation procedure to evaluate the VOC emissions for each type of flooring coating and its contribution to the TVOCs emission of the wood flooring. To simulate indoor VOC concentrations in a residential unit due to wood coating materials, some information and key parameters discussed in Eq. (1) need to be determined. The whole simulation procedure can be generally divided into three steps including:

1. Collection of basic information, indoor space geometry, and its environmental conditions
2. Selection of the wood flooring with its coating layer type and its VOC emission factor, and
3. Dynamic simulation of indoor TVOCs concentration using a simulation tool named "Indoor Air Quality Emissions Simulation Tool (IA-QUEST)

Every step in this procedure has its tools either using the field visits to using different simulation tools. A detailed discussion of each step is given in the following case study section.

3.1. Mathematical model

It is known that Pollutant distribution in a building is in general non-uniform (Haghighat et al. 1994; Brohus 1997; Wang and Emmerich 2010). However, for our study of VOC concentrations in a residential unit of a family residential building, studies indicate that the non-uniformity is not that important under normal room ventilation conditions. The equation of the VOCs concentration in a space can be written as following (Willem & Hult, 2013):

$$dc/dt = EA/V + N_h\ (C_{out}\ C) \tag{1}$$

Where C is the change in concentration over (t) time of an indoor contaminant in an enclosed space, E is the emission rate in mass per unit floor area per unit time, A is the floor area, C_{out} is the concentration of the chemical in the outdoor air, V is the volume of the space and N_h is air exchange rate in air changes per hour (ACH).

3.2. Simulation software

The Case study will undergo two main simulation phases; the Air Flow Rate simulation and Finishing Materials Selection simulation. To go through these phases, three programs will be used to build and simulate the base case and the proposed cases. These programs are Autodesk AutoCAD Software (2D,3D), Autodesk computational fluid dynamics (CFD), and Indoor Air Quality Emission Simulation Tool (IA-QUEST) Version 1.1 as shown in (Figure 4).

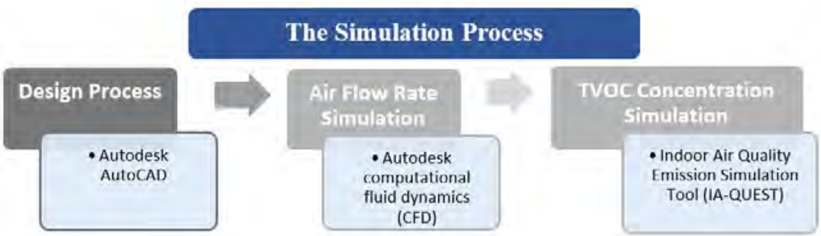

Figure 4. The simulation process concerning the programs used

4. Case Study

The above-proposed procedure with the three steps has been applied in a typical master bedroom from the apartment that was selected randomly from residential towers in Mansoura. Egypt using IA-QUEST simulation program.

4.1. Basic information collection

The basic information that is needed includes the room value V and ventilation rate Q in Eq. (1). In detail, the newly constructed residential unit was chosen to be used in the simulation procedure as shown in (Figure 5). Five cases based on coating layer selection was applied to the wood floor in the master bedroom in this unit. The floor plan of this room was defined as shown in (Table 1) to be with of 176 m^3 There are two windows with an area of 2.31 m^2, 1.75 m^2, and the flooring area was calculated to be 59 m^2.

The master bedroom was simulated to be under constant environmental conditions; *at 25 ±1.0 c°, and 50 ±5.0 % relative humidity*. Concerning the Air Flow Rate, a simulation was established with CFD simulation program with air velocity which has been set to be **3 m/s with North** direction according to national data of the *Faculty of Agriculture climate station in Mansoura University* which is the nearest data to the building site. The air flow rate from room windows was calculated according to the following equation (Santamouris & Allard, 2000):

$$Q = A * V * C \tag{2}$$

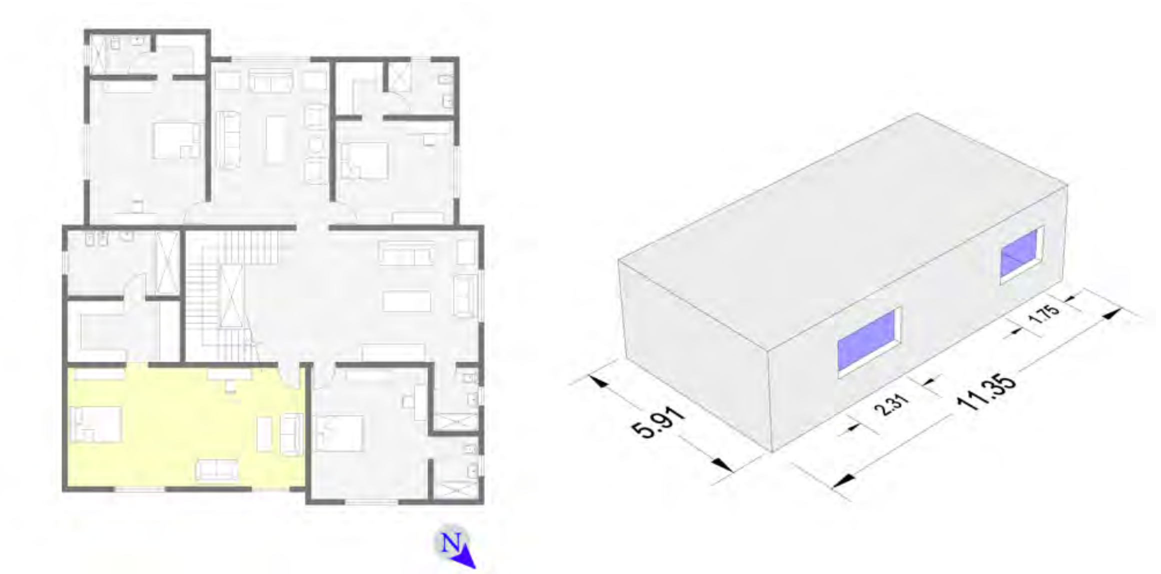

Figure 5. Layout of the residential unit and the master bedroom marked in yellow (left), the geometric model for the master bedroom (right)

Table 1. The geometric configuration of the master bedroom

Item	Room specification for all scenarios
Volume (m3)	176 m^3
Area (m2)	59m^2
Window Area (m2)	Win.1 =2.31 m^2 , Win.2 = 1.75 m^2
Ceiling/flooring surface area (m2)	59 m^2

From the above equation, the air flow rate was calculated based on the velocity resulted from CFD and inlet window area as shown in (Table 2). Also, the CFD simulation results show the air flow distribution around the building to be driven to the room inlet and outlet as illustrated in (Figure 6).

Table 2. The environmental specifications related to the ventilation aspect

Type	Value
Average air speed Vx (m/s)	0.9
Openable inlet window area (m^2)	2.31
Air flow rate (m^3/s)	0.2484
Air flow rate (m^3/h)	894.24

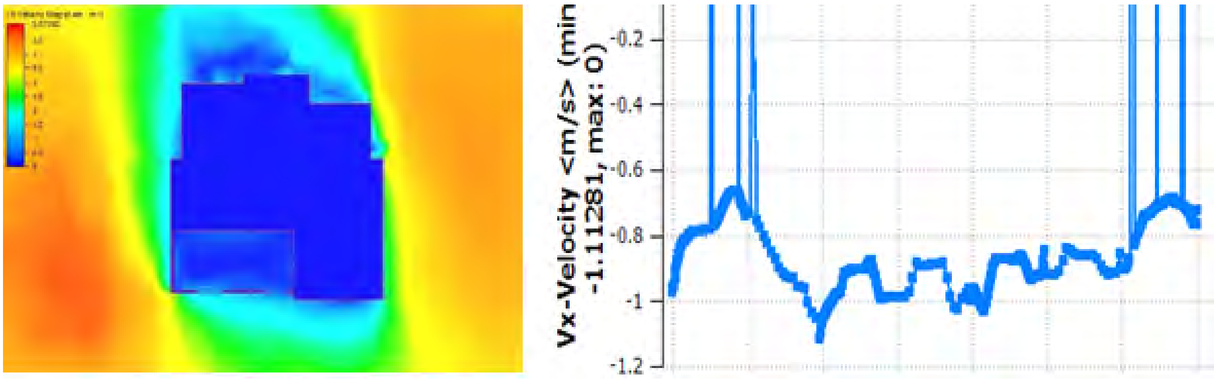

Figure 6. The air flow distribution outside and inside the master bedroom (left), the V_x velocity normal to the inletwindow (right)

4.2. Selection of the wood flooring with its coating layer type

NRC database in IA-QUEST program has a wide range of wood flooring materials; Single and assembly materials, natural and synthetic materials were all included in, i.e., natural wood including, Oakwood, engineered products with adhesives, including, laminate tile, medium-density fiberboard, and particleboard. The program also provides a database for a variety of wood floor coatings (Won et. al, 2005).

As discussed before, every wood flooring has its treatments; stain, varnish, and wax with their different steps in the procedure. Among NRC database, a natural Hardwood; Red Oak; the unfinished material was chosen to be simulated in case (1) as shown in (Table 3), while in case (2) wood Stain layer (Oil-based; applied on Oak) was added to the Natural Hardwood. The case (3) was simulated with the natural Red Oak coating with Varnish layer (Polyurethane; Oil-based; semi-gloss). In case (4), (5) the natural Red Oak was coated with a Wax, floor (paste; Oil-based) and a Wax, floor (Liquid; water-based) consecutively.

Table 3. The selected materials for cases with emission factor and ID in the NRC database (Won et. al, 2005).

Case No.	Flooring Type	Material ID	Nominal emission factor (mg/m2h)	Maximum emission factor (mg/m2h)
1	Hardwood; Red Oak; unfinished	OAk1	0.11968	0.19849
2	Hardwood; Red Oak; unfinished	OAk1	0.11968	0.19849
	Wood Stain (Oil-based; applied on Oak)	WS6a	803.30	16082.27
3	Hardwood; Red Oak; unfinished	OAk1	0.11968	0.19849
	Varnish (Polyurethane; Oil-based; semi- gloss)	UR8	154.50	10231.86
4	Hardwood; Red Oak; unfinished	OAk1	0.11968	0.19849

Continued on next page

Table 3 continued

	Wax, floor (paste; Oil-based)	WX2	408.97	40733.13
5	Hardwood; Red Oak; unfinished	OAk1	0.11968	0.19849
	Wax, floor (Liquid; water-based)	WX6	51.346	162.94

4.3. Dynamic simulation of indoor TVOCs concentration

The IA-QUEST program was used to simulate TVOCs concentration for each case based on numbers of main inputs; the volume of space, ventilation rate, material type, and its coverage space. Concerning the simulation time, the study put a simulation period with 336 hours.

5. Results and Discussion

During the emission simulation, the concentrations of TVOCs resulted from different types of wood coatings were predicted. Figures (Figure 7) show the concentration-time profiles during the 336-h test period for VOCs emitted from the eight scenarios. There are some findings as follows:

1. At the first glance, the result for using unfinished Oak wood floor without any coating layers in Case (1) record a very low VOCs concentration with a value of 0.3 mg/m3 in comparison with the results from any coating layer used in the other cases and also when compared with LEED standard as it is in line with standard and even below.
2. The highest Max.TVOCs concentration was found in Case (4) with 220 mg/m3 resulted from using the Oil-based wax layer as a coating for the Oakwood floor which represent 733 times higher than Case (1) and 440 higher than LEED standards. While the lowest Max.TVOCs concentration was mentioned in Case (5) with Water-based wax as a coating resulting in 5 mg/m3 which represent 16 times higher than Case (1) and 10 times higher than LEED standards. So, there is a wide difference in TVOCs concentration in the space result from using Oil and Water based even for the same type of coating; wax coating.
3. Using Oil-based stain as a colorant for the Oakwood flooring in Case (2) raised TVOCs concentration in the room from 0.3 mg/m3 for the unfinished Oak floor to 54 mg/m3 due to applying the stain coating. This significant increase is only due to using this slight colorant layer with 180 times higher than using the natural Oak floor. While using Oil-based varnish as a protective and polished layer for the Oak flooring in Case (3) elevated the TVOCs concentration to 35 mg/m3 which is 117 times higher than using the unfinished floor.

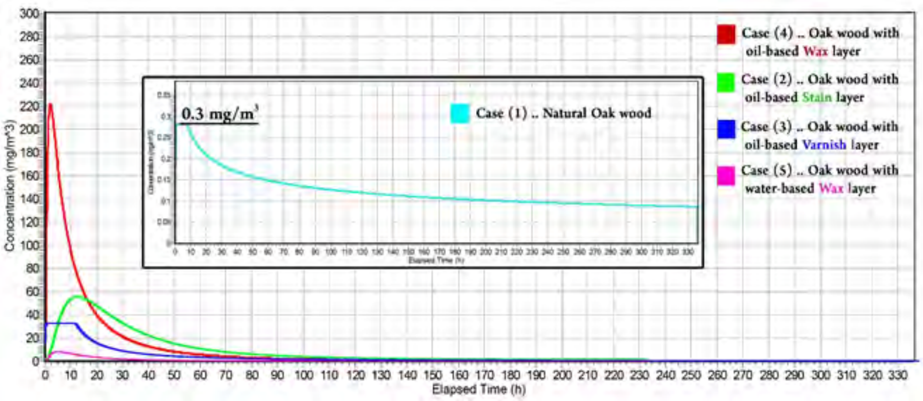

Figure 7. The analysis of TVOC concentrations of the Cases v.s elapsed time

After discussing the VOCs concentration for each case resulted from different type of coating layers, there is a necessary need for analyzing the VOCs concentration along the simulation period as shown in (Table 4) to understand the VOC behavior for each coating layer. The analyses show the following:

1. First, concerning reaching the Cases' peak point (Max.TVOC concentration) which their values are illustrated in the first previous points, there is also the time factor to be analyzed. For Case (1) with using the unfinished Oakwood without any coating layers, Case (3) with using the stain layer, and Case (4) with using Oil-based wax layer, they reached to their peak only after 1-2 hours after installation. Notice that the peak value for Case (3) was a constant for the first 14 hours. While in Case (5) with using Water-based wax layer reached after 7 hours. The Case (2) with using stain layer has the longest time to reach its peak among all cases as it took 16 hours. From these values, it is shown there is a critical VOCs behavior in the first 20 hours after installation.

2. After reaching their peaks, the cases have a rapid decay for a specific period and then a slow decay to reach their Min.TVOC concentration. For the rapid decay, all cases almost decayed rapidly until almost 60-80 hours. In spite of the highest peak; 220 mg/m3 record in the Case (4) with using Oil-based wax layer, the value after a small rapid decaying (58 hours) was lower than the Case (2) using the stain layer with the same decaying period. These results deserve to be discussed as the Case (4) peak is higher than the peak in the Case (2) with 4 times.

3. All cases spend a period in the slow decay to reach to their Min.TVOC concentration. Although Case (2) and (3) reached the same value of 1.5 mg/m3, using the Oil-based wax layer in Case (4) reach its minimum after only 90 hours while using stain layer in Case (2) reach after 190 hours. So regardless of the high peak point of Case (4), it shows interesting behavior after reaching its peak than other Cases.

4. Concerning Case (5) with using water-based wax which represents a peak with 5 mg/m^3 which is 10 times higher than LEED standards, the Min.TVOC concentration after 160 hours is 0.12 mg/m^3 recording a value lower than LEED and even almost the same Case (1) value with using the unfinished Oak wood floor.

Table 4. The analysis of TVOCs concentration during the simulation period for each case

Case No.	Decay time							LEED standard
	Peak point		Rapid decay		Slow decay	Steady value		
	Reach Time (h)	Value (mg/m3)	Decay time (h)	Value after decay period (mg/m3)	Reach Time (h)	Almost steady value (h)	Value (mg/m3)	0.5 mg/m3
1	After 1h	0.3	8-80 (72 h)	0.14	80-260 (180 h)	After 260h	0.09	
2	After 16 h	54	16-80 (58 h)	10	80-190 (110 h)	After 190	1.5	
3	After 1 h	35	13-70 (57 h)	3.0	70-170 (100 h)	From 1- 13	35	
						After 170	1.0	
4	After 2 h	220	2-60 (58 h)	7.0	60-90 (30 h)	After 90	1.5	
5	After 7 h	5	7-70 (63 h)	0.4	70- 160 (90 h)	After 160	0.12	

6. Conclusion

A method to estimate the coating layers contribution to the TVOCs emissions of wood product in the indoor environment was established. This method is essential to shed light on the importance of comprehensive analysis of wood material with all treatment coatings. The method has been done using simulation tools for the typical master bedroom to investigate the influence of three wood coating materials; stain, wax, and varnish which were applied to an area of natural hardwood Oak floor.

The TVOCs emission data resulted from the different coated wood floor was compared with VOCs emissions caused by the natural wood floor to find out the coating material contribution in TVOCs emissions of wood flooring material in the interior space. The results from the comparison show that the coating layer may be considered as the main source of emissions in the multilayer wood flooring. Also, the results show varied value for VOCs concentration due to different types of coating that indicate the importance of analyzing and studying the different type before installing. For example, there is a wide range in TVOCs concentration resulted from different coating layers for the purpose of protecting and polishing; varnish layer recorded TVOCs concentration lower than using Oil-based wax while using Water-based wax is the lowest results among the polishing materials. On the other hand, there is an essential need for analyzing the long-term behavior for each type of layers to understand the VOCs emissions mechanism that differ during their decay.

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