Emissions of VOCs, SVOCs, and mold during the construction process Contribution to indoor air quality and future occupants' exposure

Victoria Gallon, Pierre Le Cann, Mariangel Sanchez, Charline Dematteo, Barbara Le Bot

DR. BARBARA LE BOT (Orcid ID : 0000-0001-9463-0924)

Article type : Original Article

Title: Emissions of VOCs, SVOCs and mold during the construction process: contribution to indoor air quality and future occupants' exposure

Running title: Indoor air quality during construction process

Authors: Victoria Gallon[1], Pierre Le Cann[1], Mariangel Sanchez[2], Charline Dematteo[3], Barbara Le Bot[1]

[1] Univ Rennes, Inserm, EHESP, Irset (Institut de recherche en santé, environnement et travail) - UMR_S 1085, F-35043 Rennes, France

[2] AQC (Agence Qualité Construction), 29 rue de Miromesnil 75008 Paris, France

[3] INDDIGO, 367 avenue du Grand Ariétaz 73024 Chambéry, France

Corresponding author:

Le Bot, B

Univ Rennes, Inserm, EHESP, Irset (Institut de recherche en santé, environnement et travail) - UMR_S 1085, F-35043 Rennes, France

barbara.lebot@ehesp.fr

Acknowledgments

This project was support by the French Environment and Energy Management Agency (ADEME) (1504C0005). We thank Julien Gastine for sampling and we thank the Environment and Health Research Laboratory (LERES) for the analysis of samples and their contributions to this work. We also thank Nicolas Naulleau and Aurélie Béroudiaux (INTECO society) for the selection and follow-up of construction sites.

Abstract

Building materials and human activities are important sources of contamination indoors but little information is available regarding contamination during construction process which could persist during the whole life of buildings. In this study, six construction stages on two construction sites were investigated regarding the emissions of 43 volatile organic compounds (VOCs), 46 semi-volatile organic compounds (SVOCs) and the presence of 4 genera of mold. Results show that the future indoor air quality does not only depend on the emissions of each building product but that it is also closely related to the whole implementation process. Mold spore measurements can reach 1400 CFU/m^3, which is particularly high compared to the concentrations usually measured in indoor environments. Relatively low concentrations of VOCs were observed, in relation to the use of low emissive materials. Among SVOCs analyzed, some phthalates, permethrin, hydrocarbons were found in significant concentrations upon the delivery of building as well as triclosan, suspected to be endocrine disruptor and yet prohibited in the treatment of materials and construction since 2014. As some regulations exist for VOC emissions, it is necessary to implement them for SVOCs due to their toxicity.

Keywords: construction process, dwellings, offices, VOC, SVOC, mold

Practical implications

The 2012 French Thermal regulation enforces requirements on energy consumption and air permeability of the built envelope. These economic requirements could have consequences on indoor air quality by increasing the concentration levels of pollutants from building materials if they are not associated with an increase in ventilation rates. Results of this study raise questions about indoor air quality management from the early stages of the construction project, which could reduce the indoor air pollution at delivery.

Introduction

People spend about 90% of their time in closed environments and most of this time occurs at home [1, 2]. The Observatory on Indoor Air Quality (OQAI) observed that indoor pollution is different from outdoor pollution, especially in terms of the presence of some substances that are not detected outdoors or by higher concentrations indoors. In a national survey including 567 French dwellings, it has been demonstrated that the pollutants investigated were present at quantifiable levels in most French dwellings and included physical, chemical and microbiological compounds [3]. Others studies found higher concentrations of pollutants indoors than outdoors, measuring volatile organic compounds (VOCs) [4, 5] or semi-volatile organic compounds (SVOCs) [6, 7]. High mold concentrations are also often detected in dwellings [8, 9].

Pollutants found in indoor environments have or are suspected to be related to health adverse effects. VOCs are known to cause respiratory health effects such as asthma or rhinitis [10] and-are suspected to involve the development of severe diseases as cancer after a long period of inhalation exposure [11]. Formaldehyde is an example of substance classified as carcinogenic for humans by the International Agency for Research on Cancer (IARC) [12]. SVOCs are suspected to have reprotoxic or neurotoxic effects [13, 14]. They are emitted from various sources in living environments [15] and include a wide range of molecules with different properties: pesticides, biocides, plasticizers, flame retardants, surfactants, and lubricants used as active substances or additives. They are present in the gas phase, airborne particles and settled dust [16], therefore humans are exposed through different pathways including inhalation, ingestion, and dermal contact [17]. Concerning fungal contamination, the presence of mold in dwellings is correlated with the onset of asthma in children and adults [18-21].

These agents or contamination come from different sources including building materials, furnishings, cleaning supplies and human activities. High VOC concentrations have often been observed in newly built or renovated residential buildings [22-24]. Nevertheless, little information is available regarding the contamination during the construction process which could persist during the whole life of buildings. Even if some authors such as Mendell *et al.* have alerted the international research community to the risk of contamination of workers during the construction phase [25], we have focused our study on the potential health effects on future occupants. To our knowledge, only six international publications are available regarding VOC contamination during construction processes in the scope of general population and public health exposure. Liu *et al.* found a significant VOC contamination during the construction and finishing of a new museum in China and suggested that potential contaminant sources were various kinds of wall paints and sprayed glass cleaning agents [26]. Other authors found that the introduction of furniture during the construction process was responsible for emissions of the largest amount of pollutants, including toluene and formaldehyde [27,28]. Liang *et al.* measured the VOC concentrations during five construction stages of a new apartment and identified the sources of different compounds. Toluene and alpha-pinene increased considerably after the door and doorframe were installed. Likewise, propylene glycol increased after application of the wall paint and benzene after introduction of some furniture [29]. Ochs *et al.* identified that the door varnishing was responsible for a high emission of butanone and other carbonyl compounds [30]. Plaisance *et al.* measured the emissions of VOCs at six construction stages in three energy-efficient timber-frame houses and found that high m,p-xylenes and ethylbenzene concentrations at the time of the structural work was due to the emission from the polyurethane adhesive mastic used as a sealing material [31]. They also found that a large number of materials were sources of aldehydes which became the highest proportion in the chemical composition in the last stages of construction. VOC emissions from building materials decrease with time [32, 33, 34]. Therefore, occupants will be exposed to VOCs emitted by building materials during few months to several years after interior construction was completed, with, for example, secondary aldehyde emissions due to ozone reactions on building materials [35]. Regarding fungal contamination, Sautour *et al.* conducted a survey in hospital during a period of building construction and found that there were increases in airborne fungal spores at the beginning of construction work and that the most frequently recovered airborne fungi were *Penicillium* spp., *Aspergillus* spp. and *Bjerkandera adusta* [36]. Emissions of mold that have developed during the construction process may persist throughout the life of the building if mold growth occurred on non-visible materials, as drywall [37, 38]. These molds, even hidden at the delivery phase, could reappear during the occupation of buildings or remain active behind a lining wall, and could be correlated with the onset of asthma. No studies were found regarding SVOC emissions during construction stages while SVOCs persist several years after the end of the construction process or throughout the life of the building and contribute to the long term exposure of occupants [15, 39].

In France, some regulations exist regarding the emissions of construction materials. A extremely low emission factor (1 µg/m^3) has been set for four priority substances (trichloroethylene, benzene, bis(2-ethylhexyl)phthalate and dibutyl phthalate) in order to prevent the producers to add these compounds in their products [40]. A labelling has also been introduced regarding indoor air emissions from construction and decoration products [41]. This labelling indicates the level of VOC emissions, allowing a choice of products that are less harmful to health. Some indoor air quality guidelines (IAGV) exist for some VOCs but no values are available for SVOCs. Moreover, no regulations exist regarding the maximum values of pollutants allowed in the indoor air at delivery of buildings.

This project focuses on the impact of the different trades (painter, plasterer, mason, …) considering differences in process (materials, implementation conditions) and implementation of ventilation equipment to better document the impact of the different construction stages on the air quality at delivery of a building. It is the first time in France that a project aims to measure as many parameters during the different construction stages: VOCs, SVOCs and mold. The objective is to identify the potential sources of pollution that can impact the indoor air quality at the delivery of a building and thus contribute to the exposure of the future occupants to harmful contaminants.

Materials and measurement design

Construction sites

Two sites of new construction operations were investigated: an office building and a housing building. The two sites were located in the west part of France (Nantes) in a temperate oceanic climate.

Site A consists of the construction of a new office building. The building, with a net internal area (NIA) of 505 m^2, is built on two levels: a ground floor and a first floor. The building is based on concrete sails cast in place for vertical structure and prestressed slabs and sail cast in place at the top (including for the high floor) for horizontal structure. Site A was poorly ventilated (few window openings) and a dual-flow ventilation was started just before the last measurement campaign, on July 25, 2016.

Site B consists of the construction of 38 dwellings spread over a set of five buildings. Measurements were carried out in a single building (n°2) with a NIA of 600 m^2. The building comprises a total of six dwellings spread over three levels: ground floor, first floor and second floor. The construction process includes concrete sails cast in place, prefabricated concrete floors and wood frame facades. The gables in concrete veil benefit from an external insulation and the walls wood frame of a distributed insulation. Site B was more ventilated than site A (window openings) and mechanical ventilation was not used during the measurement campaigns. Contrary to site A, smoking was observed during each visit (principally by the paint company) while this is normally prohibited on construction sites.

Two locations were chosen for the measurements on site A: room A0 on the ground floor and located at the Nord corner of the building and room A1 on the first floor and facing south-east.

Measurements on site B were conducted at three locations: bedroom B0 on the ground floor at the south-east corner, living room B1 on the first floor oriented at the north-west and bedroom B2 on the second floor at the south-east corner. During the implementation of soft floors, measurements were done on the living room on the ground floor instead of B1, to study the impact of the storage of soft floors on the VOC emissions.

Building materials and energy performance

The energy performance of buildings was regulatory according the 2012 French Thermal regulation [42]. Measurements of air permeability were carried out using a Blower Door in accordance with the NF EN 13829 standard. The air permeability of the building envelope was equal to 0.61 $m^3/h.m^2$ for site A (measured on March 2, 2016) and equal to 0.80 $m^3/h.m^2$ for site B (measured at the end of construction), under 4 Pa.

All materials and products used have low emissivity with respect to compulsory labelling (class A+ for most of materials and finishing products) [41].

Construction stages and interest parameters

Six construction stages were investigated:

1. After the structural work: initial state (walls, roof, exterior joinery, building airtight)
2. During preparation of supports: application of coating and primer paint, implementation of the screed, installation of partitions and linings
3. During the application of finish paints
4. During the implementation of soft floors
5. During the last finishing works: finishing touches, setting up of wood interior joinery, before cleaning
6. At the delivery

Details of the measurement campaigns are presented in Table 1. Site A was investigated from February 22, 2016 to July 27, 2016. Site B was investigated from January 10, 2017 to October 6, 2017. Regarding VOCs, 30 measurements were carried out in total on both sites: one measurement at each construction stage in each of the five rooms investigated. Regarding SVOCs, four measurements in total of both sites were carried out: one measurement on the dust of ventilation ducts and one measurement (site A) and two measurements (site B) on PM_{10}. Regarding mold, one mold count on the dust of ventilation ducts was carried out and airborne mold concentrations were measured six times in each of the three rooms investigated of site B and outdoor, and two times in each of the two rooms of site A and outdoor.

43 VOCs, 46 SVOCs and 4 genera of molds were analyzed. List of pollutants is presented in Table 2. CAS numbers of VOCs and SVOCs are available in Tables S1-S2. Measurements focused on VOCs commonly studied in indoor environments, measured by OQAI, or VOCs from mandatory labelling on construction products, according to their toxicity. Selection of SVOCs was based on a health-based ranking of SVOCs established according contamination data and reference doses [43], on published concentrations in indoor environment and on the technical feasibility. Regarding mold measurement, the genera most frequently found in the air and dust of dwellings were studied [44].

Sampling method

Ambient parameters

Temperature and relative humidity were measured continuously in each room with recorders HOBOs (Onset, USA), outdoor under a box with three faces behind the construction panel and indoor, attached by a scratch system on the glazing (A0, A1, B0, B1) or attached on a tripod in the center of the room (B2). The time interval of the measurements was 15 minutes.

TVOCs

Total volatile organic compounds (TVOCs) were measured continuously by a Fireflies station (Hager Services, France), attached on a tripod. This station measured the overall compounds content with a carbon chain from C3 to C10. Results are expressed as toluene equivalent and take into account the following gases: nitric oxide, nitrogen dioxide, sulfur dioxide, ammoniac and carbon monoxide. The station also measured temperature and relative humidity [45]. The time interval of the measurements was 10 minutes.

Aldehydes

During the two first construction stages on site A, aldehydes were collected during 4 days using commercially available Radiello passive samplers (RAD165, Sigma-Aldrich, Saint-Louis, MO, USA) impregnated with 2,4-dinitrophenylhydrazine (DNPH). The other measurements were active sampling, on Waters Sep-Pak XPoSure cartridges (WAT047205, Waters, Milford, MA, USA) with silice impregnated with DNPH. Air was pumped (Gillian 3500, Sensidyne, St. Petersburg, FL, USA) at a constant flow rate of 500mL/min during 390 min and the pump was attached on a tripod. Samples were stored at 5 °C until analysis.

Other VOCs

During the two first construction stages on site A, other VOCs were collected during 4 days using commercially available Radiello passive samplers (RAD145, Sigma-Aldrich, Saint-Louis, MO, USA) filled with graphitized charcoal (Carbograph 4). The other measurements were active sampling on tubes filled with adsorbant Carbopack B (20273, Sigma-Aldrich, Saint-Louis, MO, USA) and Carboxen 1000 (10478-U, Sigma-Aldrich, Saint-Louis, MO, USA) with a pump (Gilian LFS 113 Sensidyne, St. Petersburg, FL, USA) attached on a tripod at a constant flow rate of 50 mL/min during 180 min. Samples were stored at 5 °C until analysis.

PM_{10}

Airborne PM_{10} particles were pumped (GilAir-5 pump, Sensidyne, St. Petersburg, FL, USA) at a constant flow rate of 3L/min through a Microvol device (Ecomesure, France) on Teflon filters (47-mm diameter and 2 µm porosity, Pall Teflo) during 72 hours on site A and through an impactor on 37-mm quartz fiber filters (TERA Environnement, France) during 96 hours on site B. Samples were stored at -18 °C until SVOC analysis.

Dust from ventilation ducts

Dust from ventilation ducts were collected with wipes (ASTM E1792 Lead Wipes, Aramsco, Thorofare, NJ, USA) for the analysis of SVOCs and swabs (020063, Dutscher, France) for the analysis of mold. Before sampling, 1 mL of saline solution of Tween® 80 (Merck KGaA, Darmstadt, Germany) was added to swabs.

Mold

Molds were collected by bio impaction (Sampl'air biocollector, AES laboratory, France). 50 liters of air were impacted on two culture media: Malt Extract Agar (Biokar Diagnostics, France) and Dichloran Glycerol 18% Agar (Merck KGaA, Darmstadt, Germany) (sampling time: 30 seconds).

Analytical method

Aldehydes

Aldehydes were extracted with acetonitrile (2 mL for Radiello samplers and 5mL for Waters Sep-Pak XPoSure cartridges) and analyzed by high-performance liquid chromatography (1260 Infinity liquid chromatography system, Agilent Technologies) coupled to UV detection (1100 Series Diode Array Detector, Agilent Technologies). The analytical method is described by Baurès *et al.* [46]. Limits of quantification (LOQ) are given in table S3.

Other VOCs

The other VOCs were thermally desorbed (Perkin Elmer ATD Turbo Matrix 150) and analyzed by gas chromatography (7890A, Agilent Technologies) coupled to mass spectrometry (Agilent Technologies 5975C inert Xl EI/CI MSD). The analytical method is described by Baurès *et al.* [46]. LOQ are given in table S4.

SVOCs

SVOCs were desorbed from PM_{10} and dust by thermal extraction (Gerstel Thermal Desorption Unit TDU 2, Gerstel GmbH & Co. KG, Mülheim an der Ruhr, Germany) and analyzed by gas chromatography (7890A, Agilent Technologies) coupled to tandem mass spectrometry (70000B Triple Quad, Agilent Technologies). The analytical method is described by Blanchard *et al.* and Mandin *et al.*[16, 47].

Mold

The cultures were incubated (Friocell, MMM Group, Germany) for 5 to 7 days at room temperature (25 °C +/- 2°C) and the fungal thalli were identified from their characteristics observed under optical microscopy (CH-2, Olympus, Japan) and quantified.

Results

VOCs

The VOC concentrations at each construction stage are presented in Table 3. Nine compounds are always under the LOQ: p-tolualdehyde, n-propanol, 1,4-dichlorobenzene, 2-ethoxyethanol, chloroforme, bromodichloromethane, dibromochloromethane, tribromomethane, trichloroethylene and are not presented. The following compounds have between 50 and 70% of their samples above the LOQ: propionaldehyde, butyraldehyde, valeraldehyde,n-decane and n-undecane, toluene, styrene, limonene. The following compounds have more than 70% of their samples above the LOQ: formaldehyde, acetaldehyde, benzaldehyde, hexaldehyde, ethylbenzene, xylenes.

Finish paints, soft floors and last finishing works were the stages with the highest variety of VOCs identified. The application of finish paints was characterized by the highest concentrations of aldehydes. Aromatic hydrocarbons were found during all the construction process. Aliphatic hydrocarbons (n-decane, n-undecane) were present during the application of soft floors on site A and these compounds were also found on B2 during the last finishing works. At delivery, glycols ethers and terpenes were identified on site A.

Overall, VOC concentrations were higher on site A, especially on A1. This was confirmed by the results of TVOC's measurements (table 4). The implementation of soft floors seemed to be the stage with the highest TVOC levels. TVOC concentrations measured were well above the TVOCs identified levels.

Figure 1 presents the VOC proportions at each construction stage according to the chemical classes. They were calculated by the sum of VOCs in each chemical class divided by the sum of all VOCs measured on the same site/floor. Chemical classes of alcohols, ketones, ethers, halogenated hydrocarbons, phenols and terpenes are grouped in the category “others” because of the very low concentrations of these compounds. The average concentration at the three floors (ground floor, first floor, second floor) was used for site B while the distinction between the garden ground and the first floor was retained for Site A because of a shift in the progress of construction works. This figure allows to identify the majority chemical classes at each construction phase on each site.

Aromatic hydrocarbons and aldehydes were the two main chemical classes of VOCs at the two first construction stages. Aldehydes were the main chemical classes in almost all the other construction stages. During the implementation of soft floors, there were a large amount of aliphatic hydrocarbons. During the last finishing works, aliphatic hydrocarbons were in high concentrations on site B. At delivery, there was an important percentage of glycol ethers on site A.

The evolution of the concentrations of the two main aldehydes measured at delivery is presented in Figures 2 and 3.

On site A, a peak of formaldehyde was observed during the application of finish paint, especially on A1. A second peak was observed on A0 and A1 during the last finishing works. Formaldehyde concentrations remained relatively high at delivery despite the start of the ventilation system, contrary to the site B where the ventilation system was not started. On Site B, formaldehyde concentrations started to increase during the application of finish paints and the peak was observed during the implementation of soft floors.

A peak of hexaldehyde was observed on A1 during the application of finish paints. A shift in the application of finish paints was observed between A0 and A1, it explains that a peak was observed on A0 during the implementation of soft floors. On site B, levels increased with the implementation of soft floors and the last finishing works to stay relatively high at delivery.

SVOCs

Results of SVOC measurements are presented in Table 5. Results with the LOQ of our samples are presented in Table S5. 22 compounds were never quantified above the LOQ: aldrine, dieldrine, 4,4’-DDT, 4-4’-DDE, lindane, alpha-endosulfan, ethyl chlorpyrifos, diazinon, PCBs 28, 31, 52, 101, 105, 118, 138, 153, 180, PBDEs 47, 85, 99, 100, 153.

Three polycyclic aromatic compounds (PAHs) were found in the dust from ventilation ducts: fluoranthene, fluorene and phenanthrene. Other PAHs were found on airborne PM_{10}. At each measured stage, phthalates were found in high concentrations on PM_{10}. DiNP and DEHP were predominant. Permethrin was also present. Musks were found on site B, especially at delivery. Triclosan was detected at each measured stage.

Mold

Results of mold analysis and associated ambient parameters measured with HOBOs are presented in Table 6.

The first two stages were characterized by a high humidity rate, reaching 80% on the two sites. During the preparation of supports, concentrations of mold indoor was higher than outdoor, especially on site A with a concentration reaching 1400 CFU/m^3 in A1 when the median percentage of humidity was the highest (81 %). On site B, all genera (*Aspergillus*, *Penicillium*, *Cladosporium* and *Alternaria*) were in higher concentrations indoor than outdoor. During the application of finish paints, the airborne mold concentrations was twofold higher on A0, reaching 1000 CFU/m^3. At delivery on site B, the mold concentrations indoor were lower than outdoors. All along the construction process, *Cladosporium* was the most commonly detected genus.

No mold was detected in ventilation ducts during the application of finish paints on ground floor on site A but the presence of mold was revealed on the first floor (1 CFU/dm^2).

Discussion

Overall, concentrations were higher on site A because this construction site was more confined than site B and succession of construction stages was quicker. The comparison between the two sites highlights the importance of natural ventilation, a delay between the sequence of tasks, the materials and products selection used during the construction process to reduce the concentrations of pollutants in indoor air.

VOCs

Concentrations of VOCs measured on site A at delivery were compared to the medians of concentrations measured in office buildings included in the European project OFFICAIR [48]. This European project comprises indoor air quality measurements in office buildings distributed among eight participated countries. 37 office buildings were included in the summer campaign (2012) and 35 in the winter campaign (2012-2013), a total of 148 rooms were investigated.

Concentrations of VOCs on site B at delivery were compared to the medians of the annual average concentrations measured in energy-efficient buildings from the OQAI's national indoor air quality reference database [49]. The study was carried out on the basis of validated and complete survey data included in the database on May 2015. 72 dwellings were investigated and they had an average air permeability of 0.54 $m^3/(h.m^2)$ for individual houses and 0.86 for collective dwellings to 4 Pa, approximatively as the buildings investigated in this project.

The comparison between the concentrations measured in this project and these two other databases are presented in Table 7.

For site A, data are of the same order of magnitude between both projects except concentrations of formaldehyde and 2-butoxyéthanol which reached twice the values observed in the project OFFICAIR.

For site B, most of compounds were measured at concentrations of the same order of magnitude of the OQAI's values. Concentrations are four times lower than the OQAI's data for formaldehyde and concentrations of hexaldehyde reached twice the value of OQAI. Concentrations of styrene are much higher than the OQAI's value. Finally, concentrations of limonene are well under the OQAI's value.

The low concentrations of benzene and trichloroethylene may be due to the regulation of 2009 on the conditions for placing on the market construction and decoration products containing carcinogenic, mutagenic and reprotoxic substances [40].

In this project, the overall compounds content measured with the Fireflies station are well above the sum of each VOCs identified concentrations. It suggests that either gas detection interferes with the measurement or a significant portion of VOCs was not identified in this project. Therefore, for future investigations, it would be necessary to expand measurements to other volatile compounds. Moreover, sensor sensitivity to alcohols (used for disinfection during mold sampling) has been highlighted during the project.

Regarding potential sources of formaldehyde, wood based panels are an important source of formaldehyde [50]. Melamine wood panels have been installed in the sill of all the windows on site A, which could explain the difference of formaldehyde concentrations between the two sites. About hexaldehyde, measured levels at delivery on site B could be linked to the wooden frame façade. Considering their high mobility, VOCs could penetrate through materials and diffuse into buildings. High concentrations of hexaldehyde with wood frame façade has also been observed during air quality measurements at delivery of an eco-district in Langoüet, France [51]. During the measurement campaign carried out during the installation of soft floors, the storage of soft floors in the living room on B0 (room used for the storage of soft floors before their installation) does not seem to have had an impact on the concentrations of VOCs in the air, as the concentrations were not different from the measurements in the other rooms. Glycol ethers and limonene present at delivery on site A, were probably emitted by the cleaning products [52, 53]. Professional cleaning products were used on site A before delivery for dust removal, removal of stains (cement), labels on certain products, cleaning of floors and glazing and joinery, disinfection of toilets (mainly on site A as it is an establishment open to the public). On site B, less emissive processes were used, including steam cleaning.

In order to assess the potential health impact for future occupants related to the presence and levels of the studied pollutants in indoor air, a comparison with recent guideline values applicable in occupied indoor environments was carried out. Values are reported in Table S6. Some IAGV, strictly based on health criteria, were proposed by the European Commission or by the French Agency for Food, Environmental and Occupational Health & Safety (Anses) [54-59]. In 2009, the French High Council for Public Health (HCSP) recommended reference values for management support in confined spaces for new buildings delivered from 2012, as well as to initiate corrective actions if necessary in existing buildings [60-61]. In France, regulatory values have been set for benzene and formaldehyde and must not be exceed indoors [62].

At delivery, concentrations measured are well under the guideline values for acetaldehyde, benzene, ethylbenzene, styrene, toluene and xylenes. The IAGV short term of 100 $\mu g/m^3$ proposed by Anses for formaldehyde has not been exceeded but the concentration on A1 reached the regulatory value and the reference value of the HCSP of 30 $\mu g/m^3$ [61, 62]. The value of 10 $\mu g/m^3$ proposed as target value to be achieved in 10 years by the HSCP was exceeded on A0 and A1. In France, this value will be a regulatory value in 2023.

On sites A and B, with the evolution of construction materials (use of less emissive materials) and with the application of the 2012 French Thermal Regulation and considering the VOCs individually, the measured levels respected the guide values at the delivery of buildings, but not the future regulatory value applicable in 2023. Nevertheless, concentrations measured at delivery (therefore over a short period of time) are compared with guidelines values intended for long-term exposure, such as for formaldehyde and benzene. This is a limitation that is important to note.

SVOCs

Regarding dust from ventilation ducts, dust can accumulate on ducts during the manufacturing process but also during the various phases of storage, transportation and construction [63]. In this project, PAHs measured in the dust from ventilation ducts probably came from degreasing oils and solvents used in the factory for the manufacture of ventilation ducts, as described by Holopainen et al. and Asikainen *et al.* [64, 65]. This project support the recommendation that ducts should be cleaned and protected against impurities during transport, storage and construction [64, 66, 67].

Regarding PM_{10}, the high concentrations of PAHs measured at delivery on site B can be explained by the use of tobacco reported on site B [68, 69]. Regarding to the high diversity of phthalates, the dominant plasticizer for flexible polyvinyl chloride flooring was DEHP for many years, but DiNP replaced phthalates such as DEHP, DBP, BBP, due to their potential adverse health effects [15, 16]. A restriction of their use was observed in several products in Europe and an emission threshold of 1 µg/m3 has been implemented for DEHP and DBP. About pesticides, permethrin is known to be used for wood protection [70]. About antimicrobial agent, triclosan is widely used in various personal care and consumer products [71, 72]. No data are available on triclosan concentrations during the construction process but Mandin *et al.* measured SVOCs on PM10 filters collected over 7 days during a nationwide survey of 285 French dwellings and found that triclosan was one of the major particle-bound SVOCS with a median concentration of 114 pg/m^3 [47]. Measurements were conducted from October 2003 to December 2005. On 2014, it has been banned for use in the treatment of construction products and materials since a decision made by the European Commission [73]. Triclosan is an endocrine disruptor and is associated with reproductive and developmental outcomes in animal and *in vitro* studies and toxicological studies suggest that it can affect endocrine function and antibiotic resistance in human [74]. In this study, triclosan was found at the three construction stages measured. The source of triclosan has not been identified in this project.

Mold

The first stages after the structural work seem to be critical stages in relation to the increase of moisture content. This is related to the increase of mold concentrations which reached and exceeded the value of 1000 CFU/m^3 proposed by Anses as abnormal concentration in total molds and requiring professional intervention for remediation [75].

These observations raise questions about the management of moisture on construction sites as long as exposure to mold in a work building was associated with the incidence and exacerbations of occupational asthma for adults and visible mold and mold odor were associated with the development and exacerbations of asthma in children [21]. Moreover, according to Caillaud *et al*., mold exposure is associated with allergic rhinitis [21].

In a recent study, Reboux *et al.* analyze indoor fungi by cultures of airborne samples from 1012 dwellings [76]. 908 patients suffering from rhinitis, conjunctivitis, and asthma were compared to

104 controls free of allergies. Reboux *et al*. stated that a threshold of 495 UFC/m^3 of *Cladosporium* is able to discriminate 90% of asthmatics. This value is almost reached at different stages suggesting the need of intervention to limit the humidity to avoid development of molds: respect of drying times, add ventilation during the construction stage, protect moisture-sensitive materials (plasterboard, insulation, wood panels, interior wood joinery) [66].

In France, Ginestet *et al.* showed fungal contamination in two buildings in use that can be considered low (< 100 CFU/m^3) [77]. Nevertheless, the authors considered that the very high rate of air exchange inside the buildings may explain these low values. This is in accordance with the BASE study carried out in the United States on 100 offices buildings showing the presence of spores (on average 274 sp/m^3) and fungi (on average 99 CFU/m^3) in the indoor environment of office buildings where no known health problems have been demonstrated [78].

Conclusion

At delivery, VOCs, SVOCs and mold were detected, including one compound banned on construction products and two compounds with limited emission rates.

- Low concentrations of VOCs were measured at delivery, in relation to the use of low emissive materials (class A+): regarding to VOCs, the construction phase involves but does not lead to exceedances of the guide values established to date, but one value exceeded the future regulatory value applicable in 2023.
- 11 PAHs, 6 phthalates, permethrin and triclosan were measured at delivery. There is no exposure limit or emission control on construction sites for SVOCs despite the endocrine disruptive effect of some of these molecules.
- Regarding mold concentrations and humidity rates, the increase of building insulation leads to an increase in humidity rates that can be related to the increased incidence of respiratory diseases, highlighting the need for moisture management measures on construction sites.

Contamination during construction can be linked to all the processes implementation: choice of materials, transportation and storage (impact of weather conditions), construction processes and assembly of the various products, sequence of tasks and construction sequencing. These results need to be confirmed by more measurements to obtain a better estimate of the distribution of concentrations. Finally, management measures must be implemented in the same time as energy-saving measures to limit the impact of SVOC concentrations or mold growth on indoor air quality and more research must be conducted to assess cumulative exposure to these pollutants and the risk for health of the future occupants.

References

1. Klepeis NE, Nelson WC, Ott WR, et al. The National Human Activity Pattern Survey (NHAPS): a resource for assessing exposure to environmental pollutants. Journal of Exposure Science & Environmental Epidemiology. 2001;11(3):231-252.
2. Matz CJ, Stieb DM, Davis K, et al. Effects of age, season, gender and urban-rural status on time-activity: CanadianHuman Activity Pattern Survey 2 (CHAPS 2). Int J Environ Res Public Health. 2014;11(2):2108-2124.
3. Kirchner S, Derbez M, Duboudin C, et al. Indoor air quality in French dwellings. Indoor Air 2008. Copenhagen, Denmark 2008:Paper ID 574, 578 pages
4. Song G, Yu A, Sakai K, et al. Levels of volatile organic compounds in homes in Dalian, China. Air Quality, Atmosphere & Health. 2016;10(2):171-181.

5. Bari MA, Kindzierski WB, Wheeler AJ, et al. Source apportionment of indoor and outdoor volatile organic compounds at homes in Edmonton, Canada. Building and Environment. 2015;90:114-124.

6. Rudel RA, Dodson RE, Perovich LJ, et al. Semivolatile Endocrine-Disrupting Compounds in Paired Indoor and Outdoor Air in Two Northern California Communities. Environmental Science & Technology. 2010;44(17):6583-6590.

7. Kristensen K, Lunderberg DM, Liu Y, et al. Sources and Dynamics of Semivolatile Organic Compounds in a Single-Family Residence in Northern California. Indoor Air. 2019;Accepted Author Manuscript.

8. Osborne M, Reponen T, Adhikari A, et al. Specific fungal exposures, allergic sensitization, and rhinitis in infants. Pediatric Allergy and Immunology. 2006;17(6):450-457.

9. Reboux G, Bellanger AP, Roussel S, et al. Indoor mold concentration in Eastern France. Indoor Air. 2009;19(6):446-453.

10. Billionnet C, Gay E, Kirchner S, et al. Quantitative assessments of indoor air pollution and respiratory health in a population-based sample of French dwellings. Environ Res. 2011;111(3):425-434.

11. Tsai W-T. An overview of health hazards of volatile organic compounds regulated as indoor air pollutants. Reviews on Environmental Health. 2019;34(1):81-89.

12. International Agency for Research on Cancer (IARC). IARC Monographs on the Evaluation of Carcinogenic Risks to Humans. Available: https://monographs.iarc.fr/wp-content/uploads/2018/06/mono88.pdf. Accessed June 25, 2019.

13. Fournier K, Glorennec P, Bonvallot N. An exposure-based framework for grouping pollutants for a cumulative risk assessment approach: Case study of indoor semi-volatile organic compounds. Environmental Research. 2014;130:20-28.

14. Fournier K, Baumont E, Glorennec P, et al. Relative toxicity for indoor semi volatile organic compounds based on neuronal death. Toxicol Lett. 2017;279:33-42.

15. Weschler CJ, Nazaroff WW. Semivolatile organic compounds in indoor environments. Atmospheric Environment. 2008;42(40):9018-9040.

16. Blanchard O, Glorennec P, Mercier F, et al. Semivolatile organic compounds in indoor air and settled dust in 30 French dwellings. Environ Sci Technol. 2014;48(7):3959-3969.

17. Pelletier M, Bonvallot N, Ramalho O, et al. Indoor residential exposure to semivolatile organic compounds in France. Environ Int. 2017;109:81-88.

18. Le Cann P, Bonvallot N, Glorennec P, et al. Indoor environment and children's health: recent developments in chemical, biological, physical and social aspects. Int J Hyg Environ Health. 2011;215(1):1-18.

19. Sharpe RA, Bearman N, Thornton CR, et al. Indoor fungal diversity and asthma: a meta-analysis and systematic review of risk factors. J Allergy Clin Immunol. 2015;135(1):110-122.

20. Oluwole O, Kirychuk SP, Lawson JA, et al. Indoor mold levels and current asthma among school-aged children in Saskatchewan, Canada. Indoor Air. 2017;27(2):311-319.

21. Caillaud D, Leynaert B, Keirsbulck M, et al. Indoor mould exposure, asthma and rhinitis: findings from systematic reviews and recent longitudinal studies. Eur Respir Rev. 2018;27(148).

22. Shin SH, Jo WK. Volatile organic compound concentrations, emission rates, and source apportionment in newly-built apartments at pre-occupancy stage. Chemosphere. 2012;89(5):569-578.

23. Hodgson AT, Rudd AF, Beal D, et al. Volatile organic compound concentrations and emission rates in new manufactured and site-built houses. Indoor Air-Int J Indoor Air Qual Clim. 2000;10(3):178-192.

24. Jang SK, Ryu JM, Park JH, et al. Comparison of indoor air quality at the pre-occupancy stage in new apartments by two different construction time in Korea. Indoor Air 2008. Copenhagen, Denmark 2008:Paper ID: 93.

25. Mendell MJ, Fisk WJ, Kreiss K, et al. Improving the health of workers in indoor environments: priority research needs for a national occupational research agenda. Am J Public Healh. 2002;92(9):1430-40.

26. Liu J, Zhai JZ, Pei J, et al. Measurement and Assessment of VOC and Formaldehyde Contamination During the Construction of a New Museum in China. ASHRAE Transactions. 2007;113(2):355-361.

27. Pang SK, Cho H, Sohn JY, et al. Assessment of the Emission Characteristics of VOCs from Interior Furniture Materials during the Construction Process. Indoor and Built Environment. 2007;16(5):444-455.

28. Park JC, Kwon YC, Jun HD. A Study on the Improvement of Indoor Air Quality of Newly-Built Apartment Houses Using Low Emission Building Materials. Journal of Asian Architecture and Building Engineering. 2011;10(1):235-240.

29. Liang W, Wang C, Yang C, et al. Volatile organic compounds in different interior construction stages of an apartment. Building and Environment. 2014;81:380-387.

30. Ochs SD, Furtado LD, Cerqueira WV, et al. Characterization of the variation of carbonyl compounds concentrations before, during, and after the renovation of an apartment at Niteroi, Brazil. Environ Sci Pollut Res. 2016;23(15):15605-15615.

31. Plaisance H, Vignau-Laulhere J, Mocho P, et al. Volatile organic compounds concentrations during the construction process in newly-built timber-frame houses: source identification and emission kinetics. Environ Sci Process Impacts. 2017;19(5):696-710.

32. Liang W, Yang C, Yang X. Long-term concentrations of volatile organic compounds in a new apartment in Beijing, China. Building and Environment. 2014;82:693-701.

33. Herbarth O, Matysik S. Decreasing concentrations of volatile organic compounds (VOC) emitted following home renovations. Indoor Air. 2010;20(2):141-146.

34. Park JS, Ikeda K. Variations of formaldehyde and VOC levels during 3 years in new and older homes. Indoor Air. 2006;16(2):129-135.

35. Nicolas M, Ramalho O, Maupetit F. Reactions between ozone and building products: Impact on primary and secondary emissions. Atmospheric Environment. 2007;41(15):3129-3138.

36. Sautour M, Sixt N, Dalle F, et al. Prospective survey of indoor fungal contamination in hospital during a period of building construction. J Hosp Infect. 2007;67(4):367-373.

37. Dedesko S, Siegel JA. Moisture parameters and fungal communities associated with gypsum drywall in buildings. Microbiome. 2015;3:71.

38. Cooper AM. Mold susceptibility of rapidly renewable materials used in wall construction. Available: https://core.ac.uk/download/pdf/4276521.pdf. Accessed June 26, 2019.

39. Weschler CJ. Changes in indoor pollutants since the 1950s. Atmospheric Environment. 2009;43(1):153-169.

40. Legifrance. Arrêté du 28 mai 2009 modifiant l'arrêté du 30 avril 2009 relatif aux conditions de mise sur le marché des produits de construction et de décoration contenant des substances cancérigènes, mutagènes ou reprotoxiques de catégorie 1 ou 2. Available:

https://www.legifrance.gouv.fr/affichTexte.do?cidTexte=LEGITEXT000020679250. Accessed June 25, 2019.

41. Legifrance. Arrêté du 19 avril 2011 relatif à l'étiquetage des produits de construction ou de revêtement de mur ou de sol et des peintures et vernis sur leurs émissions de polluants volatils. Available: https://www.legifrance.gouv.fr/affichTexte.do?cidTexte=JORFTEXT000023991852&categorieLien=id. Accessed June 25, 2019.

42. Ministère de l'Ecologie, du Développement durable, des Transports et du Logement. Réglementation thermique 2012: un saut énergétique pour les bâtiments neufs. Available: https://www.ecologique-solidaire.gouv.fr/sites/default/files/RT%202012%20-%20un%20saut%20%C3%A9nerg%C3%A9tique%20pour%20les%20b%C3%A2timents%20neufs%20-%20Avril%202011.pdf. Accessed June 25, 2019.

43. Bonvallot N, Mandin C, Mercier F, et al. Health ranking of ingested semi-volatile organic compounds in house dust: an application to France. Indoor Air. 2010;20(6):458-472.

44. Dallongeville A, Le Cann P, Zmirou-Navier D, et al. Concentration and determinants of molds and allergens in indoor air and house dust of French dwellings. Sci Total Environ. 2015;536:964-972.

45. Hager Services Environment. Fiche technique Fireflies. Available: https://pro.hagerservices.fr/wp-content/uploads/sites/2/2017/08/HSE-Fiche-technique-fireflies.pdf. Accessed June 25, 2019.

46. Baures E, Blanchard O, Mercier F, et al. Indoor air quality in two French hospitals: Measurement of chemical and microbiological contaminants. Sci Total Environ. 2018;642:168-179.

47. Mandin C, Mercier F, Ramalho O, et al. Semi-volatile organic compounds in the particulate phase in dwellings: A nationwide survey in France. Atmospheric Environment. 2016;136:82-94.

48. Mandin C, Trantallidi M, Cattaneo A, et al. Assessment of indoor air quality in office buildings across Europe - The OFFICAIR study. Sci Total Environ. 2017;579:169-178.

49. Derbez M, Wyart G, Le Ponner E, et al. Indoor air quality in energy-efficient dwellings: Levels and sources of pollutants. Indoor Air. 2018;28(2):318-338.

50. Kim S, Kim J-A, Kim H-J, et al. Determination of formaldehyde and TVOC emission factor from wood-based composites by small chamber method. Polymer Testing. 2006;25(5):605-614.

51. Blanchard O. Suivi de la qualité de l’air intérieur dans les habitations de l’éco-lotissement de la Pelousière à Langouët (35) Available: https://www.bruded.fr/wp-content/uploads/2017/08/rapportlangouet.pdf. Accessed June 27, 2019.

52. Nazaroff WW, Weschler CJ. Cleaning products and air fresheners: exposure to primary and secondary air pollutants. Atmospheric Environment. 2004;38(18):2841-2865.

53. Gerster FM, Vernez D, Wild PP, et al. Hazardous substances in frequently used professional cleaning products. Int J Occup Environ Health. 2014;20(1):46-60.

54. Anses. Proposition de valeurs guides de qualité d'air intérieur : l'acétaldéhyde. Available: https://www.anses.fr/fr/system/files/AIR2013sa0076Ra.pdf. Accessed June 25, 2016.

55. Anses. Valeurs guides de qualité d'air intérieur : le benzène. Available: https://www.anses.fr/fr/system/files/AIR2004etVG004Ra.pdf. Accessed June 25, 2019.

56. Anses. Proposition de valeurs guides de qualité d'air intérieur : l'éthylbenzène. Available: https://www.anses.fr/fr/system/files/AIR2013SA0136Ra.pdf. Accessed June 25, 2019.

57. Anses. Mise à jour de valeurs guides de qualité d'air intérieur : le formaldéhyde. Available: https://www.anses.fr/fr/system/files/AIR2017SA0041Ra.pdf. Accessed June 25, 2019.

58. Anses. Proposition de valeurs guides de qualité d'air intérieur : le toluène. Available: https://www.anses.fr/fr/system/files/AIR2016SA0043Ra.pdf. Accessed June 25, 2019.

59. European Commission. The INDEX project: critical appraisal of the setting and implementation of indoor exposure limits in the EU. Available: http://publications.jrc.ec.europa.eu/repository/bitstream/JRC31622/1622%20-%20INDEX%20%20EUR%2021590%20EN%20report[1].pdf. Accessed June 25, 2019.

60. HCSP. Valeurs repères d'aide à la gestion dans l'air des espaces clos : le benzène. Available: https://www.hcsp.fr/docspdf/avisrapports/hcspr20100616_benzenespclos.pdf. Accessed June 25, 2019.

61. HCSP. Valeurs repères d'aide à la gestion dans l'air des espaces clos : le formaldéhyde. Available: https://www.hcsp.fr/docspdf/avisrapports/hcspr20091013_airesclosForm.pdf. Accessed June 25, 2019.

62. Legifrance. Décret n° 2011-1727 du 2 décembre 2011 relatif aux valeurs-guides pour l'air intérieur pour le formaldéhyde et le benzène Available: https://www.legifrance.gouv.fr/affichTexte.do?cidTexte=JORFTEXT000024909119&categorieLien=id. Accessed July 1, 2019.
63. Pasanen P. Emissions from filters and hygiene of air ducts in the ventilation systems of office buildings: University of Kuopio, Department of Environmental Sciences 1998.
64. Holopainen R, Tuomainen M, Asikainen V, et al. The effect of cleanliness control during installation work on the amount of accumulated dust in ducts of new HVAC installations. Indoor Air. 2002;12(3):191-197.
65. Asikainen V, Pasanen P, Liesivuori J. Mineral oil residues on HVAC components: measuring methods. Building and Environment. 2003;38(8):1057-1061.
66. AQC. Penser qualité de l'air intérieur en phase chantier - Guide méthodologique Available: http://www.qualiteconstruction.com/sites/default/files/2019-05/PT-Qualite-Air-Interieur-Phase-Chantier-Guide-Methodologique.pdf. Accessed June 27, 2019.
67. AQC. Penser qualité de l'air intérieur lors de la phase chantier. Available: http://www.qualiteconstruction.com/sites/default/files/2019-05/PT-Qualite-Air-Interieur-Phase-Chantier.pdf. Accessed 10 July, 2019.
68. Ding YS, Ashley DL, Watson CH. Determination of 10 Carcinogenic Polycyclic Aromatic Hydrocarbons in Mainstream Cigarette Smoke. Journal of Agricultural and Food Chemistry. 2007;55(15):5966-5973.
69. Vu AT, Taylor KM, Holman MR, et al. Polycyclic Aromatic Hydrocarbons in the Mainstream Smoke of Popular U.S. Cigarettes. Chem Res Toxicol. 2015;28(8):1616-1626.
70. Class TJ, Kintrup J. Pyrethroids as household insecticides: analysis, indoor exposure and persistence. Fresenius' journal of analytical chemistry. 1991;340(7):446-453.
71. Bedoux G, Roig B, Thomas O, et al. Occurrence and toxicity of antimicrobial triclosan and by-products in the environment. Environ Sci Pollut Res Int. 2012;19(4):1044-1065.
72. Halden RU, Lindeman AE, Aiello AE, et al. The Florence Statement on Triclosan and Triclocarban. Environ Health Perspect. 2017;125(6):064501.
73. European Commission. Décision d'éxécution de la commission du 24 avril 2014 concernant la non-approbation de certaines substances actives biocides en vertu du règlement

(UE) no 528/2012 du Parlement européen et du Conseil Available: https://eur-lex.europa.eu/legal-content/FR/TXT/PDF/?uri=CELEX:32014D0227. Accessed June 25, 2019.

74. Goodman M, Naiman DQ, LaKind JS. Systematic review of the literature on triclosan and health outcomes in humans. Crit Rev Toxicol. 2018;48(1):1-51.

75. Anses. Moisissures dans le bâti Available: https://www.anses.fr/fr/system/files/AIR2014SA0016Ra.pdf. Accessed June 25, 2019.

76. Reboux G, Rocchi S, Laboissiere A, et al. Survey of 1012 moldy dwellings by culture fungal analysis: Threshold proposal for asthmatic patient management. Indoor Air. 2019;29(1):5-16.

77. Ginestet A, Ribot B, Henninot M, et al. Indoor air quality in two different office buildings-part 2: Indoor and outdoor airborne particulate levels and air filtration. "Proceedings of Indoor Air 2002 (9th International Conference on Indoor Air Quality and Climate) – June 30 – July 5, 2002 – Monterey, California – vol 4, pp 494-499

78. Tsai FC, Macher J.M. Concentrations of airborne culturable bacteria in 100 large US office buildings from the BASE study. Indoor Air. 2005; 15: 71-81.

Tables

Table 1 Details of the measurement campaigns realized in air and dust

Construction stage	Construction site	Measurement campaigns	Analyzed parameters [†]	Measurement matrix	Location	Sampling duration
Initial state	A	February 22 to 26, 2016	TVOCs	Air	A1	Continuously
			VOCs	Air	A0, A1	5 days
	B	January 10, 2017	TVOCs	Air	B2	Continuously
			VOCs	Air	B0, B1, B2	6,5 hours
			Mold	Air	Outdoor, B0, B1, B2	30 seconds
Preparation of supports	A	April 4, 2016	TVOCs	Air	A1	Continuously
			Mold	Air	Outdoor, A0, A1	30 seconds
		April 18 to 22, 2016	TVOCs	Air	A1	Continously
			VOCs	Air	A0, A1	5 days
	B	February 28, 2017	TVOCs	Air	B2	Continuously
			Mold	Air	Outdoor, B0, B1, B2	30 seconds
		April 13, 2017	TVOCs	Air	B2	Continuously
			VOCs	Air	B0, B1, B2	6,5 hours
		April 14, 2017	TVOCs	Air	B2	Continuously
			Mold	Air	Outdoor, B0, B1, B2	30 seconds
Finish paints	A	May 13, 2016	TVOCs	Air	A1	Continuously
			VOCs (except aldehydes)	Air	A0, A1	180 minutes
			Mold	Air	Outdoor, A0, A1	30 seconds
			SVOCs	Dust from ventilation ducts	Ground floor, first floor	-
			Mold	Dust from ventilation ducts	Ground floor, first floor	-
		May 25, 2016	TVOCs	Air	A1	Continuously
			Aldehydes	Air	A0, A1	390 minutes
	B	May 2, 2017	TVOCs	Air	B2	Continuously
			VOCs	Air	B0, B1, B2	6,5 hours
Soft floors	A	June 3, 2016	TVOCs	Air	A1	Continuously
			VOCs	Air	A0	6,5 hours
		June 8, 2016	TVOCs	Air	A1	Continously
			VOCs	Air	A1	6,5 hours
	B	August 4 to 7, 2017	TVOCs	Air	B2	Continuously
			VOCs	Air	B0, B0 living-room [‡], B2	6,5 hours
			Mold	Air	Outdoor, B0, B0 living-room, B2	30 seconds
			SVOCs	Airborne PM_{10}	B2	96 hours
Last fnishing works	A	June 21 to 24, 2016	TVOCs	Air	A1	Continuously
			VOCs	Air	A0, A1	6,5 hours
			SVOCs	Airborne PM_{10}	A1	72 hours
	B	September 19, 2017	TVOCs	Air	B2	Continously
			VOCs	Air	B0, B1, B2	6,5 hours
			Mold	Air	Outdoor, B0, B1, B2	30 seconds
Delivery	A	July 27, 2016	TVOCs	Air	A1	Continuously
			VOCs	Air	A0, A1	6,5 hours
	B	October 3 to 6, 2017	TVOCs	Air	B2	Continuously
			VOCs	Air	B0, B1, B2	6,5 hours
			Mold	Air	Outdoor, B0, B1, B2	30 seconds
			SVOCs	Airborne PM_{10}	B2	96 hours

[†] VOCs: volatile organic compounds; SVOCS: semi-volatile organic compounds; TVOCs: total volatile organic compounds; [‡] Measurement in the living-room on the ground floor

725

Table 2 List of pollutants analyzed

Types of pollutants (number of substances)		Substances
Chemical		
VOCs (43)	Aldehydes (11)	- Formaldehyde, acetaldehyde, propionaldehyde, butyraldehyde, benzaldehyde, isovaleraldehyde, valeraldehyde, hexaldehyde, o-tolualdehyde, m-tolualdehyde, p-tolualdehyde
	Alcohols (4)	- Ethanol, isopropanol, n-propanol, 2-ethyl-1-hexanol
	Ketones (2)	- Acetone, 2-butanone
	Chlorobenzenes (1)	- 1,4-Dichlorobenzene
	Ethers (1)	- Ether
	Glycol ethers (3)	- 2-butoxyethanol, 2-ethoxyethanol, phenoxyethanol
	Aliphatic hydrocarbons (3)	- n-heptane, n-decane, n-undecane
	Halogenated hydrocarbons (7)	- Chloroforme, 1,1,1-trichloroethane, trichloroethylene, bromodichloromethane, tetrachloroethylene, dibromochloromethane, tribromomethane
	Aromatic hydrocarbons (9)	- Benzene, toluene, ethylbenzene, xylenes (o, m,p), styrene, 1,2,4-trimethylbenzene, naphtalene
	Phenols (1)	- Phenol
	Terpenes (1)	- Limonene
SVOCs (46)	Phthalates (6)	- Benzylbutylphthalate (BBP), dibutylphthalate (DBP), di(2-ethylhexyl)phthalate (DEHP), diethylphthalate (DEP), diisononylphthalate (DiNP), diisobutylphthalate (DiBP)
	Musks (2)	- Galaxolide, tonalide
	Pyerthroids (1)	- Permethrin
	Organochlorine pesticides (7)	- Aldrin, dieldrin, 4,4'-DDT, 4,4'-DDE, alpha-ICH, lindane, alpha-endosulfan
	Organophosphorous pesticides (2)	- Ethyl chlorpyrifos, diazinon
	Others pesticides (1)	- Oxadiazon
	Phosphoric esters (1)	- Tributylphosphate
	Polycyclic aromatic hydrocarbons (PAHs) (11)	- Anthracene, benzo[a]pyrene,fluoranthene, fluorene, phenanthrene, pyrene, benzo[b]fluoranthene, benzo[k]fluoranthene, dibenzo[a,h]anthracene, indeno[1,2,3-cd]pyrene, benzo[a]anthracene
	Polychlorobiphenyls (PCBs) (9)	- PCB 28, PCB 31, PCB 52, PCB 101, PCB 105, PCB 118, PCB 138, PCB 153, PCB 180
	Polybromodiphenylethers (PBDEs) (5)	- PBDE 47, PBDE 85, PBDE 99, PBDE 100, PBDE 153
	Others (1)	- Triclosan
Microbiological		
Mold (4)		- *Aspergillus* , *Penicillium* , *Cladosporium* , *Alternaria*

Table 3 Volatile organic compounds concentrations (µg/m³) in air

VOCs †	Concentrations (µg/m³) ‡																													
	Intial state					Preparation of supports					Finish paints					Soft floors					Last finishing works					Delivery				
	A0	A1	B0	B1	B2	A0	A1	B0	B1	B2	A0	A1	B0	B1	B2	A0	A1	B0	B0 (living room)	B2	A0	A1	B0	B1	B2	A0	A1	B0	B1	B2
Aldehydes																														
Formaldehyde	-	-	-	-	-	5.4	6.2	-	5.5	2.4	21.8	70.8	15.5	6.1	13.5	8.6	32.2	26.5	21.8	31.6	37.2	36.8	5.7	6.3	9.4	18.3	35.9	-	4.5	4.8
Acetaldehyde	2.2	-	-	-	-	8.1	9.2	7.5	4.8	2.9	16.4	43.4	140.2	22.4	300.2	15.5	20	10	9.7	13.6	12.1	7.9	8.6	7.3	12.5	5.6	8.6	4	9.4	8.8
Propionaldehyde	-	-	-	-	15.7	-	2.7	-	-	-	-	22.2	2.3	-	3.2	14.1	4.3	2.4	2.1	2.9	3.2	-	2.6	3.1	4.7	-	-	-	2.2	-
Butyraldehyde	10.3	10	-	-	-	-	-	3	2.1	-	-	12	2.5	-	6	4	5.2	3.8	4.1	5.7	4.3	3.1	2.4	3	4.1	-	2.3	-	8.3	11.6
Benzaldehyde	-	1.1	-	68.3	21.7	1.6	1.3	-	-	-	3.4	6	6.4	7.3	28.9	-	13.2	15.9	8.2	8.4	7.8	3.1	3	4	6.4	-	-	3.7	11.8	10.9
Isovaleraldehyde	-	-	-	-	-	2	2.3	-	-	-	-	6.3	3.9	-	6	-	2.5	7	7.3	-	3.4	-	-	-	2.5	-	-	-	2.9	2.9
Valeraldehyde	-	-	-	-	-	-	-	-	-	-	4.5	63.4	7.3	-	-	14.3	15.3	5.3	5.8	9.8	6.9	4.7	4.1	5.8	7.6	3	2.7	-	5.5	5.5
Hexaldehyde	-	-		-	-	16.3	18	9.3	6.3	5.2	22.2	497.3	7.9	3.6	9.7	118.2	85.4	23.8	21.7	30	26.9	15.5	32.9	41.1	53.1	7.4	8.7	11.9	44.3	38.2
o-Tolualdehyde	NT	NT		-	-	NT	NT	-	-	-	9.1	-	-	-	-	-	14.2	-	-	-	-	-	-	2.3	5.1	-	-	-	-	-
m-Tolualdehyde	NT	NT		-	-	NT	NT	2.5	-	-	-	-	-	-	13.2	-	-	3.9	3.2	-	-	-	2.4	-	-	-	-	-	-	-
Alcohols																														
Ethanol	NT	NT	-	-	-	NT	NT	-	-	-	61.98 §	190.73 §	-	-	5.47	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Isopropanol	NT	NT	-	-	-	NT	NT	-	-	-	1.72	7.3	-	-	-	-	-	-	-	-	-	-	9.5	-	9.3	-	-	-	-	-
2-Ethyl-1-hexanol	NT	NT	-	-	-	NT	NT	-	-	-	-	-	-	-	-	-	-	-	-	-	5.67	-	-	-	16.2	-	-	-	-	7.2
Ketones																														
Acetone	NT	NT	-	-	-	NT	NT	-	-	2.48	-	1.33	-	-	-	-	-	-	-	5.44	-	-	1.4	1.6	15.1	-	-	-	-	-
2-butanone	NT	NT	10.34	16.5	5.81	NT	NT	-	-	-	5.28	22.93	-	-	-	8.73	4.63	-	-	-	-	-	-	-	20.1	-	-	-	-	-
Ethers																														
Ether	NT	NT	-	-	-	NT	NT	-	-	-	-	-	-	-	5.65	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Glycol ethers																														
2-Butoxyethanol	NT	NT	-	-	-	NT	NT	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	6.25	5.88	-	-	-
Phenoxyethanol	NT	NT	-	-	-	NT	NT	-	-	-	-	-	-	5.31	-	-	10.53	-	-	-	-	6.31	-	-	6.1	> 101.01	26.81	-	-	-
Aliphatic hydrocarbons																														
n-Heptane	NT	NT	-	-	-	NT	NT	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1.4	-	-	-	-	-
n-Decane	NT	NT	-	1.64	4.01	NT	NT	-	-	-	-	0.54	0.52	-	0.59	20.3	33.06	-	-	0.33	1.31	1.28	14.2	0.2	> 22	-	-	0.9	0.2	8.2
n-Undecane	NT	NT	-	0.71	0.81	NT	NT	-	-	-	-	0.96	0.48	0.21	0.66	20.9	27.19	-	-	0.56	1.44	1.37	6.3	-	> 22	0.29	-	1.1	0.2	9.9
Halogenated hydrocarbons																														
1.1.1.-Trichloroethane	NT	NT	-	-	-	NT	NT	-	-	-	-	-	-	-	-	-	-	-	0.6	-	-	-	-	-	-	-	-	-	-	-
1.1.2.2-Tetrachloroethylene	-	0.2	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Aromatic hydrocarbons																														
Benzene	1.48	1.56	-	-	-	1.69	1.71	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	24.17	-	-	-	-	-
Toluene	4.6	5.73	-	0.54	0.61	4.37	5.07	-	-	-	-	-	0.37	-	0.27	0.62	-	-	-	2.11	0.28	0.27	2.4	-	11.2	-	0.98	-	-	1.8
Ethylbenzene	2.61	3.11	1.62	10.75	6.26	1.81	1.93	0.51	1.01	0.26	-	0.94	1.8	0.96	3.87	4.13	2.21	-	-	2.11	0.56	0.25	2.1	-	10.6	-	-	-	-	1.3
m.p-Xylene	9.71	10.27	4.67	43.48	23.44	5.14	5.48	1.74	3.77	0.66	0.64	2.26	4.03	1.89	4.97	14.08	8.45	-	0.78	9.56	1.78	0.93	8.4	-	40.7	-	-	0.8	-	5.9
o-Xylene	3.48	3.85	1.74	17.1	10.31	2.7	2.8	0.88	1.68	0.32	0.37	1.05	1.97	0.84	2.51	6.18	4.83	-	0.44	5.56	0.73	0.44	4.9	-	18	-	-	0.6	-	3.4
Styrene	NT	NT	-	0.88	1.09	NT	NT	0.26	-	0.22	1.61	21.28	0.58	0.23	1.29	0.42	33.06	-	-	1	0.26	-	0.4	-	2.9	-	-	15.1	13.5	> 22
1.2.4-Trimethylbenzene	NT	NT	-	0.83	2.22	NT	NT	-	-	-	-	-	-	-	-	7.95	11.11	-	-	-	0.83	0.65	3	-	9	-	-	0.3	-	2.5
Naphtalene	NT	NT	-	-	-	NT	NT	-	-	-	-	0.21	-	0.21	-	-	-	-	-	-	-	-	-	-	0.2	-	-	-	-	-
Phenols																														
Phenol	NT	NT	-	-	-	NT	NT	-	-	-	-	-	-	0.53	-	-	-	-	-	-	-	-	-	-	2.1	5.34	6.25	-	-	0.7
Terpenes																														
Limonene	NT	NT	-	2.69	3.18	NT	NT	0.39	0.46	-	-	0.33	0.55	-	0.5	-	-	-	-	1.11	-	0.41	0.8	-	2.1	> 20.20	3.52	0.6	-	4.8
TVOCs identified	34.38	35.82	18.37	163.42	95.14	49.11	56.69	26.08	25.62	14.44	87.02	780.53	196.3	49.58	406.48	258.01	327.37	98.6	85.72	129.78	114.66	83.01	115.1	74.7	294.57	46.18	101.64	39	102.8	128.4

† VOCs: volatile organic compounds; ‡ A0: ground floor site A, A1: first floor site A, B0: ground floor site B, B1: first floor site B, B2: second floor site B; § Impact of alcohol used for disinfection for mold sampling; NT: non tested; "-" : value below limit of quantification

Table 4 Total volatile organic compounds, temperature and relative humidity measured with Fireflies station in air during the VOCs measurement campaigns

Construction stage	Construction site	Measurement campaigns	TVOC (µg/m^3)			Temperature (°C)			Hygrometry (%)		
			Median	Min	Max	Median	Min	Max	Median	Min	Max
Initial state	A	February 22 to 26. 2016	-	-	-	-	-	-	-	-	-
	B	January 10, 2017	2098	1678	3187	7.2	6.8	7.8	86	83	89
Preparation of supports	A	April 18 to 22, 2016	6805	2658	15350	15.8	14.5	17.5	84	73	86
	B	April 13, 2017	1004	940	1170	16.7	16.5	17.3	58	56	59
Finish paints	A	May 13, 2016	13410	5227	14630	19	18.7	19.3	84	81	85
		May 25, 2016	19070	13140	38250	19.7	19.5	20.2	69.5	66	77
	B	May 2, 2017	2741	2004	3542	14.5	14.2	15.2	78	75	80
Soft floors	A	June 3, 2016	52780	51250	53880	19.8	19.3	19.9	85	85	86
		June 8, 2016	23310	17940	30460	19.8	19.3	19.9	85	85	86
	B	August 4, 2017	1642	1451	2054	24.1	23.9	24.6	66	65	70
Last fnishing works	A	June 21 to 24, 2016	5745	4471	7745	20.7	20.2	21.2	84	83	85
	B	September 19, 2017	-	-	-	-	-	-	-	-	-
Delivery	A	July 27, 2016	-	-	-	-	-	-	-	-	-
	B	October 3, 2017	-	-	-	-	-	-	-	-	-

"-" : data not available

Table 5 Semi-volatile organic compounds concentrations adsorbed on dust from ventilation ducts and adsorbed on airborne particles

SVOCs †	Dust ‡ (ng/g)	Airbone PM_{10} (pg/m^3) §		
	A	A1	B2	
	Finish paints	Last finishing works	Soft floors	Delivery
Phthalates				
BBP	-	-	379.8	495.4
DBP	-	426	740.9	11740
DEHP	-	10 440	8325	26210
DEP	-	-	2923	7352
DiNP	-	> 38 580	8798	23120
DiBP	-	185	672.7	11190
Musks				
Galaxolide	-	-	43.2	127.1
Tonalide	-	-	8.5	29
Pyerthroids				
Permethrin	-	77	16.9	41.4
Organochlorine				
Alpha-HCH	-	-	5.2	-
Others pesticides				
Oxadiazon	-	-	-	1.4
Phosphoric esters				
Tributylphosphate	-	39	-	174.1
Polycyclic aromatic				
Anthracene	-	13	7	19.3
Benzo[a]pyrene	-	25	5.1	101.9
Fluoranthene	50	52	20.6	38.2
Fluorene	95	19	26.4	50.8
Phénanthrene	303	64	37.3	50.1
Pyrène	-	35	14.4	46.4
Benzo[b]fluoranthe	-	46	14.9	128
Benzo[k]fluoranthe	-	9	-	22
Dibenzo[a.h]anthra	-	-	-	14.7
Indeno[1.2.3-	-	21	8.6	142.8
Benzo[a]anthracen	-	13	-	36.3
Others				
Triclosan	-	38	6.5	11.1

† SVOCs: semi-volatile organic compounds; BBP: benzylbutyl phthalate; DBP: dibutyl phthalate; DEHP: bis(2-ehtylhexyl) phthalate; DEP: diethyl phthalate; DiNP: diisononyl phthalate; DiBP: diisobutyl phthalate; α-HCH: α-hexachlorocyclohexane; PAHs: polycyclic aromatic hydrocarbons; ‡ from ventilation ducts; § A1: ground floor site A, B2: second floor site B, "-" : value below limit of quantification

Table 6 Mold count on dust and airborne mold concentrations with temperature and relative humidity associated

Construction stages	Location†	Mold count on dusts‡ (CFU/dm²)	Airborne mold concentrations (CFU/m³)					Temperature (°C)			Hygrometry (%)		
			Mold	Aspergillus	Penicillium	Cladosporium	Alternaria	Median	Min	Max	Median	Min	Max
Initial state	B outdoor	-	350	100	< 20	200	< 20	8.37	7.52	11.54	75.85	62.68	82.9
	B0	-	510	< 20	360	150	< 20	7.34	6.91	10.96	76.77	62.22	78.85
	B1	-	230	20	80	110	20	-	-	-	-	-	-
	B2	-	240	70	< 20	110	< 20	7.59	6.86	11.59	77.78	58	82.85
Preparation of supports	A outdoor	-	340	-	-	-	-	11.61	7.59	20.82	72.63	45.57	85.36
	A0	-	860	-	-	-	-	13.22	11.35	26.18	73.72	44.59	77.86
	A1	-	**1400**	-	-	-	-	13.56	12.2	15.99	81.28	75.82	84.36
	B outdoor Feb 28	-	250	20	50	30	< 20	7.67	3.14	11.66	78.26	56.94	88.37
	B0 Feb 28	-	290	20	170	40	20	9.78	8.99	10.91	81.27	78.32	85.08
	B1 Feb 28	-	670	50	120	390	30	-	-	-	-	-	-
	B2 Feb 28	-	480	50	80	150	30	9.39	8.47	9.93	69.47	63.74	73.41
	B outdoor Apr 14	-	510	20	110	320	20	11.69	5.67	16.51	68.96	50.96	82.6
	B0 Apr 14	-	180	< 20	40	100	< 20	14.76	12.92	18.94	59,00	52.74	68.94
	B1 Apr 14	-	340	60	< 20	220	< 20	13.86	11.86	14.53	62.04	58.27	65.52
	B2 Apr 14	-	460	70	50	230	< 20	16.19	15.75	18.3	58.77	55.62	62.66
Finish paints	A ground floor	absence											
	A first floor	1											
	A outdoor	-	880	-	-	-	-	14.18	12.92	16.56	91.25	87.77	91.61
	A0	-	**1000**	-	-	-	-	17.65	17.15	18.91	75.86	72.31	77.32
	A1	-	520	-	-	-	-	18.43	18.03	19.18	81.06	79.21	82.07
Soft floors	B outdoor	-	110	1	2	82	< 1	20.15	16.75	22.82	81.26	68.17	87.18
	B0	-	26	3	4	16	< 1	22.73	22.27	23.64	69.33	66.94	74.74
	B0 (living-room)	-	31	1	3	21	< 1	-	-	-	-	-	-
	B2	-	22	2	3	17	< 1	24.17	23.88	24.75	64.36	61.57	67.83
Last finishing works	B outdoor	-	990	< 20	110	570	30	-	-	-	-	-	-
	B0	-	500	20	290	150	20	-	-	-	-	-	-
	B1	-	390	< 20	50	270	< 20	-	-	-	-	-	-
	B2	-	290	20	50	160	< 20	-	-	-	-	-	-
Delivery	B outdoor	-	> 2000	> 2000	> 2000	> 2000	> 2000	-	-	-	-	-	-
	B0	-	580	< 20	60	420	< 20	-	-	-	-	-	-
	B1	-	580	< 20	60	320	< 20	-	-	-	-	-	-
	B2	-	380	20	60	300	< 20	-	-	-	-	-	-

†A0: ground floor site A, A1: first floor site A, B0: ground floor site B, B1: first floor site B, B2: second floor site B; ‡ from ventilation ducts; "-" : data not available; CFU:

Table 7 Comparison of the concentrations measured in air at delivery with the medians of concentrations measured during the European project OFFICAIR for site A and the medians of the annual average concentrations in dwellings of energy efficient buildings of the OQAI's database for site B

	This project		European project OFFICAIR		This project			OQAI's french database‡
VOCs†	A0	A1	Summer	Winter	B0	B1	B2	
Formaldehyde	18.3	35.9	14	7.5	<2	4.5	4,8	17,2
Acetaldehyde	5.6	8.6	6.1	4.5	4	9.4	8,8	11,5
Propionaldehyde	<1.8	<1.9	2.4	1.2	<2	2,2	-	-
Benzaldehyde	<1.8	<1.9	0.9	< LOQ	3.7	11,8	10,9	-
Hexaldehyde	7.4	8.7	10	4.4	11.9	44,3	38,2	21,3
1,4-Dichlorobenzene	<0.2	<0.21	-	-	<0.2	<0,2	<0,2	<LOD
2-Butoxyethanol	6.25	5.88	2.5	0.4	<5.6	<5,9	<5,5	1,4
n-Decane	<0.2	<0.21	-	-	0.9	0,2	8,2	2,3
Trichloroethylene	<0.2	<0.21	<LOD	<LOD	<0.2	<0,2	<0,2	<LOD
Tetrachloroethylene	<0.2	<0.21	<LOD	<LOD	<0.2	<0,2	<0,2	<LOD
Benzene	<1.26	<1.30	1	1.7	<1.39	<1,48	<1,37	1,5
Toluene	<0.2	0.98	4.7	3.1	<0.2	<0,2	1,8	4,8
Ethylbenzene	<0.2	<0.21	1.1	1	<0.2	<0,2	1,3	1,2
(m,p)-Xylenes	<0.4	<0.41	2.5	2.2	0.8	<0,5	5,9	2,7
o-Xylene	<0.2	<0.21	-	-	0.6	<0,2	3,4	1,2
Styrene	<0.2	<0.21	0.9	0.5	15.1	13,5	>22	1,1
Limonene	>20.20	3.52	-	-	0.6	<0,2	4,8	24,2

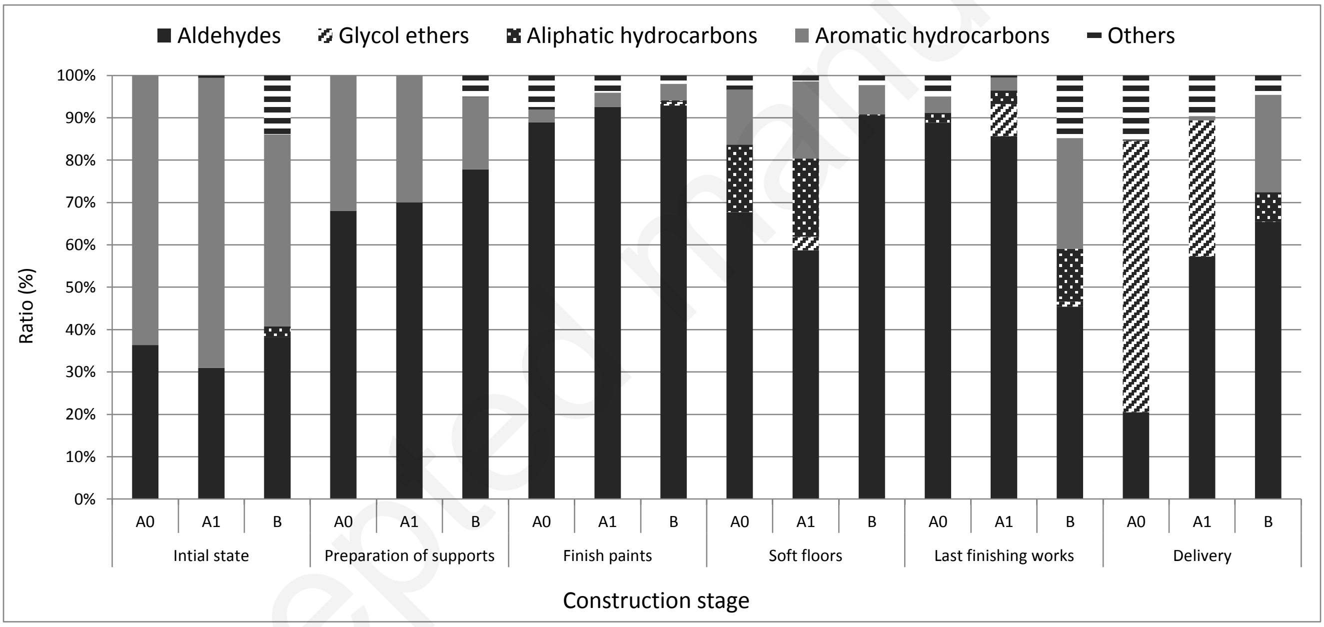
†VOCs: volatile organic compounds; ‡OQAI: observatory on indoor air quality, LOD: limit of detection, LOQ: limit of quantification; "-": data not available

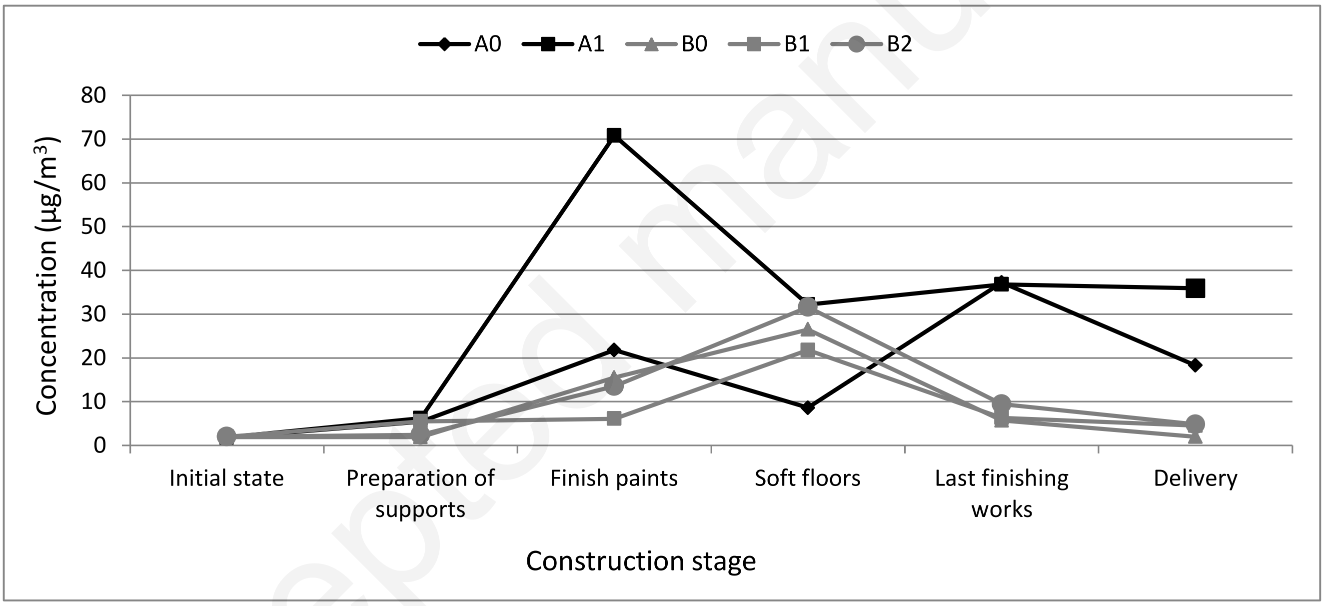
Figures

Figure 1 Proportions of volatile organic compounds chemical classes in air at each construction stage on site A (ground floor, first floor) and site B

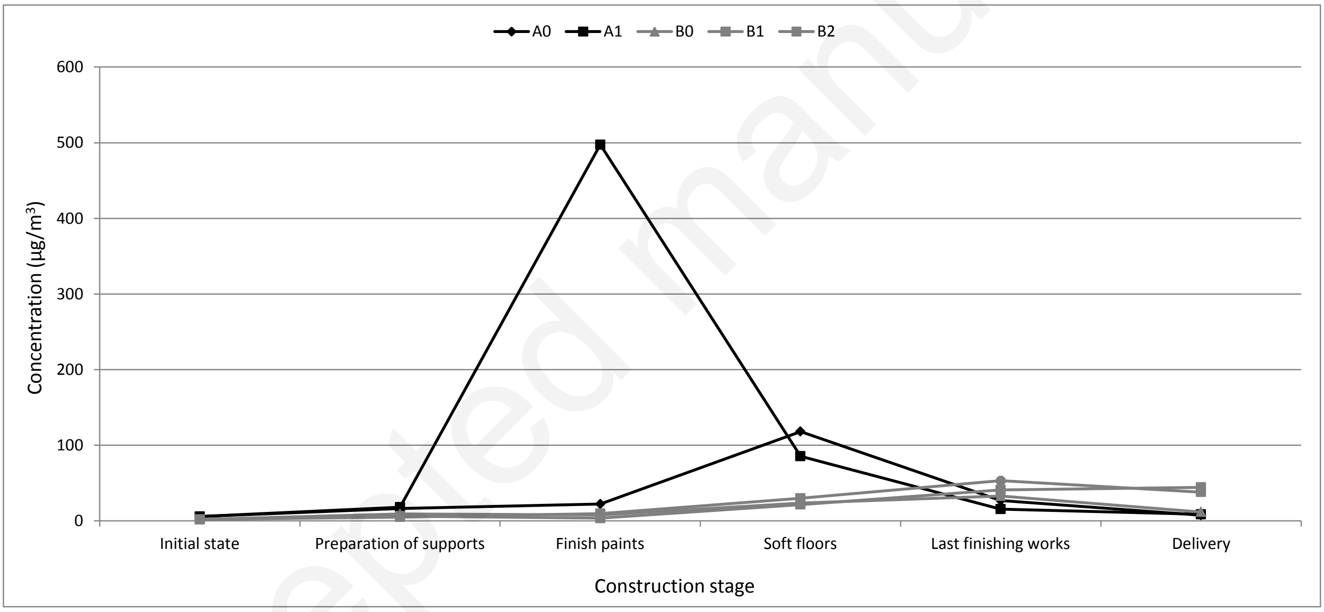
Figure 2 Formaldehyde concentrations in air at each construction stage on site A (ground floor, first floor) and site B (ground floor, first floor, second floor)

Figure 3 Hexaldehyde concentrations in air at each construction stage on site A (ground floor, first floor) and site B (ground floor, first floor, second floor)


Aldehydes
Glycol ethers
Aliphatic hydrocarbons
Aromatic hydrocarbons
Others
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
Ratio (%)
A0
A1
B
Intial state
Preparation of supports
Finish paints
Soft floors
Last finishing works
Delivery
Construction stage



A0
A1
B0
B1
B2
80
70
60
50
40
30
20
10
0
Concentration (µg/m³)
Initial state
Preparation of supports
Finish paints
Soft floors
Last finishing works
Delivery
Construction stage


A0
A1
B0
B1
B2
600
500
400
300
200
100
0
Concentration (µg/m³)
Initial state
Preparation of supports
Finish paints
Soft floors
Last finishing works
Delivery
Construction stage