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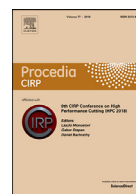
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# Monitoring Indoor Air Quality in Additive Manufacturing environment

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## ABSTRACT

An Indoor Air Quality (IAQ) monitoring and assessment is necessary in order to safeguard the well being of the occupants. This research addresses this issue in an Additive Manufacturing (AM) platform of an educational institute. Performing air monitoring requires quantifying the platform user exposures. Regulations, local policies, as well as ISO standards are well developed for office environments and industrial sites. However the indicators and the pollution levels allowed for new tools and technologies are yet to be defined. This is specifically the case in France for AM educational purpose. A practical IAQ assessment protocol is addressed in this research questioning: the type of emissions to measure, and the way to measure them on an AM platform. The method includes a selection of the assessment parameters for the IAQ, the associated IAQ indicators and the associated sensors to measure emissions rates. The assessment protocol has been applied to GINOVA S.mart Grenoble-Alps educational FabLab for students and researchers. Emissions have been measured from a variety of AM technologies, merging material and gas input resources. The choice of sensor and measurement method is discussed in this paper. The measurement results cover a variety of particles and gas emissions. This paper concludes on the limits and the opportunities of an IAQ dynamic assessment protocol to make an emerging manufacturing platform eager to develop the number of machines using various materials types, a cleaner environment for its users. The Makers community could be interested to use such a protocol in any standard FabLab.

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## 1. Introduction: quality monitoring FabLabs

Indoor Air Quality (IAQ) regulations, local policies, as well as ISO16000:2004 for office environments and industrial sites are unclear about defining the Additive Manufacturing (AM) technologies indicators and level of emissions safeguarding the well being of the machine users. AM industry is a rapidly growing market field (Mendes, 2017) producing complex structures (Graff, 2016) as well as custom parts. 3D printing and laser cutting technologies are indeed widely used at universities to support the process of design development (McDonnell, 2016). Precise recommendations about the infrastructure required to monitor and maintain an acceptable level of IAQ are particularly lacking in France in Fabrication Laboratories (FabLabs) for educational purposes. The novelty of this research is, therefore, to propose an IAQ assessment protocol based on: (1) several main relevant indicators and measurement instruments, covering specific VOCs and PM emitted in AM and laser cutting technologies (2) a method adapted to academics and FabLab contexts usage, integrating the related actors into monitoring

and assessing VOCs and PM for preventing health damage in a one year time period.

Section 2 addresses the research objectives refining the types of VOCs and PM emissions to be measured and the way to measure them based on a literature review including experimental feedbacks. Section 3 proposes an integrated protocol for IAQ management in FabLabs based on the relevant indicators and the usage of such manufacturing platforms. Section 4 studies the application of the protocol to the GINOVA platform in Grenoble and concludes on the applicability of the proposition. Recommendations to integrate this protocol to any AM context are formulated in conclusion. *Nomenclature*

AM	Additive Manufacturing
FabLab	Fabrication Laboratories
IAQ	Indoor Air Quality
VOCs	Volatile Organic Compounds
PM	Particulate Matters
UFPs	Ultrafine particles

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## 2. Paper issue: detecting and preventing exposure to new indoor pollutants emitted in FabLabs

### 2.1. FabLabs are not a safeguarded area for health

FabLabs are publicly accessible workshops providing access to digital manufacturing technology and electronics tools to everyone to facilitate approaching the *Do It Yourself* (DIY) concept (Troxler, 2016) – a ‘make (almost) anything’ place (Gershenfeld, 2012). Innovation, invention, learning and sharing ideas are then facilitated. The *Fab Foundation* counts more than 1750 FabLabs in 109 countries used at the moment. They are often owned by a school or university or are sponsored by huge corporations for educational or recreational purposes. Standard machines and processes shared include 3D printer, laser cutter for 2D and 3D structures manufacturing, high-resolution Computer Numerical Control (CNC) milling machine, as well as several electronic components and programming tools. The utilization rate of those machines and the material quantities used are however much varying in each platform.

Despite this considerable non-industrial manufacturing activity, the types and magnitude of the emissions occurring there are not often published on-site or in specific journals. Several literature studies demonstrate that 3D printers emit ultrafine particles (UFPs) besides potentially dangerous Volatile Organic Compounds (VOCs) such as Styrene, Butanol, or Ethylbenzene (Wojtyła, 2017; Azimi, 2016; Unwin, 2013). The compliance of these platforms to IAQ standards is unclear. Analysing the occupant’s exposure to the hazardous pollutants occurring there through a protocol is, therefore, a necessity.

### 2.2. Principal indoor pollutants and parameters for health damages assessments

The indoor air presents some high concentration of outdoor substances captured from outside (World Health Organization, Regional Office for Europe, 2010). Additional air components (William, 1992) are generally originated from the indoor equipment, and from the occupant’s behaviour. The indoor air pollution components are sorted in several categories, based on *physical properties, chemical properties, adverse health effects, or from a pollution source*. The *chemical properties* classification for instance commonly distinguishes: *the chemical pollutants*, such as volatile organic compounds (VOCs), nitrogen oxide (NO<sub>x</sub>), carbon monoxide (CO), polycyclic aromatic hydrocarbons (PAHs), phthalates; from *the organic contaminants* such as mold, household allergens from dust mites, pollens; and from *the physical pollutants* including particles and fibres (asbestos, artificial mineral fibres, etc.). In terms of *adverse effects on human health*, the VOCs and aldehydes are most often the cause of irritation of the eyes and respiratory tract. Some of them, such as benzene and formaldehyde, are further classified as ‘carcinogenic to humans’ by the International Agency for Research on Cancer.

Assessing the health damage caused by the potential pollutants in FabLabs is, therefore, a factor of *the pollutants toxicity and concentrations parameter*: up to 900 organic compounds, particles, microbes, and allergens. *The related exposure parameter*: inhalation, ingestion, or dermal contact (Lunetto, 2018). *The exposure-response relationship parameter* to the related body exposed to a substance.

### 2.3. Focusing on Indoor Air Quality in FabLabs

The composition and the concentration of the generated VOCs and UFPs emissions are affected by several parameters such as the filament manufactured type, the extrusion temperature, or the bed temperature (Kim, 2015). New and inventive filaments enter the

market every year. However ABS – a high emitter (Graff, 2016) – is still one of the most commonly used filaments with PLA, and High Impact Polystyrene (HIPS).

The UFPs and VOCs emissions concentration increases with the number of printers working together. This concentration affects human health (Peters, 1997). Quantifying pollutions caused by an additional machine is still not clearly established. Some effects are however scientifically proven. For instance, an Electron Beam Machine (EBM) using materials powder of 10 to 100 μm size increases the risk of dust explosions (Lunetto, 2018). As another example, the highly toxic vapours, particulates, and metal fumes from the substrate (mainly plastics, woods, and metals) produced with laser cutter (Yun-Jung, 2016), generate specks of dust that might include metals such as chromium, lead, nickel, or cadmium. This dust thickness also affects the cutting efficiency by making the beam difficult to diffuse. Those examples show that a screening process is yet missing for detecting IAQ problems in FabLabs: identifying the potential emission sources, the related measurement devices, as well as the limits not to be crossed to guaranty a healthy safe workplace (Hui, 2009).

This research, therefore, aims at determining the physical and chemical characteristics of the emitted particles and VOCs potentially released in a FabLab to define the proper device to detect them through a general protocol. Measuring the realistic human exposure to these pollutants is necessary for any IAQ improvement strategies in the given context.

## 3. Research proposition: a protocol for IAQ management in FabLabs

### 3.1. The IAQ assessment parameters and process for FabLabs

Any personal complaints are an early demonstration of IAQ problems, addressing a necessity for improvement actions. A *first assessment* is required to determine the threats, estimating the exposure, analysing the impact of the sources emissions, and providing quantified data for the appropriate measures to be taken. A *continuous measurement* of the indoor pollutants would enable identifying IAQ problems and adjust solutions. A significant amount of time, resource and effort are required to obtain some accurate results in medium to long term (Hui, 2009). *The main assessment parameters* to consider are: the FabLab internal organization, the *Makers’* practice and behaviour, their time spent inside, in addition to the energy policies and building system technologies in place, within the local requirement and standards for IAQ. Detecting the pollution patterns occurring by a *questioner* or by *interviewing* the *Makers* is crucial (e.g. daily, weekly, seasonally), as the pollution rate will be influenced by: the ventilation and extraction localisation and mode, the machines’ utilisation rate, the materials and liquids used, the human activities and movements in the rooms, aligned with the season and the time of the day. The data measurement period should, therefore, be chosen accordingly in a systematic risk assessment strategy–within a dynamic and practical protocol (Hui, 2009). *A Plan-Do-Check-Act (PDCA) as a common approach in the industry is chosen in this research to support IAQ management protocol in FabLabs* and prevent the users’ health damage.

### 3.2. Targeted pollutants in FabLabs

The frequent air pollutants contributing to weakening IAQ are CO<sub>2</sub>, NO<sub>2</sub>, formaldehyde (HCHO), CO, SO<sub>2</sub>, total volatile organic compounds (TVOCs) and airborne particulate matters (i.e. PM 2.5 and PM 10). Air temperature, velocity, and humidity levels are further IAQ factors associated with occupants’ comfort zone (Abdul-

Wahab, 2015). The oxygen is not classified as a factor that could affect poor IAQ, but a sufficient oxygen concentration level must be maintained. The most common and high-end levels of indoor air pollutants in European Countries and their comparison to WHO guideline standards can be found in Jantunen (2011). For instance, formaldehyde is typically found indoors, at a concentration rate varying from 20 to 80  $\mu\text{g}/\text{m}^3$ . However, sampling every toxic pollutant is almost impossible. Hence, the FabLab air sampling will be based on an assessment strategy, targeting specific pollutants detected during the initial assessment as *signature* pollutants, monitoring them for: a regulation requirement, checking the impact implementation of a change, a hazard evaluation in case of a new AM machine, new materials used, etc. The *signature* pollutants to target i.e. generated from typical machines used in AM platforms are taken from Particulate Matters (PM) and TVOCs.

### 3.2.1. Targeting particulate matters (PM) and health effects

PMs are solid or liquid particles distributed evenly in the air. They remain airborne for prolonged periods owing to their particle size, which could range from 1 to 10,000 nm (cf. WHO reports). The smaller the particle size, the more difficult it is to be measured and controlled. PM10 includes all particles with a diameter of fewer than 10  $\mu\text{m}$  and therefore PM2.5 – ultrafine particles. These particles can generate environmental and health damages, as well as climatic impacts (Jaffrezo, 2018). The main exposure to these particles is through inhalation. Large particles such as PM10 can be eliminated from the body by sneezing, coughing or swallowing. Particle smaller than 10  $\mu\text{m}$  in diameter may go deep into the lungs and potentially to the bloodstream. The greatest risk to health is caused by the fine particles (diameter inferior to 2.5  $\mu\text{m}$ ) or PM<sub>2.5</sub> (Graff, 2016). The effects of inhaling this particulate matter include asthma, lung cancer, respiratory diseases, cardiovascular disease, premature delivery, birth defects, low birth weight, and premature death. Understanding such properties and the processes that affect PM evolution referring to the related research fields are relevant to continuously improve the FabLab IAQ (Jaffrezo, 2018).

### 3.2.2. Targeting volatile organic compounds (VOCs)

Volatile organic compounds are a set of substances belonging to different chemical classes having in common their capacity to evaporate more or less quickly at room temperature. WHO has sorted these organic pollutants according to their boiling point into 3 categories: Very Volatile, Volatile or Semi-Volatile Organic Compounds (mainly found in the form of gas in the air). The short-term exposure to VOCs may cause eye irritation and respiratory tract, headaches, dizziness, as well as visual disorders. Long-term exposures may result in more serious symptoms like fatigue, loss of coordination, damage to the liver, kidneys, and central nervous system. VOCs include formaldehyde, d-Limonene, toluene, acetone, ethanol, 2-propanol, and hexanal substances. The summation of all detected VOCs is named Total Volatile Organic Compound (TVOC). Indoor hygiene and Indoor Air Quality consider TVOC as a major indicator. Scientific studies often indicate the TVOC rate rather than detailing the analysed VOCs. In this case, the TVOC composition should be clarified (cf. WHO Guidelines).

### 3.2.3. Guidelines values

IAQ standard guidelines edited by the European Commission are usually providing reference values in case of developing a new facility. In contrast to the outdoor air, very few specific provisions exist to date governing the quality of indoor air in non-industrial premises. Different regulations and guidelines have been however defined by various international agencies. These standards are either based on health concerns or acceptable levels for occupant comfort.

The European Harmonised Framework on Indoor Material Labelling Schemes includes common core and transitional criteria on testing and evaluation methodologies related to indoor products chemical emissions (Kephelopoulou et al., 2012). This is a reference point for harmonizing different labelling systems and for identification of potential overlapping in the existing test methodologies and sensory evaluation (Bravi, 2019). Some guidelines and policies specifically exist for preventing personal exposures. Most of these guidelines are developed by international scientific centres including WHO and the Environmental and Occupational Health & Safety (ANSES). The agreement covers the types of pollutants but differs in value definitions, and in the legally binding status of pollutants. No official guideline values have been established in the EU's European Commission (Abdul-Wahab, 2015). Some European countries as well as Canada, the USA, and Australia have their own individual regulations and recommendations for the assessment of IAQ. These proposed values depend on the methods of sampling and analysis developed by their national training partners (Bravi, 2019). Regulations and recommendations also differ in their legally binding status.

France was one of the first countries addressing indoor environmental pollutions in a form of legislation. To deal with the health issue surrounding IAQ and providing the public authorities with useful information to manage this risk, the ANSES has been conducting expert assessments for ten years on the development of IAQ Guidelines integrating the WHO and the French IAQ Observatory (OQAI) analyses. Those guidelines aim to protect the general public from any harmful effects of airborne exposure to substances. Quantitative value limits for CO<sub>2</sub>, NO<sub>2</sub>, formaldehyde, CO, SO<sub>2</sub> and some other type of VOCs are provided. Recommended measurement methods are also suggested. However, there is no clear guideline defined for PM or TVOCs.

### 3.2.4. An assessment methodology required

After the preliminary analysis of the location of interest, the number of sampling points, sampling duration and frequency and sampling methods should be determined. Each building space covering an activity can be identified as a 'zone'. A zone is defined as a set of spaces which are characterised with the following criteria: (1) ventilated with the same air diffusion strategy and be served by the same air handling unit; (2) have similar activities, thermal load and pollutant emission; and (3) spaces with similar compliant records or hosting more requiring occupants (Asadi, 2013). The minimum number of sampling points in each zone is calculated by a given formula, combining the number of sampling points N, and area of concern zones in squares meter. According to ISO standard 16000:2004, sampling must also be taking at least 1 m away from the wall and 1 to 1.5 above the floor since approximately the average breathing zone. The sampling time should be perfectly in line with the objectives. Short term sampling – about 60 min – in case of suspecting high concentrations; long term sampling – from several hours to a few weeks – for assessing average air pollution. For any IAQ guideline reference value compliance, the sampling duration must be aligned to reference value one. In addition, background measurements and post-operation measurements are recommended to highlight the decay time. The sampling methods eventually depend on the targeted pollutants. For example, a VOCs analysis is nowadays dominated by the use of purge-and-trap followed by a gas chromatography (GC) or by gas chromatography-mass spectrometry (GC/MS), or in some cases by thermal desorption (to air page). The best metric to use depends on the measurement specific focus.

In this research, the sampling methods are aligned to the ANSES guidelines.

### 3.3. A practical IAQ assessment protocol based on a PDCA management system

To sum-up, the IAQ assessment protocol addressed in this research is questioning the type of emissions to measure, and the way to measure them in a FabLab. In practice this process starts with a walk through inspection in order to understand the space usage, the activities that are taken place inside, the machines and materials used, as well as the ventilation system. Any information from the FabLab users can point-out on a new parameter to include in the assessment factors. A questioner can be used to interview them on a regular basis. The assessment factors are then used to plan the audit protocol in detail: *what should be measured and how they should be measured*, aiming to find solution to the complaints made by the *Makers*; evaluate the effectiveness of a new mitigation process to maintain a targeted IAQ level; be (at least) compliant to the competent authorities guidelines, and able to report them the related proof.

Then the implementation stage begins: the obtained results can be compared with the appropriate standards considering that the exposure time varies for each type of occupant (long term exposure for the regular staff and short term for students and researchers). If the results are not compliant with the standards, a set of risk management actions should be taken.

The planned actions at each step of this cycle assist in varying and prioritising the problems, enabling the implementation of an audit procedure, an action plan, its control, and the global continuous improvements over time.

## 4. Case study: applying the protocol for IAQ management of VOCs and PMs in a Grenoble educational FabLab

### 4.1. Step 1: Plan

*Context:* GINOVA is an inter-university technological platform including a technical platform and numerous spaces and project rooms located on the site of the Grenoble School of Industrial Engineering. It is one of the 5 platforms managed by S.mart Grenoble-Alps, former AIP Primeca Dauphiné Savoie. This platform works on the model of FacLabs, a concept similar to the FabLab one integrated within a university environment: a place of experimentation and collaboration but only open to students, researchers and school partners.

*Machines, filters, and material:* GINOVA is equipped with much-advanced equipment dedicated to the simulation of mechanical systems and workflows, prototyping and additive technologies. Besides 3D printers, Laser cutter and, CNC milling machine, the platform is equipped with EBM and Z-Ultra machines. The 3D printers are Fused Deposition Modelling (FDM) Zortax printers, equipped with HEPA filters. Materials used for 3D printing are ABS, PLA, TPE, Z-ABS, and ULTRAT, respectively. The laser cutter is used generally in 4 main modes: cutting PMMA thickness 3 mm, 5 mm, or 8 mm, and engraving. Only PMMA 5mm was chosen for cutting and engraving with the laser cut in this case study.

*Concerns:* the main issues reported by the staff and regular users are related to the laser cutter and 3D printers. 3D printers are placed in a non-ventilated area, potentially leading to fumes and particle accumulation. The laser cutter is equipped with a local ventilation exhaust system. However, despite clear instructions, most students forget to turn the ventilation on. This generates odorous fumes. In addition, the filters are sometimes overused and instead of purging the air, it discharges more polluted air in the room. This issue has led to headache, dizziness, and irritation to nose, throat, and eyes, that are the short-term effects to air pollution exposure.

Based on such problems and additional one captured at this initial stage the IAQ objectives and limits, the targeted pollutants, the type of the sensor, and the measurement procedure have been defined. The audit plan has been prepared in 3 phases: 1- Choosing appropriate guidelines from the ANSES ones. 2-Targeting pollutants: PMs (UFPs) and VOCs including benzene, trichloroethylene, tetrachloroethylene, ethylbenzene, toluene, acetaldehyde, and acrolein. 3-Organising the measurement method: choosing instruments, renting tools and sampling locations.

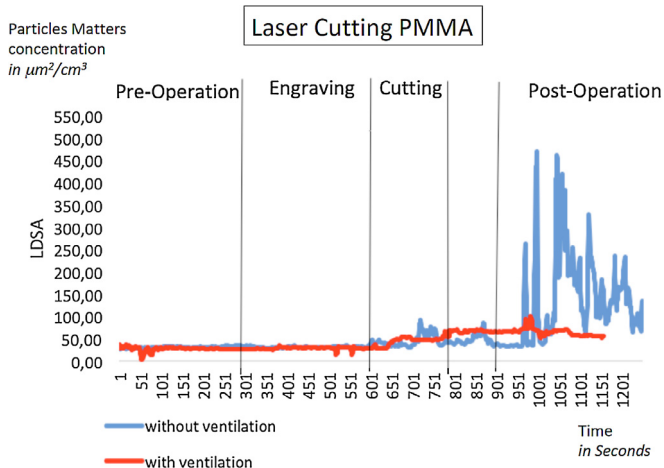
*Chosen measure instruments:* the VOCs were collected by custodian SMPE syringes, with the flow rate of 35 mL/min. Each of the measurements took place over a course of 5 min, with 175 mL air being collected and analysed by a portable gas chromatograph-mass spectrometer (GC/MS, Torion T-9, Perkin Elmer) GC/MS analysis can readily and accurately segregate complex compounds found in the air. Less volatile chemicals move slower than more volatile chemicals and are therefore separated by a GC/MS. GC/MS can measure the amount of every chemical present in a given sample simply by comparing the particular chemical to pre-measured standard. VOCs were identified by matching their spectral mass characteristics and retention times using a laboratory-specific spectral mass database. This database contains approximately 700 VOC and has been validated by the laboratory for analysis using the laboratory specific systems following a method combining EPA TO-15 and ISO standard 16000-6 guideline. The PM was detected by a Naneos – Partector instrumentation measuring the Lung Deposited Surface Area (LDSA) of nanoparticles based on a non-contact electrical detection principle. LDSA concentration is a relevant metric for evaluating the negative health effects of aerosol particles by deep penetration into the lungs. The concentration range of this sensor is from 0 to 12,000  $\mu\text{m}^2/\text{cm}^3$  and the size range of the detected particles is between 10 nm and 10  $\mu\text{m}$ . The sensor measures the particles with a time resolution of 1 s. The limits of exposure to nanoparticles measured by LDSA sensors are defined as average between 50 and 250  $\mu\text{m}^2/\text{cm}^3$  referring to the sensor manufacturer. The standard object chosen for 3D printing was a reduced size AM model proposed by the National Institute of Standards and Technology (NIST) developed as a test part to evaluate the performance of such technologies (Moylan, 2012). Sample Zone: the area of the platform has been divided into 6 different zones. Zones 1 and 2 were 'conventional test rooms' for assessing the concentration of the pollutions. 7 adjunct printers were placed in Zone 3. The EBM, laser-cut, and WAM were also placed in zones 4, 5 and 6, respectively.

### 4.2. Step 2: do

The VOC experiments were conducted over four distinct operational periods: (1) an overall background measurement of the laboratory before any operation begins, (2) a background measurement adjacent to the targeted machines and zones (i.e. close room 1 and 2), (3) during the machines operations – approximately 60 min for 3D printers, 6 min for the laser cut, (4) post-operation measurements, in order to highlight the decay time, i.e. the time necessary for having the environment concentrations. The recorded average temperature ranged from 26 °C to 28 °C. The VOC measurements were conducted in one day, with the help of 3 agents of Perkin Elmer Company and 3 researchers. The UFP measurements were conducted over a course of 5 consecutive days only with the researchers and local staff able to use the different machines (e.g. EBM). Since the case study objective was to identify the maximum concentration value of VOCs and UFPs, short-term sampling was carried out during the 60 min for 3D printers, and 6 min for the laser cut.

**Table 1**  
Particulate matters concentration for laser cutting in  $\mu\text{m}^2/\text{cm}^3$ .

Ventilation 100-1500m <sup>3</sup> /h	Average / limit ( $\mu\text{m}^2/\text{cm}^3$ )	Standard deviation	Maxi. / limit ( $\mu\text{m}^2/\text{cm}^3$ )
ON	42.92-compliant	+/- 17.78	101.54- to control
OFF	63.49 – to control	+/- 66.55	469.91-danger



**Fig. 1.** PMs concentration in  $\mu\text{m}^2/\text{cm}^3$  over time (abscise values in seconds) for PMMA 5 mm laser engraving and cutting using a LDSA machine.

#### 4.3. Step 3: check

During the measurements, the average background emission of the lab was  $25 \mu\text{m}^2/\text{cm}^3$ , the temperature and the relative humidity were  $28^\circ\text{C}$  and 45%, respectively. All the measurements, except the EBM, were conducted in 3 phases: pre-operation, during operation, and post-operation. PM results for laser cut, cf. Fig. 1: over the engraving process the emission concentration remained in a steady-state, just as the pre-operation measurement.

As soon as the cutting starts, the concentration begins to increase without much difference between with and without filtration modes. A 100-s pause after the cutting process is respected to let the remaining fumes be extracted from the chamber towards the filters, letting the machine and the cut plate to cool down. The window is opened at the post-operation phase: the highest concentration rate reaches a maximum of  $469 \mu\text{m}^2/\text{cm}^3$  for no ventilation and  $90 \mu\text{m}^2/\text{cm}^3$  with the ventilation. The steady-state was still not achieved at the end of the post-operation (decay period) measurements.

#### 4.4. Step 2: act

Table 1 addresses the sensor recommendations to the PMs concentration presented in Fig. 1 (laser cut). As an average with the ventilation PMs stay under the limited recommendation (in green-compliant). This limit is exceeded during the post-operation period without the ventilation (in red-danger). As an average without ventilation and at the maximum recorded with the ventilation, the rates recorded are dangerous for human exposure up to a given inhalation time period (in orange-to control). Similarly, to the laser cut measurement results presented in this paper in Fig. 1 and Table 1 the overall results showed relatively high PMs even if one machine at a time was considered. In addition, the platform had the lowest year utilisation rate in July and with no consideration of accumulation of PMs. Accordingly, the priority for further and more extensive investigation should be on 3D printers and the

laser cutter, due to their intensive use and relatively high emission rate. Also, an appropriate palliation method should be put in place straight away, especially for 3D printers since results showed that the filtration system was not as effective as expected. Specific mitigation: the emission of 3D printers, for instance, could be mitigated by operating the 3D printers inside a sealed enclosure with novel air filtration technologies e.g. photocatalytic filtration, which is an active technology for the decomposition of inorganic and organic pollutants (Wojtyła, 2019). Another solution is to implement a 2-layered filtration system, in order to make sure that even the smallest particles are trapped. General emission control strategies mitigating the pollution rate in all zones would include some operation of standalone air cleaners, installing a spot ventilation system and upgrading the central HVAC filtration. Some of these control strategies may be more cost-effective and practical than others. For example, a high flow rate ventilation system that exhausts outdoors is likely cost-prohibitive and impractical in many locations. While using standalone air cleaner may significantly reduce the PM concentrations in all zones a substantial energy penalty would be generated (Parham, 2017). Conclusion: in case of facing a high concentration some short term solutions including installing a spot ventilation system and upgrading the central HVAC filtration could be put in the place. However more extensive studies should be conducted to quantify the signature pollutants, pollutants generated in higher quantity, or most health affecting pollutants.

## 5. Conclusion

AM technology opens to endless design opportunities and is particularly useful for students. However, extra caution should be taken in FabLabs using many machines concurrently, especially in poorly ventilated spaces or without the aid of the particle filtration system. This research, therefore, proposes a method for assessing the IAQ in AM environments. The case study demonstrated that the PDCA based risk analysis and assessment approach proposed as a general protocol is adapted to the context of FabLabs. This method was implemented in GINOVA platform in Grenoble, to assess the occupant's exposure to potential pollutants and verify the credibility of this approach. The measurements were designed following the most ordinary usage mode of each of the machines. The results represented a potential exposure for users of this platform to a high concentration of the particles. This is especially the case for 3D printers and the laser cut, most commonly used machines in FabLabs in general. An extended analysis is now required to quantify the signature pollutant compounds for each machine in each zone and define an appropriate mitigation plan for IAQ. Current research includes the accumulation of contaminants in the case of several machines working together by the simulation software CONTAM, which is a multi-zone Indoor Air Quality and ventilation analysis computer program designed to help prediction of contaminant concentrations to determine the Indoor Air Quality performance of buildings. This will support the PDCA continuous improvement stages by investigating the impacts of implementing additional air quality control technology in a given FabLab, to make an efficient decision.

## Declaration of Conflict Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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