

Extraction System Efficiency Assessment Based on Workplace Airspace and Emissions Measurements

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Protecting air quality is crucial to protecting human health and the environment. In addition to minimising the concentration of pollutants in the atmosphere, reducing exposure to chemical agents in the workplace air is becoming increasingly important. The research will demonstrate the importance and effectiveness of technological extraction ventilation systems used in industry through a workplace air quality measurement in a 3D printer laboratory. In our study, the emissions of air pollutants into the environment were measured by emission measurements and the impact area was determined by calculation. It was clear from the results that the concentrations of methanol and phenol were below the detection limit, so this technology does not produce these substances in concentrations that can be measured. However, in the case of ϵ -caprolactam, a typical air pollutant in several 3D printing technologies, an exceedance of the limit was observed in the phase without the extraction system. The limit value was exceeded by 1.91 %, which represents an increased exposure. The tests carried out clearly demonstrated that concentrations in the workplace airspace were reduced by a tenth in all cases after the installation of the extraction system. The installed, activated carbon filtration system captured 90 % of the volatile organic compounds. The effectiveness of the system is greatly enhanced by the design of the disposal strategy, the use of Best Available Technology (BAT) and the filter incorporated in the extraction system.

1. Introduction

Protecting the quality of the air is essential for both human health and the environment. Lowering the amount of pollutants released helps to reduce the risk of respiratory diseases and supports a more sustainable future.

3D printing has become increasingly popular in various fields as a result of ongoing technological advancements and numerous advantages. Using specialised computer programs, 3D printers can produce three-dimensional objects based on unique templates. The printing process involves layering multiple materials, which maintain their desired shapes once they solidify. The available materials range from filament to resin, with different types being used to create various objects. However, these heated plastics (filaments) and resins are likely to have negative environmental consequences.

In our study, we seek to illustrate the effectiveness and significance of industrial exhaust systems by examining a 3D printing facility. Our objective is to simulate the spread of released air pollutants, delineate the area impacted by protecting air quality, and explore whether the growing adoption of innovative modern technologies in industries like 3D printing could potentially have adverse effects on human health or the environment.

2. Literature Review

The proliferation of 3D printing technology across various industrial and non-industrial sectors has highlighted its potential to generate air pollutants. The materials used and the methods employed during the printing process can result in significant emissions. Empirical studies have demonstrated (Yap et al., 2021) that thermoplastic materials utilised in 3D printing, such as PLA, ABS, and TPU, emit volatile organic compounds (VOCs) such as styrene, caprolactam, ethylbenzene and others (Zhang et al., 2019;) and particulates, which pose potential health risks (Wojnowski et al., 2022). Among the various industrial chemicals, Volatile Organic Compounds

(VOCs) are a prevalent class of air pollutants produced in significant quantities globally, particularly in industrial settings. Their impact on air quality and human health necessitates effective monitoring and regulation (Invernizzi et al., 2021).

The extent and composition of these emissions are influenced by several factors, including the specific printing technology, the type of printer, the quality and properties of the raw materials, and the operational parameters such as temperature and speed (Vežníková-Skrížovská, 2022). During the thermal processing of filaments, various pollutants, including carcinogens and respiratory irritants, may be released into the atmosphere (Yi et al., 2016).

Assessing and managing these emissions is particularly critical in industrial settings where prolonged exposure to such pollutants can occur. Research has indicated that the thermal processing of polymer materials can result in the release of numerous air pollutants, including carcinogenic substances and respiratory irritants, as well as particulates. The composition of fumes generated during the heating of plastics varies depending on the type of plastic, formulation, and processing conditions. Toxicological studies have confirmed that ultrafine particles (UFPs) can penetrate the alveolar region of the lungs, potentially eliciting inflammatory reactions, causing abdominal cramps, and affecting the cardiovascular system (Wojtyła et al., 2020). The implementation of exhaust systems and protective equipment in compliance with health and safety regulations can mitigate these risks. Additionally, further research is required to accurately characterise emissions from 3D printing and to develop appropriate protective measures (Mendes et al., 2017).

We had the opportunity to familiarise ourselves with the operation of 3D printers in several domestic factories. It became evident that the air quality in the rooms where these printers were used was often inadequate. In the absence of ventilation or extraction systems, we experienced headaches within a short period, which highlighted the potential health risks posed by this technology. Several studies confirm that the materials released during 3D printing, such as particles and gases, can indeed be harmful to human health, especially in enclosed spaces (Steinle, 2016). In the course of reviewing the literature, we did not find any analysis specifically comparing the impact on air quality between printers equipped with extraction systems, traditional printers, and rooms without ventilation. The knowledge of such comparisons would be especially important for effectively mitigating harmful effects, either through adequate ventilation or with the use of a properly designed and operated extraction system. The purpose of the study is to analyse the release of air pollutants from the increasingly widespread 3D printing technology based on workplace air and emission measurements. Pre-installation and post-installation measurements of an exhaust system will be conducted to evaluate its necessity and effectiveness according to the results.

Mandatory legislation addressing workplace air quality and chemical hazards is encapsulated in ITM Decree 5/2020 (II.6.), which focuses on the protection of the health and safety of workers exposed to chemical agents. The chemicals used in this technology are categorised based on their effects (e.g., corrosive substances, irritants, carcinogens), posing potential health risks to those exposed. It is essential to implement protective measures in the workplace to minimise exposure to such substances, including the use of appropriate protective equipment and adherence to established protocols and procedures (Mádi, 2016).

The purpose of air sampling is to determine air quality and pollutant concentrations. Specialised tools developed over the past half-century are used to conduct these measurements. Airborne particulates are measured using specific samplers. Understanding and adhering to limit values for chemical hazards can reduce the risk of occupational illnesses. Further health risks can be mitigated through technical and organisational measures, along with the use of personal protective equipment (Bayona et al., 2012).

3. Materials and Methods

During the investigation to understand the environmental impact of 3D printing technology, the following surveys were carried out:

- development of a sampling strategy and selection of sampling locations,
- description of the employed sampling method and instruments,
- measurement of workplace air quality,
- identification of hazardous chemical factors and
- analysis of properties exhibited by generated chemicals.

Before conducting air measurements in the workplace, the 3D printing laboratory staff explained the types and locations of the equipment and the properties of the materials used for 3D printing. Table 1 documents details of the chemicals used in the laboratory, including their classification, adverse effects and composition.

Based on the safety data sheets, substances that could pose a potential hazard to human health were selected for measurement.

Table 1: Classification and composition of chemicals used in 3D printing. Source: based on data of International Labour Standards, (ILO, 2023)

Product name	Classification	Composition
Fiberglass (glass wool)	Not subject to labelling	Nylon, caprolactam, fiberglass
ONYX	Not subject to labelling	Nylon, caprolactam, fiberglass
PC (polycarbonate)	Not subject to labelling	Phenol, chlorobenzene*
PVA (water-soluble filament)	Not subject to labelling	Methanol*
Rigid 10K (resin)	Skin sensitisation, Category 1, H317 (Skin Sens. 1) Hazardous to the aquatic environment - chronic hazard, Category 2, H411 (Aquatic Chronic 2) GHS07,09	Urethane dimethacrylate, 7,7,9(or 7,9,9)-trimethyl-4,13-dioxo-3,14-dioxa-5,12-diazahexadecane-1,16-diyl bismethacrylate
Rigid 4000 (glass-reinforced material)	Skin sensitisation, Category 1, H317 (Skin Sens. 1) Skin irritation, Category 2, H315 (Skin Irrit. 2) Eye irritation, Category 2, H319 (Eye Irrit. 2) Hazardous to the aquatic environment - chronic hazard, Category 2, H411 (Aquatic Chronic 2) GHS07,09	Isobornyl methacrylate, Exo-1,7,7-trimethylbicyclohept-2-yl methacrylate
FDM nylon 12 (durable nylon)	Not subject to labeling	Filler, silicon dioxide
P400sctm (soluble concentrate)	Skin corrosion, Category 1A, H314 (Skin Corr. 1A) Serious eye damage, Category 1, H318 (Eye Dam. 1) GHS05	Methacrylate monomers
Glue stick	Skin sensitisation, Category 1, H317 (Skin Sens. 1) GHS07	Isobornyl methacrylate, Exo-1,7,7-trimethylbicyclohept-2-yl methacrylate
3D adhesive spray	Flammable aerosols, Category 1, H222 (Flam. Aerosol 1) Flammable aerosols, Category 1, H229 (Flam. Aerosol 1) Eye irritation, Category 2, H319 (Eye Irrit. 2) Specific target organ toxicity – single exposure, Category 3, H336 (STOT SE 3) GHS02,07	Urethane dimethacrylate, 7,7,9(or 7,9,9)-trimethyl-4,13-dioxo-3,14-dioxa-5,12-diazahexadecane-1,16-diyl bismethacrylate
Alkonek	Flammable liquids, Category 2, H225 (Flam. Liq. 2) Eye irritation, Category 2, H319 (Eye Irrit. 2) GHS02,07	Carbon mesoporous (industrial carbon black)

The following tasks were completed:

- The levels of exposure to harmful substances affecting workers were determined through personal sampling.
- The impact of pollutants on workers was assessed based on measurement results and compliance with decree 5/2020. (II.6.) ITM related to the protection of workers' health and safety from chemical pathogenic factors.

Based on the information collected and the equipment safety data sheets, a sampling strategy was developed. The air pollutants emitted by the four printing plants and associated activities (e.g. glueing, cleaning) were measured and included the following substances: ethyl alcohol, MEK (methyl ethyl ketone), isopropyl alcohol,

inert dust, sodium hydroxide, methyl acrylate, methanol, phenol, chlorobenzene, e-caprolactam, and fibreglass dust.

The personal and stationary sampling was carried out using an SKC Aircheck 3000 personal sampler. The sampling head, which can be a dust sampling cyclone, adsorbent tube, or a special cassette, depending on the type, was connected to the sampling device with a tube. In a clean area, the airflow rate through the sample was checked and set (in accordance with the MDHS standard, measured in L/min depending on the substance being tested) using a calibrated rotameter (flow meter). For personal sampling, The airflow rate through the sample was checked and set using a calibrated rotameter (flow meter) in a clean area, according to the MDHS standard. For personal sampling, the sampler was placed within the worker's breathing zone, with the pump connected to a flexible tubing and secured with a harness. For stationary sampling, the samplers were positioned at head height, away from obstacles, fresh air intakes, or strong drafts.

The sampler was either attached to the worker or placed at a designated static point, given that only one worker was present in the room. Based on the information provided, an assumption of 8 h of work per day was made, eliminating the need for correction calculations for extended work periods. Sampling was conducted in accordance with point 5.2.2. of the MSZ EN 689:2018+AC:2019 standard, assuming consistent exposure throughout the shift. As a result, the total sampling time per point was 4 h. Peak concentrations were not measured since no process during the technology was identified that would have a significant short-term impact. For the examination of the concentration and mass flow rate of air pollutants from stationary point sources, sampling methods in compliance with the applicable regulations and standards were used. A TCR Tecora sampling pump was employed for the measurements. The necessary equipment was prepared, and proper functioning and condition were ensured. In the laboratory, the sampling circuit was assembled and checked. The main components of the sampling circuit included a Tecora integrated probe with Pitot tube, flow meter, volume meter, thermometer, pressure gauge, and air pump, with the Tecora sampler typically combining these components in one unit.

4. Result and Discussion

In the initial stages of the research, it was proposed that due to the lack of sufficient information and literature regarding the effects of this new technology on air pollution, there is a possibility that multiple components could exceed their threshold limits. The findings from the measurements indicated that both methanol and phenol were present in concentrations below detectable limits, suggesting that these substances are not produced in significant amounts by this technology.

However, e-caprolactam, a known air pollutant associated with various 3D printing processes, was found to exceed its threshold limit in the phase without an exhaust system. The measurement results for e-caprolactam can be seen in Table 2. The exceeding value amounted to 1.91 %, signifying heightened exposure. Whenever a threshold limit is surpassed, immediate action is necessary as inhalation can lead to symptoms such as abdominal cramps, dizziness, headache, and confusion. Subsequent to implementing an exhaust system, there was a reduction of 92 % in this value, which did not exceed 2 % of the threshold limit.

Table 2: E-caprolactam concentration emitted by Markforged 3D printer (Source: own editing)

Job/Process	Hazardous substance name	Measured average concentration [fibers/cm ³]		OEL (Occupational Exposure Limit) [fibres/cm ³]	STEL (Short-Term Exposure Limit) [fibres/cm ³]
		Before exhaust system installation	After the exhaust system installation		
Markforged 3D printer	E-caprolactam	11,9167	1,0417	10	40

The measurement data and Figure 1 show a clear decrease in concentrations to 0.3-10 % of the values measured prior to the installation of the exhaust system. This indicates that the workplace air quality has significantly improved, making it more comfortable and posing no risk to human health when a well-designed exhaust system is used.

In evaluating the point source of the 3D printer room, the emissions were compared to the prescribed limit values set for electronic component manufacturing technology. This assessment was conducted in accordance with air quality and emission limit standards for stationary air pollution sources outlined in Section 5 and Annex 6, point 2.3.1 of Decree 4/2011 (I.14.) VM, commonly known as the VM decree. Utilizing measured data and laboratory

test outcomes, the average concentration and mass flow rate were derived from the calculated 3x30 min concentration measurements. The measurement results and limit values are compared in Table 3.

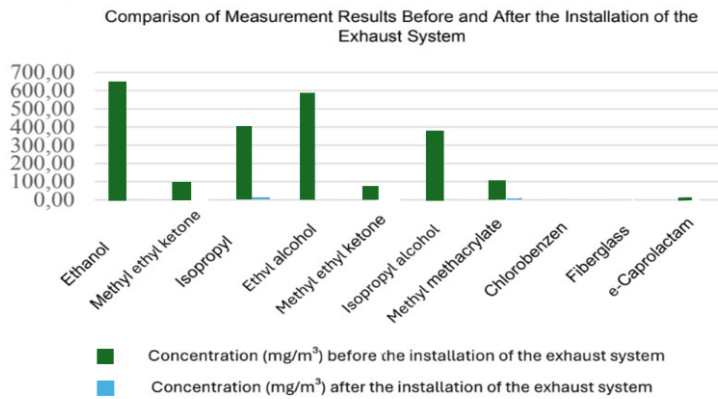


Figure 1: Comparison of Measurement Results (Source: own editing)

Table 3: Comparison of measurement results and limit values (Source: own editing)

Comparison of Measurement Results and Limit Values 3D Printer Room Exhaust					
Pollutant name/class	Mass flow rate* (kg/h)	Pollutant concentration* (mg/m ³)	Technological emission limit (kg/h)	Emission limit (mg/m ³)	Exceedance of emission limit
NaOH	<0.00004*	<0.0877*	0.3 or greater	30	-
Solid matter	0.0008	1.770	up to 0.5	150	-
Methyl methacrylate	0.0041	9.4912	3.0 or greater	150	-
Ethyl alcohol	0.0113	26.2398	3.0 or greater	150	-
Methyl ethyl ketone	0.0031	7.3216	3.0 or greater	150	-
Isopropyl alcohol	0.0260	60.4094	3.0 or greater	150	-
Phenol	<0.00004*	<0.0877*	3.0 or greater	150	-
Chlorobenzene	0.0004	0.9415	3.0 or greater	150	-
E-caprolactam	0.0001	0.2047	3.0 or greater	150	-

*Concentrations and volumetric flow rates are given for dry-end gas at -0,15 °C K and 101.3 kPa pressure.

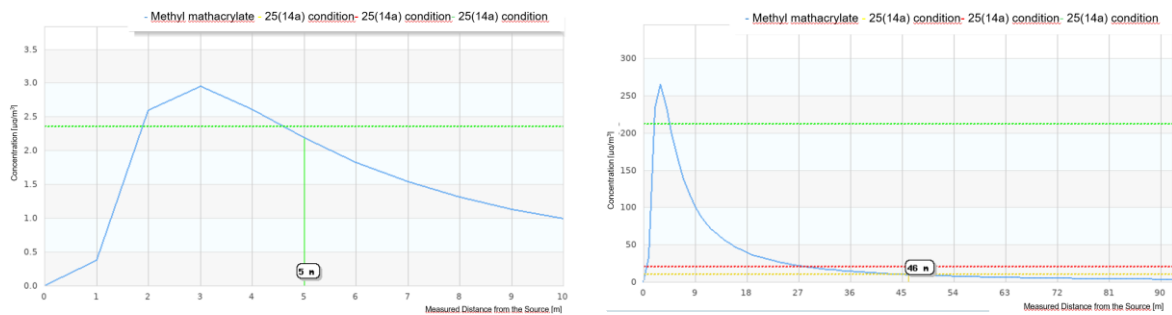


Figure 2: Impact area of point source with filter and without filter (Source: own editing using Aircalc software)

Based on the measurement findings, it can be inferred that none of the threshold values were exceeded in any instance. The integrated active carbon filter system effectively seizes 90 % of volatile organic compounds. However, filtration efficiency diminishes as filters become obstructed, emphasising the significance of regular maintenance and filter replacement

The Aircalc transmission modelling software was used to assess the affected area of the emission source without a filter(Figure 2, left) and with the filter installed (Figure 2, right).

5. Conclusions

The objective of my study is to analyze the release of air pollutants from the increasingly common 3D printing technology through workplace air and emission measurements carried out by me. The aim was to assess the need for and effectiveness of an exhaust system based on these measurements.

Research was conducted in a designated 3D printer room at a multinational company. Initially, workplace air quality was measured while the technology was operational but without an exhaust system. After installing the exhaust system, the workplace air measurements were repeated, and the results were compared. The findings clearly demonstrated a significant reduction in pollutant levels in the workplace following the implementation of the exhaust system for 3D printing activities. The results indicate that exposure within work areas is largely influenced by ventilation parameters and setup. An exhaust system serving as a point source for air pollution was developed. Emissions from the outlet into the atmosphere were also monitored and compared with the relevant regulatory limits. An active carbon filter installed in this system demonstrated 90 % efficiency, according to my evaluations. Calculations showed that due to effective filtration, there was a substantial decrease in impact area for protecting air quality – from 46 m to just 5 m. This investigation underscores how new technological processes should undergo thorough evaluation during their initial adoption phase to understand any potential adverse environmental impacts they may have. This would enable appropriate protective measures ensuring both human health preservation and maintenance of good indoor/outdoor air quality standards while minimising significant pollution resulting from possible malfunctions or accidents through proper application of pollution control technologies.

References

- Bayona J.M., Pawliszyn J., Dugo P., Le X.C., Lee H.K. (Eds.), 2012. *Comprehensive sampling and sample preparation: analytical techniques for scientists*. Elsevier, Amsterdam, The Netherlands.
- ILO, 2023, International Labour Organization: International Labour Standards., <www.ilo.org/international-labour-standards>, accessed 01. 11. 2023.
- Invernizzi M., Roveda L., Polvara E., Sironi S., 2021, Lights and Shadows of the Voc Emission Quantification. *Chemical Engineering Transactions*, 85, 109-114.
- Mádi Sarolta, 2016, The theoretical and practical aspects of the operation of the legal institutions of occupational health and safety, with particular reference to the responsibility of the employer (in Hungarian). PhD Thesis, p. 308., <hdl.handle.net/2437/223305>, accessed 22.10.2023.
- Mendes L., Kangas A., Kukko K., Mølgaard B., Säämänen A., Kanerva T., Flores Ituarte I., Huhtiniemi M., Stockmann-Juvala H., Partanen J., Hämeri K., Eleftheriadis K., Viitanen A., 2017, Characterization of Emissions from a Desktop 3D Printer. *Journal of Industrial Ecology*, 21(S1), S94-S106.
- Steinle P. 2016, Characterization of emissions from a desktop 3D printer and indoor air measurements in office settings. *Journal of Occupational and Environmental Hygiene*, 13(2), 121–132.
- Vežníková H., Skřížovská M., 2022, Time dependence of gas-phase emissions from 3D printer filaments. *Chemical Engineering Transactions*, 90, 553-558.
- Wojnowski W., Marć M., Kalinowska K., Kosmela P., Zabiegała B., 2022, Emission Profiles of Volatiles during 3D Printing with ABS, ASA, Nylon, and PETG Polymer Filaments. *Molecules*, 27, 3814, DOI: 10.3390/molecules27123814.
- Wojtyła S., Klama P., Śpiewak K., Baran T., 2020, 3D printer as a potential source of indoor air pollution. *Int. J. Environ. Sci. Technol.*, 17, 207–218.
- Yap S.H.K., Chan K.K., Yeh C.-H., Chien Y.-H., Yong K.-T., 2021, Two-Dimensional MoS₂ Nanosheet-Functionalized Optical Microfiber for Room-Temperature Volatile Organic Compound Detection. *ACS Appl. Nano Mater.*, 4, 13440–13449, DOI: 10.1021/acsanm.1c02937.
- Yi J., LeBouf R.F., Duling M.G., Nurkiewicz T., Chen B.T., Schwegler-Berry D., Virji M.A., Stefaniak A.B., 2016, Emission of particulate matter from a desktop three-dimensional (3D) printer. *Journal of Toxicology and Environmental Health, Part A*, 79(11), 453–465.
- Zhang Q., Pardo M., Rudich Y., Kaplan-Ashiri I., Wong J.P.S., Davis A.Y., Black M.S., Weber R.J., 2019, Chemical Composition and Toxicity of Particles Emitted from a Consumer-Level 3D Printer Using Various Materials. *Environmental Science & Technology*, 53(20), 12054–12061.