

INDOOR AIR QUALITY IN CHANGING WORKPLACE DYNAMICS: THE
CASE OF ADDITIVE MANUFACTURING

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THE CASE OF ADDITIVE MANUFACTURING**

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ABSTRACT

INDOOR AIR QUALITY IN CHANGING WORKPLACE DYNAMICS: THE CASE OF ADDITIVE MANUFACTURING

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As people spend a significant portion of their time indoors, such as in workplaces, workplace conditions are of great importance to their well-being. With technological advancements, Additive Manufacturing (AM) technologies are increasingly integrated into workplaces, blending production and office spaces and affecting indoor air quality (IAQ) through emissions from various processes. However, these impacts remain underexplored, particularly regarding the coexistence of production and office spaces. This study investigates the impact of AM processes, including powder bed fusion - selective laser melting (PBF-SLM), powder bed fusion - selective laser sintering (PBF-SLS), and vat photopolymerization - stereolithography (VP-SLA) on IAQ parameters, including particulate matter, volatile organic compounds, formaldehyde, benzene, ethanol, nitrogen dioxide, carbon dioxide, and oxygen along with employees' perception of IAQ in production and office spaces. Qualitative and quantitative data were acquired from semi-structured interviews, an Internet of Things-based custom-designed instrument collecting real-time pollutant data, and another custom-designed instrument gathering employee feedback on IAQ perception. The interview results highlighted employee concerns about IAQ. Field experiments

revealed emissions of varying degrees concerning IAQ parameters in both production and office spaces during PBF-SLM, PBF-SLS, and VP-SLA operations. The emissions detected in the production spaces were higher compared to those recorded in the office space. The employee feedback indicated generally positive perceptions of IAQ in the office space but noted concerns in the production spaces during certain operational phases. The findings emphasize the need for facility adjustments to mitigate IAQ challenges associated with AM operations, particularly in the production spaces.

Keywords: Additive Manufacturing, Indoor Air Quality, Internet of Things, Emissions, Workplace

ÖZ

DEĞİŞEN ÇALIŞMA YERİ DİNAMİKLERİNDE İÇ HAVA KALİTESİ: EKLEMELİ İMALAT ÖRNEĞİ

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İnsanlar zamanlarının önemli bir kısmını çalışma yerleri gibi kapalı alanlarda geçirdiği için çalışma yeri koşulları onların refahı için önemlidir. Teknolojik ilerlemelerle birlikte, Eklemeli İmalat (Eİ) teknolojileri artan bir şekilde çalışma yerlerine entegre edilmekte ve bu durum ofis ve üretim mekanlarını birleştirerek Eİ süreçlerinden kaynaklanan emisyonlar ile iç hava kalitesini (İHK) etkilemektedir. Ancak, bu etkiler, özellikle ofis ve üretim mekanlarının bir arada bulunması kapsamında yeterince araştırılmamıştır. Bu çalışma, üretim ve ofis alanlarında toz yatak füzyon birleştirme - seçici lazer ergitme (TFB-SLE), toz yatak füzyon birleştirme - seçici lazer sinterleme (TFB-SLS) ve havuz fotopolimerizasyonu - stereolitografi (HF-SLA) gibi Eİ süreçlerinin, partikül madde, uçucu organik bileşik, formaldehit, benzen, etanol, azot dioksit, karbon dioksit ve oksijen ve gibi İHK parametreleri üzerindeki etkisini ve çalışanların İHK algısını araştırmaktadır. Yarı yapılandırılmış görüşmeler, hava kirletici verilerini gerçek zamanlı toplayan nesnelerin interneti tabanlı özel tasarım bir enstrüman ve çalışanların İHK algısına yönelik geri bildirim toplayan özel tasarım bir enstrüman kullanılarak nitel ve nicel veriler elde edilmiştir. Görüşme sonuçları, çalışanların İHK kaygılarını vurgulamıştır. Alan deneyleri ile, TFB-SLM, TFB-SLS ve HF-SLA operasyonları

sırasında üretim ve ofis mekanlarında İHK parametreleri bakımından emisyonlar tespit edilmiştir. Üretim mekanlarında saptanan emisyonların, ofis mekanında kaydedilenlere göre daha yüksektir. Çalışan geri bildirimleri, ofis mekanındaki İHK algısının genellikle olumlu olduğunu, ancak üretim mekanlarında belirli aşamalarda endişeler olduğunu göstermiştir. Bulgular, özellikle üretim mekanlarında Eİ operasyonlarıyla ilişkili İHK sorunlarını önlemek için tesis koşullarının geliştirilmesi gerektiğini ortaya koymaktadır.

Anahtar Kelimeler: Eklemeli İmalat, İç Hava Kalitesi, Nesnelerin İnterneti, Emisyonlar, Çalışma Yeri



To Fine Souls

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"We always look at the mountains in front of us and forget the mountains behind us were just as hard to climb." — Marjorie, *Mom*.



TABLE OF CONTENTS

ABSTRACT	v
ÖZ.....	vii
ACKNOWLEDGMENTS.....	x
TABLE OF CONTENTS	xii
LIST OF TABLES	xv
LIST OF FIGURES.....	xviii
LIST OF ABBREVIATIONS	xxiv
LIST OF SYMBOLS.....	xxvi
CHAPTERS	
1 INTRODUCTION.....	1
1.1 Background and Motivation of the Research	1
1.2 Scope of the Research	4
1.3 Aims and Objectives of the Research.....	6
1.4 Research Questions	7
1.5 Research Structure and Disposition.....	7
2 LITERATURE REVIEW	9
2.1 Workplace.....	9
2.1.1 Production Space	10
2.1.2 Office Space	13
2.1.3 Integration of Production and Office Spaces.....	22
2.2 Additive Manufacturing	22
2.2.1 Historical Development of Additive Manufacturing.....	24

2.2.2	Technologies and Processes of Additive Manufacturing.....	27
2.3	Indoor Environmental Quality	42
2.3.1	Indoor Air Quality Phenomenon.....	43
2.3.2	Indoor Air Quality Pollutants.....	45
2.3.3	Indoor Air Quality Issues Associated with Additive Manufacturing	62
3	METHODOLOGY	75
3.1	Semi-Structured Interview	76
3.2	Indoor Network-Based Air-Sensing Ecosystem	76
3.2.1	Hardware Development	77
3.2.2	Software Development.....	91
3.2.3	Calibration.....	93
3.3	Indoor Air Quality Polling Instrument.....	98
3.3.1	Hardware Development	99
3.3.2	Software Development.....	103
3.4	Field Experiments	103
3.4.1	Field Experiments in the Production Spaces	106
3.4.2	Field Experiments in the Office Space	116
4	RESULTS AND DISCUSSION	119
4.1	Semi-Structured Interview	119
4.2	Field Experiments for Powder Bed Fusion - Selective Laser Melting	122
4.3	Field Experiments for Powder Bed Fusion - Selective Laser Sintering	151
4.4	Field Experiments for Vat Photopolymerization - Stereolithography	180
4.5	Insights into Enhancing Indoor Air Quality in the Case of Additive Manufacturing.....	211

5	CONCLUSION	213
5.1	Research Summary	213
5.2	Main Results and Discussion.....	216
5.3	Limitations and Future Directions.....	225
	REFERENCES	227
	APPENDICES	
A.	The Semi-Structured Interview in Turkish.....	245
B.	The Semi-Structured Interview in English	247



LIST OF TABLES

TABLES

Table 2.1 Example Particle Shapes (Ontario Ministry of the Environment, 2010, p.H-13).....	48
Table 2.2 Accumulation of Varying Sizes of PM in the Human Body (Aybay, 2017, p.40)	49
Table 2.3 Air Quality Guidelines for PM (Environmental Protection Agency, 2020b, p.82694; European Commission, 2008, p.152/31, 152/35; World Health Organization, 2021, p. 78, 88, 92, 97)	49
Table 2.4 Classification of VOCs based on Boiling Points and Compound Volatility (WHO, 1989, as cited in Seifert et al., 1989, p.27)	51
Table 2.5 Air Quality Guidelines for TVOC (“Beurteilung von Innenraumluftkontaminationen Mittels Referenz- Und Richtwerten,” 2007, p.993)	53
Table 2.6 Air Quality Guidelines for Formaldehyde (World Health Organization, 2000, p.90)	54
Table 2.7 Observed Health Effects of Formaldehyde Exposure (Hines et al., 1993 as cited in Jones, 1999, p. 4541)	54
Table 2.8 Workplace Exposure Limits for Ethanol (Occupational Safety and Health Administration, n.d.)	56
Table 2.9 Air Quality Guidelines for NO ₂ (Environmental Protection Agency, 2018, p. 17255; European Commission, 2008, p. 152/30; World Health Organization, 2021, p. 116, 124)	57
Table 2.10 Air Quality Guidelines for SO ₂ (Environmental Protection Agency, 2019; European Commission, 2008, p.152/30; World Health Organization, 2000, p.196)	58

Table 2.11 Air Quality Guidelines for CO with Short Averaging Times (Environmental Protection Agency, 2011, p.54296; European Commission, 2008, p.152/30; World Health Organization, 2010, p.88).....	60
Table 2.12 Air Quality Guidelines for Radon (Balanlı et al., 2004, p.7)	61
Table 2.13 Air Quality Guidelines for O ₃ (Environmental Protection Agency, 2020a, p. 87307; European Commission, 2008, p.152/24; World Health Organization, 2000, p.185).....	62
Table 3.1 Technical Specifications of HM3301 (Shenzhen Technology, 2018)	78
Table 3.2 Technical Specifications of SGP30 (Sensirion, 2020, p.2,4)	79
Table 3.3 Technical Specifications of SFA30 (Sensirion, 2020a)	81
Table 3.4 Technical Specifications of Multichannel V2 (Zhengzhou Winsen Electronics Technology, 2017, 2019, 2020b, 2020a).....	83
Table 3.5 Technical Specifications of SCD30 (Sensirion, 2018, p.2).....	85
Table 3.6 Technical Specifications of ME2-O ₂ -Φ20 (Zhengzhou Winsen Electronics, 2021).....	86
Table 3.7 Preheating Time (Zhengzhou Winsen Electronics Technology, 2017, 2019, 2020a, 2020b).....	97
Table 4.1 Semi-Structured Interview Question Contents and Response Codes....	120
Table 4.2 Semi-Structured Interview Response Themes and Codes.....	121
Table 4.3 Descriptive Statistics of PM _{1.0} Concentrations during PBF-SLM.....	123
Table 4.4 Descriptive Statistics of PM _{2.5} Concentrations during PBF-SLM.....	125
Table 4.5 Descriptive Statistics of PM ₁₀ Concentrations during PBF-SLM	128
Table 4.6 Descriptive Statistics of TVOC Concentrations during PBF-SLM.....	131
Table 4.7 Descriptive Statistics of HCHO Concentrations during PBF-SLM	133
Table 4.8 Descriptive Statistics of C ₆ H ₆ Concentrations during PBF-SLM.....	135
Table 4.9 Descriptive Statistics of C ₂ H ₅ OH Concentrations during PBF-SLM ...	138
Table 4.10 Descriptive Statistics of NO ₂ Concentrations during PBF-SLM	140
Table 4.11 Descriptive Statistics of CO ₂ Concentrations during PBF-SLM.....	143
Table 4.12 Descriptive Statistics of O ₂ Concentrations during PBF-SLM	145
Table 4.13 Descriptive Statistics of PM _{1.0} Concentrations during PBF-SLS	151

Table 4.14 Descriptive Statistics of PM _{2.5} Concentrations during PBF-SLS	154
Table 4.15 Descriptive Statistics of PM ₁₀ Concentrations during PBF-SLS	157
Table 4.16 Descriptive Statistics of TVOC Concentrations during PBF-SLS	160
Table 4.17 Descriptive Statistics of HCHO Concentrations during PBF-SLS	163
Table 4.18 Descriptive Statistics of C ₆ H ₆ Concentrations during PBF-SLS	165
Table 4.19 Descriptive Statistics of C ₂ H ₅ OH Concentrations during PBF-SLS ..	167
Table 4.20 Descriptive Statistics of NO ₂ Concentrations during PBF-SLS	170
Table 4.21 Descriptive Statistics of CO ₂ Concentrations during PBF-SLS	172
Table 4.22 Descriptive Statistics of O ₂ Concentrations during PBF-SLS	174
Table 4.23 Descriptive Statistics of PM _{1.0} Concentrations during VP-SLA	180
Table 4.24 Descriptive Statistics of PM _{2.5} Concentrations during VP-SLA	183
Table 4.25 Descriptive Statistics of PM ₁₀ Concentrations during VP-SLA	186
Table 4.26 Descriptive Statistics of TVOC Concentrations during VP-SLA	189
Table 4.27 Descriptive Statistics of HCHO Concentrations during VP-SLA	192
Table 4.28 Descriptive Statistics of C ₆ H ₆ Concentrations during VP-SLA	194
Table 4.29 Descriptive Statistics of C ₂ H ₅ OH Concentrations during VP-SLA	197
Table 4.30 Descriptive Statistics of NO ₂ Concentrations during VP-SLA	199
Table 4.31 Descriptive Statistics of CO ₂ Concentrations during VP-SLA	202
Table 4.32 Descriptive Statistics of O ₂ Concentrations during VP-SLA	205
Table 5.1 Summary of the Results of the Research	224

LIST OF FIGURES

FIGURES

Figure 2.1 Industrial Revolutions (Rojko, 2017, p.79).....	11
Figure 2.2 The Overview of Industry 4.0 (Rojko, 2017, p.81).....	13
Figure 2.3 a) East India Co., Leaden Hall Street, London, 1726-9; b) Oriel Chambers, Liverpool, 1864; c) Sears, Roebuck, and Company Mail Order, Chicago, 1905-6; d) and e) Larkin Building, Buffalo, NY, 1904 (Nag, 2019, p.6)	15
Figure 2.4 Cellular Office Layout (Left) and Wainwright Building, Louis Sullivan, St. Louis, 1890 (Right) (Anton, 2015)	16
Figure 2.5 Taylorist Open-Plan Layout (Left) and Johnson Wax Building, Frank Lloyd Wright, Racine, 1937 (Right) (Anton, 2015).....	17
Figure 2.6 Office Landscape Layout (Left) and Osram Offices, Quickborner, Munich, 1963 (Right) (Anton, 2015)	18
Figure 2.7 Centraal Beheer, Herman Hertzberger, Apeldoorn, 1970 (Anton, 2015)	19
Figure 2.8 Cubicle Layout (Left) and Chase Manhattan Bank, SOM, New York, 1961 (Right) (Anton, 2015).....	19
Figure 2.9 Combi Office Layout (Left) and SAS Offices, Niels Torp, Stockholm, 1988 (Right) (Anton, 2015).....	20
Figure 2.10 Virtual Office Layout (Left) and Interpolis Headquarters, Bonnema Architecten, Tilburg, 1995 (Right) (Anton, 2015)	21
Figure 2.11 Casual Office Layout (Left) and Chitday Offices, Clive Wilkinson Architects, Los Angeles, 1997 (Right) (Anton, 2015)	21
Figure 2.12 The First AM Technology from Hull (Gibson et al., 2015, p.38).....	25
Figure 2.13 The Historical Trajectory of Additive Manufacturing	27
Figure 2.14 Flow Chart of AM (Quan et al., 2015, p.504).....	28
Figure 2.15 Classification of AM by ASTM (Tofail et al., 2018, p.25).....	29
Figure 2.16 Operation Principles of AM Processes: (a) BJ, (b) DED, (c) ME, (d) MJ, (e) PBF, (f) SL, and (g) VP. (Stefaniak et al., 2021, p.176).....	30

Figure 2.17 The Diagram of the BJ Process (Gibson et al., 2015, p.206)	31
Figure 2.18 The Diagram of 3D Printing Technology (Hopkinson et al., 2006, p.66)	32
Figure 2.19 The Diagram of the DED Process (Gibson et al., 2015, p.246)	33
Figure 2.20 The Diagram of the ME Process (Gibson et al., 2015, p.150).....	33
Figure 2.21 The Diagram of the FDM Printer (Gupta et al., 2019, p.14)	34
Figure 2.22 The Diagram of the MJ Process (Sireesha et al., 2018, p.22462)	35
Figure 2.23 The Diagram of the SLS Process (Gibson et al., 2015, p.108).....	36
Figure 2.24 The Diagram of the EBM Apparatus (Gibson et al., 2015, p.138).....	37
Figure 2.25 The Diagram of the LOM Process (Hopkinson et al., 2006, p.78).....	38
Figure 2.26 The Diagram of Three Photopolymerization Processes (Gibson et al., 2015, p.65)	39
Figure 2.27 The Diagram of the SLA Process (Hopkinson et al., 2006, p.59)	40
Figure 2.28 Classification of AM Processes based on the Material State Employed for Printing (Chen et al., 2015).	41
Figure 2.29 Categorization of Particulate Matter (ASHRAE, 2013).....	46
Figure 2.30 Typical Outdoor PM Composition by Particle Size Fraction (Wilson & Suh, 1997, as cited in ASHRAE, 2013, p.149).....	46
Figure 2.31 Health Consequences of CO ₂ Exposure at Certain Concentrations (López et al., 2023, p.9)	59
Figure 3.1 Methodology of the Research.....	75
Figure 3.2 The Isometric (a), Top (b), and Bottom (c) Views of the PM _{2.5} Sensor - HM3301	77
Figure 3.3 PM Sensor Structure Diagram (Shenzhen Technology, 2018, p.4)	78
Figure 3.4 The Isometric (a), Top (b), and Bottom (c) Views of the TVOC Sensor - SGP30	79
Figure 3.5 The Isometric (a), Top (b), and Bottom (c) Views of the HCHO Sensor - SFA30	80
Figure 3.6 The Isometric (a), Top (b), and Bottom (c) Views of the C ₆ H ₆ , C ₂ H ₅ OH, and NO ₂ Sensor - Multichannel V2	82

Figure 3.7 The Isometric (a), Top (b), and Bottom (c) Views of the CO ₂ Sensor - SCD30	83
Figure 3.8 NDIR Technology (Nadargi et al., 2023, p. 563)	84
Figure 3.9 The Isometric (a), Top (b), and Bottom (c) Views of the O ₂ Sensor - ME2-O ₂ -Φ20	85
Figure 3.10 The Isometric (a), Top (b), and Bottom (c) Views of the Wi-Fi Module - ESP8266.....	87
Figure 3.11 The Isometric (a), Top (b), and Bottom (c) Views of the Display Unit - SSD1306.....	88
Figure 3.12 The Isometric (a), Top (b), and Bottom (c) Views of the Base Shield - Grove Base Shield V2.0	89
Figure 3.13 The Visual of the Development Board - Arduino Mega 2560 Rev3 ...	89
Figure 3.14 The Diagram of the Hardware Set-up of INBASE	90
Figure 3.15 Photographs of INBASE	91
Figure 3.16 Schematic of the Software Development.....	92
Figure 3.17 Calibration Curve of VOC (C ₆ H ₆)	95
Figure 3.18 Calibration Curve of C ₂ H ₅ OH.....	96
Figure 3.19. Calibration Curve of NO ₂	96
Figure 3.20 The Visuals of the Tact Switches and 1/4 W 1K Resistors	99
Figure 3.21 The Visuals of the Card Shield - SD Card Shield V4.....	100
Figure 3.22 The Visual of the Real-Time Clock - DS1302.....	100
Figure 3.23 The Diagram of the Hardware Set-Up of the Indoor Air Quality Polling Instrument.....	102
Figure 3.24 Photographs of the Indoor Air Quality Polling Instrument.....	102
Figure 3.25 The Plan of the Workplace.....	104
Figure 3.26 The Diagram of the Field Experiments.....	105
Figure 3.27 The Plan of the PBF-SLM Production Space of the Workplace.....	106
Figure 3.28 SLM Prototyping and Final Part Production Equipment	107
Figure 3.29 The Plan of the PBF-SLS Production Space of the Workplace	109
Figure 3.30 SLS Prototyping and Final Part Production Equipment	110

Figure 3.31 SLS Powder Management Station.....	110
Figure 3.32 The Plan of the VP-SLA Production Spaces of the Workplace	113
Figure 3.33 SLA Prototyping and Final Part Production Equipment	114
Figure 3.34 SLA Wash Equipment.....	114
Figure 3.35 SLA Cure Equipment	115
Figure 3.36 The Plan of Office Space of the Workplace	117
Figure 4.1 Demographic Profile of Interview Participants	119
Figure 4.2 PM _{1.0} Concentrations in Related Production Space during PBF-SLM	124
Figure 4.3 PM _{1.0} Concentrations in Office Space during PBF-SLM	124
Figure 4.4 PM _{2.5} Concentrations in Related Production Space during PBF-SLM	126
Figure 4.5 PM _{2.5} Concentrations in Office Space during PBF-SLM	127
Figure 4.6 PM ₁₀ Concentrations in Related Production Space during PBF-SLM	129
Figure 4.7 PM ₁₀ Concentrations in Office Space during PBF-SLM.....	130
Figure 4.8 TVOC Concentrations in Related Production Space during PBF-SLM	132
Figure 4.9 TVOC Concentrations in Office Space during PBF-SLM	132
Figure 4.10 HCHO Concentrations in Related Production Space during PBF-SLM	134
Figure 4.11 HCHO Concentrations in Office Space during PBF-SLM.....	135
Figure 4.12 C ₆ H ₆ Concentrations in Related Production Space during PBF-SLM	136
Figure 4.13 C ₆ H ₆ Concentrations in Office Space during PBF-SLM	137
Figure 4.14 C ₂ H ₅ OH Concentrations in Related Production Space during PBF-SLM	139
Figure 4.15 C ₂ H ₅ OH Concentrations in Office Space during PBF-SLM	139
Figure 4.16 NO ₂ Concentrations in Related Production Space during PBF-SLM	141
Figure 4.17 NO ₂ Concentrations in Office Space during PBF-SLM	142
Figure 4.18 CO ₂ Concentrations in Related Production Space during PBF-SLM	144
Figure 4.19 CO ₂ Concentrations in Office Space during PBF-SLM	144
Figure 4.20 O ₂ Concentrations in Related Production Space during PBF-SLM ..	146
Figure 4.21 O ₂ Concentrations in Office Space during PBF-SLM.....	147

Figure 4.22 Employee Perception of IAQ in Related Production Space during PBF-SLM.....	148
Figure 4.23 Employee Perception of IAQ in Office Space during PBF-SLM.....	149
Figure 4.24 PM _{1.0} Concentrations in Related Production Space during PBF-SLS	152
Figure 4.25 PM _{1.0} Concentrations in Office Space during PBF-SLS	153
Figure 4.26 PM _{2.5} Concentrations in Related Production Space during PBF-SLS	155
Figure 4.27 PM _{2.5} Concentrations in Office Space during PBF-SLS	156
Figure 4.28 PM ₁₀ Concentrations in Related Production Space during PBF-SLS	158
Figure 4.29 PM ₁₀ Concentrations in Office Space during PBF-SLS.....	159
Figure 4.30 TVOC Concentrations in Related Production Space during PBF-SLS	161
Figure 4.31 TVOC Concentrations in Office Space during PBF-SLS	162
Figure 4.32 HCHO Concentrations in Related Production Space during PBF-SLS	164
Figure 4.33 HCHO Concentrations in Office Space during PBF-SLS.....	164
Figure 4.34 C ₆ H ₆ Concentrations in Related Production Space during PBF-SLS	166
Figure 4.35 C ₆ H ₆ Concentrations in Office Space during PBF-SLS	166
Figure 4.36 C ₂ H ₅ OH Concentrations in Related Production Space during PBF-SLS	168
Figure 4.37 C ₂ H ₅ OH Concentrations in Office Space during PBF-SLS	169
Figure 4.38 NO ₂ Concentrations in Related Production Space during PBF-SLS .	171
Figure 4.39 NO ₂ Concentrations in Office Space during PBF-SLS	171
Figure 4.40 CO ₂ Concentrations in Related Production Space during PBF-SLS..	173
Figure 4.41 CO ₂ Concentrations in Office Space during PBF-SLS	173
Figure 4.42 O ₂ Concentrations in Related Production Space during PBF-SLS	175
Figure 4.43 O ₂ Concentrations in Office Space during PBF-SLS	176
Figure 4.44 Employee Perception of IAQ in Related Production Space during PBF-SLS	177
Figure 4.45 Employee Perception of IAQ in Office Space during PBF-SLS	178
Figure 4.46 PM _{1.0} Concentrations in Related Production Spaces during VP-SLA	181

Figure 4.47 PM _{1.0} Concentrations in Office Space during VP-SLA.....	182
Figure 4.48 PM _{2.5} Concentrations in Related Production Spaces during VP-SLA.....	184
Figure 4.49 PM _{2.5} Concentrations in Office Space during VP-SLA.....	185
Figure 4.50 PM ₁₀ Concentrations in Related Production Spaces during VP-SLA.....	187
Figure 4.51 PM ₁₀ Concentrations in Office Space during VP-SLA.....	188
Figure 4.52 TVOC Concentrations in Related Production Spaces during VP-SLA.....	190
Figure 4.53 TVOC Concentrations in Office Space during VP-SLA.....	191
Figure 4.54 HCHO Concentrations in Related Production Spaces during VP-SLA.....	193
Figure 4.55 HCHO Concentrations in Office Space during VP-SLA.....	193
Figure 4.56 C ₆ H ₆ Concentrations in Related Production Spaces during VP-SLA.....	195
Figure 4.57 C ₆ H ₆ Concentrations in Office Space during VP-SLA.....	196
Figure 4.58 C ₂ H ₅ OH Concentrations in Related Production Spaces during VP-SLA.....	198
Figure 4.59 C ₂ H ₅ OH Concentrations in Office Space during VP-SLA.....	198
Figure 4.60 NO ₂ Concentrations in Related Production Spaces during VP-SLA.....	201
Figure 4.61 NO ₂ Concentrations in Office Space during VP-SLA.....	201
Figure 4.62 CO ₂ Concentrations in Related Production Spaces during VP-SLA.....	203
Figure 4.63 CO ₂ Concentrations in Office Space during VP-SLA.....	204
Figure 4.64 O ₂ Concentrations in Related Production Spaces during VP-SLA.....	205
Figure 4.65 O ₂ Concentrations in Office Space during VP-SLA.....	206
Figure 4.66 Employee Perception of IAQ in Related Production Spaces during VP-SLA.....	207
Figure 4.67 Employee Perception of IAQ in Office Space during VP-SLA.....	209

LIST OF ABBREVIATIONS

ABBREVIATIONS

ACGIH	American Conference of Governmental Industrial Hygienists
AM	Additive Manufacturing
ANSI	American National Standards Institute
ASHRAE	American Society of Heating, Refrigerating, and Air-Conditioning Engineers
ASTM	American Society for Testing and Materials
BJ	Binder Jetting
DED	Directed Energy Deposition
DLP	Digital Light Processing
DMLS	Direct Metal Laser Sintering
EBM	Electron Beam Melting
EPA	Environmental Protection Agency
EU	European Union
FDM	Fused Deposition Modeling
FFF	Fused Filament Fabrication
FLM	Fused Layer Modeling
HVAC	Heating Ventilation and Air Conditioning
I ² C	Inter-Integrated Circuit
IAQ	Indoor Air Quality
IARC	International Agency for Research on Cancer
ICRP	International Commission on Radiological Protection
IEQ	Indoor Environmental Quality
INBASE	Indoor Network-Based Air-Sensing Ecosystem
IoT	Internet of Things
LD	Laser Deposition
LENS	Laser Engineered Net Shaping
LOM	Laminated Object Manufacturing
LPF	Laser Powder Forming

ME	Material Extrusion
MJ	Material Jetting
NAAQS	National Ambient Air Quality Standards
NIOSH	National Institute for Occupational Safety and Health
OSHA	Occupational Safety and Health Administration
PBF	Powder Bed Fusion
PM	Particulate Matter
PPE	Personal Protective Equipment
RH	Relative Humidity
SL	Sheet Lamination
SLA	Stereolithography
SLM	Selective Laser Melting
SLS	Selective Laser Sintering
TVOC	Total Volatile Organic Compound
UAM	Ultrasonic Additive Manufacturing
UART	Universal Asynchronous Receiver/Transmitter
UBA	Federal Environmental Agency (Umweltbundesamt)
UPF	Ultrafine-Mode Particles
VOC	Volatile Organic Compound
VP	Vat Photopolymerization
WHO	World Health Organization
Wi-Fi	Wireless Fidelity

LIST OF SYMBOLS

SYMBOLS

$\mu\text{g}/\text{m}^3$	Microgram per Cubic Meter
A	Ampere
$\text{C}_2\text{H}_5\text{OH}$	Ethyl Alcohol (Ethanol)
C_6H_6	Benzene
CO	Carbon Monoxide
CO_2	Carbon Dioxide
HCHO	Formaldehyde
mg/m^3	Milligram per Cubic Meter
g/mol	Gram per Mole
NO_2	Nitrogen Dioxide
O_2	Oxygen
O_3	Ozone
ppb	Parts per Billion
ppm	Parts per Million
SO_2	Sulfur Dioxide
Ti6Al4V	Titanium Alloy
V	Voltage
Vol	Volume

CHAPTER 1

INTRODUCTION

This thesis explores the impact of additive manufacturing (AM) technologies on indoor air quality (IAQ) within the context of production and office spaces. This chapter presents the background and motivation of the outlined problem, the scope of the research, the aims and objectives of the study, the research questions, and the structure and disposition of the thesis.

1.1 Background and Motivation of the Research

People spend a significant portion of their time within indoor spaces (Kosonen & Tan, 2004), with workplaces constituting a major part of these indoor spaces where people meet the necessities of their work through physical and mental effort (Felstead et al., 2003). Workplaces have been classified based on the nature of the work performed. An office space is attributed to a space where nonmanual work is carried out, focusing on administrative and managerial tasks (Felstead et al., 2003) to satisfy related functions and processes of an enterprise (Nag, 2019). It is typically equipped with desks, computers, phones, and other necessary office equipment. On the other hand, a production space is where operations, including manufacturing and assembling of products, take place (Felstead et al., 2003). Therefore, it is equipped with production machinery, assembly lines, and storage areas.

Historically, production and office spaces have been distinct entities with separate roles and physical boundaries. Nevertheless, political contexts, social conditions, and technological developments have changed these spaces throughout history

(Rassia, 2017). The evolution of these spaces is closely tied to the history of industrialization. Each industrial revolution has transformed workplace dynamics by introducing new technologies that alter the interaction between workplaces and work processes. Particularly, the advent of Industry 4.0 brings about novel production techniques that reshape the landscape of workplaces (Vaidya et al., 2018). One significant example that is becoming prevalent in Industry 4.0 is additive manufacturing (AM). This emerging manufacturing field enables three-dimensional (3D) objects to be fabricated through 3D printers by means of additive processes (Delgado Camacho et al., 2018; Gupta et al., 2019; Kietzmann et al., 2015; Labonnote et al., 2016; Mathur, 2016). It enables the fabrication of 3D objects with intricate shapes at a lower cost, reduced weight, and faster pace without using molds or templates (Gibson et al., 2015). Unlike traditional manufacturing processes that require large-scale production facilities, AM operations take place in more flexible and multipurpose spaces. Therefore, AM makes it feasible to carry out production activities within smaller footprinted spaces as a part of other workplace operations. Consequently, the boundaries between design and production processes are blurred, causing production and office spaces to be integrated in certain cases. The integration of production and office spaces positively influences the operational dynamics of AM processes. It brings about improved efficiency in task management and streamlined operations. AM is widely utilized across diverse industries. Both advanced printers and desktop-based concept modelers have become very prevalent in many businesses (Gibson et al., 2015). Consequently, there is an increasing prevalence of workplaces where production and office spaces coexist.

AM processes can be considered in seven areas with respect to the employed technology (Monzón et al., 2015). These are binder jetting (BJ), which involves layer-by-layer construction of objects using powdered materials bonded with a liquid binder; directed energy deposition (DED), which uses thermal energy sources to melt feedstock material to be deposited onto a build platform; material extrusion (ME), which extrudes material through a nozzle layer by layer to

construct a part; material jetting (MJ), which dispenses liquid photopolymer resin onto a build platform to be cured by an ultra-violet (UV) laser; powder bed fusion (PBF), which solidifies a powder-based material through a heat source; sheet lamination (SL), which laminates sheets using adhesives or ultrasonic welding to form objects; and vat photopolymerization (VP), which involves selective curing of liquid photopolymer resin into a solid state in a vat. (Stefaniak et al., 2021; Tofail et al., 2018; Wu et al., 2020). Each process involves pre-printing, printing, post-printing, and post-processing stages, contributing to potential emissions and health risks based on the technology and materials used. Stefaniak et al. (2021) state that the typical pre-printing activity in AM processes is introducing feedstock material into the 3D printer. Therefore, powder introduction in BJ, wire or powder introduction in DED, polymer introduction in ME, the introduction of resin containers in MJ, measurement and introduction of powder in PBF, the introduction of paper or polymer in sheet format and metal in tape, film, or ribbon format in SL, and resin mixing and vat loading in VP occur during pre-printing. The printing phase for all AM processes includes operating the 3D printer to print the intended object. Post-printing tasks include opening the equipment door and extracting the printed object for all AM processes, with additional tasks, including removing powder surplus in BJ and PBF. Potential post-processing activities are spray coating in BJ, machining in DED, vapor polishing and sanding in ME, detaching from the build platform and grinding in PBF, cutting or milling in SL (2021), and cleaning, UV curing, removing supports, and other processing activities in VP (Pagac et al., 2021). Each of these processes brings about certain emissions, requiring concerns for health and safety (Minář et al., 2023), as they directly affect indoor air quality (IAQ) in workplaces. Nevertheless, the expansion of AM applications lacks comprehensive attention to worker safety and health, with a limited number of publications addressing these concerns (Stefaniak et al., 2021).

All AM processes present hazards, while the nature and extent of potential exposure vary across AM categories, process phases, and operating environments

(Bours et al., 2017; Petretta et al., 2019; Roth et al., 2019). Several authors, including Petretta et al. (2019) and Roth et al. (2019), claim that major health risks associated with AM processes include particle inhalation, semi-volatile and volatile organic compounds (SVOCs and VOCs) exposure, and dermal exposure to varying matters, including powders, binders, resins, solvents, and radiation. The emissions generated during the AM processes exacerbate the microenvironment within a workplace by augmenting indoor air pollution with varying harmful compounds released into indoor air. Those emissions create risks to not only production spaces but also office spaces that work as an integrated part of production spaces.

This research is propelled by the commitment to understanding the complex relationship between AM technologies and IAQ in integrated production and office spaces. The study utilizes a combination of qualitative and quantitative methodologies to investigate a workplace engaging in additive manufacturing practices and, therefore, characterize the impact of different AM technologies on IAQ within production and office spaces. The qualitative and quantitative methodologies include a semi-structured interview and field experiments to gather real-time pollutant data within production and office spaces and capture IAQ perceptions of employees during operations of different AM technologies, including powder bed fusion - selective laser melting (PBF-SLM), powder bed fusion - selective laser sintering (PBF-SLS), and vat photopolymerization - stereolithography (VP-SLA). Hence, by combining these methodologies, the research aims to provide a holistic understanding of how different AM technologies impact the multifaceted dimensions of IAQ within production and office spaces within workplaces, offering insights into the intersection of the health and comfort of employees.

1.2 Scope of the Research

This research employs qualitative and quantitative methodologies to investigate a workplace engaged in additive manufacturing practices. A semi-structured

interview is contemplated to be conducted with employees to gain insights into workplace dynamics. The study focuses on the impact of different AM technologies on IAQ within a workplace, including production and office spaces.

The AM processes to be monitored are:

- Powder Bed Fusion - Selective Laser Melting (PBF-SLM)
- Powder Bed Fusion - Selective Laser Sintering (PBF-SLS)
- Vat Photopolymerization - Stereolithography (VP-SLA)

These processes are conducted by the SLM Prototyping and Final Part Production Equipment, SLS Prototyping and Final Part Production Equipment, and SLA Prototyping and Final Part Production Equipment within the workplace. The IAQ parameters to be monitored during these processes include particulate matter, volatile organic compounds, formaldehyde, benzene, ethanol, nitrogen dioxide, carbon dioxide, and oxygen.

A custom instrument named the Indoor Network-Based Air-Sensing Ecosystem (INBASE) is designed by the author to monitor and acquire real-time data on the concentrations of aforementioned IAQ parameters. This instrument utilizes a development board, base shield, breadboard, gas sensors, Wi-Fi module, and display unit.

In parallel, the research also examines IAQ perceptions of employees in the presence of different AM operations. Therefore, the author designs an Indoor Air Quality Polling Instrument using a development board, card shield, breadboard, real-time clock, tact switches, and resistors. It is used as a feedback mechanism to capture subjective perceptions of IAQ. Employees in the relevant spaces use this instrument to rate their perception of IAQ on a scale of very good, good, neutral, bad, and very bad.

The INBASE and polling instruments are utilized simultaneously and placed next to each other during field experiments to capture objective data and subjective

perceptions of IAQ. Due to the availability of only one of each instrument, experiments are conducted at different times based on the workplace workflow and the orders received. Consequently, even though the same AM method is monitored, variations in printed components and experiment durations may occur between production spaces and the office space. Additionally, details of the printed parts are not disclosed due to confidentiality agreements.

1.3 Aims and Objectives of the Research

The main aim of this study is to comprehensively understand the impact of varying additive manufacturing (AM) technologies on indoor air quality (IAQ) within production and office spaces. Research objectives can be listed as:

- To assess the impact of different AM processes, including PBF-SLM, PBF-SLS, and VP-SLA that take place in the related production spaces, on IAQ parameters in those production spaces and the office space during pre-printing, printing, post-printing, and post-processing.
 - To design an instrument tailored to monitor specific IAQ parameters, including particulate matter, volatile organic compounds, formaldehyde, benzene, ethanol, nitrogen dioxide, carbon dioxide, and oxygen in a workplace environment.
- To ascertain the IAQ perceptions of employees of the workplace in the related production spaces and the office space in the presence of AM operations in those production spaces.
 - To design an instrument to gather employee feedback concerning the perception of IAQ in a workplace environment.
- To identify potential correlations between variations in monitored IAQ parameters due to different AM processes and IAQ perceptions of employees in the related production spaces and the office space.

1.4 Research Questions

The main research questions can be listed as:

- How do different AM processes, including PBF-SLM, PBF-SLS, and VP-SLA that take place in the related production spaces, impact IAQ parameters—such as particulate matter, volatile organic compounds, formaldehyde, benzene, ethanol, nitrogen dioxide, carbon dioxide, and oxygen—in those production spaces during various phases of AM operations?
- How do different AM processes, including PBF-SLM, PBF-SLS, and VP-SLA that take place in the related production spaces, impact IAQ parameters—such as particulate matter, volatile organic compounds, formaldehyde, benzene, ethanol, nitrogen dioxide, carbon dioxide, and oxygen—in the office space during various phases of AM operations?
- How do workplace employees perceive IAQ in the related production spaces in the presence of different AM processes, including PBF-SLM, PBF-SLS, and VP-SLA, that occur in those production spaces?
- How do workplace employees perceive IAQ in the office space in the presence of different AM processes, including PBF-SLM, PBF-SLS, and VP-SLA, that occur in the related production spaces?
- How do variations in monitored IAQ parameters due to different AM processes correlate with IAQ perceptions of employees in the related production spaces?
- How do variations in monitored IAQ parameters due to different AM processes correlate with IAQ perceptions of employees in the office space?

1.5 Research Structure and Disposition

This thesis comprises five consecutive chapters: Introduction, Literature Review, Methodology, Results and Discussion, and Conclusion.

The first chapter is the Introduction, where the background and motivation of the outlined problem are described, the scope of the research is described, the aims and objectives of the study are presented, research questions directed to the thesis are listed, and the structure and disposition of the thesis are explained.

The second chapter, Literature Review, delves into the workplace, additive manufacturing, and indoor environmental quality. In the workplace section, office space, production space, and integration of production and office spaces are explained. The additive manufacturing section examines the historical development of additive manufacturing and the technologies and processes of additive manufacturing. Lastly, within the section on indoor environmental quality, the focus is given to indoor air quality phenomenon, indoor air quality pollutants, and indoor air quality issues associated with additive manufacturing.

In the third chapter, Methodology, the methodology followed by the study, including the semi-structured interview, two custom-designed instruments, and field experiments, are presented. The first instrument, the INBASE, is explained in terms of hardware development, software development, and calibration. The second instrument, the Indoor Air Quality Polling Instrument, is detailed in terms of hardware and software development. Lastly, field experiments in production and office spaces are explained.

The fourth chapter is the Results and Discussion, where the outcomes of the semi-structured interview are explained, the findings of field experiments in production and office spaces are demonstrated, and insights into enhancing indoor air quality in the case of additive manufacturing are presented.

The fifth chapter is the Conclusion, where the research is summarized, the main results and discussion are presented, and research limitations and future directions are indicated.

CHAPTER 2

LITERATURE REVIEW

This chapter is constructed as sections covering Workplace, Additive Manufacturing, and Indoor Environmental Quality. The Workplace section introduces Office Space, Production Space, and Integration of Production and Office Spaces. The Additive Manufacturing section discusses the Historical Development of Additive Manufacturing and the Technologies and Processes of Additive Manufacturing. The Indoor Environmental Quality section delves into Indoor Air Quality Phenomenon, Indoor Air Quality Pollutants, and Emissions and Exposures Associated with Additive Manufacturing.

2.1 Workplace

The term work, having several meanings, refers to activities, such as a job, involving physical or mental effort for a certain purpose. Place of work, workplace, refers to places where work is performed. Workplaces have been classified based on the nature of the work. To illustrate, while an office space is attributed to a building where nonmanual work is carried out, a production space is attributed to the manufacturing or assembling of goods (Felstead et al., 2003). Within this study, the workplace refers to the physical environment where work is conducted, encompassing all areas, facilities, and resources that individuals or teams utilize to perform their tasks and responsibilities. The workplace spaces include but are not limited to office spaces, production spaces, laboratories, studios, workshops, and any other designated areas where work-related activities occur. Office space refers to the area within an organization where tasks, duties, and responsibilities are

performed by individuals in an environment equipped with desks, computers, phones, and other office equipment used for office work. Production space refers to the space within an organization where production or manufacturing processes are executed, and physical products are manufactured and processed. This area may have production equipment, assembly lines, storage, and post-processing areas.

2.1.1 Production Space

Production spaces have been integral to human life from early civilizations to the contemporary era (Marsh, 2019). The evolution of these spaces is closely tied to the history of industrialization since industrial revolutions are milestones in history, transforming production technologies, techniques, and spaces.

The era before industrialization has witnessed varying proto-industrial examples. As early as the 10th century, China had large-scale, state-run industries producing goods like porcelain and silk. As a part of industrial evolution, the cottage industry relied on artisans. The guild system emerged in Europe during the Middle Ages to train artisans and to regulate trade. The putting-out system challenged the cottage system, where merchants subcontracted raw materials to workers who produced goods at home or in small shops. This system allowed households to supplement income but often led to exploitation due to a lack of wage regulation and labor oversight. Originating in India and spreading to Europe by the 13th century, the spinning wheel was a crucial pre-industrial tool primarily used by women to produce consistent yarn. As a part of the putting-out system, the spinning wheel preluded the Industrial Revolution in textiles. In the early 17th century, the term factory appeared in Europe, referring to the building used for assembling finished goods. After individual parts were made piecemeal at home, they were brought to the factory for final assembly. These early production facilities were reused and modified existing buildings rather than purposefully built spaces as the production scale was small. As the production outgrew those reused spaces, specific buildings were built to accommodate emerging space necessities for production equipment

and materials by which physical attributes such as interior dimensions, ceiling height, and span of open space are dictated. The production facilities before the Industrial Revolution were characterized by sawtooth roofs, referring to the roof line consisting of triangular trusses parallelly placed, waterwheels to capture the kinetic energy of water to operate production equipment, and line shafts that are single spinning shafts where belts and pulleys attach machinery (Marsh, 2019).

Following the proto-industrial era, four Industrial Revolutions have significantly transformed the production landscape from the 18th century onwards, as illustrated in Figure 2.1 (Rojko, 2017).

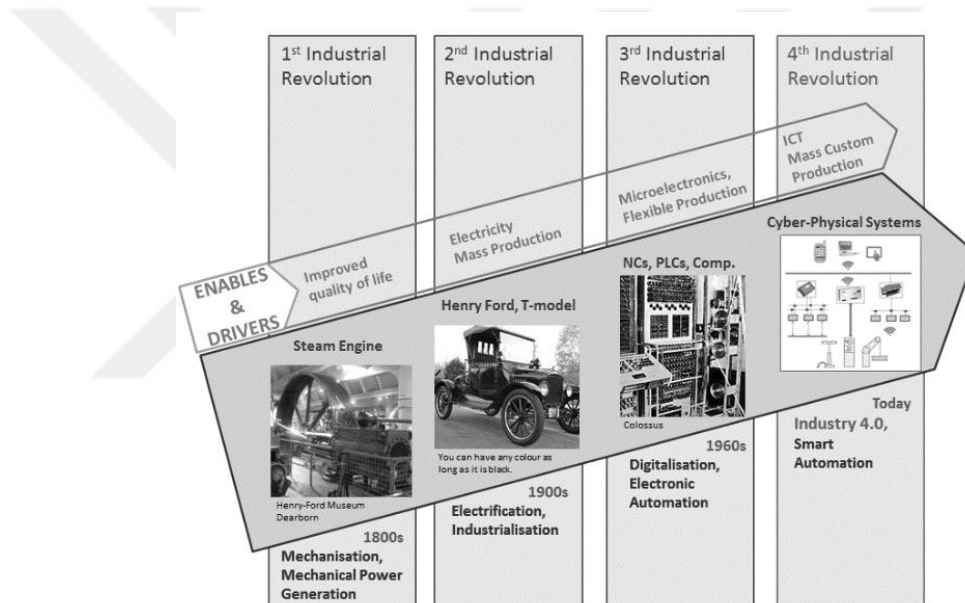


Figure 2.1 Industrial Revolutions (Rojko, 2017, p.79)

The first Industrial Revolution, Industry 1.0, starting in Britain in the mid-18th century, revolutionized production with the steam engine, leading to the rise of factories, particularly in the textile industry (Marsh, 2019). A shift was seen from manual work to the first manufacturing processes (Rojko, 2017).

The second Industrial Revolution, Industry 2.0, emerged in the 19th century when steam power was gradually replaced by electricity after dominating the manufacturing industry for more than 100 years (Marsh, 2019). Electrification

enabled further mechanization and mass production (Rojko, 2017). As its accessibility was increased, working time extended beyond daylight hours in several industries. Electrification was followed by air conditioning to control the indoor environment and improve the manufacturing process. Factories matured from hand tools to machine tools and individual artisans to factories of line workers. Machine shops equipped with used tools such as lathes, planers, and milling machines were developed alongside factories, transitioning from pre-industrial skills to a skilled profession. Despite fears of machines replacing workers, skilled machinists became crucial, requiring literacy, numeracy, and technical knowledge to produce complex and precise parts efficiently. Clocks and guns were two significant industries of the era. In the late 19th century, studies assessing worker behavior emerged, including time and motion studies by Lillian and Frank Gilbreth and shop and process management studies, known as Taylorism, by Frederick Winslow Taylor (Marsh, 2019). Production spaces were configured to maximize efficiency and output.

The third Industrial Revolution, Industry 3.0, began in the 1960s with the introduction of automation and microelectronics (Rojko, 2017; Sharma* & Singh, 2020). The term advanced manufacturing technology (AMT) emerged with innovations in the 1980s. The term involves concepts such as computer-based integrated manufacturing (CIM), computer-aided design (CAD), computer-aided manufacturing (CAM), and flexible processing mechanisms (FMS). Additionally, developments in the electronics industry, including the invention of transistors and integrated circuits, improved the machines. Integration of that electronic hardware into manufacturing systems necessitated software developments, industrializing both the electronics and IT industries (Sharma* & Singh, 2020).

The fourth Industrial Revolution, Industry 4.0, emerged in the 2010s and centered around equipping machines with self-aware and self-learning mechanisms. The Internet of Things (IoT), industrial IoT, cloud-based manufacturing, and smart manufacturing have been significant drivers of Industry 4.0, which aims for digitized and intelligent manufacturing. Big data and analytics, autonomous robots,

simulations, vertical and horizontal system integration, industrial IoT, cyber security and cyber-physical systems (CPS), cloud, additive manufacturing, and augmented reality have been considered central pillars of Industry 4.0 to acquire automated, integrated, and optimized production flow (Vaidya et al., 2018). Inevitably, production spaces have been reshaped to accommodate the demands of digital and automated manufacturing. The overview of Industry 4.0 is given in Figure 2.2.

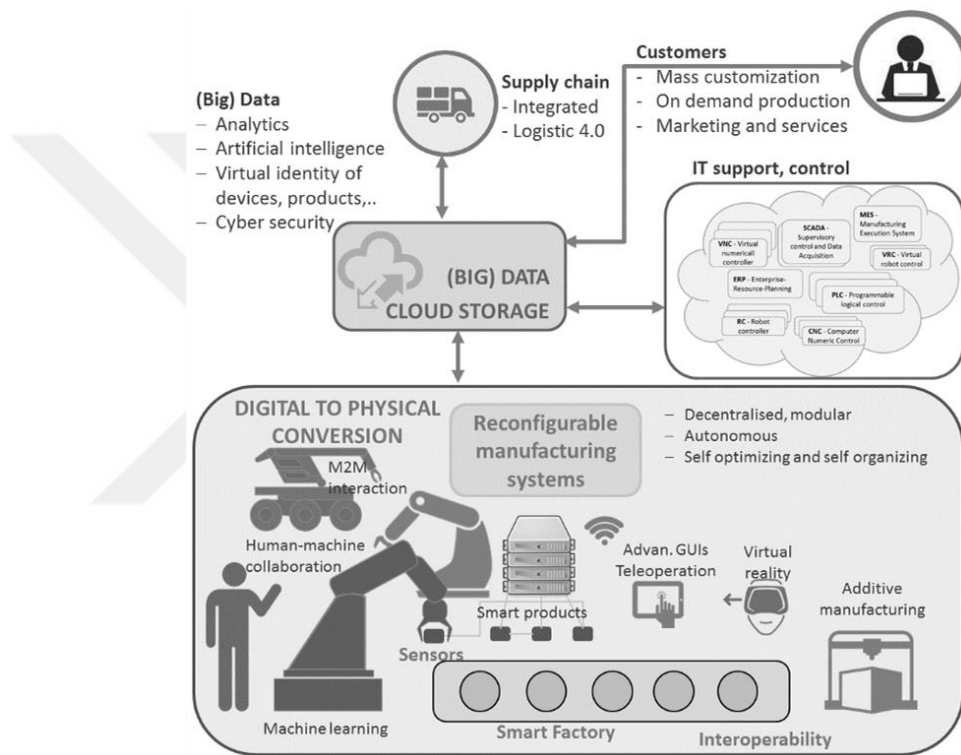


Figure 2.2 The Overview of Industry 4.0 (Rojko, 2017, p.81)

2.1.2 Office Space

Stemming from the Latin word officium, the office represents an entity composed of the spatial, physical, and built environment. Office spaces are necessary to satisfy related functions and processes of an enterprise (Nag, 2019). The understanding of office spaces has changed throughout history, mainly

characterized by interconnected phases and discontinuities due to political contexts, social conditions, and technological developments (Rassia, 2017).

In ancient civilizations such as Egypt, Greece, and Rome, administrative buildings were affected by the economy, power, and authority. Spatial organization in Egypt was dominated by hierarchy and centralization. Workplace design included spaces designated for varying tasks, including accounting, registration, and bookkeeping. Additionally, mobile work practice was observed in clerks and scribes who used two wooden boards, an inkpot, and a quill to perform their work in varying spaces. Conversely, spatial organization in Greece and Rome aimed to attract central or peripheral movement with spread centers and courtsides. Workplaces were designed close to public spaces and involved a combination of cellular and open-plan spaces (Nag, 2019; Rassia, 2017).

The modern era, followed by the collapse of ancient empires, was associated with increased private and public developments, evolving the design of office spaces. While the 15th century symbolized the emergence of multifunctional office spaces exemplified by Uffizi, composed of a U-shaped three-story multifunctional gallery, and designed by Giorgio Vasari in 1560, the 16th century was characterized by work, rank, and job classification followed by the state-central bank, its head offices, departmental offices, and banking halls (Rassia, 2017).

The 18th and 19th centuries were characterized by economic growth and increased construction. The workplace design of the 18th century included large spaces for staff and separate spaces for higher administrative positions, the early example of which is the East India Company in London handling bureaucratic documents for trading, as seen in Figure 2.3 (a). The 19th century further prioritized power and status dynamics with the help of technological developments to shape workplaces, leading to high-rise buildings. To illustrate, the Oriel Chambers in Liverpool, given in Figure 2.3 (b), is a steel-framed five-story office building with a glass curtain wall that influenced the development of skyscrapers in the following century (Nag, 2019).



Figure 2.3 a) East India Co., Leaden Hall Street, London, 1726-9; b) Oriel Chambers, Liverpool, 1864; c) Sears, Roebuck, and Company Mail Order, Chicago, 1905-6; d) and e) Larkin Building, Buffalo, NY, 1904 (Nag, 2019, p.6)

The workplace design of the 18th and 19th centuries was composed of rectilinear buildings involving spaces around a central corridor, core space, or atrium (Rassia, 2017), with cellular office plan arrangements. The cellular office plan refers to a floor space segmented into individual offices, named cells, using permanent walls. The size and location of cells reflect the job status of the employee occupying the space. While this typology provides increased privacy and a high concentration level, it represents a rigid hierarchy and creates a lack of flexibility and collaboration (Anton, 2015). The cellular office layout and its example on the Wainwright Building are given in Figure 2.4.

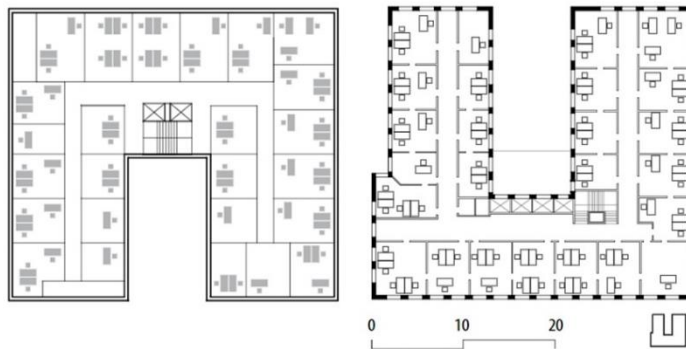


Figure 2.4 Cellular Office Layout (Left) and Wainwright Building, Louis Sullivan, St. Louis, 1890 (Right) (Anton, 2015)

The early 20th century was characterized by concerns for aesthetics and technology (Nag, 2019). Moreover, the concepts of Max Weber and Henri Fayol introduced considerations for well-being and welfare into workplace design. Affected by the principles of scientific management of Frederick Taylor, the design practice from 1900 to 1930 involved open-plan workplaces with glass partitions, prioritizing task-focused work arrangements, productivity, and close supervision. (Rassia, 2017). The primary purpose associated with this design practice is to increase efficiency (Lovell, 2017). Therefore, the Taylorist open-plan layout includes an arrangement where workers are lined up in rows in the center, and managers have their private offices around the perimeter to enable both uninterrupted workflow and visual supervision (Anton, 2015; Gou, 2016). Taylorist open-plan layout and its example on the Johnson Wax Building are given in Figure 2.5. The implementation of this typology has been noted for its potential benefits, including enhanced collaboration among employees, cost-effectiveness through efficient space utilization, and the creation of versatile multi-use environments (Anton, 2015). This typology spread globally due to these advantages (Derksen, 2014). However, it has certain disadvantages, such as the perpetuation of rigid hierarchical structures, heightened levels of ambient noise, and lack of individual privacy (Anton, 2015; Gou, 2017). Examples of office buildings of the era are the Larkin Building in Buffalo and the Sears, Roebuck, and Company Mail Order Building in Chicago. The former, designed by Frank Lloyd Wright, is a six-story high building

with an open layout featuring undifferentiated space with rows of desks for workers and closed offices for managers, given in Figure 2.3 (d,e). As shown in Figure 2.3 (c), the latter is a nine-story office building comprising two blocks accommodating 22000 employees. It is considered the most massive building of its time (Nag, 2019). The variations of the Taylorist open-plan following similar principles are the pre-war social democratic office layout (1910-1930) and the streamlined office layout (1930). While the former is considered a small-scale Taylorist open-plan layout with a focus on natural light, the latter is associated with warmer office spaces owing to the use of streamlined materials (Lovell, 2017). As World War II caused a building downturn due to the worldwide economic crisis, pre-war design practices that focused on functionality guided the post-war period (Rassia, 2017).

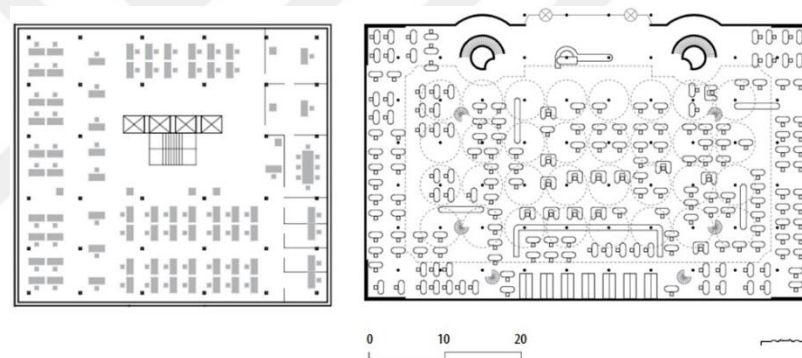


Figure 2.5 Taylorist Open-Plan Layout (Left) and Johnson Wax Building, Frank Lloyd Wright, Racine, 1937 (Right) (Anton, 2015)

After the reconstruction of the economy, workplace design of the 1950s differed in Europe, America, and Asia. European design was associated with rows of dense cellular spaces around a central corridor, while American and Asian architecture involved poorly lit open-plan layouts to save space. By the late 1950s and early 1960s, office users' needs were re-evaluated with the rise of the international modern movement focusing on steel and glass materials, open-plan layouts, artificial lighting, and air conditioning (Rassia, 2017). Bürolandschaft, the office landscape, emerged in Germany in the 1950s. The concept refers to social

democratic offices (Lovell, 2017), including clustered work zones of varying sizes to foster communication between different individuals and parts of the organization (Anton, 2015; Nag, 2019). While it fosters a non-hierarchical environment and advanced communication and collaboration among employees (Fantoni, 2013; Lovell, 2017), the main drawbacks of this typology are increased ambient noise, lack of privacy, and difficulty in concentration (Anton, 2015; Nag, 2019). Office landscape layout and its example on Osram Offices are given in Figure 2.6.



Figure 2.6 Office Landscape Layout (Left) and Osram Offices, Quickborner, Munich, 1963 (Right) (Anton, 2015)

Action offices emerged in 1960 to enhance the creativity and flexibility of social democratic offices by giving employees the ability to personalize their spaces according to their preferences and modify their privacy with panels (Lovell, 2017). Additionally, layouts stimulating a sense of belonging to a working community without feeling lost in the crowd emerged as a result of a search for patterns and human associations of the traditional city. The structuralist office layout, exemplified by the Centraal Beheer Building, given in Figure 2.7, is a deep spatial matrix arranged on a tar-tan grid of platforms with a labyrinth sense. It resembles a worker village to enable a working community. Although posing navigation challenges due to its intricate characteristics, this layout promotes communication and collaboration among employees while fostering a sense of identification with the workspace (Anton, 2015; Gou, 2017)

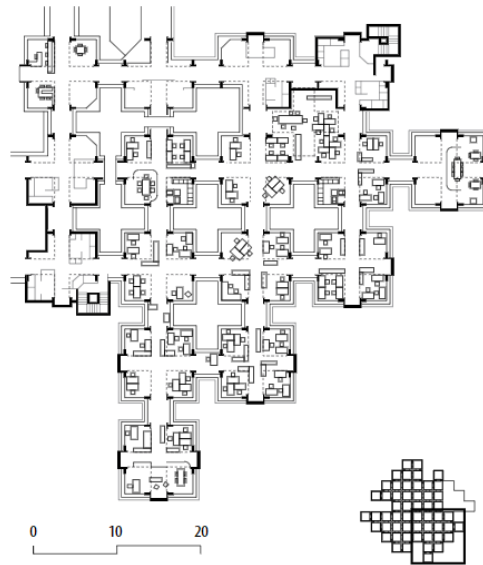


Figure 2.7 Centraal Beheer, Herman Hertzberger, Apeldoorn, 1970 (Anton, 2015)

The cubicle arrangements were utilized in office layouts with the rise of the middle class and the introduction of personal computers into offices (Fantoni, 2013). Dominating office design from the 1980s onwards (Lovell, 2017), the cubicles are semi-enclosed spaces with 1.5 to 1.8-meter-tall vertical elements to isolate workers from noise and sight of an open-plan layout (Anton, 2015). Although the cubicle arrangement provides partial privacy, it creates a lack of interaction and a sense of community (Lovell, 2017) and obstructs daylight (Anton, 2015). The cubicle layout and its example on Chase Manhattan Bank are given in Figure 2.8.

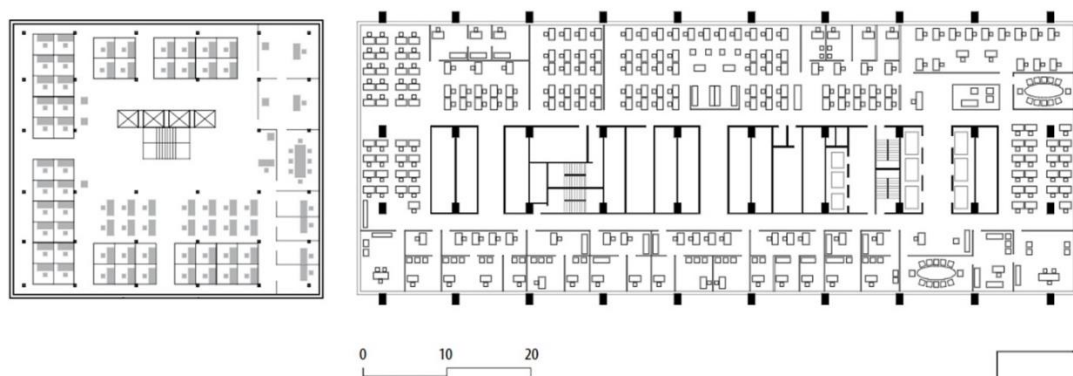


Figure 2.8 Cubicle Layout (Left) and Chase Manhattan Bank, SOM, New York, 1961 (Right) (Anton, 2015)

As a variation of cellular arrangement, combi offices are cellular offices with public corridors. This arrangement promotes individual privacy and a high level of concentration. Nonetheless, it proliferates monotonous cellular offices that are unable to express organizational culture (Anton, 2015). The combi office layout and its example on SAS Offices are given in Figure 2.9.

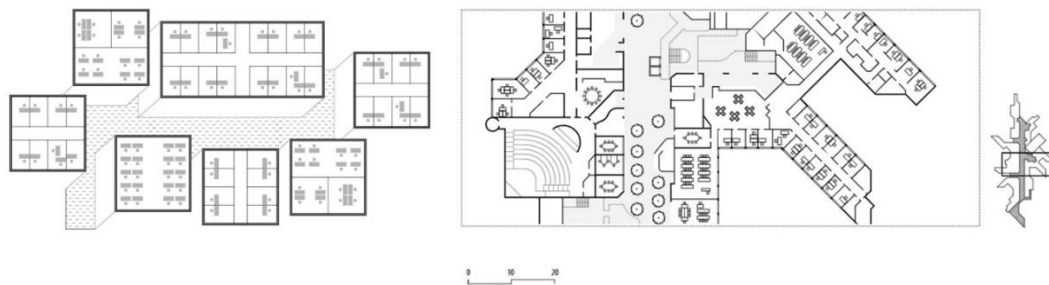


Figure 2.9 Combi Office Layout (Left) and SAS Offices, Niels Torp, Stockholm, 1988 (Right) (Anton, 2015)

Increasing access to the Internet and the economic recession faced by varying businesses as a result of growing competition in globalized markets in the 1990s profoundly affected office design. The concept of teleworking was born when laptops and mobile phones facilitated employees to work away from the office. Cost-saving advantages of the concept, such as reduced expenses for rent and transportation, gave birth to virtual offices where the work is mobile (Lovell, 2017). However, lack of interaction among team members, decline in productivity, and increase in isolation are particular challenges associated with virtual offices (Anton, 2015). The virtual office layout and its example on Interpolis Headquarters are given in Figure 2.10.

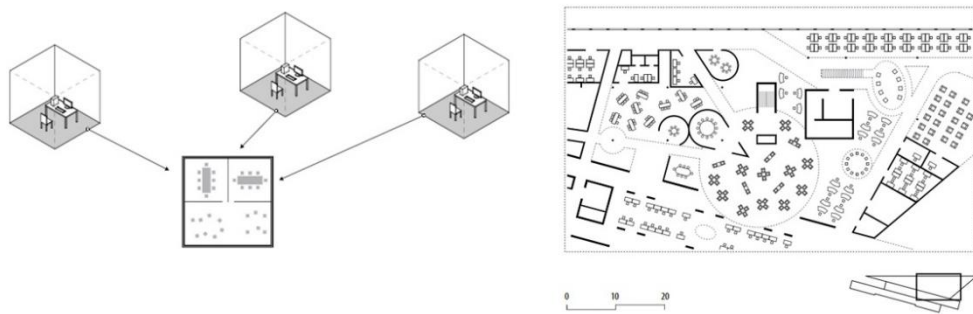


Figure 2.10 Virtual Office Layout (Left) and Interpolis Headquarters, Bonnema Architecten, Tilburg, 1995 (Right) (Anton, 2015)

The casual office concept, originating back in the 1980s, became widespread in the early 21st century. This concept also refers to networked and innovative offices embracing casual, comfortable, flexible, informal, and multi-purposed workspaces (Lovell, 2017). The focus is on effectiveness rather than efficiency (Myerson, 2009). The casual office layout and its example on Chitday Offices are given in Figure 2.11. Another 21st-century concept, activity-based working, aims to provide diverse, adaptable workspaces tailored to various working styles and needs, thereby enhancing collaboration, concentration, and productivity (Lovell, 2017).

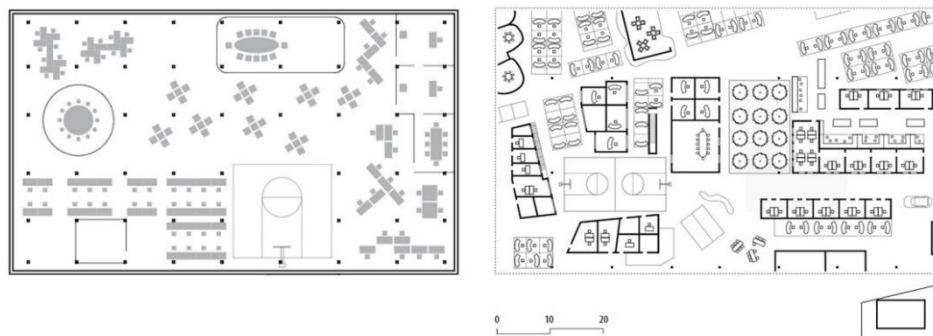


Figure 2.11 Casual Office Layout (Left) and Chitday Offices, Clive Wilkinson Architects, Los Angeles, 1997 (Right) (Anton, 2015)

2.1.3 Integration of Production and Office Spaces

Historically, production and office spaces have been separate entities with clearly defined roles and physical boundaries. Offices were designed for administrative and managerial tasks and equipped with desks, computers, phones, and other necessary office equipment. At the same time, production spaces were tailored for manufacturing processes and equipped with production machinery, assembly lines, post-processing stations, and storage areas. However, as technology has advanced, particularly with the advent of Industry 4.0, these boundaries have begun to blur. Industry 4.0 has accelerated specific manufacturing methods, such as additive manufacturing, necessitating closer integration between different aspects of manufacturing and office functions. This integration has been further supported by the rise of the casual office concept, which embraces multipurpose workspaces. Unlike traditional manufacturing processes that often require separate, large-scale production facilities, additive manufacturing processes can occur in more flexible, multipurpose, or smaller production spaces, which may increase the overlap between production and office spaces. Additionally, the models and simulations created on computers in office spaces closely approximate the scenarios encountered in production. Meanwhile, in production spaces, the manufacturing processes being automated via computer environments have led to the convergence of production and office spaces both physically and conceptually. Therefore, contemporary workplace design is the outcome of evolving concepts and strategies throughout history to accommodate the physical and conceptual necessities of related work activities.

2.2 Additive Manufacturing

Additive manufacturing is an emerging manufacturing field that contains various three-dimensional printers with different dimensions and capabilities to fabricate three-dimensional objects through additive processes (Delgado Camacho et al.,

2018; Gupta et al., 2019; Kietzmann et al., 2015; Labonnote et al., 2016; Mathur, 2016). It is a revolutionary process that fabricates intricate geometries at a lower cost, weight, and time while eliminating the need for molds or templates (Gibson et al., 2015).

The AM operations start with the design phase, which contains the generation of digital files, such as CAD files, and their conversion to an appropriate format for machine language (Mathur, 2016). Subsequently, the printing phase involves the transformation of digital data into additive layers to construct a 3D geometry (Kietzmann et al., 2015).

AM is a promising field due to its versatility, cost-effectiveness, innovation facility, and customization potential. It is widely utilized across diverse industries as it addresses the labor-intensive challenges of manual manufacturing. It is extensively employed for form, fit, function testing, and functional prototyping in product and machine component development. It is used in the jewelry field due to the complexity of objects. In addition, the automotive industry utilizes AM, particularly in motorsports, due to its advantages regarding low-volume production, enhanced customization, and removal of design constraints caused by tooling. Due to its cost-effectiveness and feasibility in limited production runs, the aerospace industry utilizes AM to serve diverse purposes, such as master patterns for investment casting and producing components to be used in real-life conditions. Furthermore, medicine and bioengineering sciences also benefit from AM, contributing to surgical diagnostics, prosthetics, and tissue engineering, employing the production of reconstructive parts for the skull, surgical guides, and custom-made prosthetics. Besides, AM is applied in dentistry through a mass customization approach for dental aligners, catering to each patient's unique requirements. Similarly, in audiometry, in-ear hearing aids are manufactured using AM technology (Gibson et al., 2015).

2.2.1 Historical Development of Additive Manufacturing

The development of AM is intertwined with the integration of computer applications in the industry, driven by decreasing computer costs and consequently increasing computer use. Progress in CAD, CAM, and Computer Numerical Control (CNC) machine tools and advancements in manufacturing systems and materials have significantly expedited the evolution of AM systems (Chua et al., 2010).

Considering AM as a computer-controlled and automated creation of three-dimensional objects from starting materials through an additive process based on solidification, the origins of AM can be traced back to 1977. This period witnessed the patent by Swainson and Kremer for "three-dimensional systems," employing radiation beams and reactive monomer systems. In 1980, a patent application was filed by Hideo Kodama for a 3D printing process that utilized a liquid photo-hardening polymer to fabricate 3D objects. Although the patent application did not advance to a complete patent, the published paper constitutes a notable historical contribution to the exponential growth of AM (Gupta et al., 2019). Stereolithography technology was pioneered in 1983, and stereolithographic apparatus was patented in 1986 by Charles Hull, marking the commencement of commercial 3D printing technology. His contributions to the field were further solidified when the first commercial 3D printer (SLA-1) was introduced by "3D Systems" in 1987 (Gupta et al., 2019), as depicted in Figure 2.12. His conceptualization of 3D printing served as the cornerstone for contemporary applications in AM, enabling the fabrication of intricate components from diverse materials and gaining widespread adoption in subsequent decades (Gupta et al., 2019; Kietzmann et al., 2015; Labonnote et al., 2016; Mathur, 2016).



Figure 2.12 The First AM Technology from Hull (Gibson et al., 2015, p.38)

In the 1990s, several pioneers introduced alternative additive manufacturing processes, securing patents and commercializing their innovations. The era witnessed significant developments, including Scott Crump's patent for fused deposition modeling (FDM) and Deckard, Beaman, and Darrah's patent for selective laser sintering (SLS) in 1992. In 1993, the foundation of what is now known as 3D inkjet printing was laid by a patent by Sachs, Haggerty, Cima, and Williams. In 1998, laminated object manufacturing (LOM) was patented by Feygin, Shkolnik, Diamond, and Dvorskiy. During the 1990s and 2000s, AM became an appealing alternative to conventional processes (Gupta et al., 2019) that employ subtractive and formative fabrication techniques (Delgado Camacho et al., 2018; Kietzmann et al., 2015). Additive processes signify a paradigm shift towards more efficient and resource-conserving fabrication methods, in contrast to formative approaches reliant on molds and subtractive approaches that yield waste with techniques such as cutting, filling, grinding, mining, drilling, and turning (Delgado Camacho et al., 2018; Kietzmann et al., 2015; Mathur, 2016). AM brought about a profound impact across a diverse spectrum of scientific, educational, social, and industrial activities, leading different terminologies to emerge to describe AM concepts in this period (Gupta et al., 2019). These

terminologies encompass 3D Printing, Automated Fabrication, Desktop Manufacturing, Layered Fabrication, and Rapid Prototyping (Mathur, 2016). Nevertheless, the term "three-dimensional printing" (3DP™) was introduced and trademarked by researchers at the Massachusetts Institute of Technology. It has gained widespread acceptance as a comprehensive description of various additive manufacturing processes across different fields (Gupta et al., 2019).

There are two main groups of commercial 3D printers: advanced printers and desktop-based concept modelers. While the former is tailored for specialized industrial applications such as medical implants, aerospace and automotive components, and jewelry, the latter is intended for less complex applications, including printing prototypes, models, small components, and objects (Gupta et al., 2019).

The growing diversity of affordable 3D printers is propelled by annual advancements, with emerging manufacturers meeting demand from small industries and a growing community of users. Internet-based crowdsourcing initiatives, exemplified by the RepRap project since 2005, have played a pivotal role in providing comprehensive manuals for users to construct their printers by printing parts of 3D printers employing another 3D printer, sparking the maker movement. In 2008, the first self-replicating printer, named Darwin, spurred the development of numerous similar systems (Gupta et al., 2019). In the 2010s, large-scale 3D printers began experimenting with small-scale structures, and multiple projects vied to be the first to 3D print a house by 2017. The historical trajectory of AM, given in Figure 2.13, is drawn utilizing the research of Chua et al. (2010, p.8) and Gupta et al. (2019, p.5).

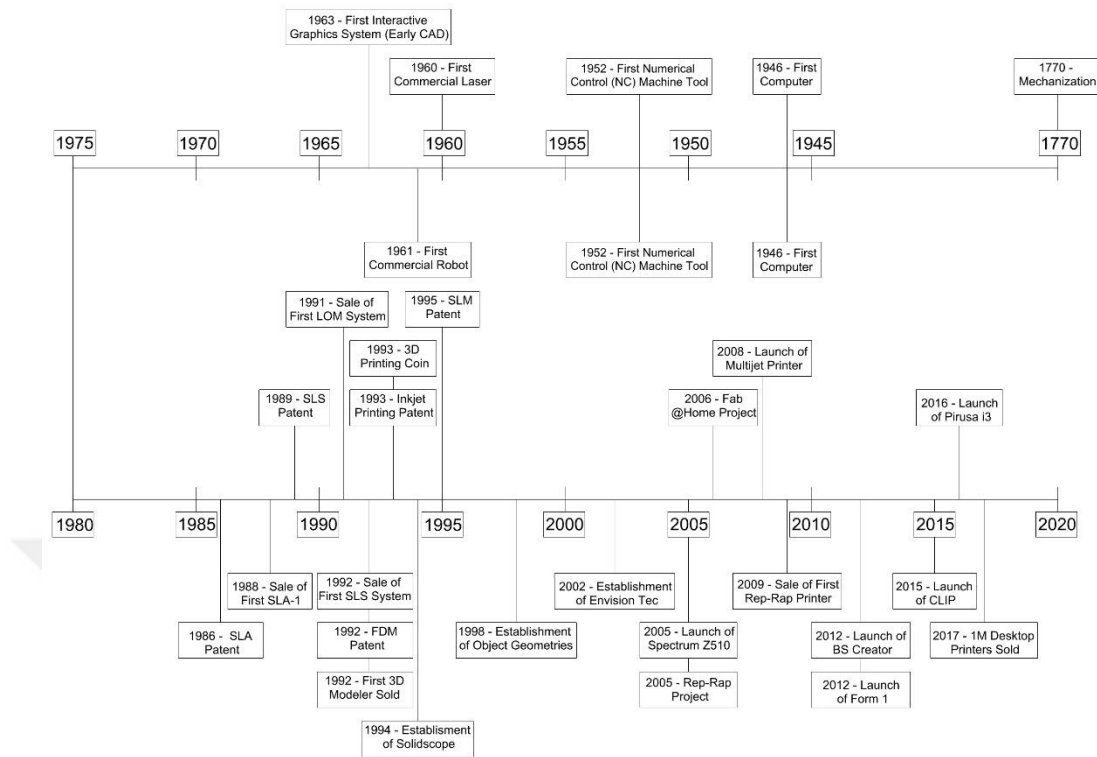


Figure 2.13 The Historical Trajectory of Additive Manufacturing

2.2.2 Technologies and Processes of Additive Manufacturing

Independent of the degree of complexity, the main principle of AM involves slicing the design model, creating repetitive sections known as horizontal cuts or layers with a preferred thickness, and printing slices successively upon each other (Quan et al., 2015). Figure 2.14 demonstrates the AM flow chart. While the consecutive layering process remains consistent, different processes necessitate distinct techniques such as sintering, melting, binding, lamination, extrusion, and polymerization.

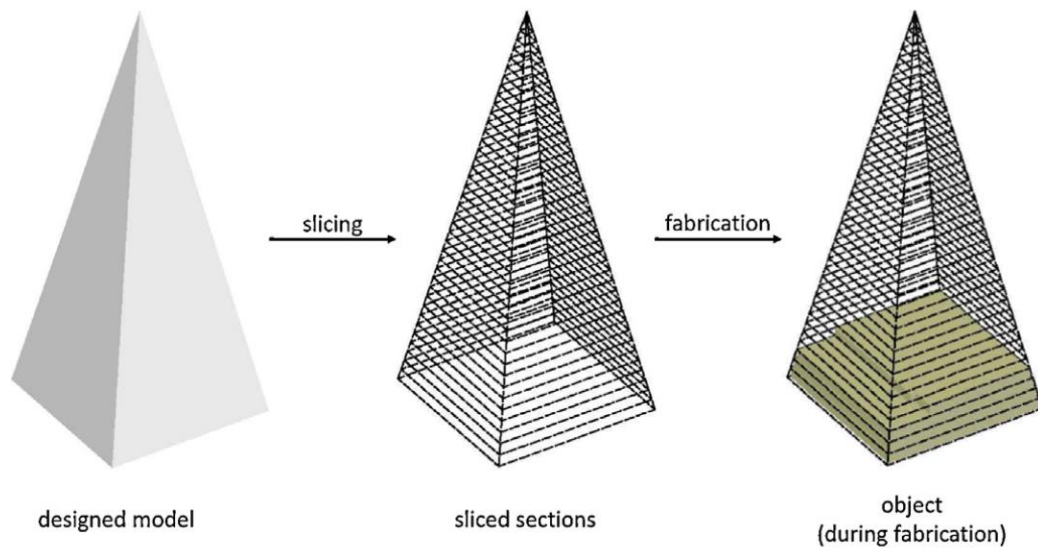


Figure 2.14 Flow Chart of AM (Quan et al., 2015, p.504)

Owing to the absence of a universally accepted classification of additive manufacturing processes, there are several classifications based on material state, type, material transformation, equipment, process, and technology employed in AM processes (Gibson et al., 2015; Jiménez et al., 2019). Among various classifications of AM, the technology-based classification introduced by the American Society for Testing and Materials (ASTM) and the material state classification proposed by Chen (2015), which is a modified classification of Kruth (1998), are addressed in this study.

The initial categorization involves AM processes into seven areas organized by ASTM with respect to the employed technology (Monzón et al., 2015). These are binder jetting (BJ), directed energy deposition (DED), material extrusion (ME), material jetting (MJ), powder bed fusion (PBF), sheet Lamination (SL), and vat photopolymerization (VP). (Monzón et al., 2015; Tofail et al., 2018). The basic principle, material, advantages and disadvantages, build volume, and tool manufacturer of each area are illustrated in Figure 2.15.

ASTM category	Basic principle	Example technology	Advantages	Disadvantages	Materials	Build volume (mm × mm × mm)
BJ	Liquid binder/s jet printed onto thin layers of powder. The part is built up layer by layer By glueing the particles together	• 3D inkjet technology	• Free of support/substrate • Design freedom • Large build volume • High print speed • Relatively low cost	• Fragile parts with limited mechanical properties • May require post processing	• Polymers • Ceramics • Composites • Metals • Hybrid	Versatile (small to large) X = <4000 Y = <2000 Z = <1000
DED	Focused thermal energy melts materials <i>during</i> deposition	• Laser deposition (LD) • Laser Engineered NetShaping (LENS) • Electron beam • Plasma arc melting	• High degree control of grain structure • High quality parts • Excellent for repair applications	• Surface quality and speed requires a balance • Limited to metals/metal based hybrids	• Metals • Hybrid	Versatile X = 600-3000 Y = 500-3500 Z = 350-5000
ME	Material is selectively pushed out through a nozzle or orifice	• Fused Deposition Modelling (FDM)/Fused Filament Fabrication (FFF), Fused Layer Modelling (FLM)	• Widespread use • Inexpensive • Scalable • Can build fully functional parts	• Vertical anisotropy • Step-structured surface • Not amenable to fine details	• Polymers • Composites	Small to medium X = <900 Y = <600 Z = <900
MJ	Droplets of build materials are deposited	• 3D inkjet technology • Direct Ink writing	• High accuracy of droplet deposition • Low waste • Multiple material parts • Multicolour	• Support material is often required • Mainly photopolymers and thermoset resins can be used	• Polymers • Ceramics • Composites • Hybrid • Biologicals	Small X = <300 Y = <200 Z = <200
PBF	Thermal energy fuses a small region of the powder bed of the build material	• Electron beam melting (EBM) • Direct Metal Laser Sintering (DMLS) • Selective Laser Sintering/Melting (SLS/SLM)	• Relatively inexpensive • Small footprint • Powder bed acts as an integrated support structure • Large range of material options	• Relatively slow • Lack of structural integrity • Size limitations • High power required • Finish depends on precursor powder size	• Metals • Ceramics • Polymers • Composites • Hybrid	Small X = 150-300 Y = 200-300 Z = 200-350
SL	Sheets/foils of materials are bonded	• Laminated Object Manufacturing (LOM) • Ultrasound consolidation/Ultrasound Additive Manufacturing (UC/UAM)	• High speed, • Low cost, • Ease of material handling	• Strength and integrity of parts depend on adhesive used • Finishes may require post processing • Limited material use	• Polymers • Metals • Ceramics • Hybrids	Small X = 150-250 Y = 200 Z = 100-150
VP	Liquid polymer in a vat is light-cured	• Stereo Lithography (SLA) • Digital Light Processing (DLP)	• Large parts • Excellent accuracy • Excellent surface finish and details	• Limited to photopolymers only • Low shelf life, poor mechanical properties of photopolymers • Expensive precursors/Slow build process	• Polymers • Ceramics	Medium X < 2100 Y < 700 Z < 800

Figure 2.15 Classification of AM by ASTM (Tofail et al., 2018, p.25)

The operating principles of AM processes, including binder jetting (BJ), directed energy deposition (DED), material extrusion (ME), material jetting (MJ), powder bed fusion (PBF), sheet Lamination (SL), and vat photopolymerization (VP), are given in Figure 2.16, where alphabetical annotations refer to these processes and numerical annotations refer to stages of the related process.

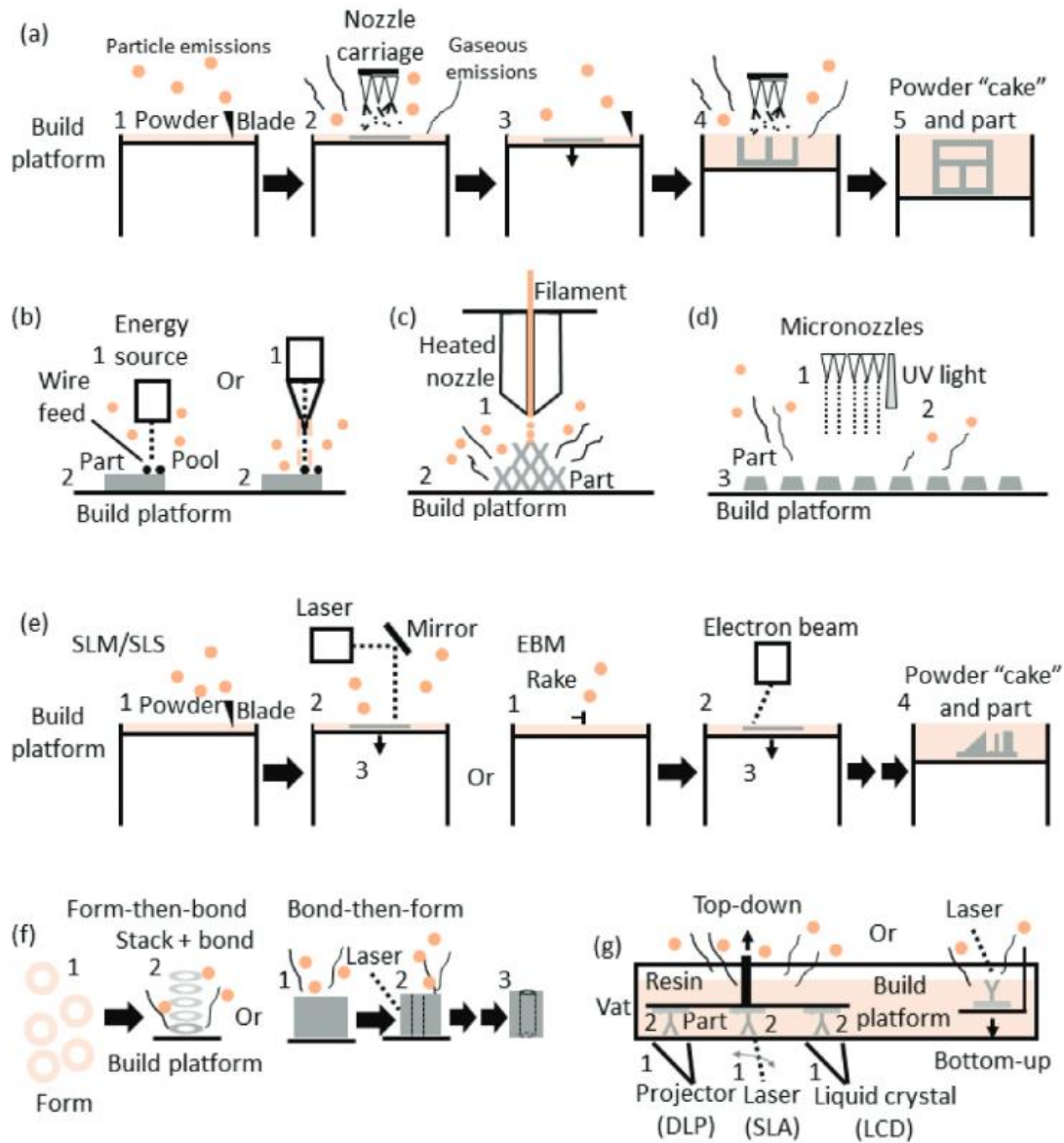


Figure 2.16 Operation Principles of AM Processes: (a) BJ, (b) DED, (c) ME, (d) MJ, (e) PBF, (f) SL, and (g) VP. (Stefaniak et al., 2021, p.176)

In binder jetting (BJ), depicted in Figure 2.16 (a), the powdered materials receive a liquid binder to form layers of bonded particles. The operational principle of BJ includes a sequential process comprising the following steps (Afshar-Mohajer et al., 2015; Stefaniak et al., 2021):

- Selectively depositing binder droplets onto the powder by a carriage with nozzles to bond particles through a chemical reaction (binder deposition phase).
- Lowering the powder bed incrementally and spreading a fresh powder layer by a blade over the previously hardened powder (powder spreading phase).
- Selectively depositing binder droplets onto the powder bed and hardening the subsequent particle layer (binder deposition phase).
- Iterative repetition of building layers until the build cycle is finalized (repetition phase)

The pre-printing tasks entail the introduction of powder into the printer. Post-printing tasks involve opening the doors of the printer and eliminating surplus powder from printed components, and post-processing tasks encompass spray coating of the printed components (Stefaniak et al., 2021). The BJ process is schematically represented in Figure 2.17.

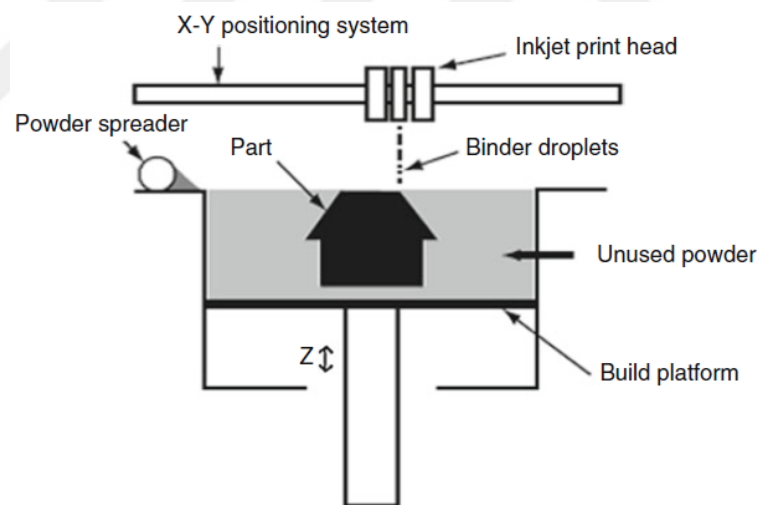


Figure 2.17 The Diagram of the BJ Process (Gibson et al., 2015, p.206)

It is suitable for metal applications, serving both prototyping and direct part manufacturing objectives. It proves advantageous for intricate molds, reducing material usage and holding design optimization potential (Chen et al., 2015). BJ exemplifies 3D inkjet technology, utilizing materials such as polymers, ceramics,

composites, metals, and hybrid materials (Tofail et al., 2018). The schematic representation of the 3D (inkjet) printing technology is given in Figure 2.18.

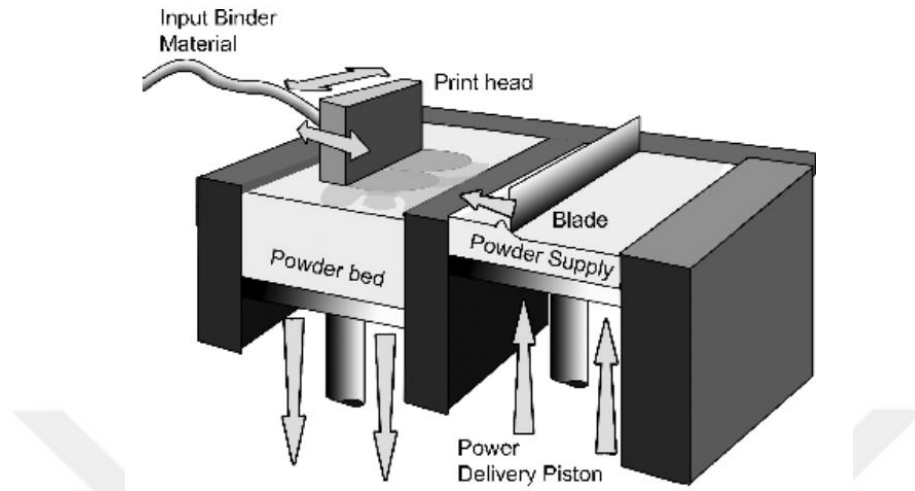


Figure 2.18 The Diagram of 3D Printing Technology (Hopkinson et al., 2006, p.66)

In directed energy deposition (DED), thermal energy sources are lasers, plasma electron beams, or electric arcs. If a wire form of feedstock material is fed into the thermal source, the feedstock is melted and dripped onto the build platform to form a shape. If a powder form of feedstock material is fed into the thermal source, it is dispensed through a nozzle, which has an outer ring dispensing the powder and an inner ring covering a laser. Both configurations are depicted in Figure 2.16 (b) (Stefaniak et al., 2021). DED exemplifies laser deposition (LD), laser-engineered net shaping (LENS), electron beam, and plasma arc melting. It is commonly used with metals and hybrid materials (Tofail et al., 2018).

Pre-printing tasks entail loading wire or powder; post-printing tasks include opening the machine to retrieve printed components; post-processing tasks encompass machining for final part dimensions (Stefaniak et al., 2021). The DED process is schematically represented in Figure 2.19.

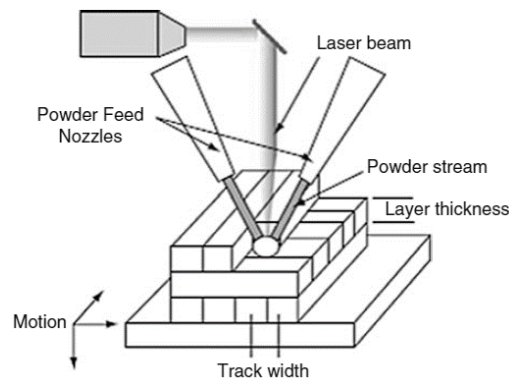


Figure 2.19 The Diagram of the DED Process (Gibson et al., 2015, p.246)

Material extrusion (ME) involves extruding a material by heating or dispensing it through a nozzle. In ME, depicted in Figure 2.16 (c), solid polymers are heated slightly above their glass transition temperature and subsequently dispensed layer by layer onto a build platform to construct a part. Various commercially available polymers are utilized in ME, each possessing distinct properties covering chemical resistance and thermal stability (Wu et al., 2020).

Pre-printing tasks entail introducing polymers as filaments or pellets to the machine. Post-printing tasks comprise opening the equipment to retrieve parts. Lastly, post-processing tasks encompass chloroform vapor polishing (CVP), acetone vapor polishing (AVP), and sanding (Stefaniak et al., 2021). The ME process is schematically represented in Figure 2.20.

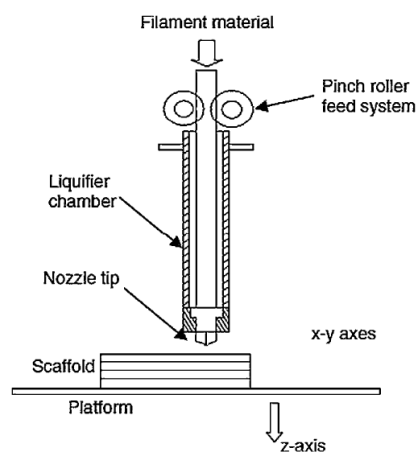


Figure 2.20 The Diagram of the ME Process (Gibson et al., 2015, p.150)

ME entails techniques called fused deposition modeling (FDM), fused filament fabrication (FFF), and fused layer modeling (FLM). FDM often denotes large-scale equipment with heated chambers, while FFF is for desktop-scale low-cost 3D printers whose modified versions are used in bioprinting applications, medical research models, and toxicity testing (Bourell, 2016; Ford, 2014; Ma et al., 2018; Shahin-Shamsabadi & Selvaganapathy, 2019; Wei et al., 2020). The schematic of the FDM printer is given in Figure 2.21.

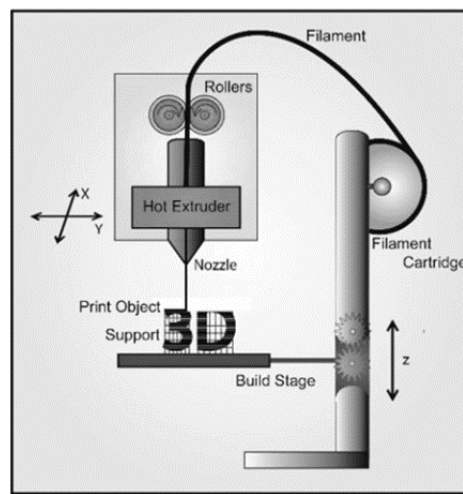


Figure 2.21 The Diagram of the FDM Printer (Gupta et al., 2019, p.14)

In material jetting (MJ), depicted in Figure 2.16 (d), numerous micronozzles dispense liquid photopolymer resin onto a build platform to be cured by the UV laser. This process is repeated layer-by-layer to create the model (Stefaniak et al., 2021).

While the standard pre-printing task entails placing resin containers into the machine with diminishing exposures owing to sealed container loading systems, the typical post-printing activity is extracting printed components from the build platform. Subsequently, post-processing tasks encompass washing with or without ultrasound treatment and rinsing in a caustic bath (Stefaniak et al., 2021).

MJ exemplifies 3D inkjet technology, as shown in Figure 2.18, and direct ink writing technologies. Typical materials used are polymers, ceramics, composites,

hybrid materials, and biologicals (Tofail et al., 2018). The MJ process is schematically represented in Figure 2.22.

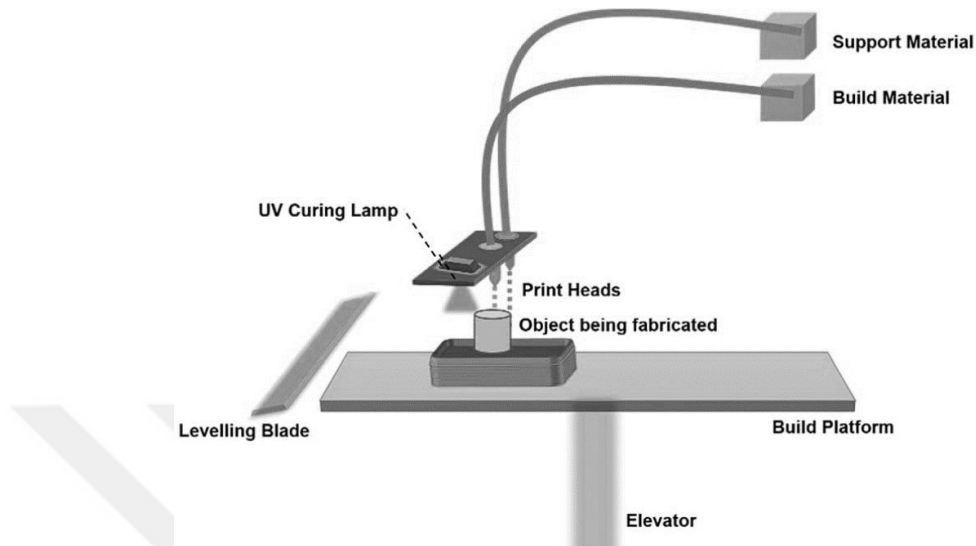


Figure 2.22 The Diagram of the MJ Process (Sireesha et al., 2018, p.22462)

In powder bed fusion (PBF) powder-based material is solidified through a heat source, yielding high dimensional accuracy and preferred mechanical properties for the parts. PBF exemplifies electron beam melting (EBM), direct metal laser sintering (DMLS), selective laser sintering (SLS), and selective laser melting (SLM) technologies (Tofail et al., 2018). The configurations of SLS/SLM, employing a laser for the energy source, and EBM, utilizing an electron beam for the energy source (Zhang et al., 2018), are depicted in Figure 2.16 (e).

Pre-printing tasks entail measuring, mixing, and introducing powder into the printer. Post-printing tasks encompass opening the printer to retrieve a printed component, removing surplus powder from the build platform, extracting the build platform with the printed component from the machine, and sieving and replenishing utilized powder. Post-processing tasks consist of detaching the printed component from the build platform and grinding (Stefaniak et al., 2021).

In the selective laser sintering (SLS) process, powder-based material is sintered using infrared radiation (Hopkinson et al., 2006) to fuse powder particles layer by

layer to acquire the intended geometry with isotropic and favorable mechanical attributes. The schematic of the SLS process is given in Figure 2.23.

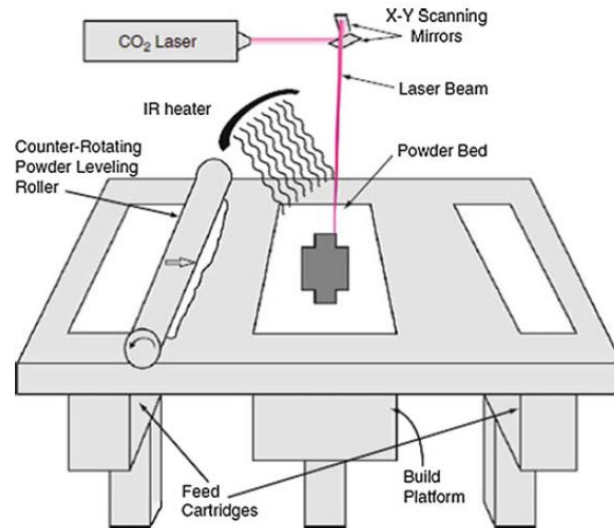


Figure 2.23 The Diagram of the SLS Process (Gibson et al., 2015, p.108)

The following steps underpin the SLM/SLS operating principle (Stefaniak et al., 2021):

- Spreading a powder layer uniformly on the build platform by a blade (powder spreading phase)
- Melting the powder selectively by directing a laser onto it through a mirror (selective melting phase)
- Incrementally lowering the powder bed and spreading a fresh powder layer by a blade over the previously hardened powder (second powder spreading phase)
- Iterative repetition of building layers until the build cycle is finalized (repetition phase)

In the EBM process, a powerful electron beam is employed to melt powder feedstock selectively in conditions approaching a vacuum. It applies to metal, serving the purposes of prototyping and direct part manufacturing. The schematic of the EBM apparatus is depicted in Figure 2.24.

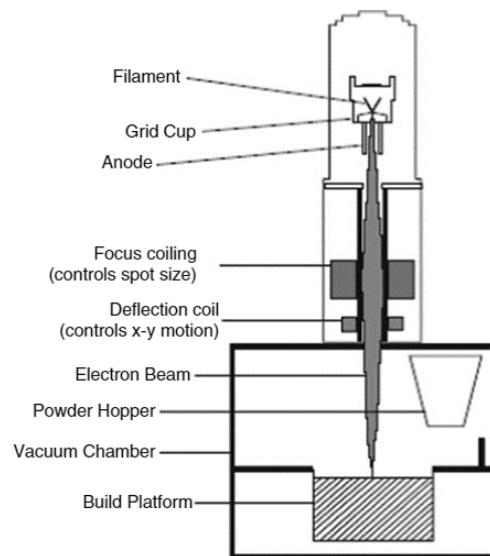


Figure 2.24 The Diagram of the EBM Apparatus (Gibson et al., 2015, p.138)

The following steps demonstrate the EBM operating principle (Stefaniak et al., 2021):

- Pushing a powder layer onto the build platform by a rake (powder pushing phase)
- Melting the powder selectively by an electron beam that is focused by a lens (selective melting phase)
- Incrementally lowering the powder bed and pushing a fresh powder layer over the previously hardened powder by a rake (second powder pushing phase).
- Iterative repetition of building layers until the build cycle is finalized (repetition phase)
- Manually recovering parts that are encased in powder (manual recovery phase)

Sheet lamination (SL) involves the lamination of sheets using adhesives, paper, and plastics or ultrasonic welding for metals to form the final object. In other words, the feedstock material in the form of a single two-dimensional layer such as paper or polymer in sheet format and metal in tape, film, or ribbon format is positioned onto the build platform, alternatively denoted as a cutting bed in this context. Various techniques of SL covering computer-aided manufacturing of laminated

engineering materials (CAM-LEM), laminated object manufacturing (LOM), plastic sheet lamination (PLS), selective deposition lamination (SDL), ultrasonic additive manufacturing (UAM), and ultrasonic consolidation (UC) differ in forming and bonding layers. While UAM is preferable for metal applications, LOM is versatile, accommodating metal, paper, and plastic. LOM allows for the interchangeable use of different metals, including bimetals with distinct thermal expansion coefficients (Chen et al., 2015). These techniques are broadly sorted into "form-then-bond" and "bond-then-form" processes, as depicted in Figure 2.16 (f). The form-then-bond processes are where the feedstock is initially cut to shape and subsequently bonded to the previous layer. Conversely, form-then-bond processes are where the feedstock is bonded through adhesives or ultrasonic welding first and then cut to shape using a blade, laser, or milling either during or after the build cycle to form a component (Stefaniak et al., 2021). The schematic representation of the LOM process is given in Figure 2.25.

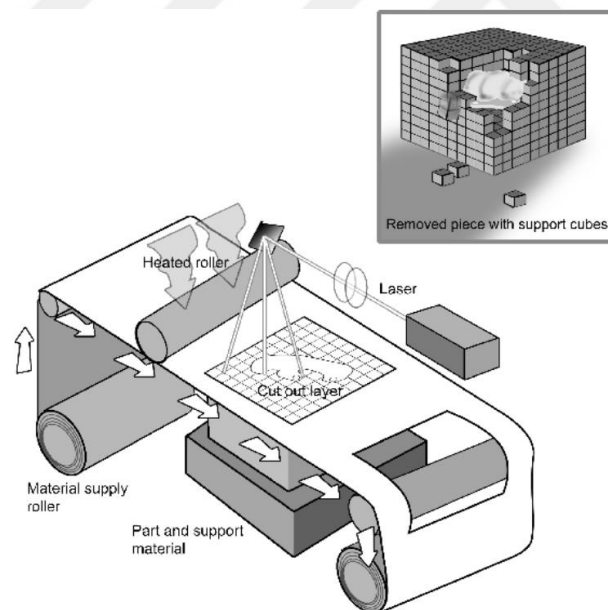


Figure 2.25 The Diagram of the LOM Process (Hopkinson et al., 2006, p.78)

In the vat photopolymerization (VP) process, a liquid photopolymer undergoes selective curing into a solid state in a vat when exposed to light through polymerization. This method is commonly employed with materials such as

polymers, ceramics, and photopolymer resins. The primary constituents of photopolymer resin are binders, photoinitiators, and monomers (Wu et al., 2020).

There are two approaches to VP to build a component, which are depicted in Figure 2.16 (g) (Wu et al., 2020). The more common approach, top-down, involves lowering the build platform to the vat, creating a thin resin layer, directing a light source upward to harden the resin, incrementally raising the platform to introduce a new resin layer, and repeating these steps until the final build cycle is finished. The bottom-up approach includes a submerged source and platform just below the resin surface, directing a downward-facing light source to harden the resin, lowering the platform gradually, pushing a new resin layer by roller over the hardened one, solidifying the new layer by the light source, and repeating these steps until the last build cycle is finalized along with attaching the first solidified layer to the build platform. (Wu et al., 2020; Zhang et al., 2018). The photopolymerization processes are schematically represented in Figure 2.26.

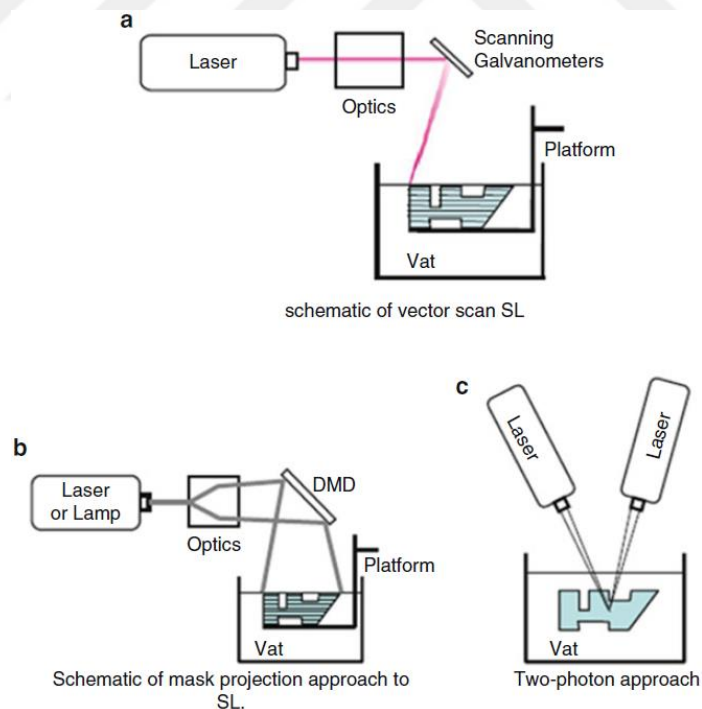


Figure 2.26 The Diagram of Three Photopolymerization Processes (Gibson et al., 2015, p.65)

Typical pre-printing tasks are mixing resin, dispensing it into vats, and loading those vats onto the machine (Stefaniak et al., 2021). Post-printing tasks involve opening the machine to retrieve the printed part. Post-processing activities aim to refine the printed component such as rinsing it in the wash solution, commonly isopropyl alcohol, to eliminate resin from part surfaces, artificially curing with UV light or naturally exposing the part to sunlight to enhance its mechanical properties, and other processes such as removing supports, grinding, gluing, sealing, painting, polishing, coating, varnishing, sterilization, inspection, and measurement (Pagac et al., 2021).

VP technologies are digital light processing (DLP), liquid crystal display (LCD), and stereolithography (SLA). In the DLP technique, a high-resolution projector flashes black-and-white image slices across the entire vat surface simultaneously and cures them. LCD uses UV light from light-emitting diodes (LEDs), flashing complete layers at the resin and screening as a mask to reveal the necessary pixels to harden the current layer. SLA technology, depicted in Figure 2.27, utilizes a scanning laser beam to selectively cure resin on the vat's bottom surface in the prescribed pattern and build objects through a series of points and lines (Gupta et al., 2019; Wu et al., 2020).

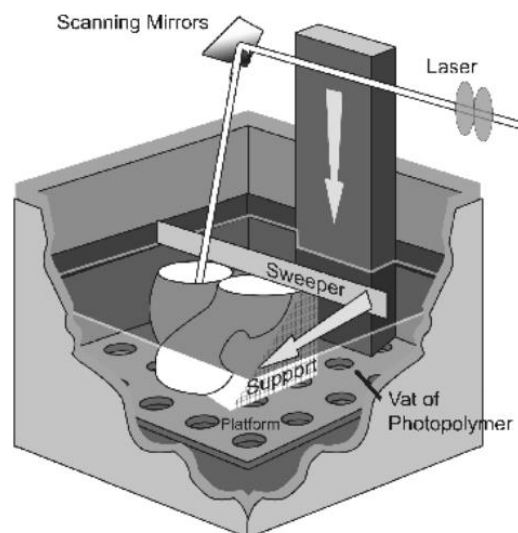


Figure 2.27 The Diagram of the SLA Process (Hopkinson et al., 2006, p.59)

According to the second classification, three categories can be assigned to AM with respect to the state of feedstock employed for printing, such as powder, solid, and liquid-based, as seen in Figure 2.28. Firstly, the techniques utilized in powder-based processes are sintering, melting, and binding (Chen et al., 2015). As powder-based materials undertake support functions for the overhanging parts, they eliminate the need for support structures as powder-based material (Hopkinson et al., 2006). Secondly, the technique employed in solid-based processes is the lamination technique to convert solid-based materials in sheet or roll form to a final product. Lastly, liquid-based processes use extrusion and polymerization techniques to form high-quality solid models through selective curing of photosensitive polymers. These models experience alterations in the physical properties, which are aimed to be mitigated by advancements in resin characteristics. Additionally, support structures that will be removed during post-processing are added for overhangs (Hopkinson et al., 2006). As the example technologies of these techniques have been addressed in the initial classification, they are not reiterated in the second classification.

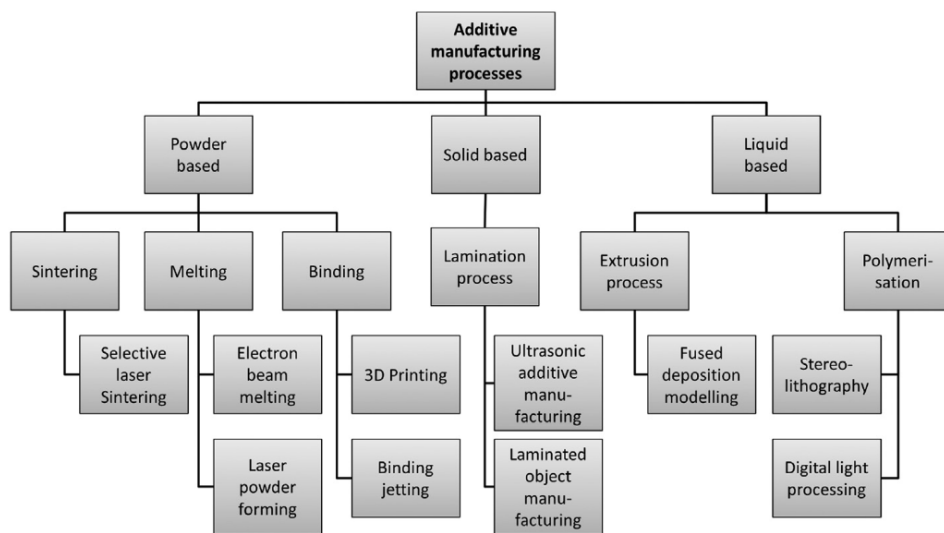


Figure 2.28 Classification of AM Processes based on the Material State Employed for Printing (Chen et al., 2015).

2.3 Indoor Environmental Quality

Given that people spend a significant portion of their time within indoor spaces, indoor environmental quality is a critical concept influencing people's lives (Kosonen & Tan, 2004). In instances where acceptable indoor environmental quality is not maintained, various physiological and psychological problems and a decline in productivity occur. Conversely, when indoor environmental quality parameters adhere to occupants' needs, suitable indoor spaces are optimized for health, comfort, efficiency, and productivity (Sakhare & Ralegaonkar, 2014).

Indoor Environmental Quality pertains to internal aspects of the building, including indoor air quality, thermal comfort, acoustic comfort, and lighting quality (Sarbu & Sebarchievici, 2013; Sulaiman et al., 2013). Firstly, indoor air quality (IAQ) is defined as acceptable when "air in which there are no known contaminants at harmful concentrations, as determined by cognizant authorities, and with which a substantial majority (80% or more) of the people exposed do not express dissatisfaction" (ANSI/ASHRAE, 2023, p.5). Secondly, thermal comfort is defined as "the condition of mind that expresses satisfaction with the thermal environment and is assessed by subjective evaluation." (ANSI/ASHRAE, 2023a, p.5). It encompasses both environmental and personal aspects. Environmental aspects entail air temperature, radiant temperature, humidity, and airspeed, while personal factors involve considerations such as metabolic rate and clothing insulation (ANSI/ASHRAE, 2023a). Thirdly, acoustic comfort pertains to an acoustic environment suitable to the building typology, providing sufficient provision and clarity of sound to occupants while protecting them from unwanted noise (Rocca, 2017) that is defined as sound pollution comprising unpleasant and unwanted sounds from various sources that negatively affect people's perceptual abilities and auditory senses (T.C. Çevre ve Orman Bakanlığı Çevre Yönetimi Genel Müdürlüğü Hava Yönetimi Dairesi Başkanlığı, 2011). Lastly, visual comfort is significantly affected by lighting design encompassing daylight and artificial light (Mandala, 2019), which is an essential phenomenon for the health, well-being, and

comfort of occupants (Dhayal & Jha, 2023). It influences the atmosphere (Mandala, 2019), aesthetics (Moscoso & Matusiak, 2018), and functionality of space (Kralikova & Wessely, 2016). While all four phenomena are critical components of IEQ, this chapter is constructed with a specific focus on IAQ. Therefore, Indoor Air Quality Phenomenon, Indoor Air Quality Pollutants, and Emissions and Exposures Associated with Additive Manufacturing are covered in this section.

2.3.1 Indoor Air Quality Phenomenon

Indoor air quality (IAQ) is a critical parameter to ensure indoor environmental quality. IAQ is achieved when the air is perceived as fresh, pleasant, and devoid of adverse effects on health (Ole Fanger, 2006). The air consists of various gases, water vapor, and airborne particles. Some of the gases are nitrogen, oxygen, carbon dioxide, and ozone, the concentrations of which can cause diseases and dissatisfaction upon reaching specific levels (Balanli et al., 2006; Nevers, 2000).

The indoor air becomes polluted over time depending on various reasons, including people and equipment due to chemicals and compounds emitted (Assimakopoulos & Helmis, 2004; Kosonen & Tan, 2004; Muhič & Butala, 2004; Niu & Burnett, 2001). Additionally, pollution load, outdoor airflow rate, ventilation efficiency, occupant density, infiltration, and the effectiveness of contamination removal in the occupied zone influence the perceived indoor air quality (Kosonen & Tan, 2004). Therefore, there are various standards on a worldwide scale to regulate indoor air quality, such as the American National Standards Institute / American Society of Heating, Refrigerating and Air-Conditioning Engineers (ANSI/ASHRAE) 62.1-2023 ventilation for acceptable indoor air quality, ANSI/ASHRAE 62.2-2023 ventilation for acceptable indoor air quality in low-rise residential buildings.

World Health Organization (WHO) (2016) recognizes that 90% of the global population is exposed to inadequate air quality, constituting a significant

environmental hazard to global public health. The impact of IAQ on occupants varies based on factors such as pollution exposure, pollution degree, and occupant characteristics. Two major health issues associated with poor IAQ are Sick Building Syndrome and Building-Related Sickneses.

Sick Building Syndrome (SBS) is a health condition associated with buildings with poor indoor air quality (Burge, 2004; Thörn, 1998). Organs such as the eyes, nose, throat, and skin are susceptible to various issues, including irritation, dryness, watering or running, blockage, soreness, and itching. Also, headaches, lethargy, and a lack of concentration may be observed (Kamaruzzaman & Sabrani, 2011). The symptoms tend to improve upon leaving the building (Thörn, 1998).

Building Related Illness (BRI) refers to diseases with clinically identifiable causes and syndromes due to extended exposure to indoor pollutants (Ambu et al., 2008). BRI encompasses infectious diseases caused by building services, diseases spread by occupants such as colds and influenza, toxic reactions to chemicals within buildings, and the presence of fungi, bacteria, or other toxins in buildings (Crook & Burton, 2010). Common symptoms include allergies, shortness of breath, coughing, high fever, chills, and muscle pain (Ambu et al., 2008; Quagraine & Boschi, 2008). Occupants require prolonged recovery times upon leaving the building (Ambu et al., 2008).

In addition to its influence on physical health, IAQ significantly affects the comfort and well-being of occupants (Kamaruzzaman & Sabrani, 2011). Therefore, detecting and identifying pollutants and enabling their adherence to the standards are crucial for avoiding indoor air pollution. Furthermore, ventilation, natural and mechanical, is an essential phenomenon in improving indoor air quality. As indoor air pollutants increase in stagnant air, air movement helps to remove pollutants from the environment. Linden (1999) explains that in natural ventilation, the process of supplying air to and removing air from an indoor space is achieved through appropriately dimensioned and oriented openings in cross façades. In

contrast, mechanical ventilation achieves these processes using ventilation equipment (Linden, 1999).

2.3.2 Indoor Air Quality Pollutants

Indoor air pollution occurs when varying compounds negatively affect indoor air quality by entering the air. Factors contributing to indoor air pollution include occupants, building materials, and interior furnishing and equipment. Within the scope of this research, compounds causing indoor air pollution and, therefore, degrading indoor air quality are called indoor air quality pollutants.

IAQ pollutants can be divided into two segments: particulate matter and gaseous pollutants (Funk et al., 2014). Particulate matter describes the particles that are dispersed in the air. Gaseous pollutants refer to chemical contaminants in the air in the form of free molecules or atoms with smaller sizes compared to particulate matter (ASHRAE, 2013).

There are numerous indoor air pollutants delineated in different sources, including Air Quality Guidelines for Europe (World Health Organization, 2000) and WHO Guidelines for Indoor Air Quality: Selected Pollutants (World Health Organization, 2010). This chapter explains particulate matter, volatile organic compounds, formaldehyde, benzene, ethyl alcohol, nitrogen dioxide, sulfur dioxide, carbon dioxide, carbon monoxide, radon, and ozone.

2.3.2.1 Particulate Matter

Particulate matter (PM), aerosol, and airborne particle terms are interchangeably used to describe particles that are dispersed in the air. Particulate Matter covers a broad spectrum of particles with varying sizes, states, and shapes whose subcategories are depicted in Figure 2.29 (ASHRAE, 2013).

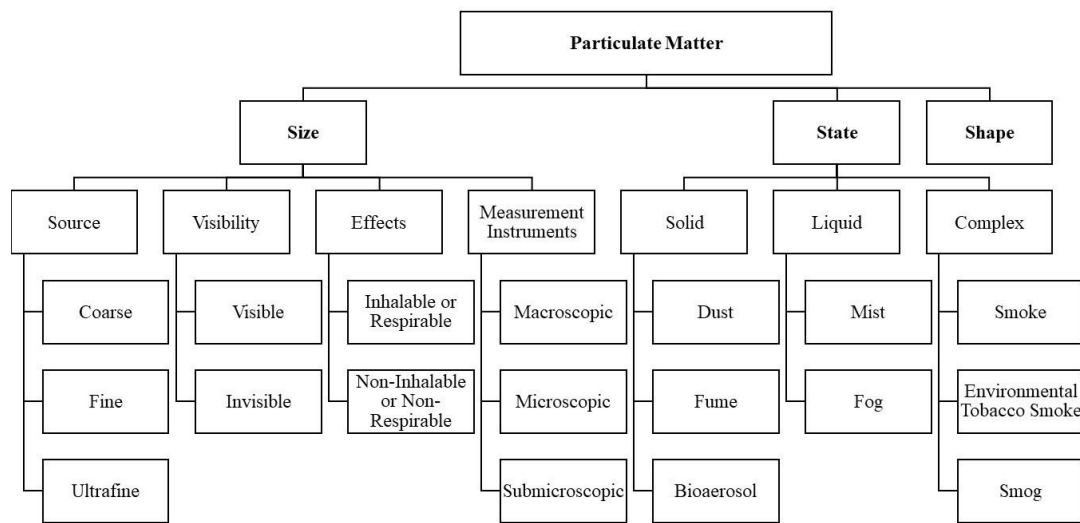


Figure 2.29 Categorization of Particulate Matter (ASHRAE, 2013)

Ranging from 0.1 to 100 microns, the categorization of particulates based on their size involves further subcategories related to the source, visibility, effects, and measurement instruments. In terms of source, there are three primary modes: coarse, fine, and ultrafine (ASHRAE, 2013). Typical particulate matter composition by particle size fraction is given in Figure 2.30.

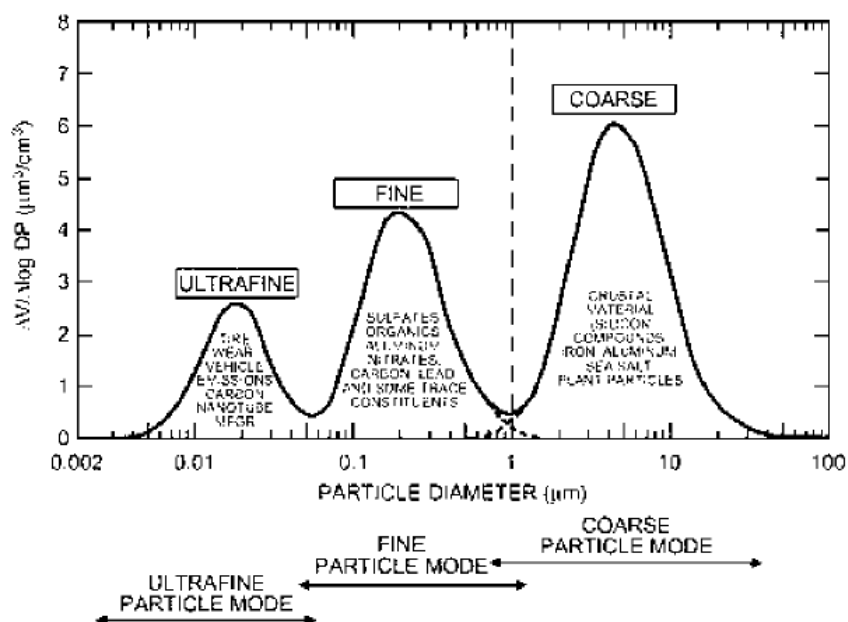


Figure 2.30 Typical Outdoor PM Composition by Particle Size Fraction (Wilson & Suh, 1997, as cited in ASHRAE, 2013, p.149)

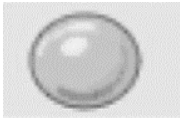
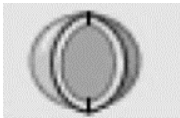
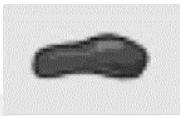
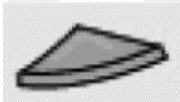
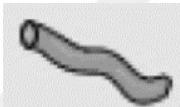
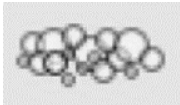
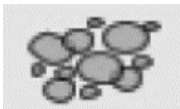
Coarse-mode particles are the largest particles formed by the mechanical breakdown of solids. They generally have a minimum size of 1 to 3 μm (ASHRAE, 2013). PM_{10} , referring to particles with diameters less than 10 μm , is categorized as coarse-mode particles (Yu, 2016). Fine-mode particles are secondary particles formed from chemical reactions or the condensation of gases. They have a maximum size of about 1 to 3 μm . Fine particles are often more chemically complex than coarse-mode particles and are a result of human activities, particularly combustion (ASHRAE, 2013). $\text{PM}_{2.5}$, referring to particles whose diameters are less than 2.5 μm , is categorized as fine-mode particles (Yu, 2016). Ultrafine-mode particles (UFP) are smaller contaminants with a maximum size of 0.1 μm (100 nm). They are complex particles, primarily originating from the reaction of gases with other particles and the degradation of larger particles. Engineered ultrafine particles are commonly termed nanoparticles (ASHRAE, 2013). $\text{PM}_{0.1}$, referring to particles with diameters less than 0.1 μm , is categorized as ultrafine-mode particles (Phairuang et al., 2022).

Furthermore, there are two primary categories regarding visibility: visible and invisible. Regarding effects and interaction with the human respiratory system, PM is considered inhalable or respirable and non-inhalable or non-respirable. Based on measurement instruments, there are three primary classes: macroscopic, microscopic, and submicroscopic (ASHRAE, 2013).

The categorization of particles based on their state includes solid, liquid, and complex particles. Solid particles encompass dust, fumes, and bioaerosols. Liquid particles consist of mist and fog. Complex particles include smoke, environmental tobacco smoke (ETS), and smog (ASHRAE, 2013).

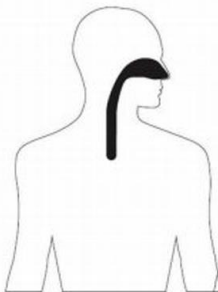
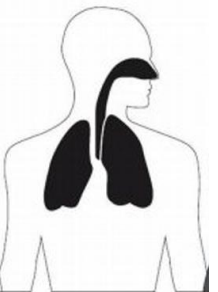
The classification of particles based on their shape includes several different shapes and densities, encompassing solid sphere, hollow sphere, solid irregular, flake, fiber, condensation floc, and aggregate (Standards Development Branch Ontario Ministry of the Environment, 2010), as seen in Table 2.1.

Table 2.1 Example Particle Shapes (Ontario Ministry of the Environment, 2010, p.H-13)

Example Particle Shape	Shape Name
	Solid Sphere
	Hollow Sphere
	Solid Irregular
	Flake
	Fiber
	Condensation Floc
	Aggregate

The indoor pollution and health problems caused by PM vary depending on PM size, the duration of exposure, physical and chemical characteristics of the particles, and their density. According to WHO (2010), PM exposure brings about problems in the respiratory and cardiovascular systems. The accumulation of varying sizes of PM in the human body is given in Table 2.2. Removing particle sources from enclosed spaces, ensuring proper ventilation, creating suitable thermal conditions, and regular cleaning can prevent the adverse effects of PM.

Table 2.2 Accumulation of Varying Sizes of PM in the Human Body (Aybay, 2017, p.40)

			
Size < 10 µm	Size < 2.5 µm	Size < 1 µm	Size < 0.1 µm
Coarse Particles	Fine Particles	Inhalable Particles	Ultrafine Particles

Air quality guideline values for PM_{2.5} and PM₁₀ provided by the National Ambient Air Quality Standards (NAAQS), European Union (EU), and WHO are given in Table 2.3.

Table 2.3 Air Quality Guidelines for PM (Environmental Protection Agency, 2020b, p.82694; European Commission, 2008, p.152/31, 152/35; World Health Organization, 2021, p. 78, 88, 92, 97)

Institution	Pollutant	Explanation	Averaging Time	Maximum Acceptable Concentration (µg/m ³)
EPA	PM _{2,5}	Primary	Annual	12
		Secondary	Annual	15
		Primary - Secondary	24-hour	35
	PM ₁₀	Primary - Secondary	24-hour	150
EU	PM _{2,5}	-	Annual	20
	PM ₁₀	-	Annual	40
	PM ₁₀	-	24-hour	50

Table 2.3 (continued)

WHO	PM _{2.5}	Interim Target 1	Annual	35
		Interim Target 2	Annual	25
		Interim Target 3	Annual	15
		Interim Target 4	Annual	10
		Air Quality Guideline	Annual	5
	PM _{2.5}	Interim Target 1	24-hour	75
		Interim Target 2	24-hour	50
		Interim Target 3	24-hour	37.5
		Interim Target 4	24-hour	25
		Air Quality Guideline	24-hour	15
	PM ₁₀	Interim Target 1	Annual	70
		Interim Target 2	Annual	50
		Interim Target 3	Annual	30
		Interim Target 4	Annual	20
		Air Quality Guideline	Annual	15
	PM ₁₀	Interim Target 1	24-hour	150
		Interim Target 2	24-hour	100
		Interim Target 3	24-hour	75
		Interim Target 4	24-hour	50
		Air Quality Guideline	24-hour	45

2.3.2.2 Volatile Organic Compounds

While ubiquitously occurring in the indoor air, volatile organic compounds encompass a broad range of compounds whose boiling points range from less than 0°C to approximately 400°C (Wolkoff, 1995). Manufacturing and installation processes, building materials, and equipment are common contributors to indoor air contamination by VOC emissions (Niu & Burnett, 2001; Wolkoff, 1999; World Health Organization, 2000).

WHO classifies VOCs into four categories based on their boiling points, thereby compound volatility, being very volatile, volatile, semi-volatile, and particulate organic matter, as seen in Table 2.4 (WHO, 1989, as cited in Seifert et al., 1989). Another classification of VOCs is based on their chemical structure. Accordingly, they are grouped into major categories: aliphatic denoting straight chain compounds; alkylated aromatics referring to ring compounds; halogenated hydrocarbons encompassing compounds with chlorine or fluorine atoms; and lastly, oxygenated compounds (Hansen, 2010).

Table 2.4 Classification of VOCs based on Boiling Points and Compound Volatility (WHO, 1989, as cited in Seifert et al., 1989, p.27)

Category	Description	Abbreviation	Boiling point range		Sampling methods typically used in field studies
			from °C	to °C*	
1	Very volatile (gaseous) organic compounds	VVOC	<0	50-100	batch sampling, adsorption on charcoal
2	Volatile organic compounds	VOC	50-100	240-260	adsorption on tenax, carbon molecular black, or charcoal
3	Semi-volatile organic compounds	SVOC	240-260	380-400	adsorption on PUF** or XAD-2
4	Organic compounds associated with particulate matter or particulate organic matter	POM	>380		collection on filters

* Polar compounds are on the higher side of the range

** Polyurethane foam

VOC emissions are influenced by various factors dynamically. Those factors are the age of the source, the type of VOC transfer process such as evaporation,

desorption, or diffusion, and environmental factors, including temperature, humidity, air velocity, and air changes (Hansen, 2010).

Although VOC levels lack a numerical standard except for formaldehyde, it is advisable to maintain VOC levels as low as possible for optimal indoor air quality (Hansen, 2010), as VOC emissions pose severe risks to human health. A common and practical approach, known as total VOC (TVOC), is employed as indoor air encompasses VOCs from various classes of organic substances. Accordingly, TVOC represents a cumulative measure of individual concentrations by summing up the measured mass of organics in a sample. Although this straightforward method has limitations for health implications, TVOC levels are essential indicators for background levels of organic compounds (Hansen, 2010). The guideline issued by the Umweltbundesamt (UBA), the Federal Environmental Agency in Germany (2007), categorizes TVOC concentrations into levels, as seen in Table 2.5. Level 1 does not indicate hygienic concerns, serving as the target value. Level 2 does not suggest significant concerns; however, it necessitates increased ventilation. Level 3 raises hygienic concerns, prompting an investigation into sources and necessitating increased ventilation. It is considered as an upper threshold over a maximum period of 12 months. Level 4 signifies substantial concerns, with a recommendation not to tolerate such levels for more than one month. Level 4 requires restricted usage, source investigation, and intensified ventilation. Level 5 represents unacceptable concentrations, permitting usage only if unavoidable and for short durations, with increased ventilation measures taken (Bekanntmachung des Umweltbundesamtes, 2007).

Table 2.5 Air Quality Guidelines for TVOC (“Beurteilung von Innenraumlufthkontaminationen Mittels Referenz- Und Richtwerten,” 2007, p.993)

Institution	Levels	TVOC Concentration (mg/m ³)
UBA	Level 1	< 0.3
	Level 2	0.3-1
	Level 3	1-3
	Level 4	3-10
	Level 5	10-25

VOC emissions are associated with severe health problems. For example, naphthalene is known to cause colon cancer, hemolytic anemia, and poisoning. Similarly, polycyclic aromatic hydrocarbons (PAH) are associated with anti-DNA adduction, asthma, bladder cancer, breast cancer, heart disease, immune system defects, low birth weight, lung cancer, and neural system defects. Furthermore, trichloroethylene (TCE) is linked to cervical cancer, depression, immune system defects, kidney defects, liver cancer, neurological damage, skin irritation, and pregnancy defects (World Health Organization, 2010). Therefore, the spaces should be adequately ventilated, and suitable thermal conditions should be provided to minimize VOC impact.

2.3.2.3 Formaldehyde

Formaldehyde is a colorless, pungent-smelling, flammable VOC (Shaham et al., 1996) composed of carbon, oxygen, and hydrogen atoms. Widely used in the chemical industry and building materials, it can be emitted from paints, solvent-based varnishes, lacquers, upholstery coatings, foam insulation materials, adhesives used in chipboard and plywood production, gas-burning appliances, diverse equipment, and cigarette smoke (Vural & Balanlı, 2005). The thermal environment and ventilation affect the concentration of formaldehyde (Myers, 1985). Furthermore, building materials, indoor furnishing, and product selections

significantly impact formaldehyde emissions. Additionally, the spaces should be adequately ventilated, and suitable thermal conditions should be provided to avoid adverse effects of formaldehyde.

Similar to other VOCs, formaldehyde poses severe health risks to occupants. It is associated with the development of nasopharyngeal cancer, poisoning upon exposure to high concentrations, and respiratory system irritation (Shaham et al., 1996; World Health Organization, 2010). WHO recommends an air quality guideline value of 0.1 mg/m³ for a 30-minute average to prevent sensory irritation in the general population, as seen in Table 2.6 (World Health Organization, 2000).

Table 2.6 Air Quality Guidelines for Formaldehyde (World Health Organization, 2000, p.90)

Institution	Averaging Time	Maximum Acceptable Concentration
WHO	30-minute	0.1 mg/m ³

The effects of formaldehyde on human health are given in Table 2.7 (Hines et al., 1993, as cited in Jones, 1999).

Table 2.7 Observed Health Effects of Formaldehyde Exposure (Hines et al., 1993 as cited in Jones, 1999, p. 4541)

HCHO Concentration	Observed Health Effects
<0.05 ppm	None Reported
0.05 ppm - 1.5 ppm	Neurophysiologic Effects
0.05 ppm - 1.0 ppm	Odor Threshold Limit
0.01 ppm - 2.0 ppm	Irritation of Eyes
0.10 ppm - 25 ppm	Irritation of the Upper Airway
5 ppm - 30 ppm	Irritation of the Lower Airway and Pulmonary Effects
50 ppm - 100 ppm	Pulmonary Edema, Inflammation, Pneumonia
>100 ppm	Coma, Death

2.3.2.4 Benzene

Benzene, C₆H₆, is a volatile organic compound and a human genotoxic carcinogen. The primary source of benzene exposure is inhalation (World Health Organization, 2010). Long-term exposure to benzene is associated with carcinogenicity, genotoxicity, and haematotoxicity (World Health Organization, 2000). It can bring about blood and bone marrow defects, fatality, fatigue, and headaches. WHO does not recommend a safe level of exposure. Therefore, it is advised to minimize indoor exposure levels as much as possible. Consequently, benzene-releasing activities such as smoking tobacco or using solvents are recommended to be eliminated or minimized (World Health Organization, 2010).

2.3.2.5 Ethyl Alcohol

Ethyl alcohol, ethanol, is a clear, colorless liquid with a characteristic wine-like odor and is highly flammable (New Jersey Department of Health, 2011). It is a volatile organic compound that can evaporate into the air from various sources. It is utilized in the production of alcoholic beverages, as a solvent, and in the synthesis of various chemicals. The odor threshold for ethanol is 84 ppm; however, this threshold alone does not indicate the potential for hazardous exposure. Ethyl alcohol can enter the body through inhalation, causing headache, drowsiness, nausea, vomiting, unconsciousness, impaired concentration, and impaired vision or dermal absorption, causing skin and eye irritation at high concentrations. Prolonged or repeated exposure may lead to skin dryness, cracking, peeling, redness, and itching. Chronic high-level exposure may adversely affect the liver and nervous system (New Jersey Department of Health, 2011). The workplace exposure limits set by the Occupational Safety and Health Administration (OSHA), the National Institute for Occupational Safety and Health (NIOSH), and the American Conference of Governmental Industrial Hygienists (ACGIH) are given in Table 2.8.

Table 2.8 Workplace Exposure Limits for Ethanol (Occupational Safety and Health Administration, n.d.)

Institution	Averaging Time	Explanation	Exposure Limit (ppm)
OSHA	8-hour	Permissible Exposure Limit (PEL)	1000
NIOSH	10-hour	Recommended Exposure Limit (REL)	1000
ACGIH	Short-term	Threshold Limit Value (TLV)	1000

2.3.2.6 Nitrogen Dioxide

Nitrogen dioxide (NO₂) is produced through the oxidation of nitric oxides in the presence of oxygen, mainly during combustion processes, forming a colorless to brown liquid. Road traffic is a major outdoor contributor to the generation of nitrogen oxides. At the same time, indoor sources include gas, wood, oil, kerosene, and coal-burning appliances such as stoves, ovens, space and water heaters, and fireplaces. Typical exposure to NO₂ occurs through inhalation at room temperature, which is in the gaseous form. NO₂ exposure is associated with various health issues, including increased risks of otitis media, eczema, ear, nose, and throat infections, sensitization to food allergens, and elevated blood coagulability. Adequate ventilation is crucial to mitigate the adverse effects of nitrogen dioxide (World Health Organization, 2010). The maximum acceptable indoor NO₂ concentrations, provided by EPA, EU, and WHO, are given in Table 2.9.

Table 2.9 Air Quality Guidelines for NO₂ (Environmental Protection Agency, 2018, p. 17255; European Commission, 2008, p. 152/30; World Health Organization, 2021, p. 116, 124)

Institution	Explanation	Averaging Time	Maximum Acceptable Concentration
EPA	-	Annual	53 ppb
	-	1-hour	100 ppb
EU	-	Annual	40 µg/m ³
	-	1-hour	200 µg/m ³
WHO	Interim Target 1	Annual	40 µg/m ³
	Interim Target 2	Annual	30 µg/m ³
	Interim Target 3	Annual	20 µg/m ³
	Air Quality Guideline	Annual	10 µg/m ³
	Interim Target 1	24-hour	120 µg/m ³
	Interim Target 2	24-hour	50 µg/m ³
	Air Quality Guideline	24-hour	25 µg/m ³

2.3.2.7 Sulfur Dioxide

Sulfur dioxide (SO₂) is mainly the result of industrial activity using sulfur-containing fuels, leading to respiratory issues and heart and lung diseases. The maximum acceptable indoor SO₂ concentrations, provided by EPA, EU, and WHO, are given in Table 2.10.

Table 2.10 Air Quality Guidelines for SO₂ (Environmental Protection Agency, 2019; European Commission, 2008, p.152/30; World Health Organization, 2000, p.196)

Institution	Averaging Time	Maximum Acceptable Concentration
EPA	1-hour	75 ppb
	3-hour	0.5 ppm
EU	24-hour	125 µg/m ³
	1-hour	350 µg/m ³
WHO	Annual	50 µg/m ³
	24-hour	125 µg/m ³
	10-minute	500 µg/m ³

2.3.2.8 Carbon Dioxide

Carbon dioxide (CO₂), a colorless and odorless gas, contains a carbon atom bonded to two oxygen atoms on either side. It is generated by the combustion of fossil fuels and oxygen use. Population growth, technological advances, industrialization, and burning of fossil fuels increase atmospheric CO₂ levels (Volk, 2010). Commonly used as an IAQ metric, CO₂ release by metabolic activities, such as respiration, elevates indoor CO₂ concentration significantly. Therefore, indoor concentration usually surpasses outdoor concentration. The health consequences of CO₂ exposure encompass decreased cognitive and decision-making performance, headaches, sleepiness, fatigue, increased arousal, blood acidosis, and respiratory failure (López et al., 2023), as seen in Figure 2.31.

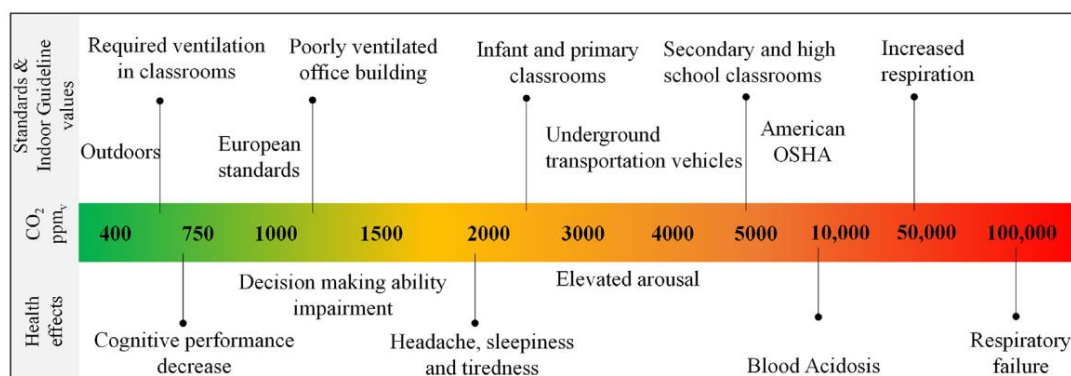


Figure 2.31 Health Consequences of CO₂ Exposure at Certain Concentrations (López et al., 2023, p.9)

Mandatory or guideline values for indoor CO₂ concentration are provided by varying institutions, ranging from 1000 to 1500 ppm, to manage IAQ concerns and SBS incidents. Although initially, ANSI/ASHRAE Standard 62 of 1989 states a limit value for indoor CO₂ as 1000 ppm, later editions of the standard, Standard 62.1, do not include a limit value for indoor CO₂, contrary to the common misconception (ASHRAE, 2022).

2.3.2.9 Carbon Monoxide

Carbon monoxide (CO) is a lightweight, colorless, odorless, yet toxic gas. It is generated through incomplete combustion of carbon-containing fuels. Common indoor sources encompass fireplaces, kerosene heaters, gas stoves, fossil fuel-burning appliances, other equipment, and tobacco smoke. CO poisoning carries a fatal risk (Environmental Protection Agency, 1996). Exposure to low levels of CO results in shortness of breath, mild nausea, and headaches, while exposure to moderate levels of CO is known to cause dizziness, headache, nausea, mental confusion, and loss of consciousness. Additionally, heart failure, stroke, asthma, and fatality may arise with prolonged exposure (Environmental Protection Agency, 1996; World Health Organization, 2010). To prevent adverse effects of CO, gas-operated devices and CO-emitting equipment should be carefully used, gas leakage

should be prevented, and ventilation systems should be cleaned routinely (Environmental Protection Agency, 1996).

Global background concentrations of CO range from 0.06 mg/m³ to 0.14 mg/m³, equivalent to 0.05 ppm to 0.12 ppm (World Health Organization, 2000). The maximum acceptable indoor CO concentrations provided by EPA, EU, and WHO are given in Table 2.11.

Table 2.11 Air Quality Guidelines for CO with Short Averaging Times (Environmental Protection Agency, 2011, p.54296; European Commission, 2008, p.152/30; World Health Organization, 2010, p.88)

Institution	Averaging Time	Maximum Acceptable Concentration
EPA	8-hour	9 ppm
	1-hour	35 ppm
EU	8-hour	10 mg/m ³
	24-hour	7 mg/m ³
WHO	8-hour	10 mg/m ³
	1-hour	35 mg/m ³
	15-minute	100 mg/m ³

2.3.2.10 Radon

Radon, a colorless and odorless gas (Başdemir & Yalçın, 2023), enters the building through cracks, sewage systems, plumbing, and ventilation ducts (World Health Organization, 2009). It originates primarily from soil and rocks. Additionally, building materials such as sand, cement, and brick affect indoor radon concentrations. As radon is not recognizable by human senses (Başdemir & Yalçın, 2023), it is detected through specialized measurements (World Health Organization, 2009).

While other risks are not consistently demonstrated, radon exposure is known to cause lung cancer (World Health Organization, 2010). Radioactivity analysis of

building materials and fuels used for heating, ventilation, and air conditioning (HVAC) systems, proper ventilation, and preventing soil contact are crucial measures to mitigate radon exposure (Örgün & Çelebi, 2016). The acceptable indoor radon concentrations are provided by varying institutions, including EPA, the International Commission on Radiological Protection (ICRP), WHO, ASHRAE, and the Turkish Atomic Energy Commission (TAEK), as given in Table 2.12.

Table 2.12 Air Quality Guidelines for Radon (Balanlı et al., 2004, p.7)

Institution	Maximum Acceptable Value of Indoor Radon Concentration for Existing Buildings (Bq/m³)	Maximum Acceptable Value of Indoor Radon Concentration for New Constructions (Bq/m³)
EPA	148	148
ICRP	200	200
WHO	370	111
ASHRAE	-	37
TAEK	400	400

2.3.2.11 Ozone

Occurring out of the action of short-wavelength radiation from the sun on nitrogen dioxide (World Health Organization, 2000), ozone (O₃) is a colorless and odorless gas with three oxygen atoms (Campbell, 2014). Short-term O₃ exposure is associated with respiratory symptoms, elevated airway responsiveness, airway inflammation, and changes in pulmonary function. More critical effects are seen in prolonged exposure to higher concentrations (World Health Organization, 2000). The maximum acceptable indoor O₃ concentrations, provided by EPA, EU, and WHO, are given in Table 2.13.

Table 2.13 Air Quality Guidelines for O₃ (Environmental Protection Agency, 2020a, p. 87307; European Commission, 2008, p.152/24; World Health Organization, 2000, p.185)

Institution	Averaging Time	Acceptable Concentration
EPA	8-hour	0.070 ppm
EU	8-hour	120 µg/m ³
WHO	8-hour	150-200 µg/m ³

2.3.3 Indoor Air Quality Issues Associated with Additive Manufacturing

In spite of its benefits, AM gives rise to concerns for health and safety (Minář et al., 2023). Nevertheless, the expansion of AM applications lacks comprehensive attention to worker safety and health, with only a limited number of publications addressing these concerns (Stefaniak et al., 2021). Initial calls for safe work practices in AM were raised by Deak (1999), emphasizing potential exposure to chemicals and their long-term effects. Subsequent studies by Short et al. (2015), Ryan and Hubbard (2016), and Petretta et al. (2019) assessed the risks and hazards of AM processes, highlighting the risks regarding exposure to toxic chemicals and flammable and explosive materials.

Although all additive manufacturing (AM) processes involve certain hazards, the type and level of potential exposure can differ depending on the specific AM category, the phase of the process, and the operating environment (Bours et al., 2017; Petretta et al., 2019; Roth et al., 2019). Critical health hazards associated with AM include particle inhalation, exposure to SVOCs and VOCs exposure, and dermal exposure to powders, binders, resins, solvents, and radiation (Petretta et al., 2019; Roth et al., 2019). The VOC reported in AM includes acids, alcohols, aldehydes, benzene, caprolactam, ethylbenzene, ketones, lactide, styrene, toluene, xylene, and various others (Azimi et al., 2016; Bernatikova et al., 2021; Davis et al., 2019; Gu et al., 2019; Wojnowski et al., 2020, 2022). Benzene and formaldehyde are proven carcinogens. Styrene is a probable carcinogen.

Acetaldehyde and ethylbenzene are potential carcinogens (Minář et al., 2023). Additionally, the interaction of VOC with other substances exerts deleterious effects on health, including allergies, sensory irritation, pulmonary diseases, and carcinogenic effects (Rumchev et al., 2007). UFP is absorbed by the pulmonary system, thereby raising arterial blood pressure, susceptibility to pulmonary or systemic inflammation, and autonomic tone (Ohlwein et al., 2019). UFP poses additional challenges depending on the dose, surface area, shape, and chemistry of the contaminant and the length of exposure (Elder & Oberdörster, 2006). Additional hazards in AM include developmental and reproductive toxicity with exposure to toluene (Minář et al., 2023), electrical shock, thermal burns, mechanical injuries, noise, contact with biological agents, fatigue, and psychosocial stress. Control measures encompassing proper facility design, proper process design, adequate ventilation, regular collection of dust, and use of personal protective equipment (PPE) are crucial to prevent or reduce exposures in AM environments (Dunn et al., 2020; Katz et al., 2020; Pelley, 2018; Roth et al., 2019).

In the context of this study, indoor air quality issues associated with additive manufacturing are considered in terms of emission and exposure, utilizing the definitions provided by Stefaniak et al. (2021). The term emission is delineated as any substance released from an AM during pre-printing (cleaning and feedstock infusing), printing, post-printing (printed part salvaging and feedstock evacuation), and post-processing (cleaning and polishing) activities, while the term exposure is defined as the quantifiable substance amount in biological fluids, breathing zone, or skin of a person (Stefaniak et al., 2021).

2.3.3.1 Indoor Air Quality Issues Associated with Binder Jetting

The studies of Afshar-Mhajer et al. (2015) and Lewinski et al. (2019) address indoor air quality issues in terms of emissions and exposures associated with the BJ process.

In their study, Afshar-Mohajer et al. (2015) examined pre-printing, printing, and post-printing periods of BJ operations using gypsum powder as feedstock material. They conducted real-time monitoring of TVOC and PM concentrations in a 157 m³ lab with two air exchanges per hour (ACH). The highest concentrations were recorded during post-printing when the printer was opened to extract printed objects after the completion of printing. While PM levels significantly exceeded the related PM_{2.5} and PM₁₀ standards, TVOC concentration exceeded the values recommended by the Environment Institute of the European Commission. Most of the particles were in the size range of 205-407 nm, while the number of particles in the size range of 352 and 407 was the highest, with a rate of around 4.4×10^4 particles per minute (#/min) during ejection. The reported PM concentrations were in the range of 1×10^4 to 3×10^4 particles per cubic centimeter (#/cm³). TVOC concentrations were reported to reach 1725 µg/m³. Recommended strategies to mitigate potential health risks included providing proper enclosure, ventilation, respiratory protection, and storage (Afshar-Mohajer et al., 2015).

Lewinski et al. (2019) examined PM concentrations at pre-printing, i.e., printer setup, printing, and post-printing periods using stainless steel powder as feedstock material in their 70 m³ labs with unreported ACH. The peak PM concentration was recorded as 7×10^3 #/cm³ during printing. They reported slight changes in average particle number concentrations compared to background levels during printer setup, printing, and post-printing. Those levels were 3.3×10^4 , 3.5×10^4 , 3.8×10^4 , and 3.3×10^4 #/cm³, respectively (Lewinski et al., 2019).

2.3.3.2 Indoor Air Quality Issues Associated with Directed Energy Deposition

In their research, Bau et al. (2020) explored indoor air quality issues in terms of emissions produced during the DED process using steel and powder feedstocks. They observed that PM concentrations ranged from 0.5×10^6 to 1.5×10^6 particles per cubic centimeter (#/cm³) during printing, increasing to 5.0×10^6 #/cm³ after

each production cycle. The study recommended several strategies to mitigate health risks, such as using a sealed enclosure, ensuring proper ventilation, implementing an 8-minute delay between the end of printing and opening the printer, and the use of PPE (Bau et al., 2020).

2.3.3.3 Indoor Air Quality Issues Associated with Material Extrusion

Several studies investigated indoor air quality issues in terms of emissions associated with ME in different spaces, including classrooms, dorms, labs, manufacturing workplaces, and offices, focusing on emission characteristics and factors affecting emissions and exposures.

Numerous studies (Chan et al., 2020; Chýlek et al., 2019; Ding et al., 2020; Dunn et al., 2020; Katz et al., 2020; Mendes et al., 2017; Oberbek et al., 2019; Stabile et al., 2017; Stefaniak, Johnson, du Preez, Hammond, Wells, Ham, LeBouf, Menchaca, et al., 2019; Stephens et al., 2013; Vance et al., 2017; Wojtyła et al., 2020; Yi et al., 2016; Youn et al., 2019; Zhou et al., 2015; Zontek et al., 2019) have explored emissions from FFF employing acrylonitrile butadiene styrene (ABS) and polylactic acid (PLA) filaments. The particles released during printing were frequently in the ultrafine size range, with some studies also noting nanoscale particles. The chemical composition of particles varied depending on polymer type and extrusion temperature. Thermo-gravimetric analysis and spectroscopy techniques were employed to characterize both feedstock materials and emitted particles. Real-world studies were complemented by chamber evaluations, affirming the presence of volatile and semi-volatile organic compounds. Furthermore, specific chemical analyses of bulk filaments and aerosol emissions were conducted, revealing discernible differences in composition (Stefaniak et al., 2021).

Varying factors that influence particle emissions were explored, such as additives, extruder nozzle temperature, filament feed rate, machine configuration, polymer

type, print step, printer status, and the number of printers. For instance, different emissions were noted for various polymers like ABS, PLA, and others. The inclusion of metal additives in feedstock filaments escalated particle emissions. Furthermore, elevated extruder nozzle temperatures contributed to heightened particle release, particularly during the initial heating step of the print process. As the filament feed rate increased, emissions increased. Moreover, it was discovered that the presence of an enclosure in the printer can mitigate particle concentrations during printing, and malfunctions in FFF 3D printers lacking feedback mechanisms may result in emissions surpassing normal operational levels (Stefaniak et al., 2021).

Exposures during ME pre-printing tasks lack comprehensive data in the literature, yet exposures during printing, post-printing, and post-processing activities have been extensively documented. Workers operating FFF 3D printers and industrial FDM™ machines exhibited diverse exposures to particles and gases, some surpassing recommended limits. Exposure to VOCs, particularly to acetone and isopropyl alcohol, was revealed. Opening the build chamber, being a post-printing task, increased TVOC concentrations. Post-processing activities, such as polishing and drilling, also contributed to exposure to contaminants. Additionally, the ventilation status of the space influenced emissions, with ventilated spaces exhibiting lower emission concentrations (Stefaniak et al., 2021).

2.3.3.4 Indoor Air Quality Issues Associated with Material Jetting

The studies of Ryan and Hubbard (2016), Stefaniak et al. (2019), Väisänen et al. (2019), and Zisook et al. (2020) presented indoor air quality issues in terms of emissions associated with material jetting (MJ) in various workplaces spanning from 48 m³ to 466 m³.

Ryan and Hubbard (2016) investigated particles and VOCs inside and outside of the build chamber while printing with liquid resin as feedstock. Particle mass

concentrations varied from $3 \mu\text{g}/\text{m}^3$ for PM_{10} outside the printer and $30 \mu\text{g}/\text{m}^3$ for $\text{PM}_{1.0}$ inside the printer. While $\text{PM}_{1.0}$ concentration decreased, $\text{PM}_{2.5}$ concentration increased during printing. The VOCs found in the room air are toluene, isopropyl alcohol, ethanol, acetone, n-but-anone, 2-butanone, and 1,4-dioxane. 1,4-dioxane was at high concentrations, reaching $100 \mu\text{g}/\text{m}^3$, while others were in the range of 2.4 to $14 \mu\text{g}/\text{m}^3$. The room volume and ventilation conditions were unreported in the study (Ryan & Hubbard, 2016).

Stefaniak, Johnson, du Preez, Hammond, Wells, Ham, LeBouf, Martin, Duling, Bowers, Knepp, du Beer, and du Plessis (Stefaniak, Johnson, du Preez, Hammond, Wells, Ham, LeBouf, Martin, et al., 2019) assessed MJ emissions from two premises with 90 m^3 and 466 m^3 room volumes and estimated 0.22 ACH and 2 ACH respectively. Those premises were equipped with the same printer employing different resins. Emission rates based on particle number varied with the lid position, ranging from 1.5×10^9 to 2.3×10^{10} #/min for different size ranges. SEM analysis identified clusters of ultrafine carbon particles. TVOC emission rates remain consistent regardless of the lid position, ranging from 4.5×10^4 to $2.5 \times 10^4 \mu\text{g TVOC}/\text{min}$. Individual VOC concentrations, including acetaldehyde, were generally below 1.4% of their respective exposure limits. Ethanol, used for machine cleaning, contributed to elevated room contaminant levels during non-printing tasks. The machine operators at one facility were exposed to various VOCs encompassing acetone, ethanol, isopropyl alcohol, naphtha, and pentane (Stefaniak, Johnson, du Preez, Hammond, Wells, Ham, LeBouf, Martin, et al., 2019).

The research conducted by Väisänen et al. (2019) investigated the change in indoor air quality and emissions during printing and post-processing while utilizing a transparent liquid photopolymer resin as feedstock in 48m^3 office and ACH not reported. Dust concentrations remained consistent with background levels, very low, during printing, recorded at levels below $30 \mu\text{g}/\text{m}^3$. Various VOCs encompassing aromatic hydrocarbons, butylated hydroxytoluene, ethylbenzene, isobornyl acrylate, styrene, toluene, xylenes, and 2-furan-propanoic acid were detected. No short-chained carbonyl compounds were found during printing.

Average TVOC levels were 2496 $\mu\text{g}/\text{m}^3$ during printing and 1809 $\mu\text{g}/\text{m}^3$ during post-processing. Carbon monoxide was detected at low concentrations during printing, averaging 0.5 ppm. Carbon dioxide concentrations during printing, at an average of 560 ppm, were similar to background levels of 540 ppm (A. J. K. Väisänen et al., 2019b).

Zisook et al. (2020) explored VOC and particle emissions during 8 hours of printing and 80 minutes of post-processing in a 353 m^3 laboratory with 6.3 ACH. The feedstock material, resin, involved compounds of acrylate and glycerin. The post-processing activities were rinsing in soapy water and a lye bath. The study did not report particle emission data, which may suggest that emissions were either undetected or very low. The concentrations of TVOCs during both the printing and post-processing phases were similar to background levels (Zisook et al., 2020).

2.3.3.5 Indoor Air Quality Issues Associated with Powder Bed Fusion

Various researchers have been studying metal feedstock environments. Various studies conducted static area monitoring by direct reading instruments in several facilities such as university laboratories, manufacturing premises, and research institutes to report particle number concentration, particle mass concentration, and TVOC concentration. While mainly metal polymers and nylon polymers are studied, some researchers characterized virgin and recycled metal feedstock powders. Additionally, some researchers explored personal exposures using microscopic techniques for particle characterization in workplace air.

The research conducted by Beisser et al. (2017) focused on inhaling hazardous metal substances such as alloyed steels, nickel, aluminum, titanium, and copper-based alloys during PBF processes. Accordingly, machines processing certain metal powders such as alloyed steels, aluminum alloys, and titanium alloys complied with the related assessment criteria. The results also indicated that

chromium compounds were not detected when processing chromium materials. Lastly, processing nickel-based alloys generated additional hazardous substances.

Similarly, Graff et al. (2017) studied particle emissions and exposure-related risks during metal additive manufacturing, particularly with chromium, nickel, and cobalt powders. Nanosized particles, particularly particles larger than 300 nm, posing a potential health risk were identified. The operations conducted with recycled powder caused emissions of smaller particle sizes. The findings suggested a need for improved powder handling systems, advanced monitoring technologies for nanosized particles, and updated workplace regulations.

In their research, Kolb et al. (2017) measured dust levels with an aerosol spectrometer, filter-based air samplers, and a condensation particle counter during laser beam melting techniques. Although the results were within German occupational safety limits, they found significant emissions during specific phases, including machinery cleaning, powder refills, building platform removal, and manual post-processing. They suggested increased automation for materials containing hazardous substances, reduction in exposure time, and use of respirators and PPE to mitigate potential health risks.

Ljunggren et al. (2019) examined metal exposure in AM and welding facilities over two consecutive years, implementing preventive measures between assessments. The findings demonstrated that total and inhalable dust levels were mainly below occupational exposure limits; nonetheless, AM operators experienced cobalt exposure notably compared to welders. Although the AM facility saw occasional peaks in airborne particle concentrations, these levels were still lower than those in the welding facility. The study highlighted the need for preventive measures to mitigate metal exposure, the importance of design and regulation of facilities, and the need for monitoring exposure markers and biomonitoring of urine and dermal contamination.

Walter et al. (2018) addressed concerns about inhalation exposure during PBF processes. They conducted workplace measurements to monitor particles and

volatile compounds, focusing on metal-containing powders, alloys, and polymer powders to derive guidelines for reducing inhalation exposure. Their results indicated that the considered processes complied with the related rules and standards.

Philippot et al. (2018) studied various metal-based powders during PBF processes. They reported that major factors influencing emissions and exposures were powder pouring, machine opening and parts recovery, and cleaning. In addition to dust concentrations associated with metallic powders, there was potential exposure to nanometer-sized particles generated as a by-product of laser beam melting, which was not adequately addressed in OELs. Therefore, the authors highlighted the importance of additional measurements covering various particle sizes at each process step, properly designing AM equipment and AM premise, and employing protective equipment such as local exhaust ventilation and PPE.

Damanhuri et al. (2019a, 2019b) conducted two studies regarding the emissions from PBF processes utilizing SLS technologies in the same facility on different occasions. The research included real-time monitoring of PM_{2.5}, TVOC, formaldehyde, and CO₂ during the background, pre-printing, printing, and post-printing phases. The first study (Damanhuri et al., 2019a) focused on printing calibration blocks with virgin polyamide nylon (PA12) powder. Accordingly, CO₂ and PM_{2.5} concentrations during pre-printing exceeded related limits, indicating 1000 ppm and 0.15 mg/m³ at 1218 ppm and 1070 µg/m³ respectively. The second study (Damanhuri et al., 2019b) compared these emissions while printing with virgin PA12 powder and recycled PA12 powder. Accordingly, PM_{2.5} and CO₂ concentrations were reported highest during the pre-printing process, with recycled powder showing higher levels at 1450 µg/m³. TVOC concentration from recycled powder was slightly higher during the post-printing phase, ranging from 1150 to 1600 µg/m³, influenced by the powder cake and PA12 temperature. As a result of both studies, the authors suggested employing mechanical ventilation and PPE to mitigate potential hazards.

Zisook et al. (2020) studied emissions from PBF-SLS using nylon-12. Dust concentrations were reported elevated during post-printing, averaging $400 \mu\text{g}/\text{m}^3$, with no detection of inorganic gases. Additionally, during the pre-printing and post-printing phases, respirable and total particle concentrations exceeded background levels, although they remained within the threshold limits of ACGIH.

Väisänen et al. (2022) investigated emissions from glass-reinforced nylon (polyamide) powder feedstock. Dust concentrations were reported in the range of $0.01 \text{ mg}/\text{m}^3$ to $0.47 \text{ mg}/\text{m}^3$ during printing and $0.1 \text{ mg}/\text{m}^3$ to $2.57 \text{ mg}/\text{m}^3$ during post-processing. Particle concentrations were reported in the range of $1.5 \times 10^4 \text{ \#}/\text{cm}^3$ to $2.2 \times 10^4 \text{ \#}/\text{cm}^3$ exceeding the background concentrations. Despite low TVOC concentrations, formaldehyde concentration was measured at $40 \mu\text{g}/\text{m}^3$.

The study conducted by Gomes et al. (2019) assessed the exposure to nanoparticles during tasks in workstations to produce metallic parts using laser welding. The research, conducted in an industrial unit with controlled temperature and humidity, revealed a significant amount of nanoparticles in the air, matching the composition of the stainless steel powder used. Particle number concentrations and lung-deposited surface area values were reported as $1.1 \times 10^4 \text{ \#}/\text{cm}^3$ to $1.8 \times 10^4 \text{ \#}/\text{cm}^3$ and $294 \mu\text{m}^2/\text{cm}^3$ to $457 \mu\text{m}^2/\text{cm}^3$, respectively. The findings indicated high levels of exposure to nanoparticles, around 15 nm, raising concerns about their potential to penetrate the alveoli and enter the bloodstream, potentially accumulating in the body.

Jensen et al. (2020) studied the particle exposure associated with micrometer-sized metal powders in the SLM technique of PBF during five activities: emptying the printing chamber, closed powder removal, open powder removal, baking, and grinding. Emptying the printing chamber, open powder removal, and grinding activities increased particle concentrations above $8 \times 10^2 \text{ \#}/\text{cm}^3$ background levels. The particle concentrations were $10^4 \text{ \#}/\text{cm}^3$, $5 \times 10^3 \text{ \#}/\text{cm}^3$, and $2.5 \times 10^5 \text{ \#}/\text{cm}^3$, respectively. The size distributions showed particles mainly below 200 nm, and respirable mass concentrations, measured at $50.4 \mu\text{g}/\text{m}^3$ by collecting on filters and

58.4 $\mu\text{g}/\text{m}^3$ by monitoring instrument, were below eight-hour occupational exposure limits in Denmark.

Mellin et al. (2016) assessed the nanoscale particle creation during SLM and SLS techniques using alloy feedstock containing Ni, Cr, and Co. They observed 1.2 μm to 5.8 μm sized particles, called satellites, attached to larger particles up to 23.4 μm in size during processing. These satellites detached during power handling when the feedstock was recycled powder. Additionally, the generation of respirable and potentially carcinogenic metal particles was observed during processing.

Sutton et al. (2020) remarked on the impact of continuous exposure to the SLM/SLS techniques during the PBF environment on the properties of recycled AISI304L stainless steel powder. The study revealed morphological, chemical, and microstructural changes in the recycled powder by seven consecutive reuses, which also simulated a worst-case scenario. Despite coarsening, increased sphericity, oxygen accumulation, and the presence of delta ferrite, the recycled powder demonstrated improved flowability compared to the virgin powder.

Du Preez, de Beer, and du Plessis (2018) analyzed the characterization of three titanium powders in terms of particle size, shape, and elemental composition to assess the findings in terms of safety and respiratory health. The presence of thoracic ($<10 \mu\text{m}$) and respirable ($<4 \mu\text{m}$) particles in both virgin and used powders was revealed, emphasizing the potential health risks upon inhalation. Discrepancies were identified in particle size and elemental composition compared to safety data sheets. Consequently, the authors recommended employing measures aligning with occupational health and safety recommendations.

2.3.3.6 Indoor Air Quality Issues Associated with Sheet Lamination

The literature lacks discernible documentation regarding indoor air quality issues associated with sheet lamination (SL) processes (Stefaniak et al., 2021).

2.3.3.7 Indoor Air Quality Issues Associated with Vat Photopolymerization

The studies of Freiser et al. (2018), Yang and Li (2018), Väisänen et al. (2019), and Zisook et al. (2020) presented indoor air quality issues in terms of emissions associated with vat photopolymerization (VP) in various settings, including an apartment, industrial lab, medical lab, and university research lab.

Freiser et al. (Freiser et al., 2018) assessed personal exposures to PM and VOCs during surgical drilling of 3D printed temporal bone models made from photo acrylic resin, occurring within one hour of post-processing, involving the use of isopropyl alcohol on the printed part. The room volume of the medical lab was reported to be 55 m³, while ACH was not reported. Total particle mass concentrations remained below the limit of detection (LOD) at 1.4 mg/m³. The sole VOC at detection levels during the 40-minute drilling simulation was isopropyl alcohol, registering at 0.24 ppm. Total PM and VOC count exposures were at acceptable levels defined by OSHA (Freiser et al., 2018).

Yang and Li (2018) developed a theoretical framework for indoor air quality estimation for VP processes utilizing SLA, considering both emissions from volatilization processes and manufacturing processes. The emission model was validated through experimental measurements in a 123 m³ (41 m² x 3m) room volume with no ACH reported. The experiments used a feedstock resin based on methyl methacrylate. VOCs were measured during three phases: when the machine was idle (reference/background) for 10 minutes, during printing for 93 minutes, and post-processing UV-curing and ethanol cleaning for 10 minutes. The mean concentrations of TVOCs during these phases were 122.70 µg/m³, 1052.71 µg/m³, and 1774.15 µg/m³, respectively, peaking during post-processing at 6177 µg/m³. These values were significantly higher than those reported in the literature and the guideline values of environmental agencies (Yang & Li, 2018).

The research conducted by Väisänen et al. (2019) investigated the change in indoor air quality and emissions during printing and post-processing phases for two

scenarios involving different machine and feedstock material combinations in a 55 m³ apartment room with natural ventilation and a 195 m³ university research lab with mechanical ventilation. Scenario one utilized a DLP printer for dental products, while scenario two involved an SLA printer for miscellaneous parts. Particle number concentrations in scenario one fluctuated between 4510 and 13510 #/cm³ with an average of 8020 ± 1780 #/cm³, while the background values ranged from 1920 to 11680 #/cm³, with a mean value of 4420 #/cm³. Dust mass concentrations ranged from below the limit of detection to 120 µg/m³ during post-processing. In contrast, particle number and mass concentration values in scenario two were equivalent to background levels. TVOC concentrations in scenario one increased during printing, peaking at 427 µg/m³, and decreased afterward. The minimum concentration recorded was 182 µg/m³, with an average concentration of 277 µg/m³. TVOC concentrations in scenario two were in the range of 84 µg/m³ to 176 µg/m³, with an average concentration of 138 µg/m³. The formaldehyde concentrations were 12 µg/m³ and 3 µg/m³ in those scenarios, respectively. Additionally, 11084 µg/m³ TVOC was recorded during post-processing. While there was no detection of CO, a slight increase was observed in CO₂ levels. (A. J. K. Väisänen et al., 2019a).

Zisook et al. (2020) conducted a 4.5-hour monitoring of VOC and particle emissions during SLA printing employing a liquid photopolymer epoxy mixture. In a 128.8 m³ (28 m² x 4.6 m) well-ventilated industrial lab with 8.6 ACH, no data on particle emissions were reported, referring to emissions being very low or unidentified. Concentrations of TVOC were indistinguishable from background levels during printing, with fluorine being detected above the limit of quantitation (LOQ) in one sample and below LOQ in the other sample. 245 ppb of acetone and 560 ppb of isopropanol, on average, were detected at concentrations higher than the background levels of 240 ppb and 380 ppb, respectively (Zisook et al., 2020).

CHAPTER 3

METHODOLOGY

This chapter is organized into four main sections. Firstly, in the Semi-Structured Interview section, the interview conducted to gather relevant data and feedback from participants is explained. Secondly, the Indoor Network-Based Air-Sensing Ecosystem section delves into hardware development, software development, and calibration of the real-time indoor air quality monitor that is designed by the author of this research. Thirdly, the Indoor Air Quality Polling Instrument section explains the hardware development and software development of the polling device, that is designed by the author this research. Lastly, the Field Experiments section details the additive manufacturing facility and experimental procedures for different AM processes, including powder bed fusion and vat photopolymerization. The methodology followed in this research is schematically given in Figure 3.1.

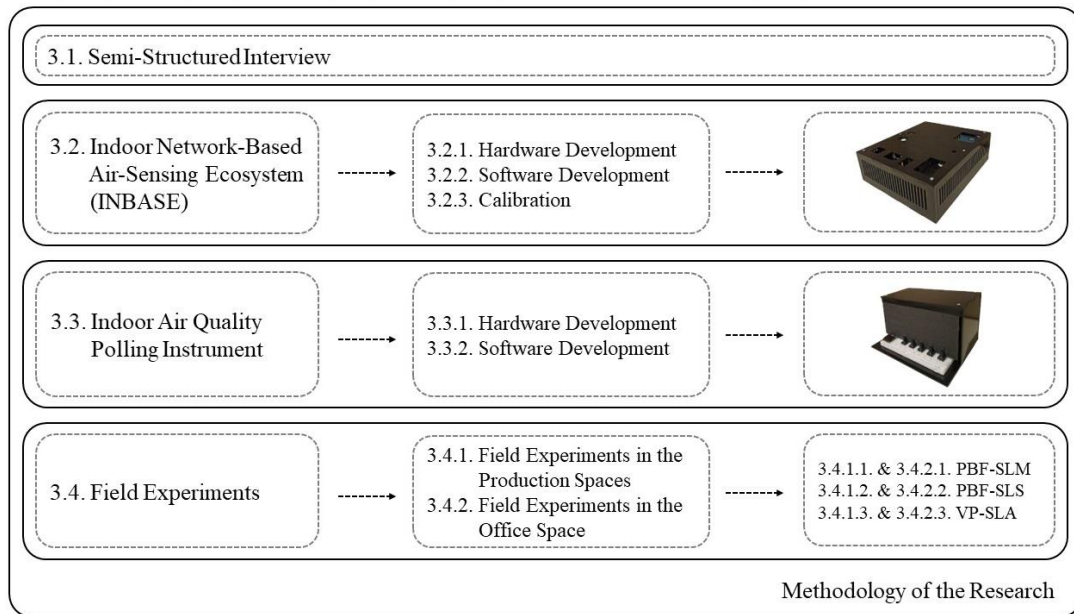


Figure 3.1 Methodology of the Research

3.1 Semi-Structured Interview

A semi-structured interview was designed to be conducted with employees working in a workplace practicing AM operations. The interview aims to gather information regarding the workplace dynamics of the workplace. The interview includes eight questions created in both English and Turkish, which can be found in Appendices A and B. The interview starts with definitions of three terms frequently used in the questions to clarify the context of the questions. These are “office space,” “production space,” and “workplace.” Afterward, it involves six questions covering the roles and responsibilities of the participants, their perception of space integration, benefits of integration, drawbacks of integration, the impact of integration on communication and collaboration, and the impact of integration on workflow efficiency. Following the sixth question, a definition of the term “indoor environmental quality” is provided. Lastly, the interview includes two other questions regarding IEQ alignments and conflicts with respect to the integration of production and office spaces and IEQ's impact on comfort and productivity. Hence, in total, eight questions were asked to eight participants who were employees of the workplace with varying roles. The responses of the participants were written during the interview, and transcripts were generated before the analysis.

3.2 Indoor Network-Based Air-Sensing Ecosystem

A real-time indoor air quality monitor is an equipment, measuring various air pollutants continuously at a given location. Within the scope of this research, an IoT-based multi-sensor arrayed real-time indoor air quality monitor was designed by the author of this research to measure the concentration of indoor air quality pollutants, including $PM_{1.0}$, $PM_{2.5}$, PM_{10} , TVOC, HCHO, C_6H_6 , C_2H_5OH , CO_2 , O_2 , and NO_2 . This designed equipment was named Indoor Network-Based Air-Sensing Ecosystem (INBASE) by the author. Hardware development, software development, and calibration of INBASE are given in this section.

3.2.1 Hardware Development

The hardware of the real-time indoor air quality monitor, INBASE, developed by the author, includes quantitative sensors for $PM_{1.0}$, $PM_{2.5}$, PM_{10} , TVOC, HCHO, CO_2 , and O_2 , a qualitative sensor for C_6H_6 , C_2H_5OH , and NO_2 , a Wi-Fi module, a display unit, a base shield, a breadboard, and a development board.

3.2.1.1 PM Sensor

HM3301 grove manufactured by Seeed Studio, depicted in Figure 3.2, was selected as a detection module for $PM_{1.0}$, $PM_{2.5}$, and PM_{10} concentration.



Figure 3.2 The Isometric (a), Top (b), and Bottom (c) Views of the $PM_{2.5}$ Sensor - HM3301

The sensor utilizes laser scattering technology to optimize its accuracy, stability, and consistency. The light scattering phenomenon occurs when light passes through particles whose size equals or exceeds the wavelength of the light. The scattered light is directed towards a highly sensitive photodiode, where it is amplified and processed by a circuit. The count and mass concentration of dust particles are obtained by specific mathematical models and algorithms. The sensor employs a fan, an infrared laser source, a condensing mirror, a photosensitive tube, a signal amplifying circuit, and a signal sorting circuit. The sensor structure diagram is given in Figure 3.3. The airflow within the detection chamber serves as a test sample to perform real-time and continuous tests on the dust of different

particle sizes in the air, including 0.3 μm , 0.5 μm , 1.0 μm , 2.5 μm , 5 μm , 10 μm (Shenzhen Technology, 2018).

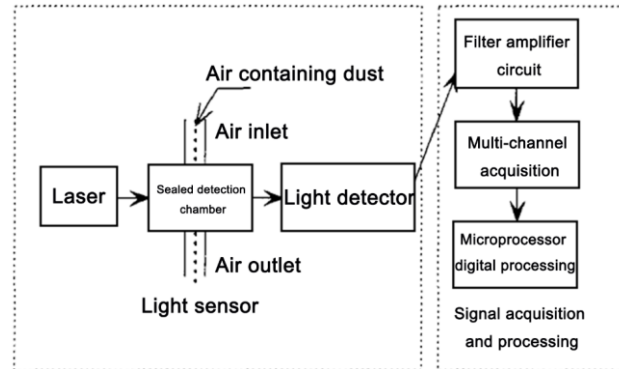


Figure 3.3 PM Sensor Structure Diagram (Shenzhen Technology, 2018, p.4)

The measurement range for PM_{1.0}, PM_{2.5}, and PM₁₀ is 1 $\mu\text{g}/\text{m}^3$ to 1000 $\mu\text{g}/\text{m}^3$ with 1 $\mu\text{g}/\text{m}^3$ resolution. The sensor supports the Inter-Integrated Circuit (I²C) interface. The sensor has an estimated operational lifespan of 2 years. The main areas where this sensor is employed are air conditioners, air purifiers, air quality testing equipment, environmental testing equipment, industrial PM value analysis, and dust and smoke detection and analysis. Technical specifications of HM3301 are given in Table 3.1.

Table 3.1 Technical Specifications of HM3301 (Shenzhen Technology, 2018)

Item	Technical Parameters	
Measurement Range (PM _{2.5} standard value)	Effective Range	1-500 $\mu\text{g}/\text{m}^3$
	Maximum Range	1-1000 $\mu\text{g}/\text{m}^3$
Particle Size	6 channels	0.3, 0.5, 1.0, 2.5, 5, and 10 μm
Output Value	PM _{1.0} , PM _{2.5} , PM ₁₀ concentration ($\mu\text{g}/\text{m}^3$)	
Resolution	Concentration	1 $\mu\text{g}/\text{m}^3$
	Counting	1s / 0.1 L
Stability Time	30 seconds after powering on	
Sensitivity	Refreshing data once every 1 second	
Operating Temperature	-10°C-60°C	
Operating Humidity	10%-90% RH (non-condensing)	

3.2.1.2 TVOC Sensor

SGP30 grove manufactured by Seeed Studio, depicted in Figure 3.4, was selected as a detection module for TVOC concentration.

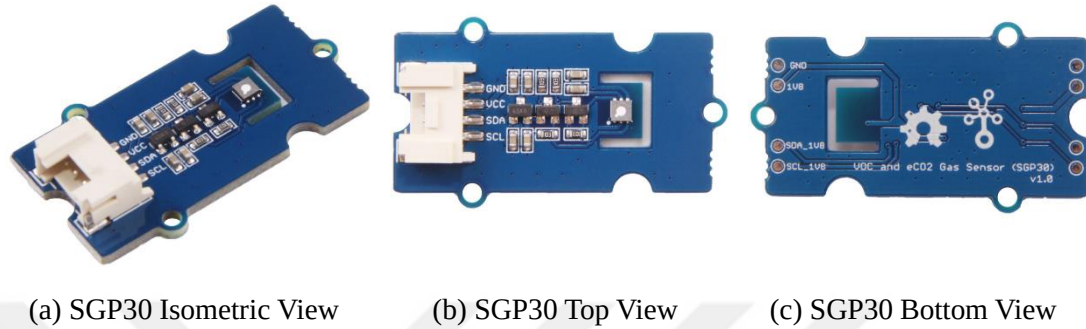


Figure 3.4 The Isometric (a), Top (b), and Bottom (c) Views of the TVOC Sensor - SGP30

It is a metal-oxide gas sensor based on complementary metal-oxide-semiconductor sensor (CMOSens) technology developed by Sensirion. The sensor chip has an I²C interface, a temperature-controlled micro hotplate, and two pre-processed indoor air quality signals, TVOC and CO_{2eq}. Its measurement range is 0 to 1000 ppm for ethanol and H₂ signals. The output range for TVOC and CO_{2eq} is 0 ppb to 60000 ppb and 400 ppm to 60000 ppm, respectively, with varying resolutions based on the measured range. This sensor is mainly employed in air purifiers, demand-controlled ventilation, and IoT applications (Sensirion, 2020b). Gas sensing specifications of the sensor at 25°C and 50% relative humidity (RH) are given in Table 3.2.

Table 3.2 Technical Specifications of SGP30 (Sensirion, 2020, p.2,4)

Parameter	Signal	Values
Measurement Range	Ethanol	0-1000 ppm
	H ₂	0-1000 ppm
Output Range	TVOC	0-60000 ppb
	CO _{2eq}	400-60000 ppm

Table 3.2 (continued)

Resolution		Range	Resolution
	TVOC	0-2008 ppb	1 ppb
		2008-11110 ppb	6 ppb
		11110-60000 ppb	32 ppb
	CO _{2eq}	400-1479 ppm	1 ppm
		1479-5144 ppm	3 ppm
		5144-17597 ppm	9 ppm
		17597-60000 ppm	31 ppm

3.2.1.3 HCHO Sensor

SFA30 grove manufactured by Seeed Studio, depicted in Figure 3.5, was selected as a detection module for formaldehyde concentration.

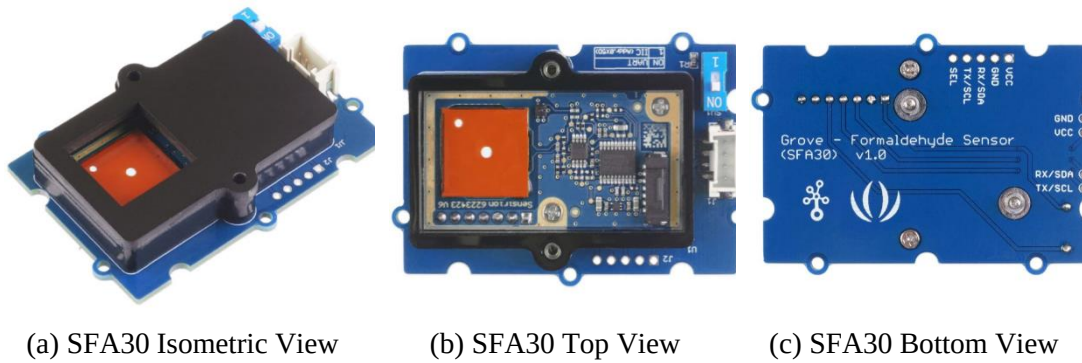


Figure 3.5 The Isometric (a), Top (b), and Bottom (c) Views of the HCHO Sensor - SFA30

The sensor is based on electrochemical sensing technology to optimize its accuracy. It demonstrates low cross-sensitivity to ethanol to increase its accuracy in detecting low concentrations. In other words, its detection limit is less than 20 ppb. Its measurement range is 0 ppb to 1000 ppb with 1 ppb resolution. The sensor's response time is less than two minutes. The sensor comes as factory calibrated. It

has both I²C and Universal Asynchronous Receiver-Transmitter (UART) interfaces. It has an embedded relative humidity and temperature sensor and microprocessor manufactured by Sensirion to maintain its performance in changing indoor environments. The sensor is robust, with an estimated operational lifespan of 6 years. It is primarily employed in air conditioners, air exchangers, air purifiers, and indoor air quality monitors (Sensirion, 2020a). The sensor's formaldehyde sensing specifications at 25°C when 3.3 V is supplied are given in Table 3.3.

Table 3.3 Technical Specifications of SFA30 (Sensirion, 2020a)

Parameter	Conditions	Value
Measurement Range	-	0-1000 ppb
Output Value	The value at which the output saturates	5000 ppb
Resolution	-	1 ppb
Accuracy	(50±5)% RH, (25±3)°C HCHO concentration	± 20 ppb or ± 20% (whichever is larger)
Repeatability	0....200 ppb in otherwise clean air	± 5 ppb or ± 5% (whichever is larger)
Cross Sensitivity to Ethanol	Tested at 5.0 ppm ethanol	<0.5% (<25 ppb)
Operating Temperature	-	0°C-40°C
Operating Humidity	Non-condensing	10-90% RH
Response Time	To concentration change	<2 min
Service Life	At standard conditions	>6 years
Long-term Drift (per year)	At standard conditions	<5 ppb or <5% (whichever is larger)

3.2.1.4 C₆H₆, C₂H₅OH, and NO₂ Sensor

The Multichannel V2 grove manufactured by Seeed Studio, depicted in Figure 3.6, was selected as a detection module for VOC (calibrated against C₆H₆), C₂H₅OH, and NO₂ concentration.

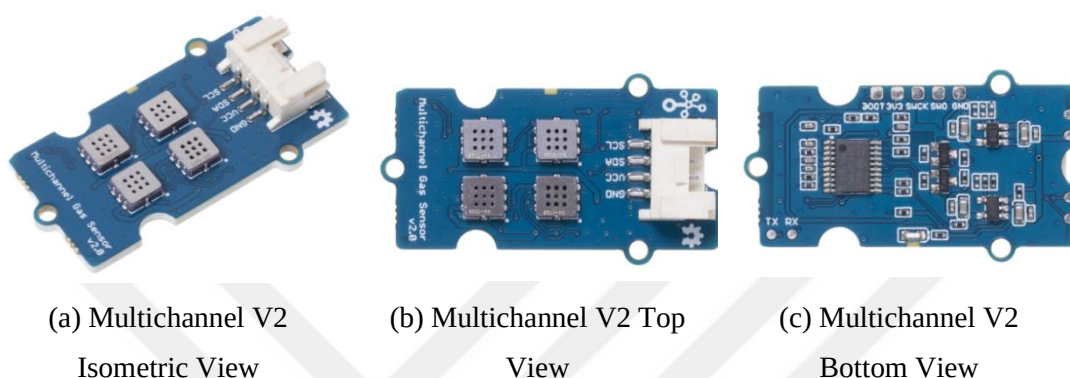


Figure 3.6 The Isometric (a), Top (b), and Bottom (c) Views of the C₆H₆, C₂H₅OH, and NO₂ Sensor - Multichannel V2

The sensor is equipped with an I²C interface. It is composed of 4 independent sensors: GM-702B, GM-502B, GM-302B, and GM-102B. Within the scope of this research, GM-502B, GM-302B, and GM-102B were used, which are sensitive to VOC (calibrated against C₆H₆), C₂H₅OH, and NO₂, respectively. Each of the sensors embedded in Multichannel V2 is based on the technology involving micro-electromechanical systems (MEMS) micro-fabrication on a Silicium (Si) substrate base, utilizing low-conductivity metal oxide semiconductor materials as gas-sensitive elements whose conductivity changes based on gas concentration when exposed to gas. Accordingly, a simple circuit converts this conductivity change into an output signal. It is mainly employed for qualitative measurement. The measurement ranges are 1 ppm to 500 ppm for VOC, 1 ppm to 500 ppm for C₂H₅OH, and 0.1 ppm to 10 ppm for NO₂. Major areas where this sensor is employed are gas leak detection, gas alarms, testing of consumer electronics products, and vehicle safety in terms of gasoline vapor detection, car ventilation

control, and alcohol breath test (Zhengzhou Winsen Electronics Technology, 2019, 2020a, 2020b). Technical specifications for the gas sensor are given in Table 3.4.

Table 3.4 Technical Specifications of Multichannel V2 (Zhengzhou Winsen Electronics Technology, 2017, 2019, 2020b, 2020a)

Part No	GM-502 B	GM-302 B	GM-102 B
Sensor Type	MEMS	MEMS	MEMS
Standard Encapsulation	Ceramic	Ceramic	Ceramic
Detection Gas	VOCs	Ethanol Vapor	NO ₂
Detection Range	1-500 ppm	1-500 ppm	0.1-10 ppm
Sensitivity (S)	$R_s \text{ (in air)} / R_s \text{ (in 5000 ppm ethanol)} \geq 3.0$	$R_s \text{ (in air)} / R_s \text{ (in 5000 ppm ethanol)} \geq 3.0$	$R_s \text{ (in air)} / R_s \text{ (in 2 ppm NO}_2\text{)} \leq 0.5$
Preheating Time	-	≥ 48 hours	-

3.2.1.5 Carbon Dioxide Sensor

SCD30 grove manufactured by Seeed Studio, depicted in Figure 3.7, was selected as a detection module for CO₂ concentration.



Figure 3.7 The Isometric (a), Top (b), and Bottom (c) Views of the CO₂ Sensor - SCD30

The sensor is based on Non-Dispersive Infrared (NDIR) technology, depicted in Figure 3.8. The fundamental principle of NDIR is the absorption of infrared radiation by molecules, particularly dissymmetry diatomic and polyatomic gases, as the radiation passes through them (Tan et al., 2015). The Lambert-Beer absorption relationship is given in Equation 3-1.

Equation 3-1 Lambert-Beer Absorption Relationship (Tan et al., 2015, p.104)

$$I = I_0 e^{-KCL}$$

In the formula, I is the intensity of light transmitted after absorbing the target gas. I_0 is the intensity of the light before absorbing the target gas. K is the absorption coefficient of gas. C is the gas concentration. L is the cell length.

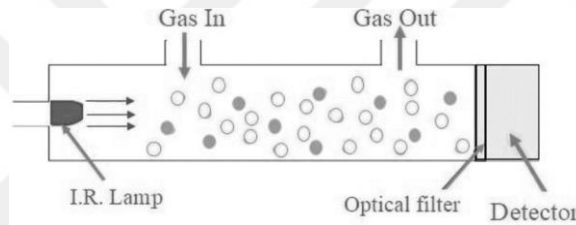


Figure 3.8 NDIR Technology (Nadargi et al., 2023, p. 563)

Its measurement range spans from 400 ppm to 10000 ppm with $\pm (30 \text{ ppm} + 3\%)$ accuracy. The response time of the sensor is 20 seconds. Additionally, the sensor includes temperature and relative humidity sensing elements whose measurement ranges are -40°C to 120°C with $\pm 0.5^{\circ}\text{C}$ accuracy and 0 to 100% RH with $\pm 2\%$ RH accuracy. Their response times are 2 seconds and 8 seconds, respectively. The chip of the sensor has an I²C interface. The sensor has an estimated operational lifespan of 15 years. This sensor is primarily employed in air purifiers, environmental monitoring, plant monitoring, and Arduino weather stations (Sensirion, 2018). Technical specifications of the sensor are given in Table 3.5.

Table 3.5 Technical Specifications of SCD30 (Sensirion, 2018, p.2)

Parameter	CO ₂	Temperature	Humidity
Measurement Range	Effective Range	400 ppm - 10000 ppm	-40°C - 120°C
	Maximum Range	0 ppm - 40000 ppm	0 % - 100% RH
Accuracy	± (30 ppm + 3%)	± 0.5°C	± 2% RH
Response Time	20 sec	> 2 sec	8 sec
Operating Temp & Relative Humidity	0°C - 50°C 0% RH - 95% RH	-	-
Service Life	15 years		

3.2.1.6 Oxygen Sensor

ME2-O₂-Φ20 grove manufactured by Seeed Studio, depicted in Figure 3.9, was selected as a detection module for oxygen concentration.



Figure 3.9 The Isometric (a), Top (b), and Bottom (c) Views of the O₂ Sensor - ME2-O₂-Φ20

The sensor is based on an electrochemical principle employing the electrochemical oxidation process of the gas on the working electrode inside the electrolytic cell. The current produced in the electrochemical reaction of the target gas is directly

proportional to its concentration, following Faraday's law. Gas concentration can be determined by measuring the value of the current. Its measurement range is 0 to 25% vol with a response time of less than 15 seconds. The sensor's communication protocol is analog. The sensor has an estimated operational lifespan of 2 years. It has an analog interface. It is mainly employed in air purifiers, oxygen analyzers, and environmental monitors (Zhengzhou Winsen Electronics, 2021). The sensor's gas sensing specifications are given in Table 3.6.

When inert gases such as helium, nitrogen, and argon are introduced into indoor air, they displace oxygen, leading to a decrease in oxygen levels. This change in oxygen concentration can serve as an indicator of the presence of inert gases in the environment (Pure Aire Monitoring Systems, 2016).

Table 3.6 Technical Specifications of ME2-O₂-Φ20 (Zhengzhou Winsen Electronics, 2021)

Item	Value
Measurement Range	0% - 25% Vol
Max Detecting Concentration	30% Vol
Sensitivity	(0.1 - 0.3) mA (in air)
Response Time	≤15 sec
Zero Drift (-20°C - 50°C)	≤ 0.1% vol
Storage Temperature and Humidity	-20°C - 50°C and 0% - 99% RH
Service Life	2 years

3.2.1.7 Wi-Fi Module

The ESP8266 Serial Wi-Fi Wireless Transceiver Module manufactured by Seeed Studio, depicted in Figure 3.10, was selected as a Wireless Fidelity (Wi-Fi) module.

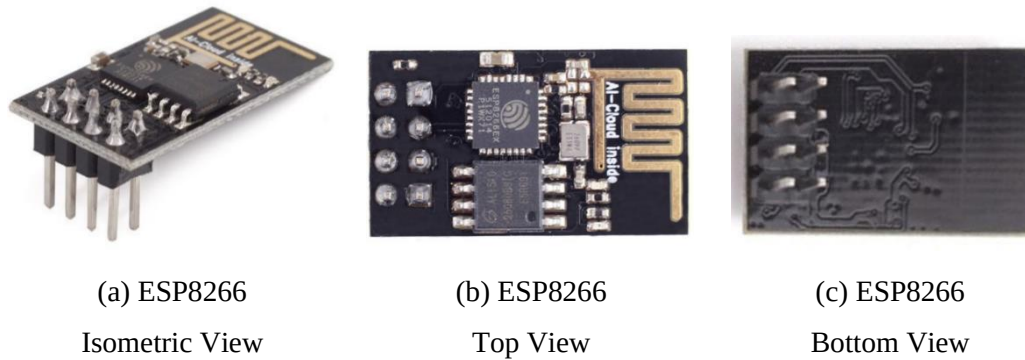
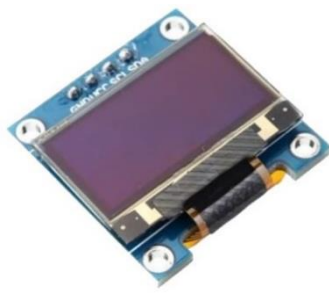


Figure 3.10 The Isometric (a), Top (b), and Bottom (c) Views of the Wi-Fi Module - ESP8266

The module is equipped with a Wi-Fi microchip produced by Espressif Systems to facilitate IoT applications by enabling microcontrollers to connect to 2.4 GHz Wi-Fi networks. It supports the Institute of Electrical and Electronics Engineers (IEEE) 802.11 b/g/n standards and interfaces with Serial Peripheral Interface (SPI) / Secure Digital Input Output (SDIO) or I²C / UART. It can be used as a microcontroller unit (MCU) by running a software development kit (SDK). Alternatively, it can provide Wi-Fi connectivity to external host MCUs with Espressif Serial Protocol (ESP-AT) firmware. The module provides data processing, reads, and controls of General-Purpose Input/Output (GPIOs). It has a full Transmission Control Protocol/Internet Protocol (TCP/IP) stack (Espressif Systems, 2016).

3.2.1.8 Display Unit

SSD1306 Organic Light Emitting Diode (OLED) driver, distributed by Robolink and depicted in Figure 3.11, was selected as a display component.



SSD1306 Isometric View



SSD1306 Top View



SSD1306 Bottom View

Figure 3.11 The Isometric (a), Top (b), and Bottom (c) Views of the Display Unit - SSD1306

SSD1306 has a resolution of 128x64 dot matrix panel, referring to 128 segments and 64 commons. It includes contrast control, brightness control, display RAM, and oscillator, minimizing the power consumption and the need for external components. It receives commands or data from an MCU by means of I²C, SPI, or hardware-selectable 6800/8000 series compatible Parallel Interface. It is mainly used in compact portable applications such as calculators, mobile phone sub-displays, and MP3 players (Solomon Systech, 2008).

3.2.1.9 Base Shield

Grove Base Shield V2.0, manufactured by Seeed Studio and depicted in Figure 3.12, was selected as a base shield to connect multiple sensors to the development board with grove cables. It is equipped with 16 onboard grove connectors, comprising four analog, four I²C, one UART, and seven digital grove connectors. Its peripheral pins are compatible with the Arduino Mega 2560 Rev3 development board.



(a) Grove Base Shield V2.0 Isometric View (b) Grove Base Shield V2.0 Top View (c) Grove Base Shield V2.0 Bottom View

Figure 3.12 The Isometric (a), Top (b), and Bottom (c) Views of the Base Shield - Grove Base Shield V2.0

3.2.1.10 Development Board

Arduino Mega 2560 Rev3 development board, depicted in Figure 3.13, which is based on the ATmega2560 microcontroller chip, was selected as a microprocessor due to its computational power, electrical power, memory, and compatibility with the selected sensors, base shield, and card shield.

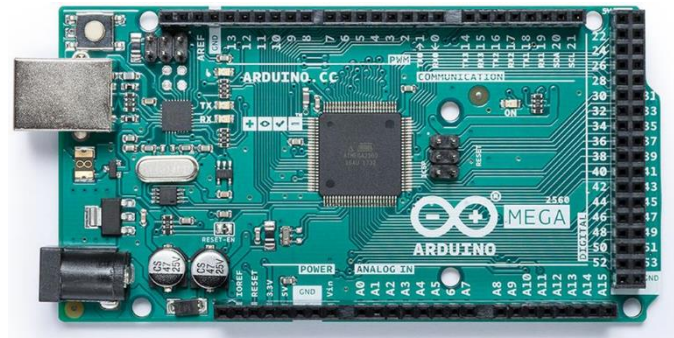


Figure 3.13 The Visual of the Development Board - Arduino Mega 2560 Rev3

The operating voltage of the development board is 5V, complying with the selected sensors. Additionally, it can support up to 800 mA current to feed the hardware connected, which is sufficient to run the selected hardware.

In the hardware development of INBASE, Arduino Mega 2560 Rev3 served as a foundation at the bottom, onto which the Grove Base Shield V2.0 was plugged. The HM3301 PM sensor, SG30 TVOC sensor, Multichannel V2 multi-gas sensor, and SCD30 CO₂ sensor were connected to the I²C interface of the base shield by grove cables. ME-O₂-Φ20 O₂ sensor was connected to the analog interface of the base shield by a grove cable. The SFA30 HCHO sensor, ESP8266 Wi-Fi Serial Transceiver Module, and SSD1306 OLED display unit were connected to the power and ground segments of the breadboard and I²C and UART communication pins of the development board by jumper wires. Additionally, the development board was powered by a Universal Serial Bus (USB) port wall plug adaptor with properties of 5V-2A. The schematical representation and the photographs of the hardware set-up are given in Figure 3.14 and Figure 3.15, respectively.

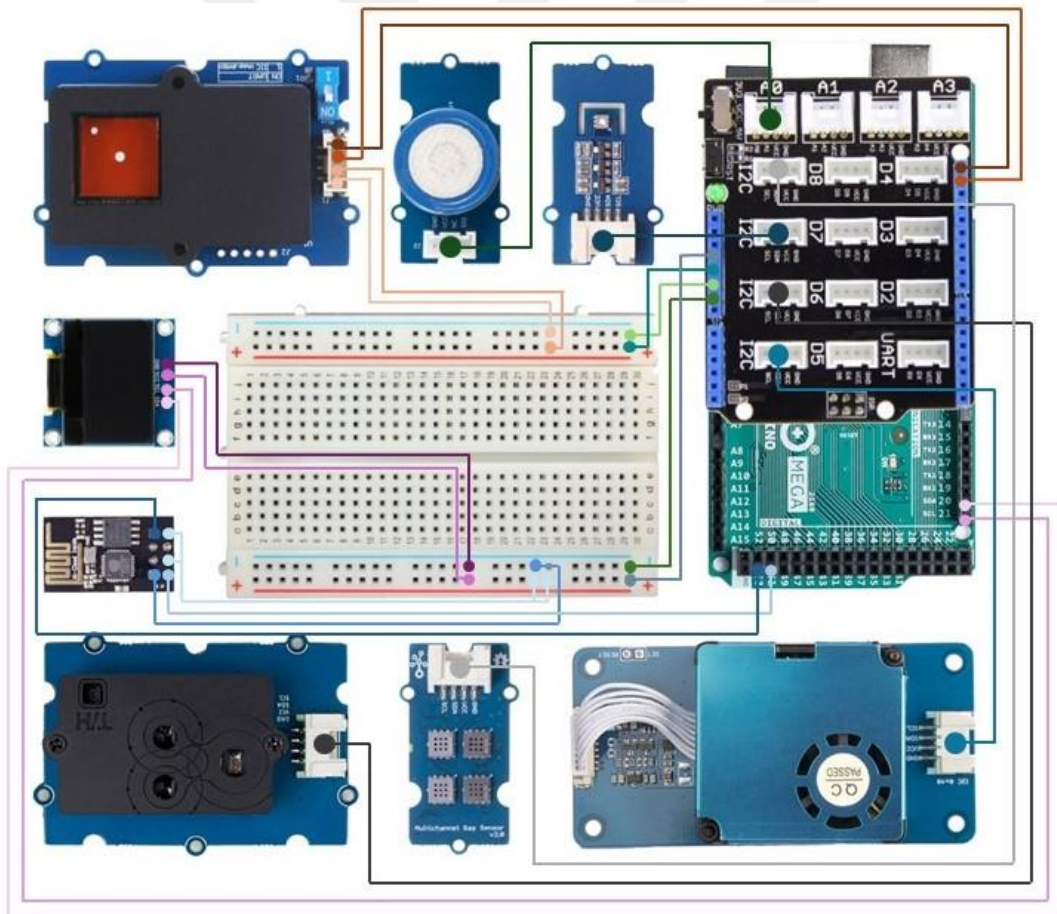


Figure 3.14 The Diagram of the Hardware Set-up of INBASE

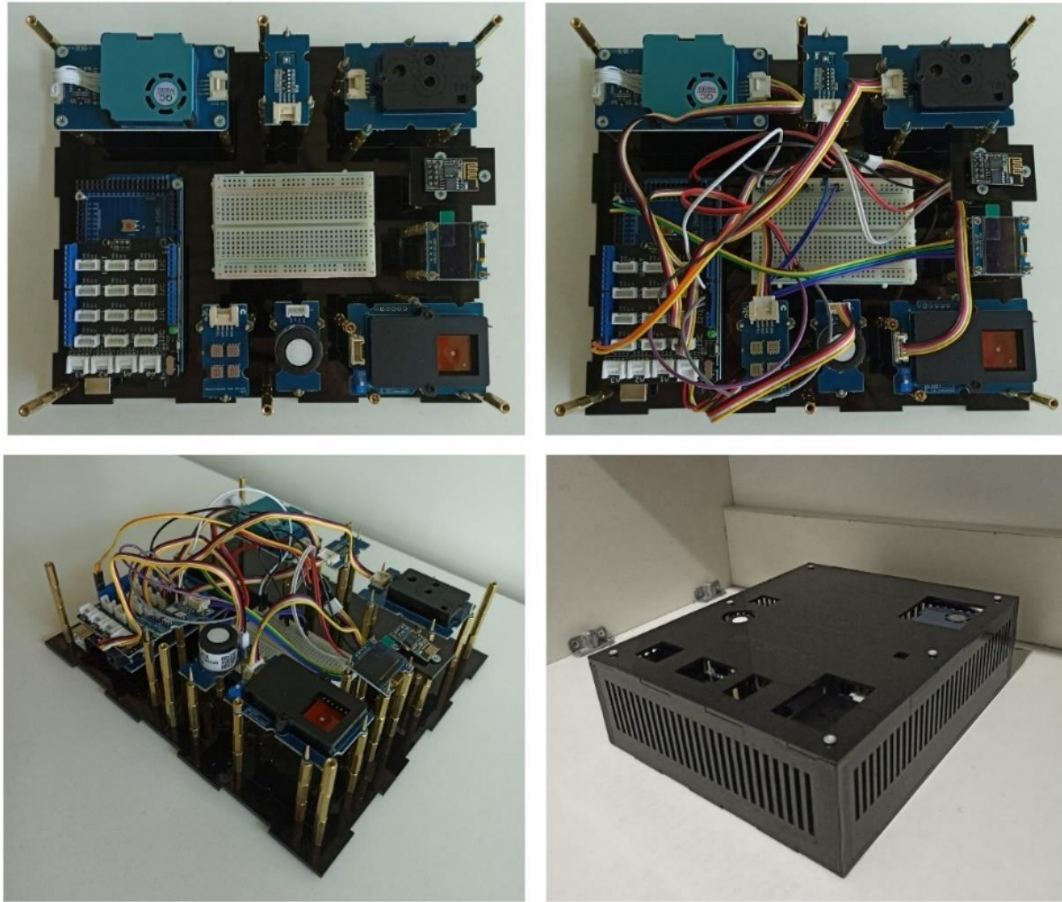


Figure 3.15 Photographs of INBASE

3.2.2 Software Development

Software development of INBASE, conducted by the author, entails configuring the development board and Wi-Fi module, reading sensor data, formatting it for transmission, and sending it to a server over a Transmission Control Protocol (TCP) connection, as depicted in Figure 3.16.

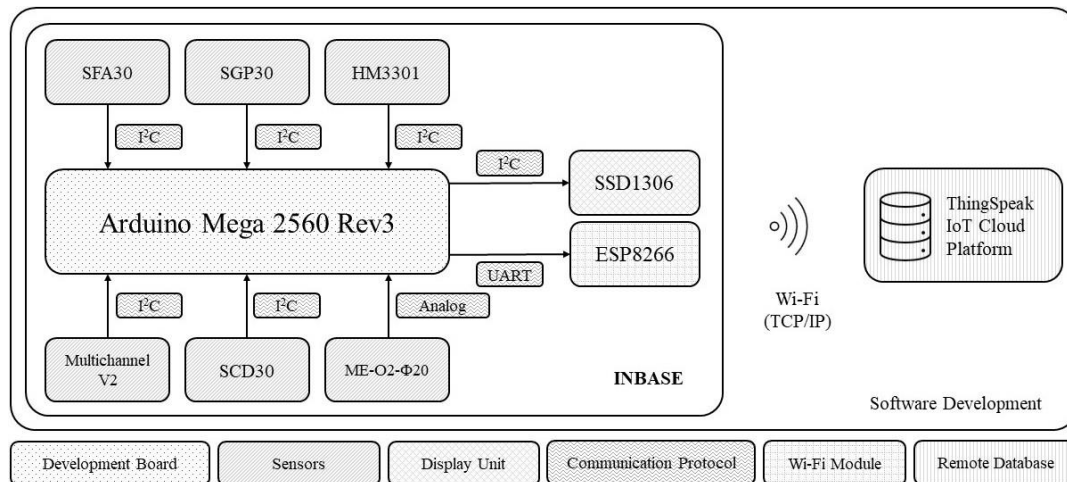


Figure 3.16 Schematic of the Software Development

Arduino IDE software was utilized for configuration when the developed hardware was plugged into the computer via a USB port, as the Arduino Mega 2560 Rev3 module was employed as a development board. Open-source sensor libraries were installed from the Arduino IDE to read sensor data. The configuration code was written in Arduino IDE. It briefly includes the following:

- Sensor libraries,
- Connection methods of sensors to the development board,
- Credentials of the connected Wi-Fi network, including Service Set Identifier (SSID) and password,
- The Internet Protocol (IP) address of the connected server,
- Application Programming Interface (API) keys of the channel created in the server,
- Formatting and organizing the data obtained from sensors for transmission,
- Sending data to the Wi-Fi module,
- Sending data from the Wi-Fi module to the server and
- Continuously repeating the process from step 4 onwards.

Once the code was uploaded and compiled, it was installed on the Arduino Mega 2560 Rev3 development board. Consequently, the code allows sensor readings to be printed on the Arduino IDE monitor when connected to the computer or

powered by a wall plug via a USB port. The microprocessor embedded in the development board facilitates the transmission of sensor data to a predefined Wi-Fi network through the ESP8266 Wi-Fi serial transceiver module. Subsequently, the data is sent to the ThingSpeak server, an IoT analytics platform service developed by MathWorks, enabling data aggregation, preprocessing, visualization, and analysis of live data streams in the cloud. The selection of ThingSpeak was based on its integration with MATLAB, a common software for data analytics, enabling the execution of MATLAB code within ThingSpeak and eliminating the need to set up a server or develop web software.

3.2.3 Calibration

Calibration is the process of detecting, correlating, adjusting, rectifying, and documenting the accuracy of an instrument based on a standard instrument or value. Periodic calibration is necessary for both new instruments and old instruments as instruments are subjected to errors due to drift, environmental change, fluctuations in electrical supply, modifications to the output loop, and process change (Cable, 2011).

As calibration is necessary to maintain the accuracy and precision of an instrument, the sensors are subjected to calibration to optimize their response so that the sensor output is proportional to the measured quantity. While some of the sensors employed to design INBASE are factory-calibrated, some sensors require user calibration. The sensors requiring user calibration were calibrated according to manufacturer recommendations.

The PM sensor, HM3301, is factory calibrated. As it is calibrated during manufacturing, it does not require user calibration. However, the potential accumulation of dust in the sensor affects the accuracy of the experiment. Therefore, the PM sensor was cleaned to eliminate any accumulated dust particles. Subsequently, it was placed in a clean and controlled environment to verify that it

did not measure dust in the environment. The basic demo code provided by the manufacturer was used and integrated into the configuration code to run the sensor simultaneously with other components.

The TVOC sensor, SGP30, necessitates user calibration. Initially, the sensor was activated by sending an initialization command. Initialization took 15 seconds, during which the sensor provided values of 400 ppm CO_{2eq} and 0 ppb TVOC. The baseline operation example code, including a dynamic baseline calibration algorithm provided by the manufacturer, was used. Hence, a baseline setting command was issued where the absolute humidity value is taken at 11.57 g/m³ by default. The sensor was placed on an electrostatic discharge (ESD) sheet and powered continuously for 12 hours to store baseline values and complete calibration. Subsequently, the baseline operation example code was integrated into the configuration code to run the sensor simultaneously with other components.

The HCHO sensor, SFA30, is factory calibrated. As it is calibrated during the manufacturing process, it does not require user calibration. The sample code provided by the manufacturer was integrated into the configuration code to run the sensor simultaneously with other components.

The multi-gas sensor, Multichannel V2, is factory calibrated. However, as the sensor has been giving inauthentic values consistently, the sensor was recalibrated. The example code was used to read direct sensor values in volts. The calibration curves provided by the manufacturer for C₆H₆, C₂H₅OH, and NO₂ were utilized to be interpolated to derive the formulas converting voltage output to gas concentration in ppm values.

The calibration curve of VOC (C₆H₆) is given in Figure 3.17. The formula, given in Equation 3-2, was derived from the calibration curve by interpolation. The inverse function of this equation was derived to convert voltage output to gas concentration, as given in Equation 3-3.

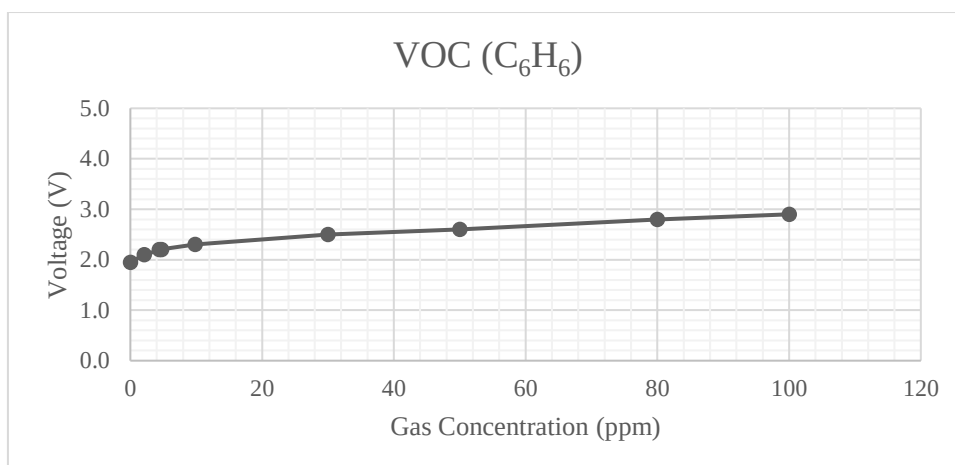


Figure 3.17 Calibration Curve of VOC (C₆H₆)

Equation 3-2 Interpolated Equation of VOC (C₆H₆) Calibration Curve

$$f(x) = 0.120596 \times x^{0.444117} + 1.95213$$

Equation 3-3 Inverse Function of Interpolated Equation of VOC (C₆H₆) Calibration Curve

$$x = \left(\frac{f(x) - 1.95213}{0.120596} \right)^{2.2517026}$$

The calibration curve of C₂H₅OH is given in Figure 3.18. The formula, given in Equation 3-4, was derived from the calibration curve by interpolation. The inverse function of this equation was derived to convert voltage output to gas concentration, which is given in Equation 3-5.

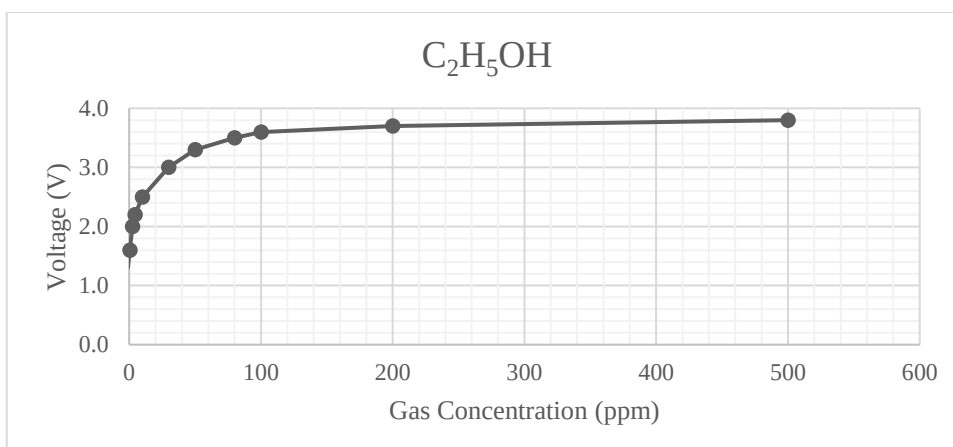


Figure 3.18 Calibration Curve of C₂H₅OH

Equation 3-4 Interpolated Equation of C₂H₅OH Calibration Curve

$$f(x) = 0.451351 \times \ln(1.76473 \times x + 3.47768) + 1.08935$$

Equation 3-5 Inverse Function of Interpolated Equation of C₂H₅OH Calibration Curve

$$x = e^{\frac{\left(\frac{f(x)-1.08935}{0.451351}\right)-3.47768}{1.76473}}$$

The calibration curve of NO₂ is given in Figure 3.19. The formula, given in Equation 3-6, was derived from the calibration curve by interpolation. The inverse function of this equation was derived to convert voltage output to gas concentration, as given in Equation 3-7.

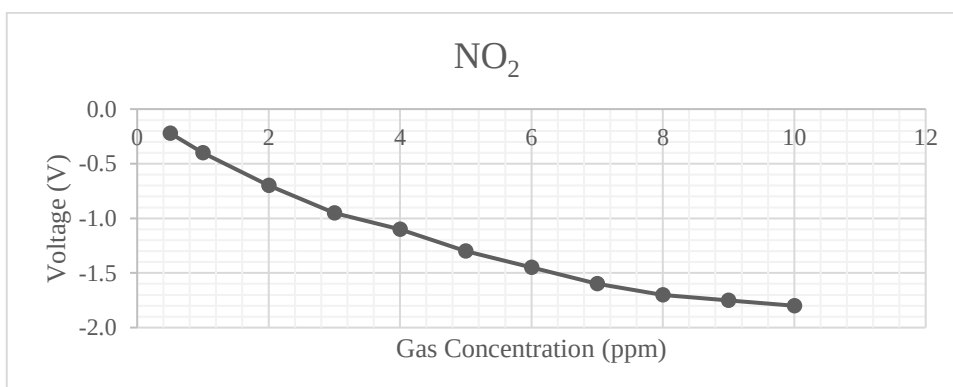


Figure 3.19. Calibration Curve of NO₂

Equation 3-6 Interpolated Equation of NO₂ Calibration Curve

$$f(x) = 0.625353 - 1.04157 \times x^{0.377839}$$

Equation 3-7 Inverse Function of Interpolated Equation of NO₂ Calibration Curve

$$x = \left(\frac{f(x) - 0.625353}{1.04157} \right)^{2.6459}$$

These equations, provided in Equation 3-7, Equation 3-5, and Equation 3-3, were embedded in the configuration code so that the voltage output can be converted into gas concentration accurately. Additionally, the sensor was placed on an ESD sheet. In accordance with the manufacturer's recommendation, it was powered to be preheated via heater voltage to acquire chemical equilibrium and, thereby, accurate results. Each sensor component necessitates varying minimum preheating times, as outlined in Table 3.7. The maximum value of 168 hours was selected as the preheating duration to ensure uniformity. Subsequently, the sensor was operated for 168 hours between 22.03.2024 and 29.03.2024 to complete the preheating process.

Table 3.7 Preheating Time (Zhengzhou Winsen Electronics Technology, 2017, 2019, 2020a, 2020b)

Sensor Part	Storage Time	Suggested Aging Time	Heater Voltage
GM502-B	<1 month	>24 hours	2.5V±0.1V AC or DC
(VOC -	1-6 months	>48 hours	
Calibrated	>6 months	>72 hours	
against C₆H₆)	1-6 months	>72 hours	
	>6 months	>168 hours	
GM102-B	<1 month	>24 hours	2.0V±0.1V AC or DC
(NO₂)	1-6 months	>48 hours	
	>6 months	>72 hours	
GM302-B	<1 month	>48 hours	2.5V±0.1V AC or DC
(C₂H₅OH)	1-6 months	>72 hours	
	>6 months	>168 hours	

The CO₂ sensor, SCD30, necessitates user calibration by utilizing outside air as a reference for adjustment. Following the manufacturer's instructions, the auto-calibration file provided by the manufacturer was uploaded to the development board. The sensor was placed on an ESD sheet and connected to a power supply. It was operated continuously for seven days between 18/03/2024 and 25/03/2024 with 1-hour daily exposure to fresh air to allow the algorithm to find its initial Automatic Self-Calibration (ASC) parameter set. The calculated parameters were stored in the sensor's non-volatile memory to ensure their retention after restart. Hence, the calibration process was completed. Subsequently, the sensor was connected to the computer. The auto-calibration command was stopped while the sample code was integrated into the configuration code to run the sensor simultaneously with other components.

The O₂ sensor, ME2-O₂-Φ20, requires user calibration. The current range of the sensor falls between 80 μA to 160 μA. The sensor output voltage varies accordingly. The sensor was placed on an ESD sheet and preheated for 30 minutes with the manufacturer's instructions. During this preheating period, the sensor was exposed to fresh air, and the output voltage readings were recorded to serve as a reference for calibration. Subsequently, the sensor was connected to the computer. The sample calibration code provided by the manufacturer, which converts voltage output into gas concentration in percentages, was uploaded to the development board. Hence, the calibration process was completed. The sample code was integrated into the configuration code to run the sensor simultaneously with other components.

3.3 Indoor Air Quality Polling Instrument

The Indoor Air Quality Polling Instrument is an equipment designed by the author for this research where the employees of the AM facility can vote the space in terms of their perception of indoor air quality at the moment when they vote as very good, good, neutral, bad, and very bad. This feedback mechanism was

designed to capture subjective perceptions of IAQ alongside the objective data collected by the INBASE. Hardware development and software development of the instrument are given in this section.

3.3.1 Hardware Development

The hardware of the Indoor Air Quality Polling Instrument, developed by the author, includes five tact switches, five resistors, a card shield, a real-time clock, a display unit, a breadboard, and a development board.

3.3.1.1 Tact Switches and Resistors

The tact switches, distributed by Robolink and depicted in Figure 3.20 (a), were used as push buttons for the Indoor Air Quality Polling Instrument. They include four pins with a bottom mount type to be placed on a breadboard. Their sizes are 12x12x15mm. Additionally, 1/4W 1K resistors, depicted in Figure 3.20 (b), were placed on the breadboard in connection to tact switches as pull-down resistors to ensure that the input to the microcontroller is in a logic 0 state when the tact switch is not pressed.



Figure 3.20 The Visuals of the Tact Switches and 1/4 W 1K Resistors

3.3.1.2 Card Shield

SD Card Shield V4 manufactured by Seeed Studio, depicted in Figure 3.21, was employed to connect the SD card with the development board with a card shield. An SD Card with 16 GB memory was inserted into the card shield to store data.

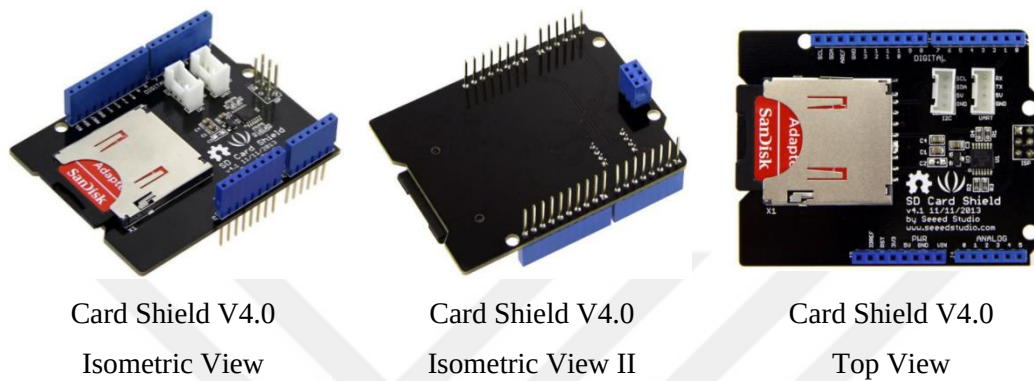


Figure 3.21 The Visuals of the Card Shield - SD Card Shield V4

3.3.1.3 Real-Time Clock

DS1302 real-time clock, distributed by Robotistan and depicted in Figure 3.22, was integrated into the system so that the data can be recorded to the SD card with a timestamp. DS1302 was connected to the system using ground, power, and digital pins of the development board.



Figure 3.22 The Visual of the Real-Time Clock - DS1302

3.3.1.4 Display Unit

The SSD1306 Organic Light Emitting Diode (OLED) driver, which was used in the INBASE model display unit, was also employed for the polling instrument. The visuals and technical specifications are not reiterated in this section as given in 3.2.1.8.

3.3.1.5 Development Board

The identical model of the development board, Arduino Mega 2560 Rev3, used in INBASE, was also employed for the polling instrument. The visuals and technical specifications are not reiterated in this section as given in 3.2.1.10.

The Arduino Mega 2560 Rev3 development board served as a foundation at the bottom where the SD Card Shield V4 was plugged. The ground and power pins of the development board were connected to the breadboard. The tact switches and 1/4W 1K resistors were placed on the breadboard. One of the four pins of each tact switch was connected to the power segment of the breadboard directly through jumper wires. One of their other pins was connected to the ground segment of the breadboard using jumper wires, passing through resistors. This setup serves as a pull-down resistor configuration to ensure stable input when the corresponding tact switch is not pressed. Consequently, this pin was also connected to a digital pin of the development board. The DS1302 real-time clock was connected to the ground and power segment of the breadboard, as well as the digital pins of the development board. Lastly, the SSD1306 OLED display unit was placed on the breadboard and connected to the development board with jumper wires through the I²C interface. The schematic diagram and photographs of the hardware set-up are given in Figure 3.23 and Figure 3.24, respectively.

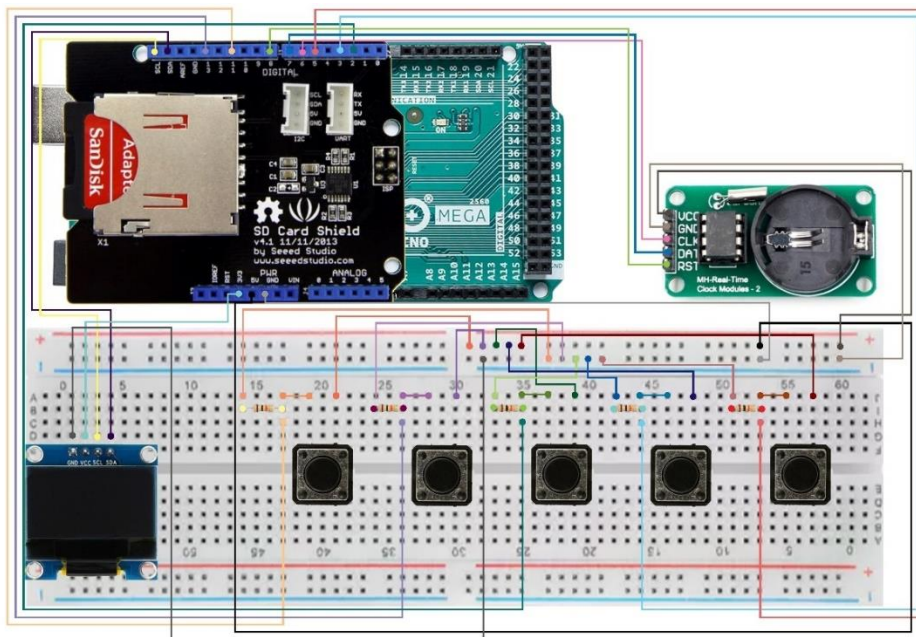


Figure 3.23 The Diagram of the Hardware Set-Up of the Indoor Air Quality Polling Instrument

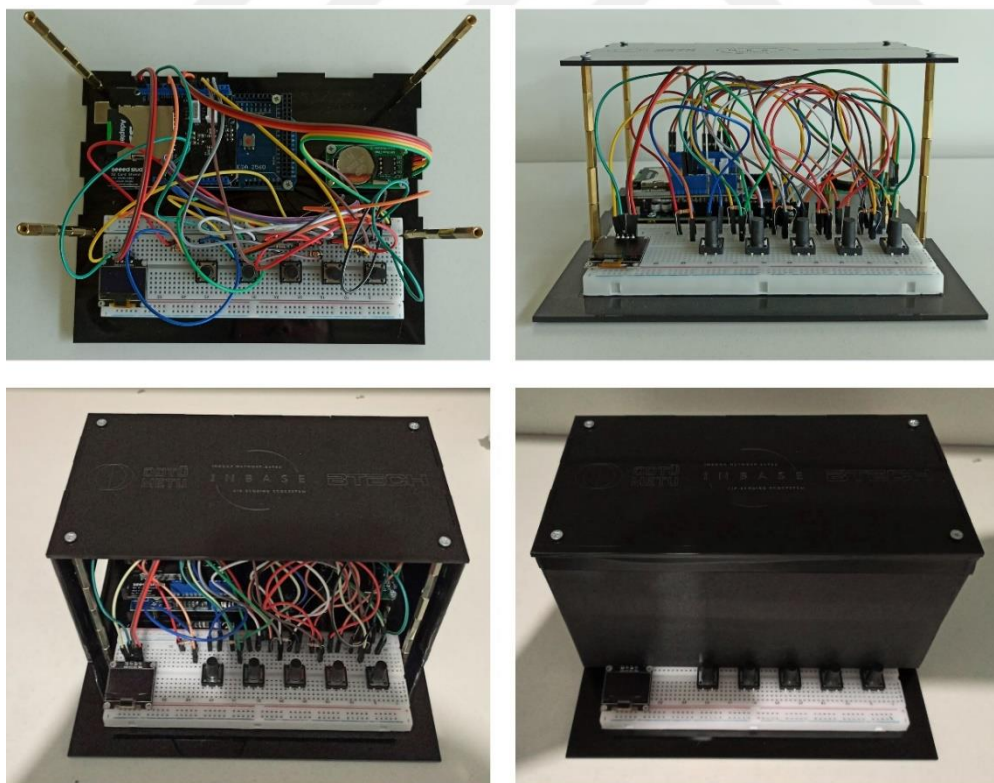


Figure 3.24 Photographs of the Indoor Air Quality Polling Instrument

3.3.2 Software Development

The software of the Indoor Air Quality Polling Instrument is developed by the author utilizing Arduino IDE software. The developed hardware was plugged into the computer via a USB port. The configuration code was written and uploaded to the development board. The developed code briefly includes the following:

- Hardware libraries,
- Connection methods of hardware to the development board,
- Formatting, organizing, and recording the data obtained from tact switches and the real-time clock
- Display of the data.

3.4 Field Experiments

The field experiments were conducted in a workplace practicing additive manufacturing for contract manufacturing, prototyping, and product design and development. This workplace is equipped with production and office spaces, as indicated by the different colors in Figure 3.25. It has a total floor area of approximately 375 m² and a ceiling height of approximately 3.7 m. It is equipped with a mechanical ventilation system that was operated during the experiments. The intake and exhaust functions were set to the third level out of five, representing a medium ventilation rate. The production spaces accommodate varying AM equipment with diverse processes, including powder bed fusion, colored in green and purple, and vat photopolymerization, colored in turquoise. Additionally, the space colored in pink is allocated for post-processing equipment and operations. Lastly, the blue-colored space is the office space furnished with an open-plan layout.



Figure 3.25 The Plan of the Workplace

Field experiments were conducted both in production and office spaces during operations of powder bed fusion process - selective laser melting (PBF-SLM) technology, powder bed fusion process - selective laser sintering (PBF-SLS) technology, and vat photopolymerization process - stereolithography (VP-SLA) technology. The diagram of the field experiments is given in Figure 3.26.

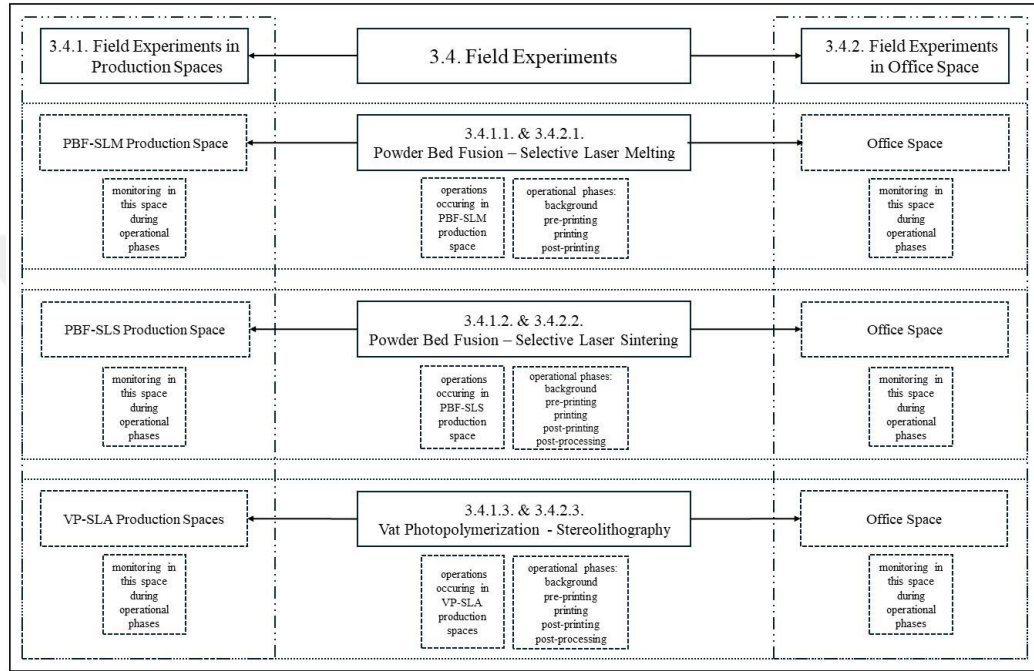


Figure 3.26 The Diagram of the Field Experiments

Two types of instruments, INBASE and polling instruments, were utilized during these experiments. As only one of each type is available, these experiments were conducted at different times. Additionally, all data collected during these were obtained from the workplace workflow with respect to the orders received. Due to this, even though the same AM method was monitored, the printed components and experiment duration varied between the production spaces and the office space. For example, when monitoring the production space during PBF-SLM and monitoring the office space during PBF-SLM, the specifics of the printed components and the duration of the experiments differed. The same variation applies to the PBF-SLS and VP-SLA experiments as well. Finally, the details of the printed components during these operations cannot be disclosed owing to confidentiality principles.

3.4.1 Field Experiments in the Production Spaces

Real-time indoor air quality monitoring was conducted in the production spaces with INBASE for powder bed fusion process - selective laser melting (PBF-SLM) technology, powder bed fusion process - selective laser sintering (PBF-SLS) technology, and vat photopolymerization process - stereolithography (VP-SLA) technology during the pre-printing, printing, post-printing, and post-processing phases. Additionally, the Indoor Air Quality Polling Instrument is placed next to INBASE during all monitoring sessions so that the employees in the production spaces can vote the space in terms of their perception of indoor air quality at the moment when they vote as very good, good, neutral, bad, and very bad. Detailed descriptions of monitoring sessions are given in the subsequent sections.

3.4.1.1 Powder Bed Fusion - Selective Laser Melting

Real-time air quality monitoring was conducted with INBASE for powder bed fusion process - selective laser melting (PBF-SLM) technology during the pre-printing, printing, and post-printing phases of AM. As post-processing operations of SLM were not conducted in the workplace, that process was not monitored. The pre-printing, printing, and post-printing phases were conducted in 127.7 m^3 ($34.5 \text{ m}^2 \times 3.7 \text{ m}$) space, indicated by green color in Figure 3.27.

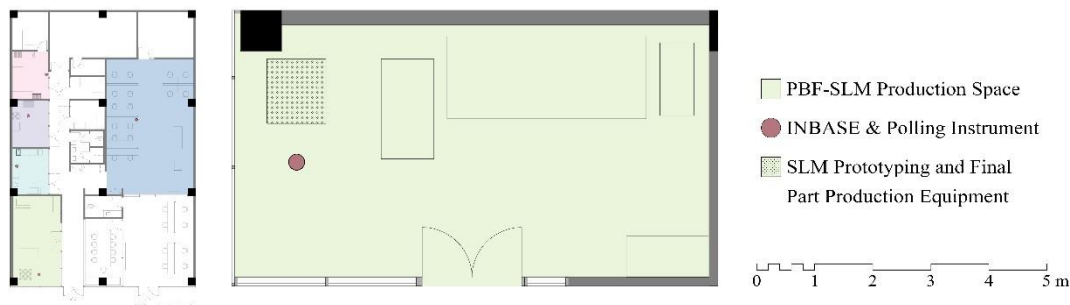


Figure 3.27 The Plan of the PBF-SLM Production Space of the Workplace

This space is equipped with two SLM Prototyping and Final Part Production equipment, briefly referred to as SLM printers, with varying building volumes and

brands, and a table for pre-printing activities. The utilized SLM printer, depicted in Figure 3.28, has a building volume of 160 mm × 160 mm × 100 mm. The layer thickness and laser power of the equipment are 10-40 µm and 500 W, respectively. Powder forms of titanium alloy and cobalt-chromium alloy are used as feedstock materials to be inserted into the equipment. As pre-printing, printing, and post-printing operations were conducted in this space, INBASE was positioned on top of the 1.2-meter-tall movable stand, 1 meter away from the SLM printer, to characterize background measurements and emissions generated during the pre-printing, printing, and post-printing phases. The placement of INBASE is highlighted by the burgundy circle in Figure 3.27. The intake and exhaust functions of the mechanical ventilation were set to the third level out of five, representing a medium ventilation rate.



Figure 3.28 SLM Prototyping and Final Part Production Equipment

The activities performed during these phases are as follows:

a) Background Phase:

The background measurements were conducted for 46 minutes during the period of inactivity. The average room temperature was 22.56°C and the relative humidity was 32.01%.

b) Pre-printing Phase:

The pre-printing phase contained the preparation activities for the manufacturing process. Titanium alloy powder (Ti-6Al-4V) was used as feedstock material. The titanium alloy powder was measured, mixed, and introduced to the SLM printer. The build platform was cleaned to eliminate debris or residue and fixed into the build chamber. The design file was uploaded into the control software. This process spanned 26 minutes. The average room temperature was 24.29°C and the relative humidity was 32.40%.

c) Printing Phase:

The printing period, referring to the continuous operation of the SLM printer to print the intended object, took 66 minutes. The average room temperature was 25.47°C and the relative humidity was 30.72%.

d) Post-Printing Phase:

In the post-printing phase, taking 14 minutes, the cover of the SLM printer was opened. As the printed component was embedded within the uncured powder, the excess powder was vacuumed. The build platform was removed from the SLM printer. Any remaining powder on the build platform was transferred into a tray for reuse. The reused powder was sieved and replenished. The average room temperature was 25.57°C and the relative humidity was 30.53%.

Following the post-printing phase, the printed component with the build platform was sent to another facility for post-processing activities. Hence, the post-processing phase was not monitored.

3.4.1.2 Powder Bed Fusion - Selective Laser Sintering

Real-time air quality monitoring was conducted with INBASE for powder bed fusion process - selective laser sintering (PBF-SLS) technology during the pre-printing, printing, post-printing, and post-processing phases of AM. These phases were conducted in 49.2 m³ (13.3 m² × 3.7 m) space, indicated by purple color in Figure 3.29. INBASE was positioned on top of the 1.2-meter-tall movable stand, which was 1 meter away from the SLS printer and SLS powder management station to characterize background measurements and emissions generated during the pre-printing, printing, post-printing, and post-processing phases. The intake and exhaust functions of the mechanical ventilation were set to the third level out of five, representing a medium ventilation rate. The placement of INBASE is highlighted by the burgundy circle in Figure 3.29.

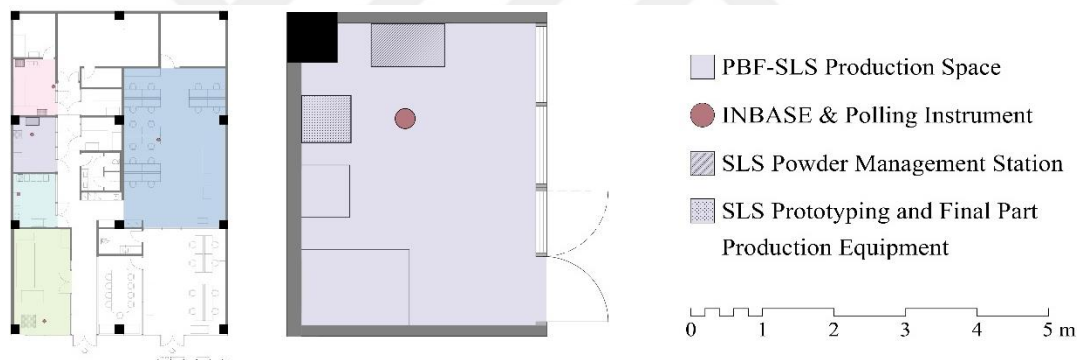


Figure 3.29 The Plan of the PBF-SLS Production Space of the Workplace

This space is equipped with an SLS Prototyping and Final Part Production equipment, briefly referred to as an SLS printer, an SLS powder management station, and an FDM Prototyping and Final Part Production equipment. The SLS printer, depicted in Figure 3.30, has a building volume of 165 mm × 165 mm × 300 mm. The layer thickness is 110 microns. Nylon 12 powder, Nylon 12 GF powder, Nylon 11 powder, Nylon 11 Carbon Fiber (CF) powder, and Thermoplastic Polyurethane (TPU) 90A powder are used as feedstock materials to be inserted into the equipment. The SLS printer is equipped with an intake filter to remove contaminants from air being drawn into the printer and an exhaust filter to remove

powder and sintering byproducts from its exhaust to avoid expelling into the workplace.



Figure 3.30 SLS Prototyping and Final Part Production Equipment

The SLS powder management station, depicted in Figure 3.31, is a powder management equipment where printed components are extracted, the unsintered powder is collected and sifted to remove debris so that the powder can be reclaimed after it is automatically measured, mixed with fresh powder, and stored. It is equipped with a high-efficiency particulate air (HEPA) filter and a negative air pressure system, keeping the powder inside during post-printing and post-processing operations.



Figure 3.31 SLS Powder Management Station

The activities performed during these phases are as follows:

a) Background Phase:

The background measurements were conducted for 54 minutes during the period of inactivity. The average room temperature was 25.56°C and the relative humidity was 38.55%.

b) Pre-printing Phase:

The pre-printing phase contained the preparation activities for the manufacturing process. The powder cartridge was filled with Nylon 12 powder that was recovered from the powder management station. Nylon 12 powder was loaded into the printer's hopper using a powder cartridge. The door was opened, and a clean optical cassette was inserted. The build chamber was inserted. The door of the printer was closed. The design file was uploaded into the control software. This process took 33 minutes. The average room temperature was 26.76°C and the relative humidity was 35.79%.

c) Printing Phase:

The printing phase comprised three subsequent steps occurring inside the SLS printer. These steps were pre-heating, where the building chamber was heated up to 179°C, printing where the plastic powder was fused layer by layer to print the intended object; and cooling, where the printed object waited inside the printer to acquire the desired mechanical properties until the bed temperature decreased to 40°C. These steps took 51, 105, and 313 minutes, respectively. Therefore, the total duration of the printing phase was 469 minutes. The average room temperature was 24.17°C and the relative humidity was 42.29%.

d) Post-Printing Phase:

After the print phase was completed, the door of the printer was opened. The build chamber was extracted from the printer and transferred to the powder management

station. In total, this process took 6 minutes. The average room temperature was 24.69°C and the relative humidity was 45.28%.

e) Post-Processing Phase

The print cake, which was composed of the printed components and unfused and semi-fused powder that supported them, was gradually ejected from the build chamber to the workspace of the powder management station. The unfused powder was scrubbed and scraped from the printed components using picks and brushes. Afterward, these components were collected in a wire basket. The powder accumulated in the workspace was wiped into the sifter and recaptured for later use. The sieve filtered out the particles to be remixed with new powder and reused in future prints. Any remaining powder on the workspace was collected using a vacuum. In total, this process took 154 minutes. The average room temperature was 25.73°C and the relative humidity was 44.24%.

3.4.1.3 Vat Photopolymerization - Stereolithography

Real-time air quality monitoring was conducted with INBASE for vat photopolymerization process - stereolithography (VP-SLA) technology in production spaces, including VP-SLA production space and post-processing atelier, during the pre-printing, printing, post-printing, and post-processing phases of AM. The pre-printing, printing, and post-printing phases were conducted in 48.1 m³ (13.0 m² × 3.7 m) space, indicated by the turquoise color in Figure 3.32.

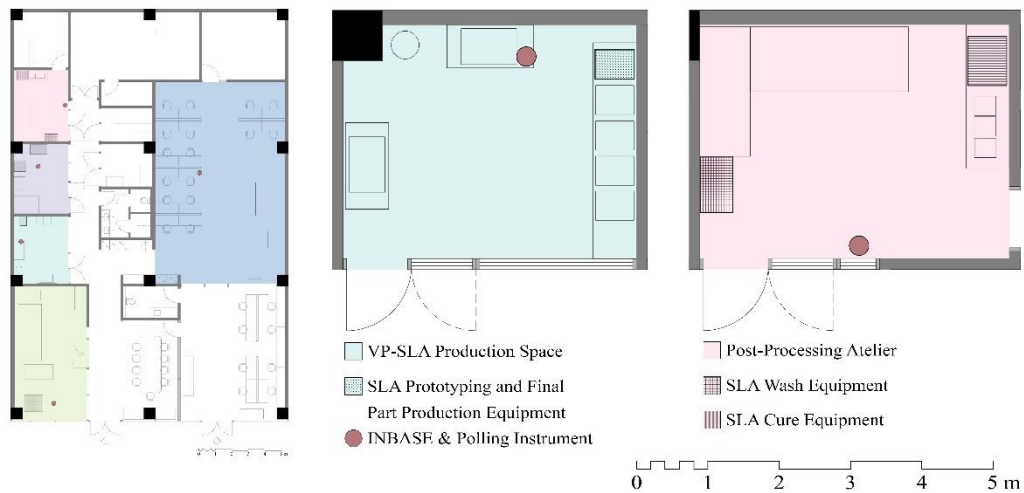


Figure 3.32 The Plan of the VP-SLA Production Spaces of the Workplace

This space is equipped with seven SLA Prototyping and Final Part Production equipment, briefly referred to as SLA printers, with three varying building volumes, a DLP Prototyping and Final Part Production equipment, and an open shelf system containing sealed resin cartridges. All of the SLA printers are placed on cabinets and shelves that are 1.2 meters tall. The utilized SLA printer, depicted in Figure 3.33, has a building volume of $145 \text{ mm} \times 145 \text{ mm} \times 193 \text{ mm}$. The layer thickness and laser power of the equipment are $25\text{-}300 \text{ }\mu\text{m}$ and 250 mW , respectively. Resin cartridges are used as feedstock material to be inserted into the equipment. The SLA printer does not include a filter or other form of emissions capture. As pre-printing, printing, and post-printing operations were conducted in this space, INBASE was positioned on top of the 1.2-meter-tall cabinet, which was 1 meter away from the SLA printer to characterize background measurements and emissions generated during the pre-printing and printing phases. The intake and exhaust functions of the mechanical ventilation were set to the third level out of five, representing a medium ventilation rate. The placement of INBASE is highlighted by the burgundy circle in Figure 3.32.

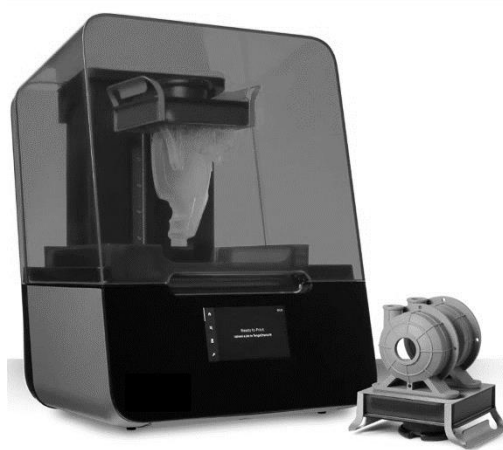


Figure 3.33 SLA Prototyping and Final Part Production Equipment

The post-processing phase was conducted in the 51.4 m³ (13.9 m² × 3.7 m) post-processing atelier, indicated by the pink color in Figure 3.32. This space is equipped with two atelier tables, one chair, an air compressor, post-processing gadgets, large wash equipment located on the ground, a shelf carrying small wash equipment, and UV cure equipment.

The utilized wash equipment, depicted in Figure 3.34, is equipped with a wash bucket, wash basket, electric solvent pump, flexible scraper, scraper, flush cutters, rinse bottle, gloves, and build platform adaptor.



Figure 3.34 SLA Wash Equipment

The cure equipment, depicted in Figure 3.35, includes 500 W dual heaters to increase the temperature up to 80°C during curing. INBASE was positioned on a 1.2-meter-tall movable stand in front of the glass wall to characterize emissions generated during post-processing activities. The intake and exhaust functions of the mechanical ventilation were set to the third level out of five, representing a medium ventilation rate. The placement of INBASE is highlighted by the burgundy circle in Figure 3.32.

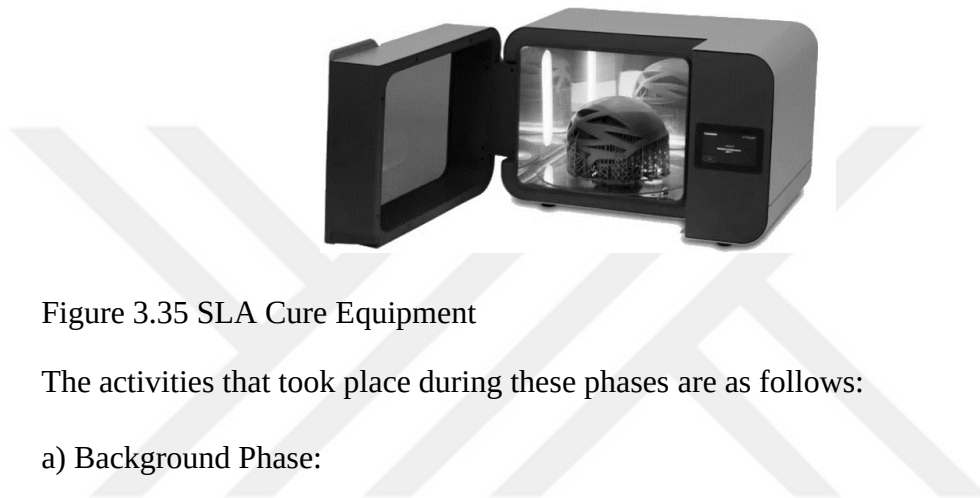


Figure 3.35 SLA Cure Equipment

The activities that took place during these phases are as follows:

a) Background Phase:

The background measurements were conducted for 60 minutes during the period of inactivity. The average room temperature was 23.88°C and the relative humidity was 31.74%.

b) Pre-printing Phase:

The pre-printing phase contained the preparation activities for the manufacturing process. The printer was powered on. The design file was uploaded into the control software. The general-purpose standard grey resin was used as feedstock material. The resin cartridge was shaken to ensure the resin was mixed thoroughly. The resin cartridge was inserted into the printer after its protective valve cover had been removed. This process spanned 15 minutes. The average room temperature was 24.27°C and the relative humidity was 30.03%.

c) Printing Phase:

The printing period, referring to the continuous operation of the SLA printer to print the intended object, took 573 minutes. The average room temperature was 24.29°C and the relative humidity was 31.13%.

d) Post-Printing Phase:

In the post-printing phase, taking 2 minutes, the cover of the SLA printer was opened, and the resin tank was removed. The building platform was extracted with the printed component. The cover of the printer was closed. The average room temperature was 24.04°C and the relative humidity was 31.90%.

e) Post Processing Phase

During the post-processing phase, taking 232 minutes, the printed component was moved to the post-processing atelier. It was washed with isopropyl alcohol in the large wash equipment to rinse residual liquid resin from its surfaces. It was dried with an air compressor. It was placed in cure equipment for 60 minutes, exposing it to light and heat to stabilize its performance. Once the post-curing was completed, the printed component was placed on the post-processing table. It was detached from the build platform, and its supports were removed to finalize the post-processing procedure. As the printed component did not require sanding, no sanding activity occurred. The average room temperature was 22.43°C and the relative humidity was 39.56%.

3.4.2 Field Experiments in the Office Space

The field experiments that were carried out in the production spaces were also conducted in the office space to understand the impact of those AM processes on the office space, identifiable by blue in Figure 3.36. The same AM processes were repeated in the production spaces while the office space was monitored. The placement of INBASE during these sessions is highlighted by the burgundy circle

in Figure 3.36. Additionally, the Indoor Air Quality Polling Instrument was placed next to INBASE during all monitoring sessions so that the employees in the office space can vote the space in terms of their perception of indoor air quality at the moment when they vote as very good, good, neutral, bad, and very bad. Detailed descriptions of monitoring sessions are given in the subsequent sections.

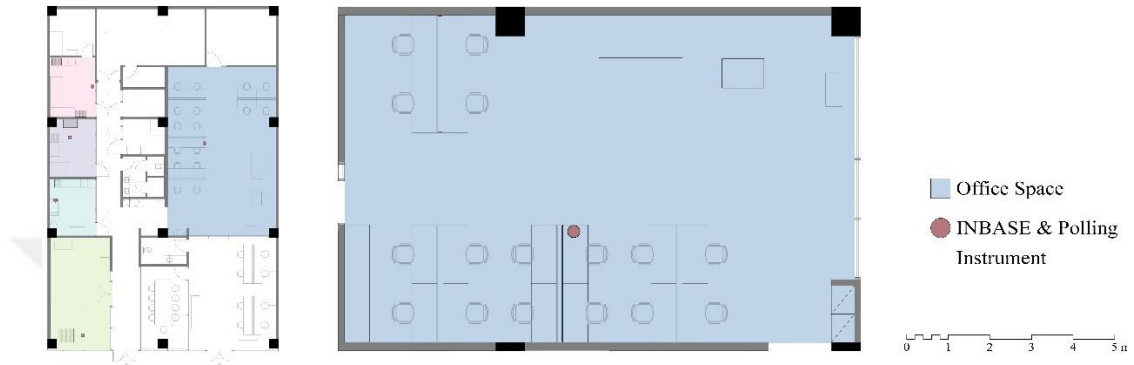


Figure 3.36 The Plan of Office Space of the Workplace

3.4.2.1 Powder Bed Fusion - Selective Laser Melting

The real-time monitoring of the office space was conducted during the pre-printing, printing, and post-printing phases of the powder bed fusion process - selective laser melting (PBF-SLM) technology. The placement of INBASE is highlighted by the burgundy circle in Figure 3.36. The pre-printing, printing, and post-printing phases were conducted in the space colored in green in Figure 3.27. The same SLM equipment mentioned in 3.4.1.1 was utilized for the experiment. The same pre-printing, printing, and post-printing operations took place. These operations lasted 30, 12, 260, and 14 minutes, respectively. While the average temperatures were 24.39°C, 23.66°C, 23.03°C, and 22.45°C the average relative humidity values were 30.97%, 32.08%, 31.98%, and 31.81%.

3.4.2.2 Powder Bed Fusion - Selective Laser Sintering

The real-time monitoring of the office space was conducted during the pre-printing, printing, post-printing, and post-processing phases of the powder bed fusion process - selective laser sintering (PBF-SLS) technology. The placement of INBASE is highlighted by the burgundy circle in Figure 3.36. The pre-printing, printing, post-printing, and post-processing phases were conducted in the space colored purple in Figure 3.29. The same SLS equipment mentioned in 3.4.1.2 was utilized for the experiment. The same pre-printing, printing, post-printing, and post-processing operations took place. These operations lasted 39, 25, 321, 6, and 28 minutes, respectively. While the average temperatures were 25.06°C, 25.77°C, 26.24°C, 26.25°C, and 26.13°C the average relative humidity values were 49.53%, 48.17%, 45.88%, 45.42%, and 44.53%.

3.4.2.3 Vat Photopolymerization - Stereolithography

The real-time monitoring of the office space was conducted during the pre-printing, printing, post-printing, and post-processing phases of the vat photopolymerization process - stereolithography (VP-SLA) technology. The placement of INBASE is highlighted by the burgundy circle in Figure 3.36. The pre-printing, printing, and post-printing phases were conducted in the VP-SLA production space, colored turquoise in Figure 3.32. The post-processing phase was conducted in the post-processing atelier, colored pink in Figure 3.32. The same SLA equipment mentioned in 3.4.1.3 is utilized for the experiment. The same pre-printing, printing, post-printing, and post-processing operations took place. These operations lasted 42, 16, 94, 2, and 101 minutes, respectively. While the average temperatures were 23.25°C, 26.46°C, 23.46°C, 27.30°C, and 26.24°C the average relative humidity values were 27.12%, 34.35%, 30.91%, 29.27%, and 35.26%.

CHAPTER 4

RESULTS AND DISCUSSION

This chapter outlines the results and discussion of the semi-structured interview and the field experiments of the research, including field experiments for powder bed fusion - selective laser melting, powder bed fusion - selective laser sintering, and vat photopolymerization - stereolithography.

4.1 Semi-Structured Interview

The semi-structured interview was conducted with eight employees, whose demographic profiles are disclosed in Figure 4.1, who are working in a workplace practicing AM operations.

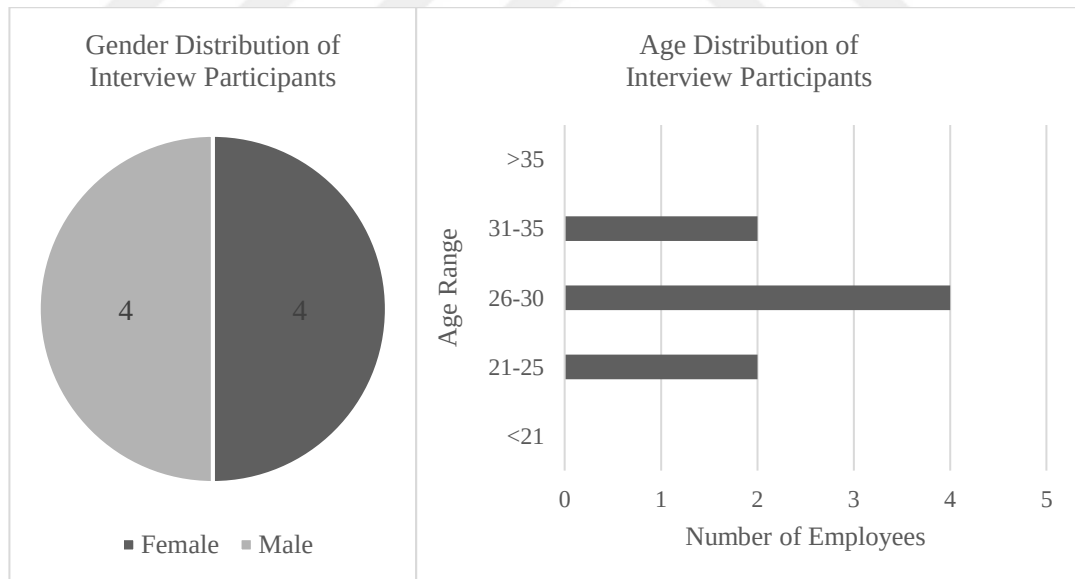


Figure 4.1 Demographic Profile of Interview Participants

The transcripts of employee interviews were generated and thoroughly reviewed prior to conducting the thematic analysis. Meanings and patterns were observed.

The codes representing those meanings and patterns were created. Those codes were collated with supporting data. The content of the question and the codes created based on the responses given to each question are given in Table 4.1.

Table 4.1 Semi-Structured Interview Question Contents and Response Codes

Question Content	Codes
Role and Responsibilities	engineering, customer relations and support, quality control, purchase responsibilities, information technology
Perception of Integration	neutral impact, spatial challenges, practical benefits
Benefits of Integration	efficiency in task management, improved observation and control, immediate problem solving, convenience, communication facilitation, productivity gains
Drawbacks of Integration	indoor air quality issues, distractions, inadequate facilities
Impact on Communication and Collaboration	enhanced collaboration, better understanding of operations, immediate problem-solving, increased teamwork, cross-disciplinary benefits
Impact on Workflow Efficiency	streamlined operations, reduced travel time, immediate access to production, immediate problem-solving
IEQ Alignment and Conflicts	specific temperature needs, inadequate ventilation, lighting issues, personalized environmental control, infrastructural inadequacies
Impact on Comfort and Productivity	environmental stress, health concerns, acoustical problems, adaptability to space, workflow acceleration

Codes were grouped into three themes: operational dynamics, health impacts, and workplace design and functionality. The first theme includes codes concerning the impact of the integration of production and office spaces on workflow efficiency and process dynamics. The second theme includes codes concerning the impact of the integration of production and office spaces on employee health, well-being, and productivity. Lastly, the third theme includes codes concerning the ability of the workplace to support intended operational and health requirements. These themes and related codes are given in Table 4.2.

Table 4.2 Semi-Structured Interview Response Themes and Codes

Themes	Codes
Operational Dynamics	efficiency in task management, immediate problem solving, convenience, communication facilitation, streamlined operations, improved operational insights, reduced travel time, access to production, enhanced collaboration, cross-disciplinary benefits
Health Concerns	indoor air quality issues, health concerns
Workplace Design and Functionality	spatial challenges, inadequate facilities, infrastructural inadequacies, adaptability to space

As a result of these employee interviews, significant insights were revealed across operational dynamics, environmental and health impacts, and workplace design and functionality. Employees reported that the integration of production and office spaces influenced operational dynamics positively. The responses revealed that this integration was convenient, bringing about improved efficiency in task management, streamlined operations, and reduced travel time. Furthermore, this integration facilitated immediate access to production and problem-solving, enhanced communication and collaboration, and fostered a better understanding of operations across departments, leading to significant cross-disciplinary benefits. However, particular challenges were reported regarding health concerns, including challenges with indoor air quality, while the need for improved environmental controls within the workplace was underlined. Additionally, structural and spatial challenges were addressed regarding the adequacy of facilities and infrastructural support, occasionally failing to accommodate the integrated functionality of the workplace, hindering the full potential of the integrated design.

Overall, it was concluded that while the integration of production and office spaces at the workplace brought notable advantages in operational dynamics and collaboration, it also introduced health concerns. Therefore, it is essential to investigate the impact of production operations on indoor air quality in response to

those concerns. Such scrutiny provides significant insights, furnishing essential data to inform the optimization of workplace design and functionality.

4.2 Field Experiments for Powder Bed Fusion - Selective Laser Melting

This section presents the real-time air quality monitoring results obtained from INBASE and employee feedback obtained from the Indoor Air Quality Polling Instrument for the PBF-SLM production space and the office space during PBF-SLM operations. Each parameter, including PM_{1.0}, PM_{2.5}, PM₁₀, TVOC, HCHO, C₆H₆, C₂H₅OH, NO₂, CO₂, and O₂, was evaluated for both production and office spaces with respect to the established thresholds based on guidelines and standards provided by certain authorities each of which was detailed in the corresponding parts of the section. The unit conversion was applied when necessary using Equation 4-1, Equation 4-2, Equation 4-3, and Equation 4-4 to align the units of specific sensor outputs to the commonly used units in the guidelines.

Equation 4-1 The relationship between ppm and ppb (Boguski, 2006, p.1)

$$\text{Concentration (ppm)} = \frac{\text{Concentration (ppb)}}{1000}$$

Equation 4-2 The relationship between mg/m³ and ppm (Boguski, 2006, p.2)

$$\text{Concentration} \left(\frac{\text{mg}}{\text{m}^3} \right) = 0.0409 \times \text{Concentration (ppm)} \times \text{Molecular Weight}$$

Equation 4-3 The relationship between µg and mg (Boguski, 2006, p.1)

$$\mu\text{g} = \text{mg} \times 1000$$

Equation 4-4 The relationship between µg/m³ and mg/m³ according to Equation 4-3

$$\text{Concentration} \left(\frac{\mu\text{g}}{\text{m}^3} \right) = \text{Concentration} \left(\frac{\text{mg}}{\text{m}^3} \right) \times 1000$$

Air quality guidelines for PM issued by WHO (2021) do not cover PM_{1.0}. Therefore, no safety limit was indicated in Figure 4.2 and Figure 4.3.

Minimum, maximum, and average PM_{1.0} concentrations in the PBF-SLM production space and the office space during PBF-SLM operations, along with the duration of each phase, average temperature, and relative humidity of the space during each phase, are given in Table 4.3.

Table 4.3 Descriptive Statistics of PM_{1.0} Concentrations during PBF-SLM

		Background	Pre-Printing	Printing	Post-Printing
PRODUCTION SPACE	Min (µg/m ³)	2.00	4.00	3.00	4.00
	Max (µg/m ³)	4.00	11.00	5.00	10.00
	Avg (µg/m ³)	3.00	7.75	3.60	8.15
	Time (min)	46	26	66	14
	Temp (°C)	22.56	24.29	25.47	25.57
	RH (%)	31.02	32.40	30.72	30.53
OFFICE SPACE	Min (µg/m ³)	3.00	3.00	3.00	2.00
	Max (µg/m ³)	9.00	4.00	7.00	3.00
	Avg (µg/m ³)	4.13	3.72	3.75	2.07
	Time (min)	30	12	260	14
	Temp (°C)	24.39	23.66	23.03	22.45
	RH (%)	30.97	32.08	31.98	31.81

The results of PM_{1.0} concentrations in The PBF-SLM production space during PBF-SLM operations indicated variations in PM_{1.0} concentrations during different phases compared to the background levels. The average PM_{1.0} concentration during the background measurements was 3.00 µg/m³. The mean measurements for the pre-printing, printing, and post-printing phases were 7.75 µg/m³, 3.60 µg/m³, and 8.15 µg/m³, respectively. Although there were PM_{1.0} emissions associated with each phase, they did not drastically differ from background levels. Therefore, it can be concluded that PBF-SLM operations did not create significant differences in PM_{1.0} concentrations in the related production space. PM_{1.0} concentrations in this production space during PBF-SLM operations are illustrated in Figure 4.2.

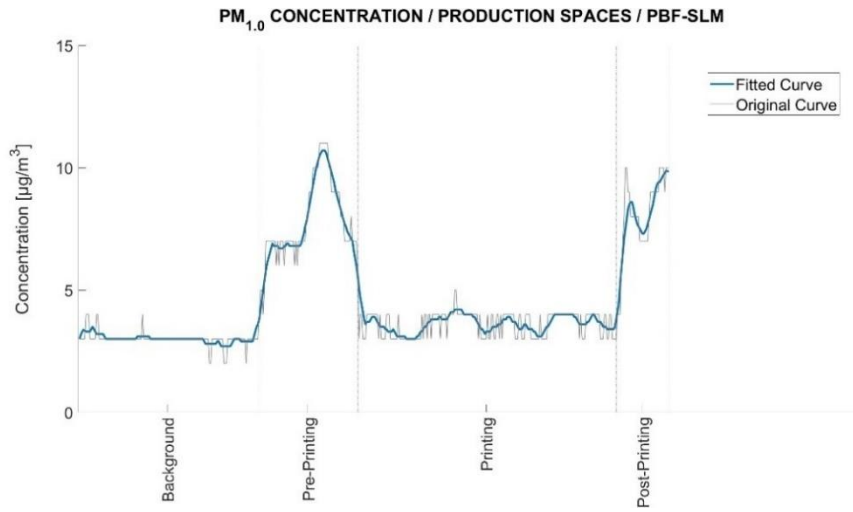


Figure 4.2 PM_{1.0} Concentrations in Related Production Space during PBF-SLM

The results of PM_{1.0} concentrations in the office space during PBF-SLM operations indicated minor variations and a decrease in PM_{1.0} concentrations during different phases compared to the background levels. The average PM_{1.0} concentration during the background measurements was 4.13 µg/m³. The mean measurements for the pre-printing, printing, and post-printing phases were 3.72 µg/m³, 3.75 µg/m³, and 2.07 µg/m³, respectively. Hence, it can be concluded that PBF-SLM operations did not necessarily contribute to the PM_{1.0} concentrations in the office space. PM_{1.0} levels in the office space during PBF-SLM operations are presented in Figure 4.3.

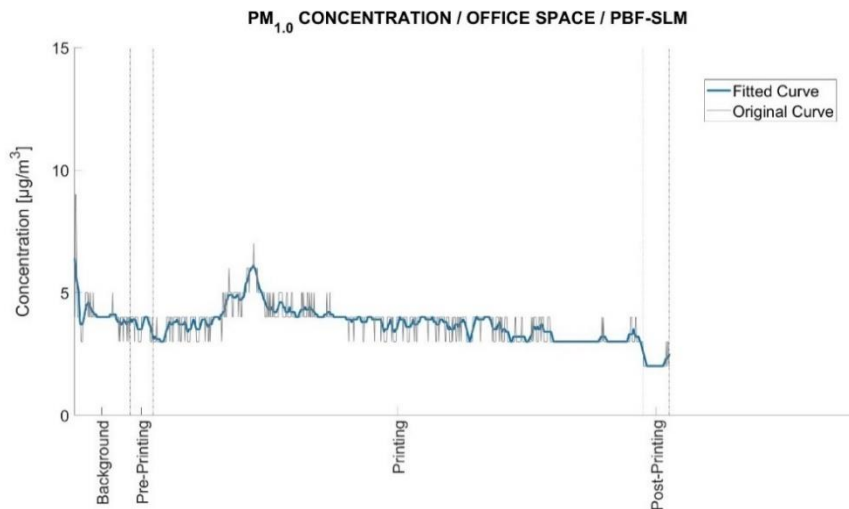


Figure 4.3 PM_{1.0} Concentrations in Office Space during PBF-SLM

Air quality guidelines issued by WHO (2021) are used as threshold values to evaluate PM_{2.5} concentrations. The guideline includes four interim target values and one air quality guideline, with values specified for both annual and 24-hour periods. The annual values are 35, 25, 15, 10, and 5 µg/m³, while the 24-hour values are 75, 50, 37.5, 25, and 15 µg/m³, respectively (World Health Organization, 2021). In Figure 4.4 and Figure 4.5, the annual interim target 1 of PM_{2.5} was labeled as the "Maximum Tolerable Level (Annual)," and the annual air quality guideline of PM_{2.5} was labeled as the "Target Level (Annual)." Similarly, the 24-hour interim target 1 of PM_{2.5} is labeled as the "Maximum Tolerable Level (24-hour)," and the 24-hour air quality guideline of PM_{2.5} is labeled as the "Target Level (24-hour)."

Minimum, maximum, and average PM_{2.5} concentrations in the PBF-SLM production space and the office space during PBF-SLM operations, along with the duration of each phase, average temperature, and relative humidity of the space during each phase, are tabulated in Table 4.4.

Table 4.4 Descriptive Statistics of PM_{2.5} Concentrations during PBF-SLM

		Background	Pre-Printing	Printing	Post-Printing
PRODUCTION SPACE	Min (µg/m ³)	3.00	6.00	4.00	5.00
	Max (µg/m ³)	5.00	16.00	7.00	14.00
	Avg (µg/m ³)	4.00	11.03	4.69	11.50
	Time (min)	46	26	66	14
	Temp (°C)	22.56	24.29	25.47	25.57
	RH (%)	31.02	32.40	30.72	30.53
OFFICE SPACE	Min (µg/m ³)	3.00	4.00	4.00	3.00
	Max (µg/m ³)	12.00	6.00	10.00	4.00
	Avg (µg/m ³)	4.52	4.86	4.97	3.07
	Time (min)	30	12	260	14
	Temp (°C)	24.39	23.66	23.03	22.45
	RH (%)	30.97	32.08	31.98	31.81

The results of PM_{2.5} concentrations in the PBF-SLM production space during PBF-SLM operations exhibited fluctuations relative to the background levels. The average measurements of the pre-printing, printing, and post-printing phases were 11.03 µg/m³, 4.69 µg/m³, and 11.50 µg/m³ respectively where the background level was 4.00 µg/m³. These values, when compared to established thresholds, showed that all phases remained below the maximum tolerable levels for both 24-hour and annual exposure. The target level for 24-hour exposure was achieved for all phases except peak points observed during the pre-printing phase. The target level for annual exposure was met during the background and printing phase. Given that the PM_{2.5} concentrations remained below maximum tolerable levels both for 24-hour and annual exposure throughout all phases, despite increases observed during pre-printing and post-printing phases, it can be concluded that PBF-SLM operations did not substantially increase PM_{2.5} emissions in the related production space. PM_{2.5} concentrations in this production space during PBF-SLM operations are inserted in Figure 4.4.

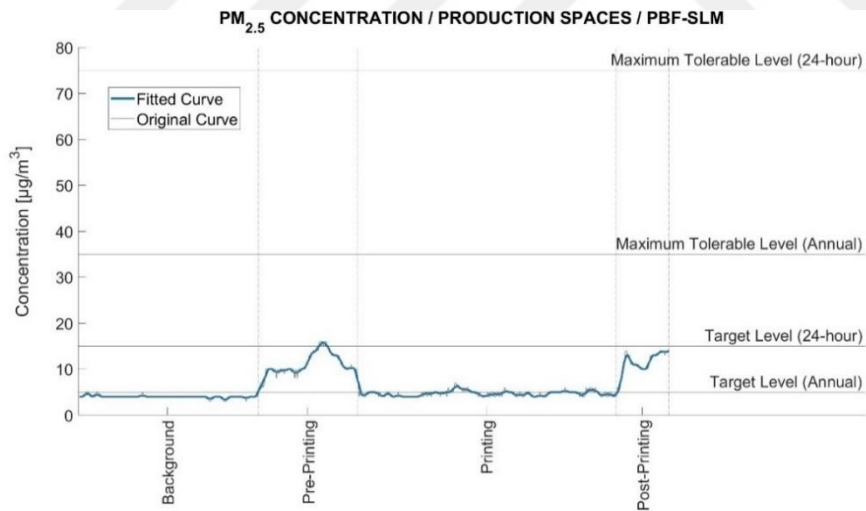


Figure 4.4 PM_{2.5} Concentrations in Related Production Space during PBF-SLM

The results of PM_{2.5} concentrations in the office space during PBF-SLM operations exhibited a stable trend with minor variations relative to the background levels that had an average of 4.52 µg/m³, while the measured values varied between 3.00 µg/m³ and 12.00 µg/m³. The average measurements of the pre-printing, printing,

and post-printing phases were $4.86 \mu\text{g}/\text{m}^3$, $4.97 \mu\text{g}/\text{m}^3$, and $3.07 \mu\text{g}/\text{m}^3$ respectively. The concentrations during these phases varied between $4.00 \mu\text{g}/\text{m}^3$ and $6.00 \mu\text{g}/\text{m}^3$, $4.00 \mu\text{g}/\text{m}^3$ and $10.00 \mu\text{g}/\text{m}^3$, and lastly $3.00 \mu\text{g}/\text{m}^3$ and $4.00 \mu\text{g}/\text{m}^3$, respectively. Comparing these concentrations to established thresholds revealed that all phases remained within the thresholds of maximum tolerable levels for 24-hour and annual exposure and target level for 24-hour exposure. The target level for annual exposure was achieved for all phases except background levels, clarifying that PBF-SLM operations did not cause an increase in $\text{PM}_{2.5}$ emissions in the office space. $\text{PM}_{2.5}$ concentrations in the office space during PBF-SLM operations are inserted in Figure 4.5.

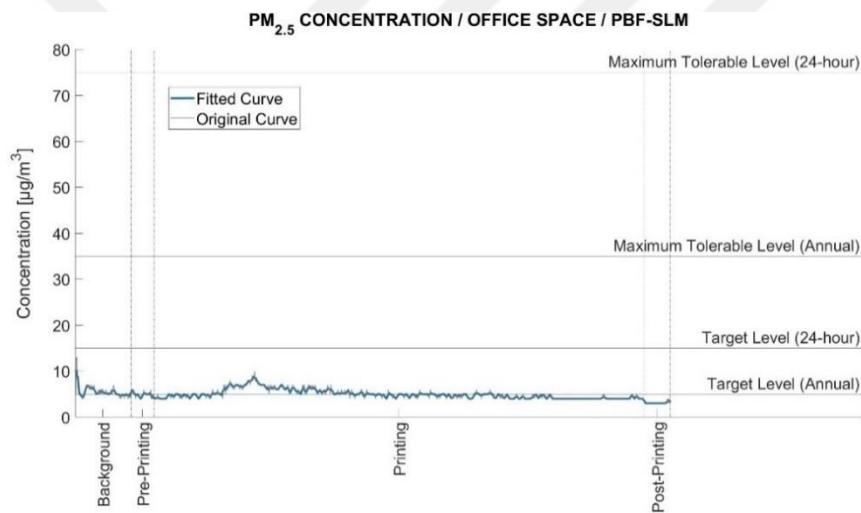


Figure 4.5 $\text{PM}_{2.5}$ Concentrations in Office Space during PBF-SLM

Air quality guidelines issued by WHO (2021) are used as threshold values to evaluate PM_{10} concentrations. The annual values are 70, 50, 30, 20, and $15 \mu\text{g}/\text{m}^3$, and the 24-hour values are 150, 100, 75, 50, and $45 \mu\text{g}/\text{m}^3$, respectively (World Health Organization, 2021). In Figure 4.6 and Figure 4.7, the annual interim target 1 of PM_{10} was labeled as the "Maximum Tolerable Level (Annual)," and the annual air quality guideline of PM_{10} was labeled as the "Target Value (Annual)." Similarly, the 24-hour interim target 1 of PM_{10} was labeled as the "Maximum Tolerable Level (24-hour)," and the 24-hour air quality guideline of PM_{10} was labeled as the "Target Value (24-hour)".

Minimum, maximum, and average PM₁₀ concentrations in the PBF-SLM production space and the office space during PBF-SLM operations, along with the duration of each phase, average temperature, and relative humidity of the space during each phase, are given in Table 4.5.

Table 4.5 Descriptive Statistics of PM₁₀ Concentrations during PBF-SLM

		Background	Pre-Printing	Printing	Post-Printing
PRODUCTION SPACE	Min (µg/m ³)	3.00	6.00	4.00	5.00
	Max (µg/m ³)	5.00	18.00	7.00	15.00
	Avg (µg/m ³)	4.00	11.25	4.69	11.53
	Time (min)	46	26	66	14
	Temp (°C)	22.56	24.29	25.47	25.57
	RH (%)	31.02	32.40	30.72	30.53
OFFICE SPACE	Min (µg/m ³)	4.00	4.00	4.00	3.00
	Max (µg/m ³)	13.00	6.00	10.00	4.00
	Avg (µg/m ³)	5.52	4.86	4.97	3.07
	Time (min)	30	12	260	14
	Temp (°C)	24.39	23.66	23.03	22.45
	RH (%)	30.97	32.08	31.98	31.81

The results of PM₁₀ concentrations in the PBF-SLM production space during PBF-SLM operations implied certain variations relative to the background levels. The minimum PM₁₀ concentration during the background measurements was 3.00 µg/m³, while the maximum was 5.00 µg/m³, with an average of 4.00 µg/m³. Throughout the pre-printing and post-printing phases, PM₁₀ concentrations experienced modest increases, with average values of 11.25 µg/m³ and 11.53 µg/m³, respectively. The PM₁₀ concentrations were indistinguishable from background levels during the printing phase, with an average of 4.69 µg/m³. All phases remained within the established thresholds except for intermittent peaks observed during the pre-printing phase. Thus, it can be concluded that PBF-SLM operations did not significantly influence PM₁₀ emissions in the related production

space. PM₁₀ concentrations in this production space during PBF-SLM operations are illustrated in Figure 4.6.

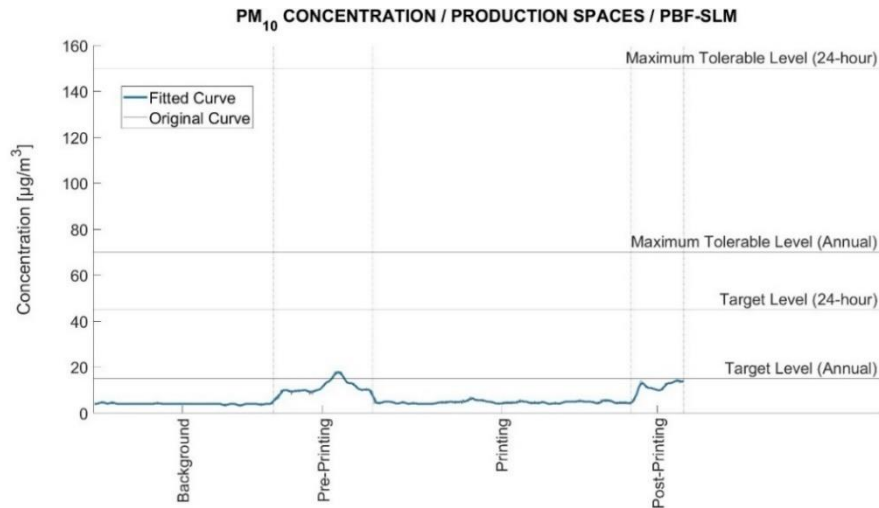


Figure 4.6 PM₁₀ Concentrations in Related Production Space during PBF-SLM

The results of PM₁₀ concentrations in the office space during PBF-SLM operations exhibited a stable trend with minor variations relative to the background levels. The minimum PM₁₀ concentration during the background measurements was 4.00 µg/m³, while the maximum was 13.00 µg/m³, with an average of 5.52 µg/m³. Throughout the pre-printing, printing, and post-printing phases, PM₁₀ concentrations experienced modest declines, with average values of 4.86 µg/m³, 4.97 µg/m³, and 3.07 µg/m³, respectively. Given that the PM₁₀ concentrations remained consistently within the established thresholds and did not notably drift from background levels during any phase, it can be concluded that PBF-SLM operations did not significantly affect PM₁₀ emissions in the office space. PM₁₀ concentrations in the office space during PBF-SLM operations are presented in Figure 4.7.

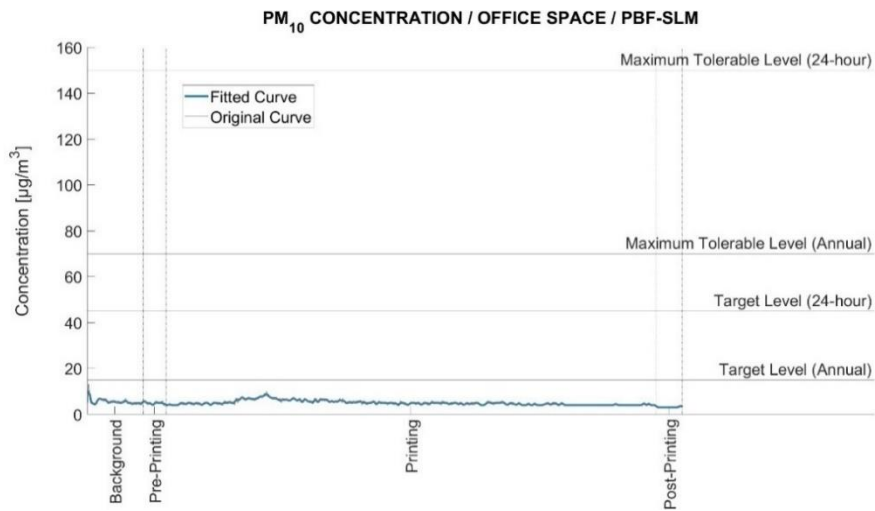


Figure 4.7 PM₁₀ Concentrations in Office Space during PBF-SLM

The categorization of TVOC levels issued by the Umweltbundesamt (UBA), the Federal Environmental Agency in Germany (2007), was adopted to evaluate TVOC concentration. Accordingly, in Figure 4.8 and Figure 4.9, delineations were made based on five levels: Level 1 ($< 0.3 \text{ mg/m}^3$), Level 2 ($0.3\text{-}1 \text{ mg/m}^3$), Level 3 ($1\text{-}3 \text{ mg/m}^3$), Level 4 ($3\text{-}10 \text{ mg/m}^3$), and Level 5 ($10\text{-}25 \text{ mg/m}^3$). Level 1 serves as a target value without hygienic concerns. Level 2 does not indicate significant issues but necessitates increased ventilation. At Level 3, hygienic concerns arise, prompting source investigation and increased ventilation, particularly over a maximum duration of 12 months. Level 4 indicates significant concerns, with a maximum toleration duration of a month, necessitating restricted usage and intensified ventilation. Level 5 signifies unacceptable concentrations, permitting usage only if unavoidable and for short durations, with increased ventilation measures (Bekanntmachung des Umweltbundesamtes, 2007).

The commonly used unit and the units specified in this guideline for TVOC concentration are mg/m^3 . Given that the TVOC sensor outputs data in ppb, Equation 4-1 and Equation 4-2 were employed to convert the ppb readings to mg/m^3 . The molecular weight of TVOC is 110 g/mol (Sensirion, 2019).

Minimum, maximum, and average TVOC concentrations in the PBF-SLM production space and the office space during PBF-SLM operations, along with the

duration of each phase, average temperature, and relative humidity of the space during each phase, are tabulated in Table 4.6.

Table 4.6 Descriptive Statistics of TVOC Concentrations during PBF-SLM

		Background	Pre-Printing	Printing	Post-Printing
PRODUCTION SPACE	Min (mg/m ³)	0.00	0.00	0.05	0.63
	Max (mg/m ³)	0.13	0.12	1.72	1.02
	Avg (mg/m ³)	0.05	0.04	0.67	0.82
	Time (min)	46	26	66	14
	Temp (°C)	22.56	24.29	25.47	25.57
	RH (%)	31.02	32.40	30.72	30.53
OFFICE SPACE	Min (mg/m ³)	0.00	0.04	0.00	0.09
	Max (mg/m ³)	0.25	0.25	0.31	0.28
	Avg (mg/m ³)	0.13	0.14	0.07	0.19
	Time (min)	30	12	260	14
	Temp (°C)	24.39	23.66	23.03	22.45
	RH (%)	30.97	32.08	31.98	31.81

The results of TVOC concentrations in the PBF-SLM production space during PBF-SLM operations suggested indistinguishable variations in different phases compared to background levels. The average TVOC concentration during the background, pre-printing, printing, and post-printing phases were 0.05 mg/m³, 0.04 mg/m³, 0.67 mg/m³, and 0.82 mg/m³. Throughout the background and pre-printing phases, TVOC concentrations remained below level 1, the target value without hygienic concerns. The TVOC levels during the printing phase rose to level 2, requiring ventilation while without significant concerns, and level 3, raising hygienic concerns and necessitating increased ventilation. TVOC concentrations decreased to level 2 during post-printing. Hence, it can be concluded that PBF-SLM operations necessitate increased ventilation in the related production space, particularly during the printing and post-printing phases. TVOC concentrations in this production space during PBF-SLM operations are inserted in Figure 4.8.

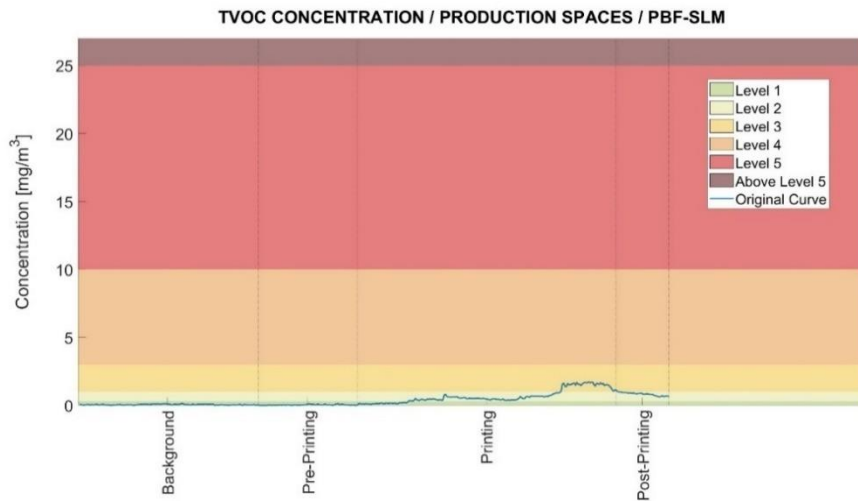


Figure 4.8 TVOC Concentrations in Related Production Space during PBF-SLM

The results of TVOC concentrations in the office space during PBF-SLM operations suggested a stable trend during all phases. The mean concentrations of the background, pre-printing, printing, and post-printing were 0.13 mg/m³, 0.14 mg/m³, 0.07 mg/m³, and 0.19 mg/m³ respectively, remaining below level 1, indicating target value without hygienic concerns. Hence, it can be concluded that PBF-SLM operations occurring in the related production space did not cause notable TVOC levels in the office space. TVOC concentrations in the office space during PBF-SLM operations are given in Figure 4.9.

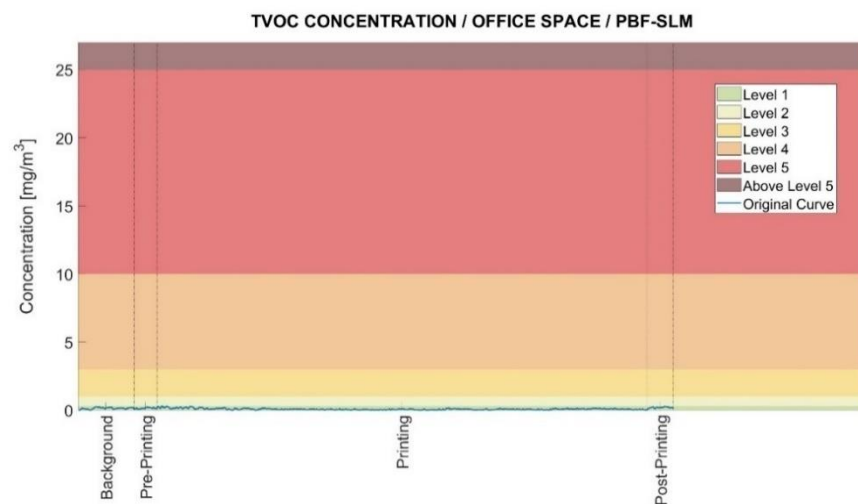


Figure 4.9 TVOC Concentrations in Office Space during PBF-SLM

The HCHO guideline value of 0.1 mg/m³ given by WHO (2000) for a 30-minute average is taken as the threshold value. Consequently, in Figure 4.10 and Figure 4.11, 0.1 mg/m³ was delineated as the “Maximum Safe Level (30-minute).”

The commonly used unit and the unit specified in this guideline for HCHO concentration are mg/m³. Given that the HCHO sensor outputs data in ppb, Equation 4-1 and Equation 4-2 were employed to convert the ppb readings to mg/m³. The molecular weight of HCHO is 30.026 g/mol (National Center for Biotechnology Information, 2024b).

Minimum, maximum, and average HCHO concentrations in the PBF-SLM production space and the office space during PBF-SLM operations, along with the duration of each phase, average temperature, and relative humidity of the space during each phase, are given in Table 4.7.

Table 4.7 Descriptive Statistics of HCHO Concentrations during PBF-SLM

		Background	Pre-Printing	Printing	Post-Printing
PRODUCTION SPACE	Min (mg/m ³)	0.003	0.000	0.002	0.002
	Max (mg/m ³)	0.004	0.004	0.004	0.004
	Avg (mg/m ³)	0.004	0.003	0.003	0.003
	Time (min)	46	26	66	14
	Temp (°C)	22.56	24.29	25.47	25.57
	RH (%)	31.02	32.40	30.72	30.53
OFFICE SPACE	Min (mg/m ³)	0.001	0.002	0.002	0.003
	Max (mg/m ³)	0.003	0.003	0.004	0.004
	Avg (mg/m ³)	0.002	0.003	0.003	0.004
	Time (min)	30	12	260	14
	Temp (°C)	24.39	23.66	23.03	22.45
	RH (%)	30.97	32.08	31.98	31.81

The results of HCHO concentrations in the PBF-SLM production space during PBF-SLM operations indicated almost indistinguishable variations in HCHO

concentrations during different phases compared to the background levels. The mean HCHO concentrations during the background, pre-printing, printing, and post-printing phases were 0.004 mg/m³, 0.003 mg/m³, 0.003 mg/m³, and 0.003 mg/m³. As HCHO emissions were way below the 30-minute maximum safety level and indistinguishable from background levels, it can be concluded that PBF-SLM operations did not contribute to HCHO concentrations in the related production space. HCHO concentrations in this production space during PBF-SLM operations are illustrated in Figure 4.10.

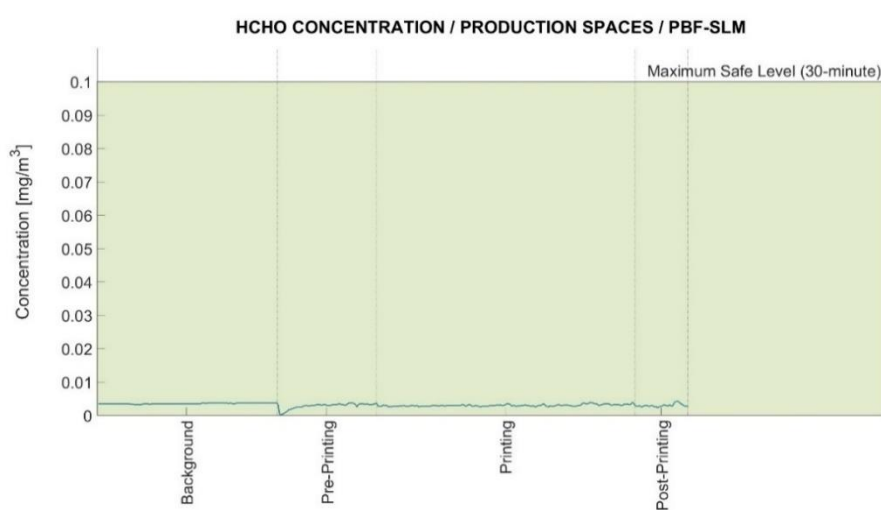


Figure 4.10 HCHO Concentrations in Related Production Space during PBF-SLM

The results of HCHO concentrations in the office space during PBF-SLM operations indicated levels between 0.001 mg/m³ and 0.004 mg/m³ during measurements. As phase measurements did not deviate from background levels and were way below the 30-minute maximum safety level, it can be concluded that PBF-SLM operations taking place in the related production space did not contribute to HCHO concentrations in the office space. HCHO concentrations in the office space during PBF-SLM operations are presented in Figure 4.11.

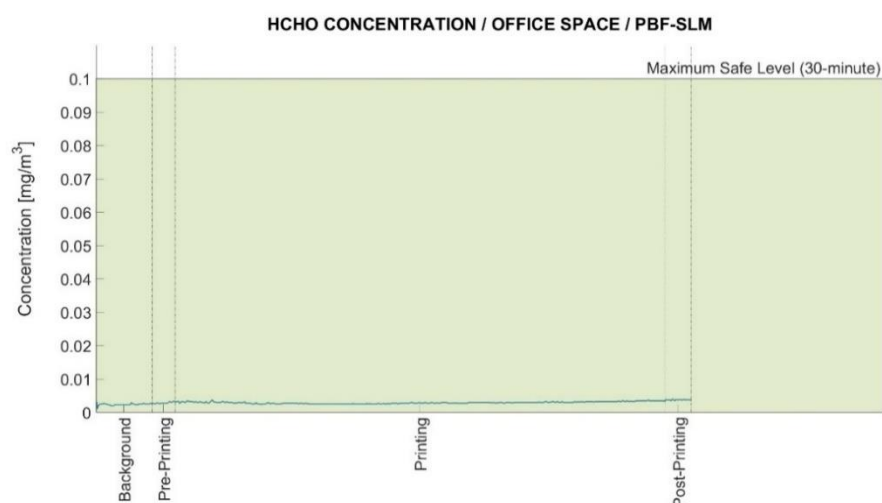


Figure 4.11 HCHO Concentrations in Office Space during PBF-SLM

WHO does not state a safe level of exposure for C_6H_6 . Thus, no safety limit was indicated in Figure 4.12 and Figure 4.13.

The commonly used unit for C_6H_6 concentration is mg/m^3 . Given that the C_6H_6 sensor outputs data in ppm, Equation 4-2 and Equation 4-4 were employed to convert the mg/m^3 readings to $\mu g/m^3$. The molecular weight of C_6H_6 is 78.11 g/mol (National Center for Biotechnology Information, 2024a).

Minimum, maximum, and average C_6H_6 concentrations in the PBF-SLM production space and the office space during PBF-SLM operations, along with the duration of each phase, average temperature, and relative humidity of the space during each phase, are tabulated in Table 4.8.

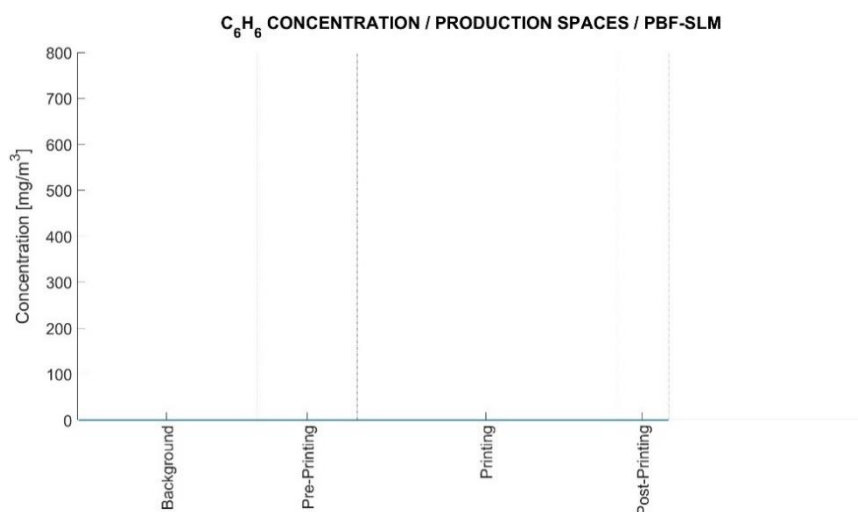
Table 4.8 Descriptive Statistics of C_6H_6 Concentrations during PBF-SLM

		Background	Pre-Printing	Printing	Post-Printing
PRODUCTION SPACE	Min (mg/m^3)	0.00	0.00	0.00	0.00
	Max (mg/m^3)	0.00	0.00	0.00	0.00
	Avg (mg/m^3)	0.00	0.00	0.00	0.00
	Time (min)	0.00	0.00	0.00	0.00
	Temp ($^{\circ}C$)	22.56	24.29	25.47	25.57
	RH (%)	31.02	32.40	30.72	30.53

Table 4.8 (continued)

OFFICE SPACE	Min (mg/m ³)	0.00	0.00	0.00	0.00
	Max (mg/m ³)	0.00	0.00	0.00	0.00
	Avg (mg/m ³)	0.00	0.00	0.00	0.00
	Time (min)	30	12	260	14
	Temp (°C)	24.39	23.66	23.03	22.45
	RH (%)	30.97	32.08	31.98	31.81

The results of C₆H₆ concentrations in the PBF-SLM production space during PBF-SLM operations revealed that the C₆H₆ concentrations remained at a consistent minimum of 0.00 mg/m³ during the background, printing, and post-printing phases, indicating no detectable emissions during these periods. However, the pre-printing phase witnessed a singular peak at 725.42 mg/m³, with the remaining values being 0.00 mg/m³. As this anomalous peak was caused by a sensor error, this value was accepted as 0.00 mg/m³. Therefore, it can be concluded that PBF-SLM operations did not cause C₆H₆ emissions. C₆H₆ concentrations in the related production space during PBF-SLM operations are inserted in Figure 4.12.

Figure 4.12 C₆H₆ Concentrations in Related Production Space during PBF-SLM

The results of C_6H_6 concentrations in the office space during PBF-SLM operations revealed that C_6H_6 concentrations remained at a consistent minimum of 0.00 mg/m^3 during the background, pre-printing, printing, and post-printing, indicating no detectable emissions during these periods. Accordingly, it can be concluded that PBF-SLM operations taking place in the related production space did not cause C_6H_6 emissions in the office space. C_6H_6 concentrations in the office space during PBF-SLM operations are given in Figure 4.13.

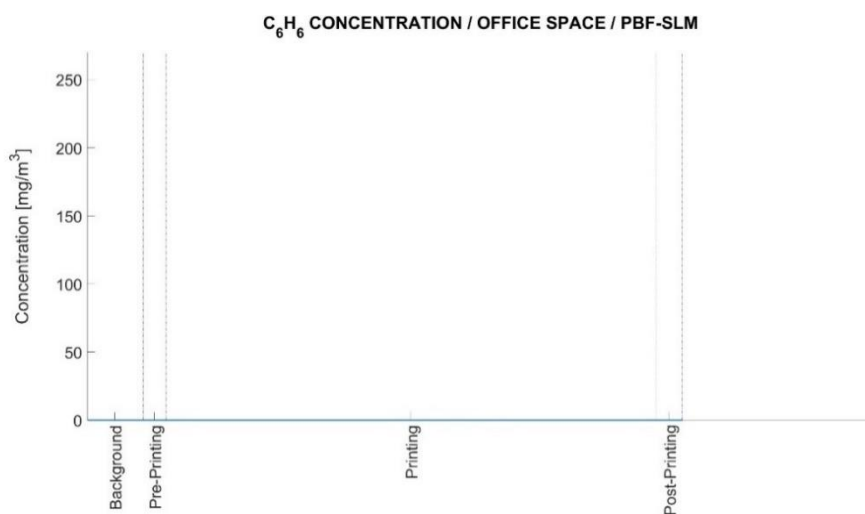


Figure 4.13 C_6H_6 Concentrations in Office Space during PBF-SLM

Not being a typical indoor air quality pollutant, OSHA, NIOSH, and ACGIH set the workplace exposure limit to 1000 ppm for an 8-hour permissible exposure limit, 10-hour recommended exposure limit, and short-term threshold limit value (Occupational Safety and Health Administration, n.d.) for C_2H_5OH exposure. The odor threshold of C_2H_5OH is 84 ppm (New Jersey Department of Health, 2011). In Figure 4.14 and Figure 4.15, 84 ppm was delineated as the “Odor Threshold.” As the concentrations were below each of these values, the Workplace Exposure Limit of 1000 ppm was not indicated in those figures.

Minimum, maximum, and average C_2H_5OH concentrations in the PBF-SLM production space and the office space during PBF-SLM operations, along with the duration of each phase, average temperature, and relative humidity of the space during each phase, are illustrated in Table 4.9.

Table 4.9 Descriptive Statistics of C_2H_5OH Concentrations during PBF-SLM

		Background	Pre-Printing	Printing	Post-Printing
PRODUCTION SPACE	Min (ppm)	0.00	0.00	0.00	0.00
	Max (ppm)	0.00	0.00	0.00	0.00
	Avg (ppm)	0.00	0.00	0.00	0.00
	Time (min)	46	26	66	14
	Temp ($^{\circ}C$)	22.56	24.29	25.47	25.57
	RH (%)	31.02	32.40	30.72	30.53
OFFICE SPACE	Min (ppm)	0.00	0.00	0.00	0.00
	Max (ppm)	0.00	0.00	0.00	0.00
	Avg (ppm)	0.00	0.00	0.00	0.00
	Time (min)	30	12	260	14
	Temp ($^{\circ}C$)	24.39	23.66	23.03	22.45
	RH (%)	30.97	32.08	31.98	31.81

The results of C_2H_5OH concentrations in the PBF-SLM production space during PBF-SLM operations suggested that the C_2H_5OH concentrations remained at a consistent minimum of 0.00 ppm during the background, printing, and post-printing phases, indicating no detectable emissions during any of the periods. However, the pre-printing phase witnessed a singular peak at 47.71 ppm, with the remaining values being 0.00 ppm. As this anomalous peak was caused by a sensor error, this value was accepted as 0.00 ppm. Therefore, it can be concluded that PBF-SLM operations did not cause C_2H_5OH emissions. C_2H_5OH concentrations in the related production space during PBF-SLM operations are inserted in Figure 4.14.

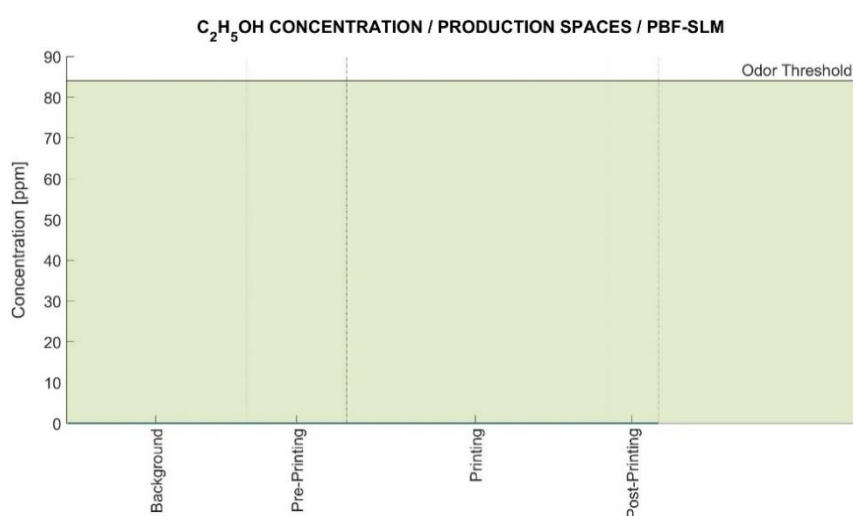


Figure 4.14 C₂H₅OH Concentrations in Related Production Space during PBF-SLM

The results of C₂H₅OH concentrations in the office space during PBF-SLM operations suggested that the C₂H₅OH concentrations remained at a consistent minimum of 0.00 ppm during the background, pre-printing, printing, and post-printing, indicating no detectable emissions during any of the periods. Consequently, it can be concluded that PBF-SLM operations taking place in the related production space did not cause C₂H₅OH concentrations in the office space. C₂H₅OH concentrations in the office space during PBF-SLM operations are given in Figure 4.15.

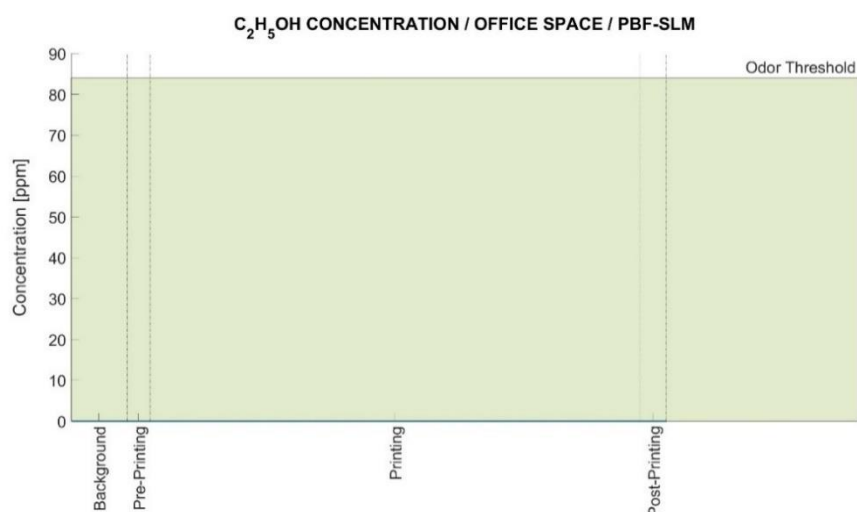


Figure 4.15 C₂H₅OH Concentrations in Office Space during PBF-SLM

Air quality guidelines issued by WHO (2021) are used as threshold values to evaluate NO₂ concentrations. The guideline includes three interim target values for annual exposure, one air quality guideline value for annual exposure, two interim target values for 24-hour exposure, and one air quality guideline value for 24-hour exposure. The annual values are 40, 30, 20, and 10 µg/m³, while the 24-hour values are 120, 50, and 25 µg/m³, respectively (World Health Organization, 2021). In Figure 4.16 and Figure 4.17, the annual interim target 1 is labeled as the "Maximum Tolerable Level (Annual)," and the annual air quality guideline value is labeled as the "Target Level (Annual)." Similarly, the 24-hour interim target 1 is labeled as the "Maximum Tolerable Level (24-hour)," and the 24-hour air quality guideline value is labeled as the "Target Level (24-hour)."

The commonly used unit and the units specified in this guideline for NO₂ concentration are µg/m³. Given that the NO₂ sensor outputs data in ppm, Equation 4-2 and Equation 4-4 were employed to convert the mg/m³ readings to µg/m³. The molecular weight of NO₂ is 46.006 g/mol (National Center for Biotechnology Information, 2024c).

Minimum, maximum, and average NO₂ concentrations in the PBF-SLM production space and the office space during PBF-SLM operations, along with the duration of each phase, average temperature, and relative humidity of the space during each phase, are illustrated in Table 4.10.

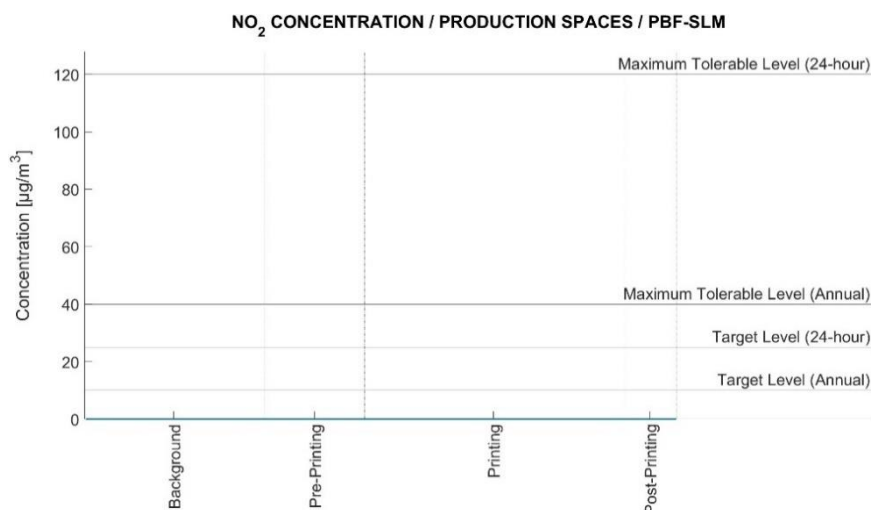
Table 4.10 Descriptive Statistics of NO₂ Concentrations during PBF-SLM

		Background	Pre-Printing	Printing	Post-Printing
PRODUCTION SPACE	Min (µg/m ³)	0.00	0.00	0.00	0.00
	Max (µg/m ³)	0.00	0.00	0.00	0.00
	Avg (µg/m ³)	0.00	0.00	0.00	0.00
	Time (min)	46	26	66	14
	Temp (°C)	22.56	24.29	25.47	25.57
	RH (%)	31.02	32.40	30.72	30.53

Table 4.10 (continued)

OFFICE SPACE	Min ($\mu\text{g}/\text{m}^3$)	0.00	0.00	0.00	0.00
	Max ($\mu\text{g}/\text{m}^3$)	0.00	0.00	0.00	0.00
	Avg ($\mu\text{g}/\text{m}^3$)	0.00	0.00	0.00	0.00
	Time (min)	30	12	260	14
	Temp ($^{\circ}\text{C}$)	24.39	23.66	23.03	22.45
	RH (%)	30.97	32.08	31.98	31.81

The results of NO_2 concentrations in the PBF-SLM production space during PBF-SLM operations suggested that the NO_2 concentrations remained at a consistent minimum of $0.00 \mu\text{g}/\text{m}^3$ during the background, printing, and post-printing phases, indicating no detectable emissions. However, the pre-printing phase witnessed a singular peak at $7056.17 \mu\text{g}/\text{m}^3$, with the remaining values being $0.00 \mu\text{g}/\text{m}^3$. Since this anomalous peak was caused by a sensor error, this value was accepted as $0.00 \mu\text{g}/\text{m}^3$. Therefore, it can be concluded that PBF-SLM operations did not cause NO_2 emissions. NO_2 concentrations in the related production space during PBF-SLM operations are presented in Figure 4.16.

Figure 4.16 NO_2 Concentrations in Related Production Space during PBF-SLM

The results of NO₂ concentrations in the office space during PBF-SLM operations suggested that the NO₂ concentrations remained consistent at 0.00 µg/m³ during the background, pre-printing, printing, and post-printing phases, indicating no detectable emissions. Therefore, it can be concluded that PBF-SLM operations taking place in the related production space did not cause NO₂ emissions in the office space. NO₂ concentrations in the office space during PBF-SLM operations are tabulated in Figure 4.17.

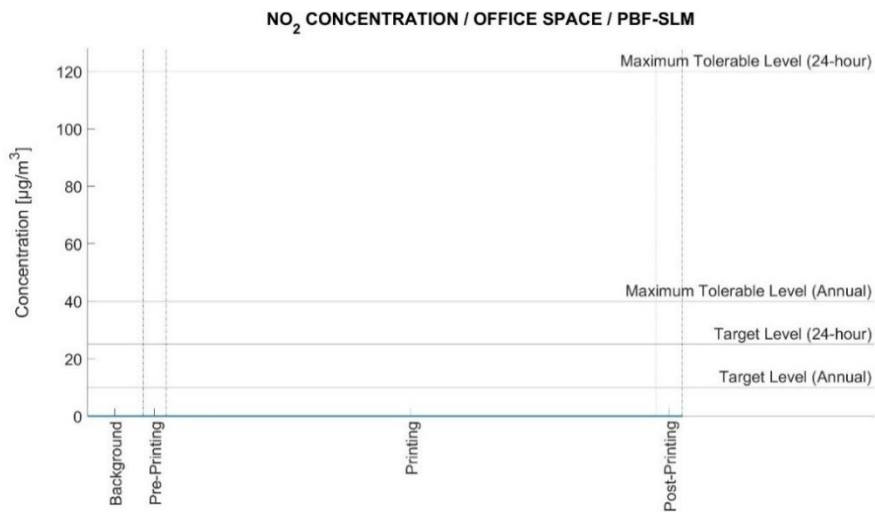


Figure 4.17 NO₂ Concentrations in Office Space during PBF-SLM

The typical outdoor CO₂ concentration is 400 ppm. The indoor CO₂ concentration of a poorly ventilated space corresponds to 1100 ppm (López et al., 2023). Hence, these values were taken as threshold values to evaluate CO₂ concentration. In Figure 4.18 and Figure 4.19, 400 ppm was delineated as the “Typical Outdoor Level,” while 1100 ppm was given as the “Maximum Indoor Level.” Consequently, the values between 400-1100 ppm were considered acceptable.

Minimum, maximum, and average CO₂ concentrations in the PBF-SLM production space and the office space during PBF-SLM operations, along with the duration of each phase, average temperature, and relative humidity of the space during each phase, illustrated in Table 4.11.

Table 4.11 Descriptive Statistics of CO₂ Concentrations during PBF-SLM

		Background	Pre-Printing	Printing	Post-Printing
PRODUCTION SPACE	Min (ppm)	430.72	685.54	709.58	780.14
	Max (ppm)	452.47	1110.21	819.64	842.71
	Avg (ppm)	439.75	718.97	765.39	804.64
	Time (min)	46	26	66	14
	Temp (°C)	22.56	24.29	25.47	25.57
	RH (%)	31.02	32.40	30.72	30.53
OFFICE SPACE	Min (ppm)	736.40	718.88	441.85	384.99
	Max (ppm)	880.19	739.69	714.28	394.00
	Avg (ppm)	758.48	728.83	563.30	388.63
	Time (min)	30	12	260	14
	Temp (°C)	24.39	23.66	23.03	22.45
	RH (%)	30.97	32.08	31.98	31.81

According to the results of CO₂ concentrations in the PBF-SLM production space during PBF-SLM operations, the measured CO₂ concentrations revealed a notable pattern across different phases. During the background phase, the average concentration was 439.75 ppm, close to the typical outdoor level of 400 ppm. During the pre-printing phase, there was a notable increase, with an average of 718.97 ppm. The printing and post-printing phases had an average concentration of 765.39 ppm and 804.64 ppm, respectively. Despite deviations from background levels in the related production space caused by PBF-SLM operations, CO₂ concentrations during pre-printing, printing, and post-printing phases fell within the acceptable range of 400-1100 ppm. CO₂ concentrations in the related production space during PBF-SLM operations are presented in Figure 4.18.

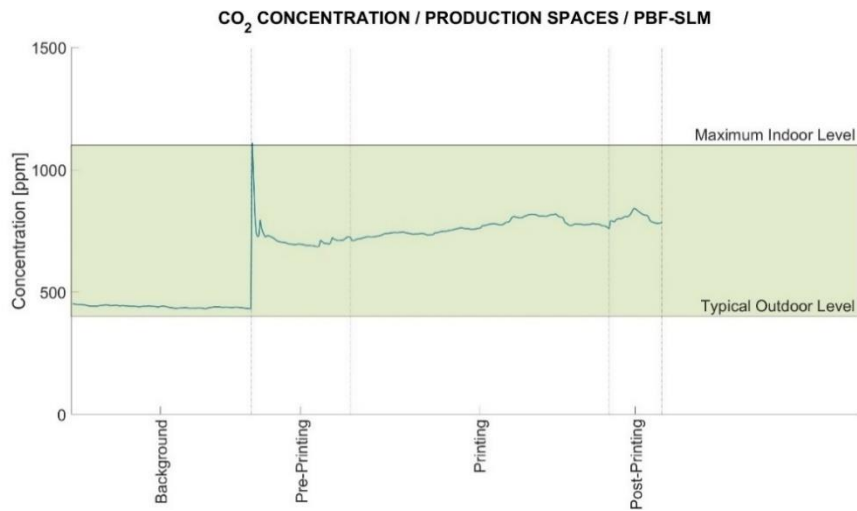


Figure 4.18 CO₂ Concentrations in Related Production Space during PBF-SLM

According to CO₂ concentrations in the office space during PBF-SLM operations, the measured CO₂ concentrations revealed variations between 384.99 ppm and 880.19 ppm. There was a declining trend in CO₂ concentrations from the background of the post-printing phases, attributed to the decline in the number of people in the office during measurements. Therefore, it can be concluded that PBF-SLM operations in the related production space did not contribute to the CO₂ concentrations in the office space. CO₂ concentrations in the office space during PBF-SLM operations are tabulated in Figure 4.19.

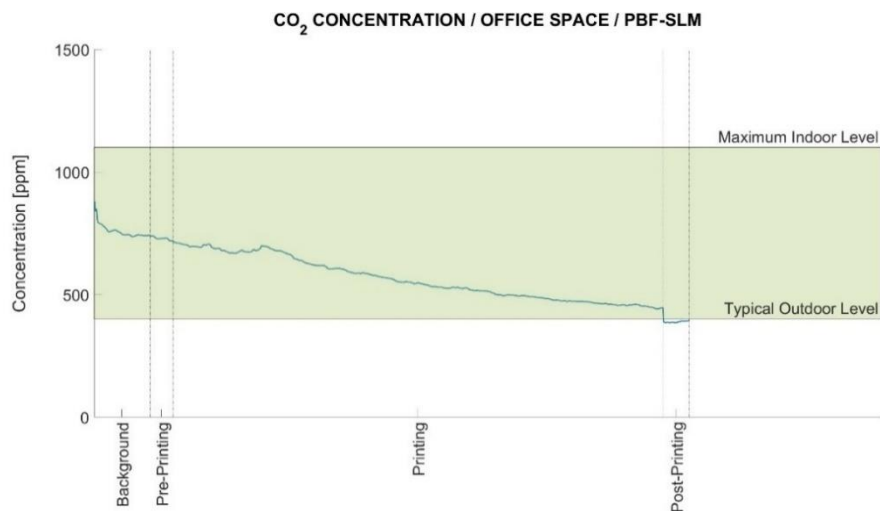


Figure 4.19 CO₂ Concentrations in Office Space during PBF-SLM

An oxygen concentration below 19.5% by volume is classified as deficient in oxygen content. The atmospheric air necessitates oxygen levels ranging from 19.5% to 23.5% at sea level. The volume of oxygen in atmospheric air is typically 20.95% across every elevation (Spelce et al., 2016). Therefore, these values were adopted as threshold values to evaluate O₂ concentration. In Figure 4.20 and Figure 4.21, 19.5% was delineated as the “Minimum Safe Level, while 23.5% was given as the “Maximum Safe Level.” Additionally, 20.95% was depicted as “Typical O₂ Concentration”.

Minimum, maximum, and average O₂ concentrations in the PBF-SLM production space and the office space during PBF-SLM operations, along with the duration of each phase, average temperature, and relative humidity of the space during each phase, are inserted in Table 4.12.

Table 4.12 Descriptive Statistics of O₂ Concentrations during PBF-SLM

		Background	Pre-Printing	Printing	Post-Printing
PRODUCTION SPACE	Min (%)	20.68	20.91	21.00	21.00
	Max (%)	21.23	21.27	21.32	21.32
	Avg (%)	20.89	21.02	21.10	21.07
	Time (min)	46	26	66	14
	Temp (°C)	22.56	24.29	25.47	25.57
	RH (%)	31.02	32.40	30.72	30.53
OFFICE SPACE	Min (%)	20.73	20.86	20.68	20.68
	Max (%)	21.32	21.14	21.32	21.23
	Avg (%)	20.98	20.93	20.92	20.93
	Time (min)	30	12	260	14
	Temp (°C)	24.39	23.66	23.03	22.45
	RH (%)	30.97	32.08	31.98	31.81

The results of O₂ concentrations in the PBF-SLM production space during PBF-SLM operations pointed out that O₂ concentrations remained stable and maintained within safe limits throughout all phases, indistinguishable from background levels.

While the minimum recorded concentration was 20.68%, the maximum concentration was 21.32%. Thus, it can be concluded that PBF-SLM operations did not influence O₂ concentration in the related production space. O₂ concentrations in this production space during PBF-SLM operations are provided in Figure 4.20.

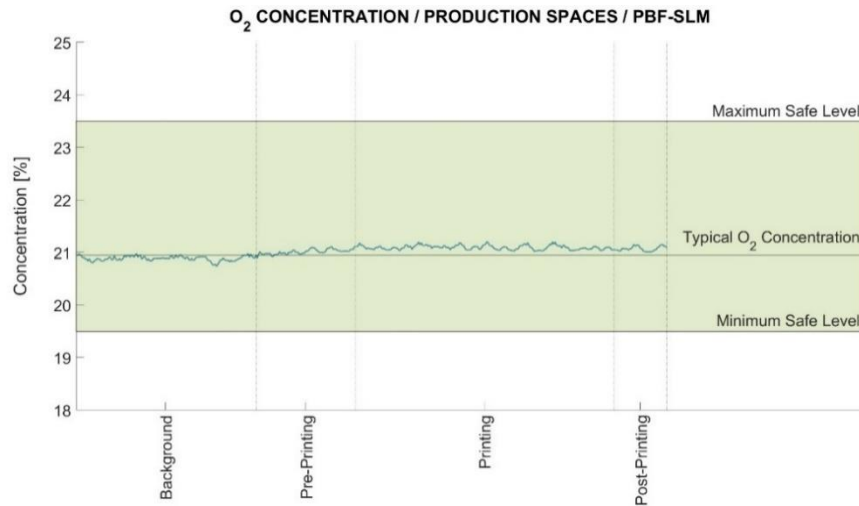


Figure 4.20 O₂ Concentrations in Related Production Space during PBF-SLM

The results of O₂ concentrations in the office space during PBF-SLM operations pointed out that O₂ concentrations remained relatively stable and maintained within safe limits, particularly around typical O₂ concentrations throughout all phases. While the minimum recorded concentration was 20.68%, the maximum concentration was 21.32%. The average concentrations were 20.98%, 20.93%, 20.92%, and 20.93% during the background, pre-printing, printing, and post-printing phases, respectively. Accordingly, it can be concluded that PBF-SLM operations taking place in the related production space did not influence O₂ concentration in the office space. O₂ concentrations in the office space during PBF-SLM operations are given in Figure 4.21.

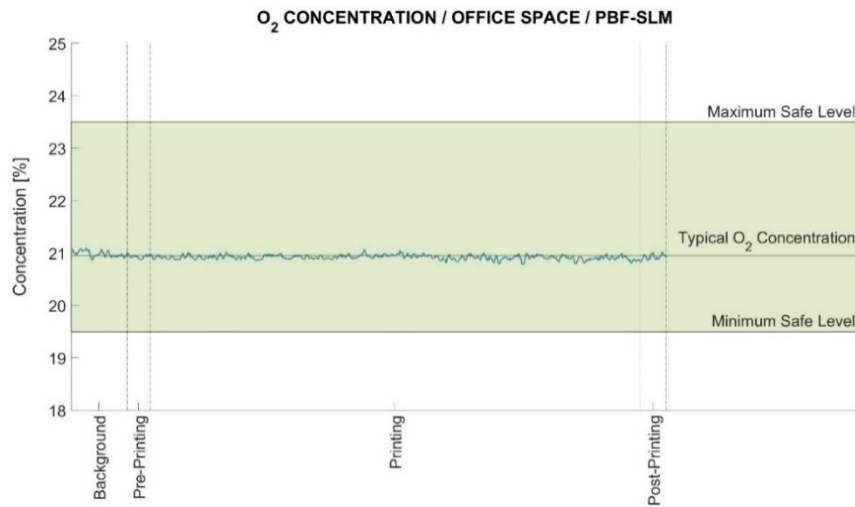


Figure 4.21 O₂ Concentrations in Office Space during PBF-SLM

Employee feedback regarding the perception of IAQ on a scale ranging from very good to very bad, gathered from the Indoor Air Quality Polling Instrument, was quantified using a weighted average method, with the following coefficients assigned to each category: "very bad" (1), "bad" (2), "neutral" (3), "good" (4), and "very good" (5). In Figure 4.22 and Figure 4.23, the categories from very bad to very good were represented by colors ranging from red to green.

The results of employee perception of IAQ in the related production space during PBF-SLM operations indicated that weighted averages of ratings during the background, pre-printing, printing, and post-printing phases were 4.00, 3.00, 2.80, and 1.00 out of 5.00, respectively. This suggested that IAQ in the related production space was perceived positively during the background. While there was a slight decline during the pre-printing and printing phases, the post-printing phase witnessed a severe decline. The employee perception of IAQ in the related production space during PBF-SLM operations gathered from the polling instrument is illustrated in Figure 4.22.

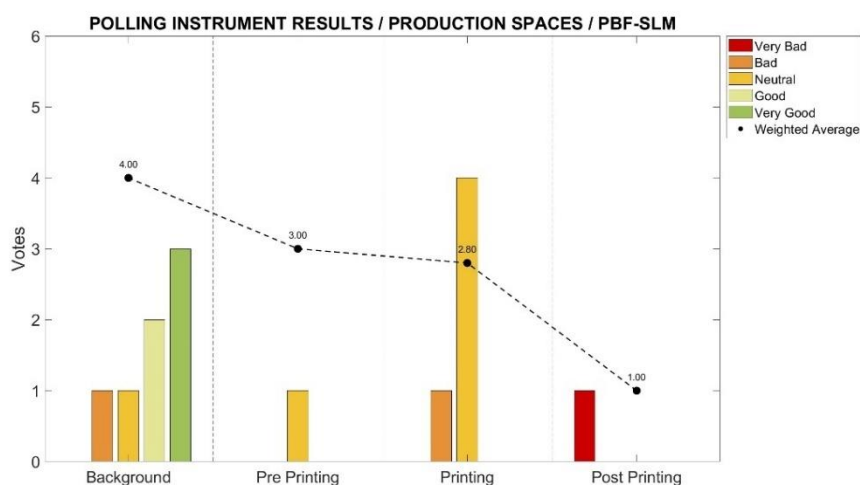


Figure 4.22 Employee Perception of IAQ in Related Production Space during PBF-SLM

The results of INBASE and the polling instrument were considered together to identify potential correlations between IAQ variations due to PBF-SLM operations and the perception of employees within the context of the PBF-SLM production space. The employee feedback in the related production space indicated a worsening trend during and particularly after the printing phase. Although IAQ parameters presented various fluctuations across different phases, a correlation was not captured between the majority of the parameters, including PM, HCHO, C₆H₆, C₂H₅OH, NO₂, CO₂, and O₂, and the employee perception of IAQ. Although changes in TVOC concentrations are not directly correlated with the employee perception of IAQ, elevated levels observed during operational phases, particularly printing, and post-printing might be influential on perceived IAQ in the related production space.

The results of employee perception of IAQ in the office space during PBF-SLM operations indicated that weighted averages of ratings during the background, pre-printing, printing, and post-printing phases were 3.67, 3.00, 3.56, and 3.33 out of 5.00, respectively. These suggested that the IAQ in the office space was generally perceived as neutral to good but with slight variations across different phases.

While the perception was closer to good during the background and printing phases, it was closer to neutral during the pre-printing and post-printing phases. Given that the ratings were at or above the neutral point overall, it can be concluded that IAQ was perceived as relatively good in the office space during these phases. The employee perception of IAQ in the office space during PBF-SLM operations gathered from the polling instrument is illustrated in Figure 4.23.

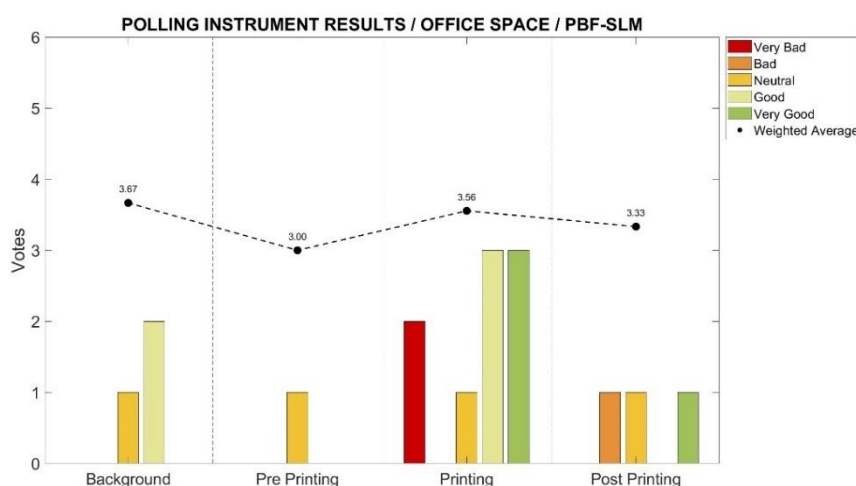


Figure 4.23 Employee Perception of IAQ in Office Space during PBF-SLM

The results of INBASE and the polling instrument were considered together to identify potential correlations between IAQ variations due to PBF-SLM operations and the perception of employees within the context of the office space. The employee feedback remained relatively positive throughout all phases in the office space, with only minor variations. Similarly, the IAQ parameters mainly did not exhibit any major variations but only slight variations within established thresholds. Although a correlation was not observed between the changes in the IAQ parameters and employee perception of IAQ, the IAQ parameters being stable and within established thresholds likely contributed to the employees' positive perception. This highlights the importance of maintaining IAQ within acceptable thresholds to foster a favorable perception of indoor air quality.

To sum up, based on all these observations, the variations in the ten measured parameters during PBF-SLM operations were presented in both the PBF-SLM production space and the office space. In the related production space, it was observed that PM values were mainly influenced by the different phases of production. PM_{1.0}, PM_{2.5}, and PM₁₀ levels were notably higher during the pre-printing and post-printing phases compared to the background and printing phases. Despite these fluctuations, the PM_{2.5} and PM₁₀ levels remained below the maximum tolerable levels for both short-term and long-term exposure. For TVOC values, no toxic environment was formed throughout the entire production process. Only a short-term rise necessitating ventilation was observed at the final stage of printing. The values for HCHO remained within the established safe ranges, and no adverse conditions were identified. The concentrations of C₆H₆, C₂H₅OH, and NO₂ were below detectable levels for almost the entire production process. There was a single peak recorded. The fact that this peak was recorded only once suggests it was a momentary spike caused by the sensor. Therefore, the space was considered safe concerning C₆H₆, C₂H₅OH, and NO₂. Lastly, CO₂ and O₂ levels remained within the established safe ranges, and no adverse conditions were identified. When the office space was considered, no adverse conditions were identified for PM_{1.0}, PM_{2.5}, PM₁₀, TVOC, HCHO, C₆H₆, C₂H₅OH, NO₂, CO₂, and O₂ values. Employee perception of IAQ followed a declining pattern in the related production space, while it was mainly positive in the office space across different phases. Additionally, when the results of INBASE and the polling instrument were considered together, no definitive correlation was found between IAQ variations due to PBF-SLM operations and the IAQ perception of employees. However, TVOC concentrations emerged as potentially influential factors on perceived IAQ in the related production space. In the office space, despite the lack of a clear correlation between IAQ parameter changes and employee perception, the stability and maintenance of IAQ within established thresholds likely contributed to the employees' positive perception.

4.3 Field Experiments for Powder Bed Fusion - Selective Laser Sintering

This section presents the real-time air quality monitoring results obtained from INBASE and employee feedback acquired from the Indoor Air Quality Polling Instrument for the PBF-SLS production space and the office space during PBF-SLS operations. Each parameter, including PM_{1.0}, PM_{2.5}, PM₁₀, TVOC, HCHO, C₆H₆, C₂H₅OH, NO₂, CO₂, and O₂, was evaluated for production and office spaces with respect to the established thresholds based on guidelines and standards provided by certain authorities each of which was detailed in the corresponding parts of the section. The unit conversion was applied when necessary using Equation 4-1, Equation 4-2, Equation 4-3, and Equation 4-4 to align the units of specific sensor outputs to the commonly used units in the guidelines.

Air quality guidelines for PM issued by WHO (2021) do not cover PM_{1.0}. Therefore, no safety limit was indicated in Figure 4.24 and Figure 4.25.

Minimum, maximum, and average PM_{1.0} concentrations in the PBF-SLS production space and the office space during PBF-SLS operations, along with the duration of each phase, average temperature, and relative humidity of the space during each phase, are given in Table 4.13.

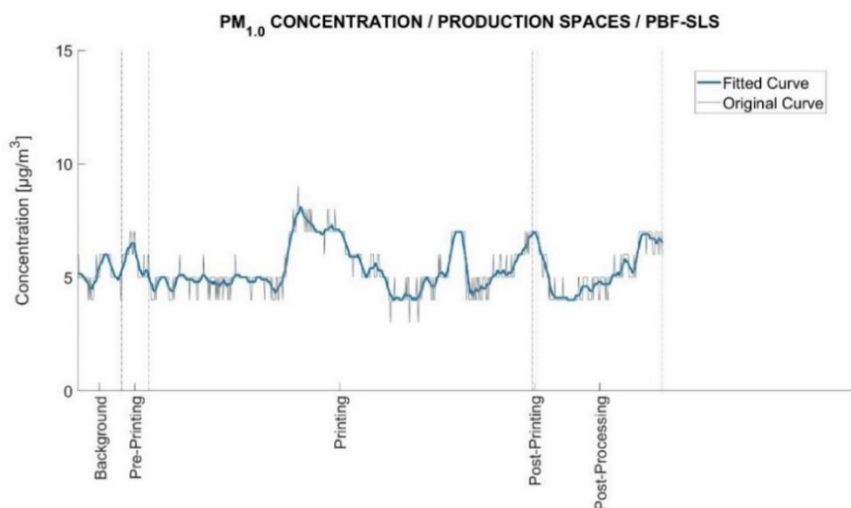
Table 4.13 Descriptive Statistics of PM_{1.0} Concentrations during PBF-SLS

PRODUCTION SPACE		Background	Pre-Printing	Printing	Post-Printing	Post-Processing
	Min (µg/m ³)	4.00	5.00	3.00	7.00	4.00
	Max (µg/m ³)	6.00	7.00	9.00	7.00	7.00
	Avg (µg/m ³)	5.17	5.82	5.36	7.00	5.19
	Time (min)	54	33	469	6	154
	Temp (°C)	25.56	26.76	24.17	24.69	25.73
	RH (%)	38.55	35.79	42.29	45.28	44.24

Table 4.13 (continued)

OFFICE SPACE	Min ($\mu\text{g}/\text{m}^3$)	6.00	6.00	6.00	10.00	10.00
	Max ($\mu\text{g}/\text{m}^3$)	8.00	8.00	11.00	11.00	10.00
	Avg ($\mu\text{g}/\text{m}^3$)	7.21	7.06	8.74	10.42	10.00
	Time (min)	39	25	321	6	28
	Temp ($^{\circ}\text{C}$)	25.06	25.77	26.24	26.25	26.13
	RH (%)	49.53	48.17	45.88	45.42	44.53

The results of $\text{PM}_{1.0}$ concentrations in the PBF-SLS production space during PBF-SLS operations indicated slight variations in $\text{PM}_{1.0}$ concentrations during different phases compared to the background levels. The mean of measurements for background, pre-printing, printing, post-printing, and post-processing were $5.17 \mu\text{g}/\text{m}^3$, $5.82 \mu\text{g}/\text{m}^3$, $5.36 \mu\text{g}/\text{m}^3$, $7.00 \mu\text{g}/\text{m}^3$, and $5.19 \mu\text{g}/\text{m}^3$, respectively. $\text{PM}_{1.0}$ emissions observed in each phase did not drastically differ from background levels. Although PBF-SLS operations are powder-based, the powder management system notably eliminated PM emissions. It can be concluded that PBF-SLS operations did not create significant differences in $\text{PM}_{1.0}$ concentrations in the related production space where these operations took place. $\text{PM}_{1.0}$ concentrations in this production space during PBF-SLS operations in those spaces are illustrated in Figure 4.24.

Figure 4.24 $\text{PM}_{1.0}$ Concentrations in Related Production Space during PBF-SLS

The results of PM_{1.0} concentrations in the office space during PBF-SLS operations indicated minor variations in PM_{1.0} concentrations at different phases. The mean background level was 7.21 µg/m³. The mean values during the pre-printing, printing, post-printing, and post-processing phases did not notably differ from the background with averages of 7.06 µg/m³, 8.74 µg/m³, 10.42 µg/m³, and 10.00 µg/m³, respectively. It can be concluded that PBF-SLS operations did not create major differences in PM_{1.0} concentrations in the office space. PM_{1.0} concentrations in the office space during PBF-SLS operations are presented in Figure 4.25.

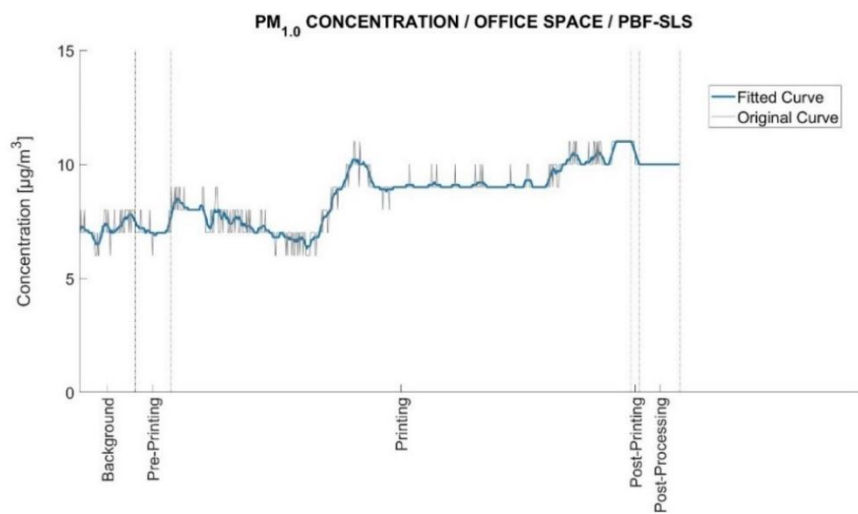


Figure 4.25 PM_{1.0} Concentrations in Office Space during PBF-SLS

Air quality guidelines issued by WHO (2021) are used as threshold values to evaluate PM_{2.5} concentrations. The guideline includes four interim target values and one air quality guideline, with values specified for both annual and 24-hour periods. The annual values are 35, 25, 15, 10, and 5 µg/m³, while the 24-hour values are 75, 50, 37.5, 25, and 15 µg/m³, respectively (World Health Organization, 2021). In Figure 4.26 and Figure 4.27, the annual interim target 1 of PM_{2.5} was labeled as the "Maximum Tolerable Level (Annual)," and the annual air quality guideline of PM_{2.5} was labeled as the "Target Level (Annual)." Similarly, the 24-hour interim target 1 of PM_{2.5} is labeled as the "Maximum Tolerable Level (24-hour)," and the 24-hour air quality guideline of PM_{2.5} is labeled as the "Target Level (24-hour)."

Minimum, maximum, and average PM_{2.5} concentrations in the PBF-SLS production space and the office space during PBF-SLS operations, along with the duration of each phase, average temperature, and relative humidity of the space during each phase, are tabulated in Table 4.14.

Table 4.14 Descriptive Statistics of PM_{2.5} Concentrations during PBF-SLS

		Background	Pre- Printing	Printing	Post- Printing	Post- Processing
PRODUCTION SPACE	Min (µg/m ³)	6.00	7.00	4.00	10.00	5.00
	Max (µg/m ³)	9.00	10.00	13.00	10.00	10.00
	Avg (µg/m ³)	7.48	8.03	7.52	10.00	7.27
	Time (min)	54	33	469	6	154
	Temp (°C)	25.56	26.76	24.17	24.69	25.73
	RH (%)	38.55	35.79	42.29	45.28	44.24
OFFICE SPACE	Min (µg/m ³)	8.00	9.00	8.00	14.00	14.00
	Max (µg/m ³)	11.00	11.00	16.00	16.00	14.00
	Avg (µg/m ³)	10.17	10.06	12.43	14.83	14.00
	Time (min)	39	25	321	6	28
	Temp (°C)	25.06	25.77	26.24	26.25	26.13
	RH (%)	49.53	48.17	45.88	45.42	44.53

The results of PM_{2.5} concentrations in the PBF-SLS production space during PBF-SLS operations exhibited minor variations relative to the background levels. The pre-printing, printing, post-printing, and post-processing average measurements were 8.03 µg/m³, 7.52 µg/m³, 10.00 µg/m³, and 7.27 µg/m³, respectively, where the background level was 7.48 µg/m³. Accordingly, all phases remained below the established thresholds except for the target level for annual exposure. Given that the PM_{2.5} concentrations at any phase did not notably alter from background levels, it can be concluded that PBF-SLS operations did not significantly influence PM_{2.5} emissions in the related production space. PM_{2.5} concentrations in this production space during PBF-SLS operations are inserted in Figure 4.26.

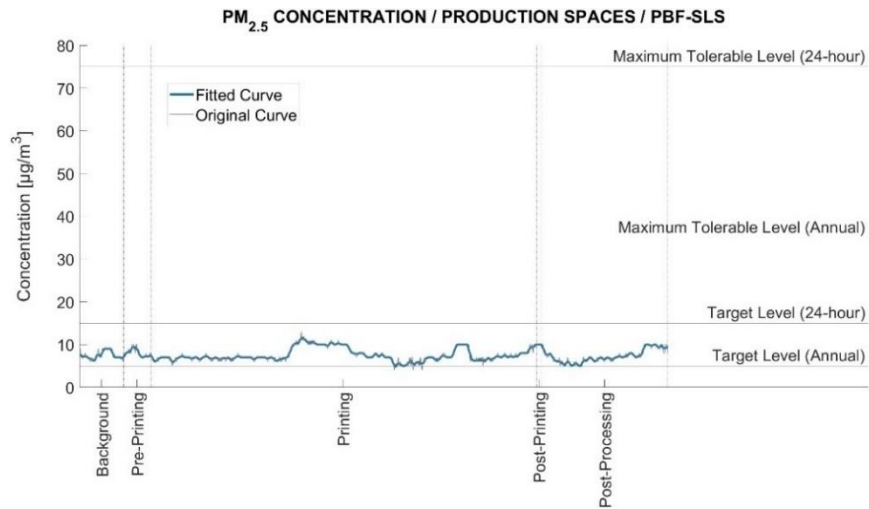


Figure 4.26 PM_{2.5} Concentrations in Related Production Space during PBF-SLS

The results of PM_{2.5} concentrations in the office space during PBF-SLS operations exhibited slight variations relative to the background levels. Pre-printing, printing, post-printing, and post-processing average measurements were 10.06 µg/m³, 12.43 µg/m³, 14.83 µg/m³, and 14.00 µg/m³ respectively where the background level was 10.17 µg/m³. These concentrations, when compared to established thresholds, showed that they remained within the thresholds of maximum tolerable levels for 24-hour and annual exposure durations. However, while the target level for 24-hour exposure was met across all phases, except for slight exceedances observed during the printing phase, attainment of the target level for annual exposure was not achieved across any phase. Given that the PM_{2.5} concentrations at any phase did not significantly differ from background levels, it can be concluded that PBF-SLS operations did not notably influence PM_{2.5} emissions in the office space. PM_{2.5} concentrations in the office space during PBF-SLS operations are provided in Figure 4.27.

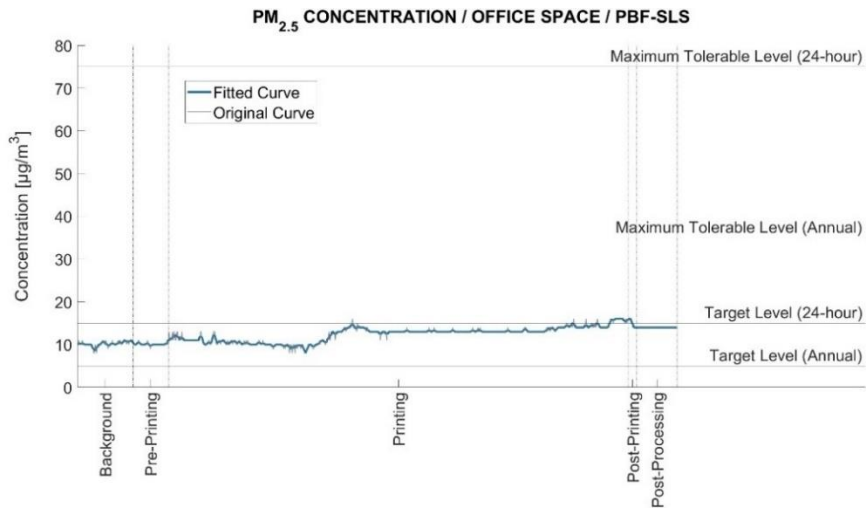


Figure 4.27 PM_{2.5} Concentrations in Office Space during PBF-SLS

Air quality guidelines issued by WHO (2021) are used as threshold values to evaluate PM₁₀ concentrations. The annual values are 70, 50, 30, 20, and 15 $\mu\text{g}/\text{m}^3$, and the 24-hour values are 150, 100, 75, 50, and 45 $\mu\text{g}/\text{m}^3$, respectively (World Health Organization, 2021). In Figure 4.28 and Figure 4.29, the annual interim target 1 of PM₁₀ was labeled as the "Maximum Tolerable Level (Annual)," and the annual air quality guideline of PM₁₀ was labeled as the "Target Value (Annual)." Similarly, the 24-hour interim target 1 of PM₁₀ was labeled as the "Maximum Tolerable Level (24-hour)," and the 24-hour air quality guideline of PM₁₀ was labeled as the "Target Value (24-hour)".

Minimum, maximum, and average PM₁₀ concentrations in the PBF-SLS production space and the office space during PBF-SLS operations, along with the duration of each phase, average temperature, and relative humidity of the space during each phase, are given in Table 4.15.

Table 4.15 Descriptive Statistics of PM₁₀ Concentrations during PBF-SLS

		Background	Pre- Printing	Printing	Post- Printing	Post- Processing
PRODUCTION SPACE	Min (µg/m ³)	6.00	7.00	4.00	10.00	5.00
	Max (µg/m ³)	9.00	10.00	13.00	10.00	10.00
	Avg (µg/m ³)	7.48	8.03	7.47	10.00	7.27
	Time (min)	54	33	469	6	154
	Temp (°C)	25.56	26.76	24.17	24.69	25.73
	RH (%)	38.55	35.79	42.29	45.28	44.24
OFFICE SPACE	Min (µg/m ³)	8.00	9.00	8.00	14.00	14.00
	Max (µg/m ³)	11.00	11.00	18.00	18.00	15.00
	Avg (µg/m ³)	10.17	10.06	12.62	16.17	14.09
	Time (min)	39	25	321	6	28
	Temp (°C)	25.06	25.77	26.24	26.25	26.13
	RH (%)	49.53	48.17	45.88	45.42	44.53

The results of PM₁₀ concentrations in the PBF-SLS production space during PBF-SLS operations implied slight variations relative to the background levels. The minimum PM₁₀ concentration during the background measurements was 6.00 µg/m³, while the maximum was 9.00 µg/m³, with an average of 7.48 µg/m³. Throughout the pre-printing, printing, post-printing, and post-processing phases, PM₁₀ concentrations experienced modest changes, with average values of 8.03 µg/m³, 7.47 µg/m³, 10.00 µg/m³, and 7.27 µg/m³ respectively. These values, when compared to established thresholds, showed that all phases remained within the thresholds of maximum tolerable levels for 24-hour and annual exposure and target levels for 24-hour and annual average exposure. Given that the PM₁₀ concentrations at any phase did not notably deviate from background levels, it can be concluded that PBF-SLS operations did not significantly influence PM₁₀ emissions in the related production space. PM₁₀ concentrations in this production space during PBF-SLS operations are illustrated in Figure 4.28.

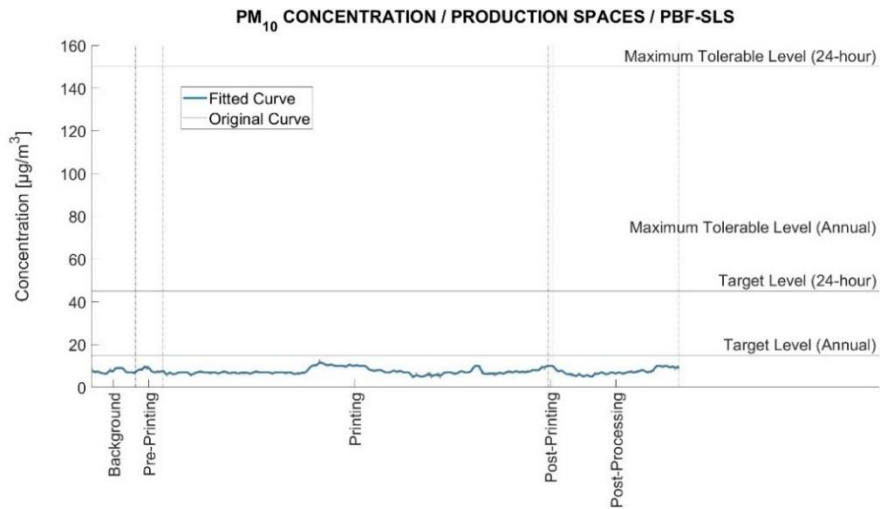


Figure 4.28 PM₁₀ Concentrations in Related Production Space during PBF-SLS

The results of PM₁₀ concentrations in the office space during PBF-SLS operations implied slight variations relative to the background levels. The minimum PM₁₀ concentration during the background measurements was 8.00 µg/m³, while the maximum reached 11.00 µg/m³, with an average of 10.17 µg/m³. Throughout the pre-printing, printing, post-printing, and post-processing phases, PM₁₀ concentrations experienced modest increases, with average values of 10.06 µg/m³, 12.62 µg/m³, 16.17 µg/m³, and 14.09 µg/m³ respectively. The maximum concentration, 18.00 µg/m³, was recorded during the printing and post-printing phases. These values, when compared to established thresholds, showed that all phases remained below threshold values except for slight exceedances observed during the printing and post-printing phases. Given that the PM₁₀ concentrations at any phase did not notably drift from background levels, it can be concluded that PBF-SLS operations did not significantly affect PM₁₀ emissions in the office space. PM₁₀ concentrations in the office space during PBF-SLS operations are presented in Figure 4.29.

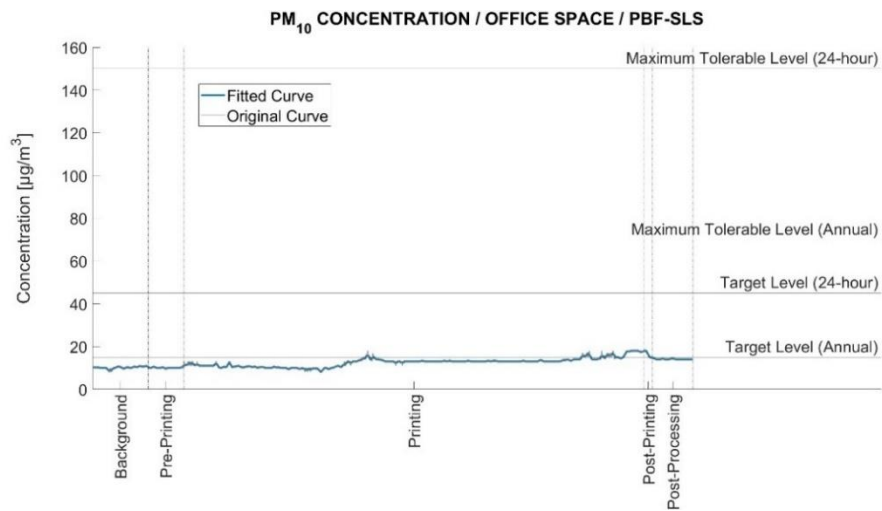


Figure 4.29 PM₁₀ Concentrations in Office Space during PBF-SLS

The categorization of TVOC levels issued by the Umweltbundesamt (UBA), the Federal Environmental Agency in Germany (2007), was adopted to evaluate TVOC concentration. Accordingly, in Figure 4.30 and Figure 4.31, delineations were made based on five levels: Level 1 ($< 0.3 \text{ mg/m}^3$), Level 2 ($0.3\text{-}1 \text{ mg/m}^3$), Level 3 ($1\text{-}3 \text{ mg/m}^3$), Level 4 ($3\text{-}10 \text{ mg/m}^3$), and Level 5 ($10\text{-}25 \text{ mg/m}^3$). Level 1 serves as a target value without hygienic concerns. Level 2 does not indicate significant issues but necessitates increased ventilation. At Level 3, hygienic concerns arise, prompting source investigation and increased ventilation, particularly over a maximum duration of 12 months. Level 4 indicates significant concerns, with a maximum toleration duration of a month, necessitating restricted usage and intensified ventilation. Level 5 signifies unacceptable concentrations, permitting usage only if unavoidable and for short durations, with increased ventilation measures (Bekanntmachung des Umweltbundesamtes, 2007).

The commonly used unit and the units specified in this guideline for TVOC concentration are mg/m^3 . Given that the TVOC sensor outputs data in ppb, Equation 4-1 and Equation 4-2 were employed to convert the ppb readings to mg/m^3 . The molecular weight of TVOC is 110 g/mol (Sensirion, 2019).

Minimum, maximum, and average TVOC concentrations in the PBF-SLS production space and the office space during PBF-SLS operations, along with the

duration of each phase, average temperature, and relative humidity of the space during each phase, are tabulated in Table 4.16.

Table 4.16 Descriptive Statistics of TVOC Concentrations during PBF-SLS

		Background	Pre- Printing	Printing	Post- Printing	Post- Processing
PRODUCTION SPACE	Min (mg/m ³)	0.00	0.01	0.00	0.10	0.00
	Max (mg/m ³)	0.16	0.32	2.28	0.22	0.85
	Avg (mg/m ³)	0.05	0.13	0.26	0.18	0.22
	Time (min)	54	33	469	6	154
	Temp (°C)	25.56	26.76	24.17	24.69	25.73
	RH (%)	38.55	35.79	42.29	45.28	44.24
OFFICE SPACE	Min (mg/m ³)	0.00	0.00	0.00	0.75	0.56
	Max (mg/m ³)	0.65	0.04	1.70	0.85	1.22
	Avg (mg/m ³)	0.28	0.01	0.33	0.81	0.72
	Time (min)	39	25	321	6	28
	Temp (°C)	25.06	25.77	26.24	26.25	26.13
	RH (%)	49.53	48.17	45.88	45.42	44.53

The results of TVOC concentrations in the PBF-SLS production space during PBF-SLS operations suggested slight variations in different phases compared to background levels and established threshold values. The average TVOC concentration during the background measurements was 0.05 mg/m³. Throughout the pre-printing, post-printing, and post-processing phases, TVOC concentrations remained relatively low, with average values of 0.13 mg/m³, 0.18 mg/m³, and 0.22 mg/m³ respectively. The TVOC levels during background levels and these phases, except for the last segment of the post-processing phase, remained mainly below level 1, indicating target value without hygienic concerns. On the other hand, the TVOC levels during the printing phase fall within levels 1 to 3, necessitating increased ventilation. However, TVOC levels did not reach unacceptable levels at any point, and certain phases witnessed levels requiring increased ventilation and

source investigation in the related production space. TVOC concentrations in this production space during PBF-SLS operations are inserted in Figure 4.30.

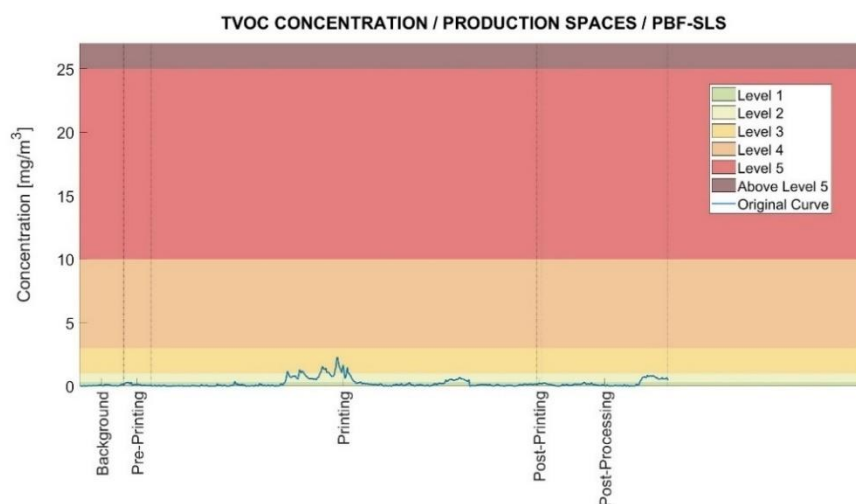


Figure 4.30 TVOC Concentrations in Related Production Space during PBF-SLS

The results of TVOC concentrations in the office space during PBF-SLS operations suggested slight variations in TVOC concentrations during different phases compared to the background levels. The average background level was 0.28 mg/m³. Although the average value remained below level 1, several values recorded during this phase fall between level 1 and level 2, requiring ventilation while not indicating significant concerns. The mean measurements for pre-printing, printing, post-printing, and post-processing were 0.01 mg/m³, 0.33 mg/m³, 0.81 mg/m³, and 0.72 mg/m³, respectively. The pre-printing phase remained below level 1 without any hygienic concerns. The printing phase included values exceeding level 1 and reaching level 3, requiring increased ventilation and source investigation. The post-printing phase remained below level 2, requiring ventilation while not indicating significant concerns. The post-processing phase remained below level 3 except for an intermittent peak, therefore requiring increased ventilation and source investigation. Consequently, although PBF-SLS operations occurring in the PBF-SLS production space did not cause TVOC levels in the office space to diverge from background levels, increased ventilation is necessary to eliminate any

concentration above level 1. TVOC concentrations in the office space during PBF-SLS operations are provided in Figure 4.31.

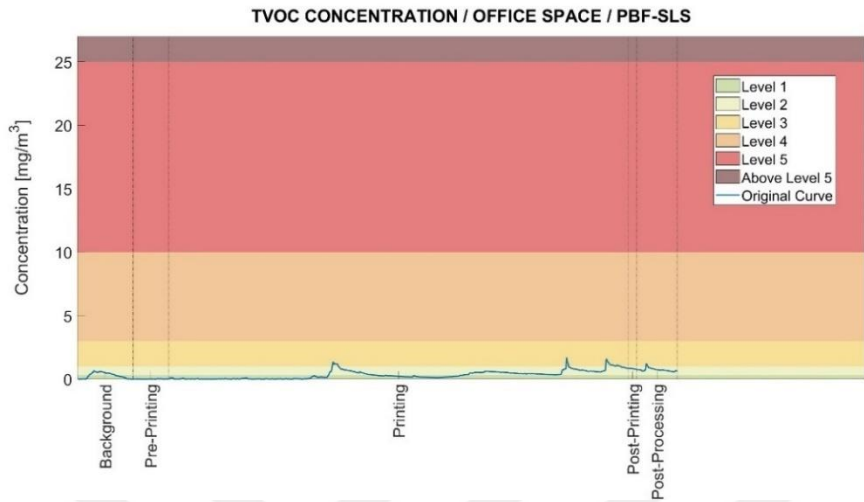


Figure 4.31 TVOC Concentrations in Office Space during PBF-SLS

The HCHO guideline value of 0.1 mg/m³ given by WHO (2000) for a 30-minute average is taken as the threshold value. Consequently, in Figure 4.32 and Figure 4.33, 0.1 mg/m³ was delineated as the “Maximum Safe Level (30-minute).”

The commonly used unit and the unit specified in this guideline for HCHO concentration are mg/m³. Given that the HCHO sensor outputs data in ppb, Equation 4-1 and Equation 4-2 were employed to convert the ppb readings to mg/m³. The molecular weight of HCHO is 30.026 g/mol (National Center for Biotechnology Information, 2024b).

Minimum, maximum, and average HCHO concentrations in the PBF-SLS production space and the office space during PBF-SLS operations, along with the duration of each phase, average temperature, and relative humidity of the space during each phase, are given in Table 4.17.

Table 4.17 Descriptive Statistics of HCHO Concentrations during PBF-SLS

		Background	Pre- Printing	Printing	Post- Printing	Post- Processing
PRODUCTION SPACE	Min (mg/m ³)	0.002	0.001	0.001	0.002	0.001
	Max (mg/m ³)	0.002	0.001	0.004	0.002	0.005
	Avg (mg/m ³)	0.002	0.001	0.002	0.002	0.002
	Time (min)	54	33	469	6	154
	Temp (°C)	25.56	26.76	24.17	24.69	25.73
	RH (%)	38.55	35.79	42.29	45.28	44.24
OFFICE SPACE	Min (mg/m ³)	0.002	0.002	0.001	0.002	0.002
	Max (mg/m ³)	0.002	0.002	0.003	0.002	0.002
	Avg (mg/m ³)	0.002	0.002	0.002	0.002	0.002
	Time (min)	39	25	321	6	28
	Temp (°C)	25.06	25.77	26.24	26.25	26.13
	RH (%)	49.53	48.17	45.88	45.42	44.53

The results of HCHO concentrations in the PBF-SLS production space during PBF-SLS operations indicated almost indistinguishable variations in HCHO concentrations during different phases compared to the background levels. The mean HCHO concentrations during the background, pre-printing, printing, post-printing, and post-processing phases were 0.002 mg/m³, 0.001 mg/m³, 0.002 mg/m³, 0.002 mg/m³, and 0.002 mg/m³. Although there were HCHO emissions associated with each phase, they were way below the 30-minute maximum safety level and indistinguishable from background levels. Accordingly, it can be concluded that PBF-SLS operations did not contribute to HCHO concentrations in the related production space where these operations took place. HCHO concentrations in this production space during PBF-SLS operations are illustrated in Figure 4.32.

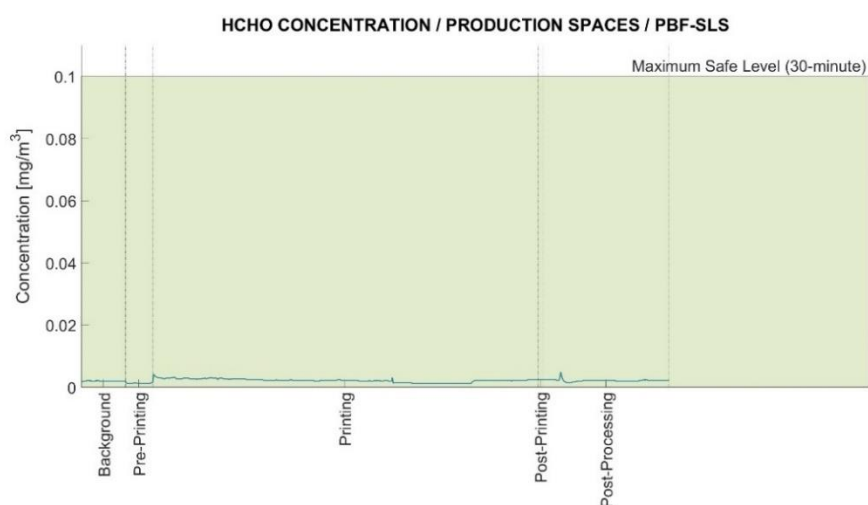


Figure 4.32 HCHO Concentrations in Related Production Space during PBF-SLS

The HCHO concentrations in the office space during PBF-SLS operations varied between 0.001 mg/m³ and 0.003 mg/m³. The values did not differ from background levels and were way below the 30-minute maximum safety level. Hence, it can be concluded that PBF-SLS operations taking place in the PBF-SLS production space did not cause HCHO concentrations in the office space. HCHO concentrations in the office space during PBF-SLS operations are presented in Figure 4.33.

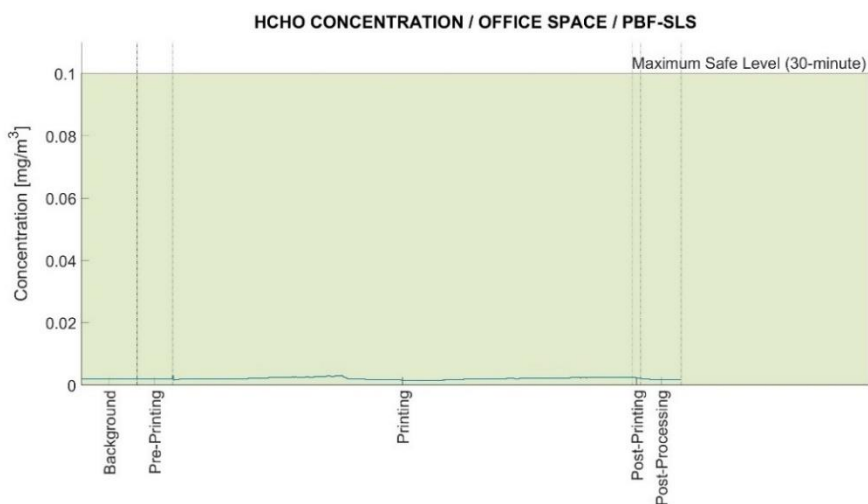


Figure 4.33 HCHO Concentrations in Office Space during PBF-SLS

WHO does not state a safe level of exposure for C₆H₆. Thus, no safety limit was indicated in Figure 4.34 and Figure 4.35.

The commonly used unit for C_6H_6 concentration is mg/m^3 . Given that the C_6H_6 sensor outputs data in ppm, Equation 4-2 and Equation 4-4 were employed to convert the mg/m^3 readings to $\mu g/m^3$. The molecular weight of C_6H_6 is 78.11 g/mol (National Center for Biotechnology Information, 2024a).

Minimum, maximum, and average C_6H_6 concentrations in the PBF-SLS production space and the office space during PBF-SLS operations, along with the duration of each phase, average temperature, and relative humidity of the space during each phase, are tabulated in Table 4.18.

Table 4.18 Descriptive Statistics of C_6H_6 Concentrations during PBF-SLS

		Background	Pre- Printing	Printing	Post- Printing	Post- Processing
PRODUCTION SPACE	Min (mg/m^3)	0.00	0.00	0.00	0.00	0.00
	Max (mg/m^3)	0.00	0.00	0.00	0.00	0.00
	Avg (mg/m^3)	0.00	0.00	0.00	0.00	0.00
	Time (min)	54	33	469	6	154
	Temp ($^{\circ}C$)	25.56	26.76	24.17	24.69	25.73
	RH (%)	38.55	35.79	42.29	45.28	44.24
OFFICE SPACE	Min (mg/m^3)	0.00	0.00	0.00	0.00	0.00
	Max (mg/m^3)	0.00	0.00	0.00	0.00	0.00
	Avg (mg/m^3)	0.00	0.00	0.00	0.00	0.00
	Time (min)	39	25	321	6	28
	Temp ($^{\circ}C$)	25.06	25.77	26.24	26.25	26.13
	RH (%)	49.53	48.17	45.88	45.42	44.53

The results of C_6H_6 concentrations in the PBF-SLS production space during PBF-SLS operations revealed that the C_6H_6 concentrations remained at a consistent minimum of $0.00\ mg/m^3$ during all of the phases, indicating no detectable emissions during these periods. Hence, it can be concluded that PBF-SLS operations did not cause C_6H_6 emissions. C_6H_6 concentrations in the related production space during PBF-SLS operations are inserted in Figure 4.34.

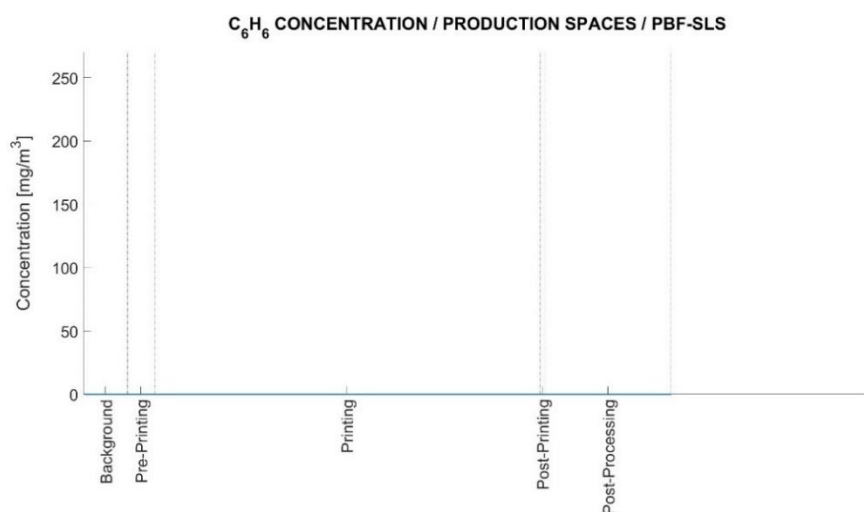


Figure 4.34 C_6H_6 Concentrations in Related Production Space during PBF-SLS

The results of C_6H_6 concentrations in the office space during PBF-SLS operations revealed that C_6H_6 concentrations remained at a consistent minimum of 0.00 mg/m^3 during the background, pre-printing, printing, post-printing, and post-processing phases, indicating no detectable emissions during these periods. Hence, it can be concluded that PBF-SLS operations taking place in the PBF-SLS production space did not cause C_6H_6 emissions in the office space. C_6H_6 concentrations in the office space during PBF-SLS operations are given in Figure 4.35.

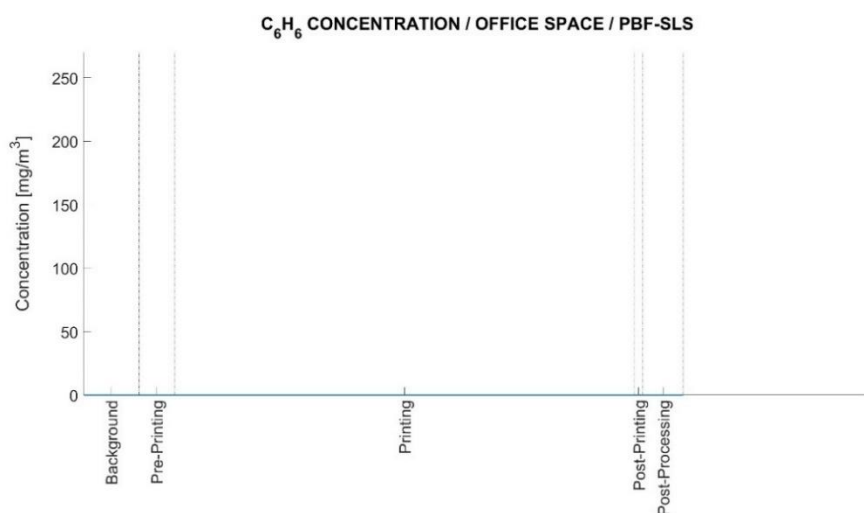


Figure 4.35 C_6H_6 Concentrations in Office Space during PBF-SLS

Not being a typical indoor air quality pollutant, OSHA, NIOSH, and ACGIH set the workplace exposure limit to 1000 ppm for an 8-hour permissible exposure limit, 10-hour recommended exposure limit, and short-term threshold limit value (Occupational Safety and Health Administration, n.d.) for C₂H₅OH exposure. The odor threshold of C₂H₅OH is 84 ppm (New Jersey Department of Health, 2011). In Figure 4.36 and Figure 4.37, 84 ppm was delineated as the “Odor Threshold.” As the concentrations were below each of these values, the Workplace Exposure Limit of 1000 ppm was not indicated in those figures.

Minimum, maximum, and average C₂H₅OH concentrations in the PBF-SLS production space and the office space during PBF-SLS operations, along with the duration of each phase, average temperature, and relative humidity of the space during each phase, are illustrated in Table 4.19.

Table 4.19 Descriptive Statistics of C₂H₅OH Concentrations during PBF-SLS

		Background	Pre- Printing	Printing	Post- Printing	Post- Processing
PRODUCTION SPACE	Min (ppm)	0.00	0.00	0.00	0.00	0.00
	Max (ppm)	0.00	0.00	0.00	0.00	0.00
	Avg (ppm)	0.00	0.00	0.00	0.00	0.00
	Time (min)	54	33	469	6	154
	Temp (°C)	25.56	26.76	24.17	24.69	25.73
	RH (%)	38.55	35.79	42.29	45.28	44.24
OFFICE SPACE	Min (ppm)	0.00	0.00	0.00	0.00	0.00
	Max (ppm)	0.00	0.00	0.00	0.00	0.00
	Avg (ppm)	0.00	0.00	0.00	0.00	0.00
	Time (min)	39	25	321	6	28
	Temp (°C)	25.06	25.77	26.24	26.25	26.13
	RH (%)	49.53	48.17	45.88	45.42	44.53

The results of C_2H_5OH concentrations in the PBF-SLS production space during PBF-SLS operations suggested that the C_2H_5OH concentrations remained at a consistent minimum of 0.00 ppm during all of the phases, indicating no detectable emissions during any of the periods. Therefore, it can be concluded that PBF-SLS operations did not cause C_2H_5OH emissions. C_2H_5OH concentrations in the related production space during PBF-SLS operations are inserted in Figure 4.36.

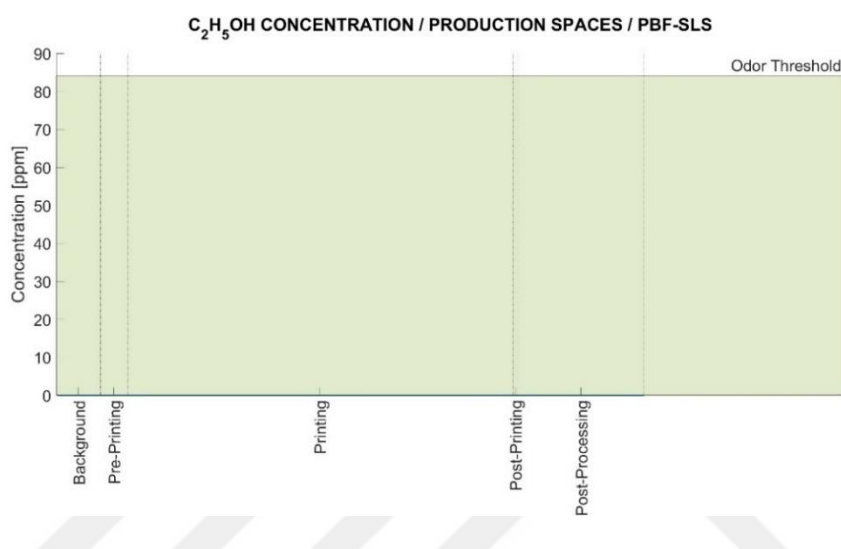


Figure 4.36 C_2H_5OH Concentrations in Related Production Space during PBF-SLS

The results of C_2H_5OH concentrations in the office space during PBF-SLS operations suggested that the C_2H_5OH concentrations remained at a consistent minimum of 0.00 ppm during the background, pre-printing, printing, post-printing, and post-processing phases, indicating no detectable emissions during any of the periods. Consequently, it can be concluded that PBF-SLS operations taking place in the related production space did not cause C_2H_5OH concentrations in the office space. C_2H_5OH concentrations in the office space during PBF-SLS operations are given in Figure 4.37.

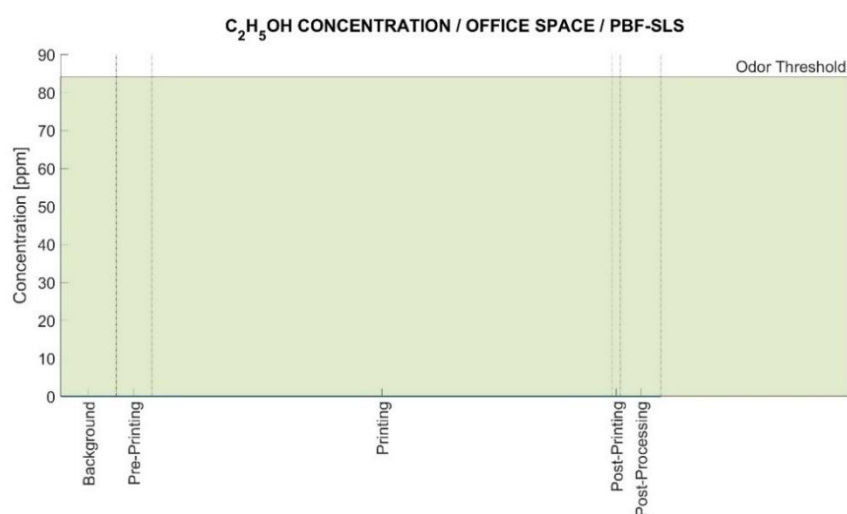


Figure 4.37 C₂H₅OH Concentrations in Office Space during PBF-SLS

Air quality guidelines issued by WHO (2021) are used as threshold values to evaluate NO₂ concentrations. The guideline includes three interim target values for annual exposure, one air quality guideline value for annual exposure, two interim target values for 24-hour exposure, and one air quality guideline value for 24-hour exposure. The annual values are 40, 30, 20, and 10 µg/m³, while the 24-hour values are 120, 50, and 25 µg/m³, respectively (World Health Organization, 2021). In Figure 4.38 and Figure 4.39, the annual interim target 1 is labeled as the "Maximum Tolerable Level (Annual)," and the annual air quality guideline value is labeled as the "Target Level (Annual)." Similarly, the 24-hour interim target 1 is labeled as the "Maximum Tolerable Level (24-hour)," and the 24-hour air quality guideline value is labeled as the "Target Level (24-hour)."

The commonly used unit and the units specified in this guideline for NO₂ concentration are µg/m³. Given that the NO₂ sensor outputs data in ppm, Equation 4-2 and Equation 4-4 were employed to convert the mg/m³ readings to µg/m³. The molecular weight of NO₂ is 46.006 g/mol (National Center for Biotechnology Information, 2024c).

Minimum, maximum, and average NO₂ concentrations in the PBF-SLS production space and the office space during PBF-SLS operations, along with the duration of

each phase, average temperature, and relative humidity of the space during each phase, are illustrated in Table 4.20.

Table 4.20 Descriptive Statistics of NO₂ Concentrations during PBF-SLS

		Background	Pre- Printing	Printing	Post- Printing	Post- Processing
PRODUCTION SPACE	Min (µg/m ³)	0.00	0.00	0.00	0.00	0.00
	Max (µg/m ³)	0.00	0.00	23.93	0.00	0.00
	Avg (µg/m ³)	0.00	0.00	2.91	0.00	0.00
	Time (min)	54	33	469	6	154
	Temp (°C)	25.56	26.76	24.17	24.69	25.73
	RH (%)	38.55	35.79	42.29	45.28	44.24
OFFICE SPACE	Min (µg/m ³)	0.00	0.00	0.00	0.00	0.00
	Max (µg/m ³)	0.00	0.00	0.00	0.00	0.00
	Avg (µg/m ³)	0.00	0.00	0.00	0.00	0.00
	Time (min)	39	25	321	6	28
	Temp (°C)	25.06	25.77	26.24	26.25	26.13
	RH (%)	49.53	48.17	45.88	45.42	44.53

The results of NO₂ concentrations in the PBF-SLS production space during PBF-SLS operations suggested that the NO₂ concentrations remained at a consistent minimum of 0.00 µg/m³ during the background, pre-printing, post-printing, and post-processing phases, indicating no detectable emissions. However, during the printing phase, NO₂ levels showed a notable increase, with a peak at 23.93 µg/m³. Although the average value in the pre-printing phase was below the established thresholds, the peaks observed in this phase exceeded the target level for annual exposure. Given that the Multichannel V2 is a qualitative sensor, the quantified values may not represent exact measurements but rather approximate estimates. Thus, while there were some exceedances during the printing phase, NO₂ emissions mostly remained within acceptable safety thresholds. NO₂ concentrations in the related production space during PBF-SLS operations are presented in Figure 4.38.

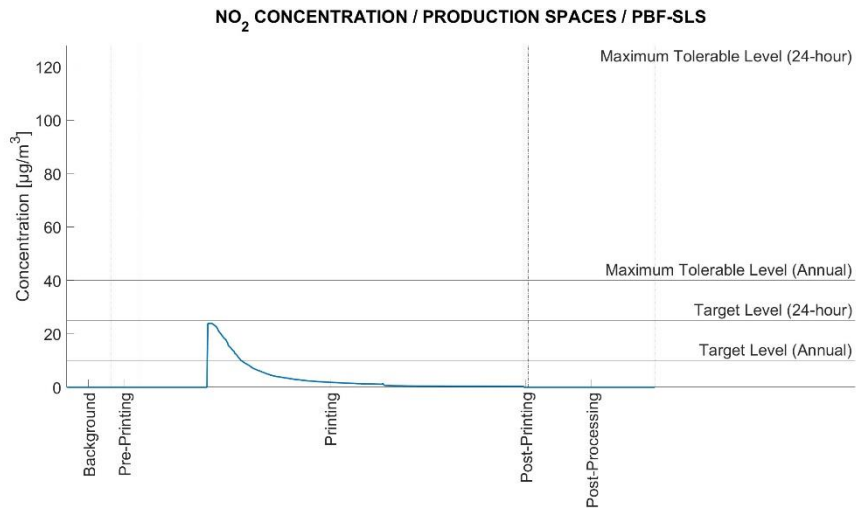


Figure 4.38 NO₂ Concentrations in Related Production Space during PBF-SLS

The results of NO₂ concentrations in the office space during PBF-SLS operations suggested that the NO₂ concentrations remained at 0.00 µg/m³ during all of the phases. It can be concluded that PBF-SLS operations in the related production space did not cause NO₂ concentrations in the office space. NO₂ concentrations in the office space during PBF-SLS operations are tabulated in Figure 4.39.

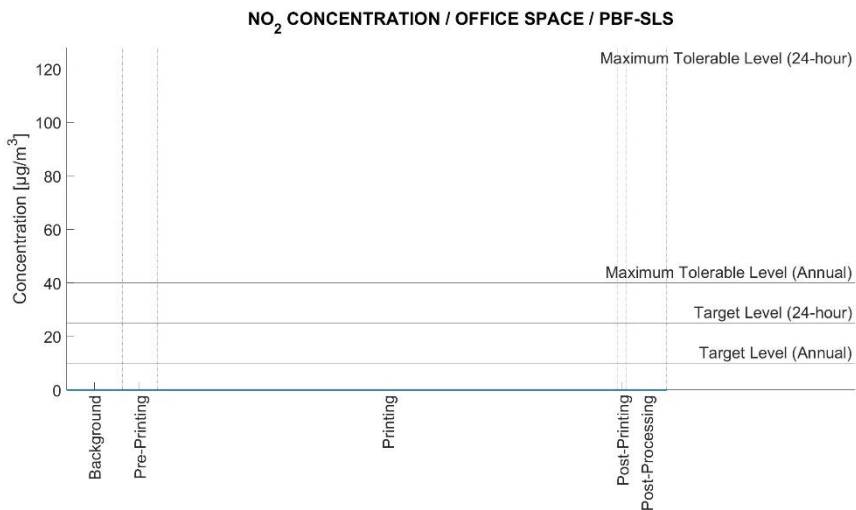


Figure 4.39 NO₂ Concentrations in Office Space during PBF-SLS

The typical outdoor CO₂ concentration is 400 ppm. The indoor CO₂ concentration of a poorly ventilated space corresponds to 1100 ppm (López et al., 2023). Hence, these values were taken as threshold values to evaluate CO₂ concentration. In

Figure 4.40 and Figure 4.41, 400 ppm was delineated as the “Typical Outdoor Level,” while 1100 ppm was given as the “Maximum Indoor Level.” Consequently, the values between 400-1100 ppm were considered acceptable.

Minimum, maximum, and average CO₂ concentrations in the PBF-SLS production space and the office space during PBF-SLS operations, along with the duration of each phase, average temperature, and relative humidity of the space during each phase, are illustrated in Table 4.21.

Table 4.21 Descriptive Statistics of CO₂ Concentrations during PBF-SLS

		Background	Pre- Printing	Printing	Post- Printing	Post- Processing
PRODUCTION SPACE	Min (ppm)	393.77	392.59	368.58	410.78	412.92
	Max (ppm)	432.48	503.40	630.56	412.40	994.53
	Avg (ppm)	408.12	459.21	405.20	411.73	514.67
	Time (min)	54	33	469	6	154
	Temp (°C)	25.56	26.76	24.17	24.69	25.73
	RH (%)	38.55	35.79	42.29	45.28	44.24
OFFICE SPACE	Min (ppm)	441.41	493.17	443.01	666.79	576.39
	Max (ppm)	537.40	545.97	920.95	710.65	664.81
	Avg (ppm)	481.28	518.26	585.70	684.33	602.53
	Time (min)	39	25	321	6	28
	Temp (°C)	25.06	25.77	26.24	26.25	26.13
	RH (%)	49.53	48.17	45.88	45.42	44.53

According to the results of CO₂ concentrations in the PBF-SLS production space during PBF-SLS operations, the mean concentrations during the background, pre-printing, printing, and post-printing phases were 408.12 ppm, 459.21 ppm, 405.20 ppm, and 411.73 ppm. The post-processing phase demonstrated an increase, with an average concentration of 514.67 ppm and a maximum of 994.53 ppm. Despite deviations from background levels in the related production space caused by PBF-SLS operations, CO₂ concentrations were in the acceptable range of 400-1100 ppm.

CO₂ concentrations in this production space during PBF-SLS operations are presented in Figure 4.40.

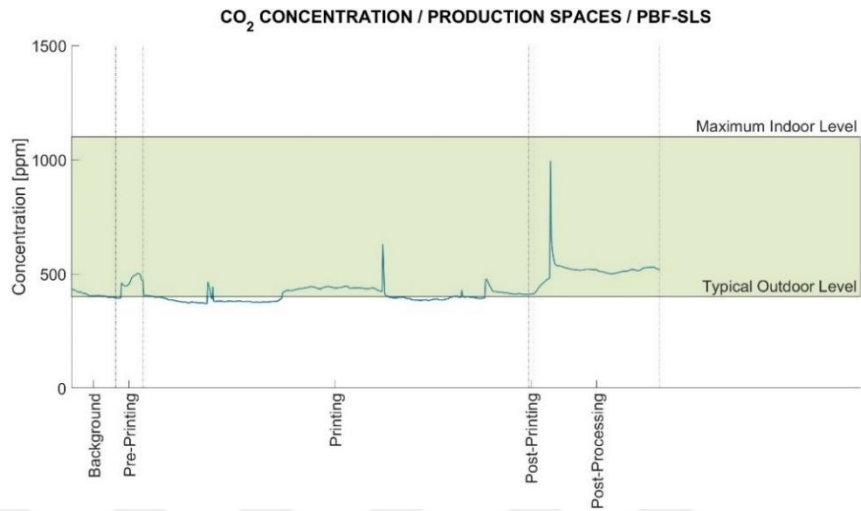


Figure 4.40 CO₂ Concentrations in Related Production Space during PBF-SLS

According to CO₂ concentrations in the office space during PBF-SLS operations, the measured CO₂ concentrations revealed variations between 441.41 ppm and 920.95 ppm. All the recorded values fell within the acceptable range of 400-1100 ppm. CO₂ concentrations in the office space during PBF-SLS operations are tabulated in Figure 4.41.

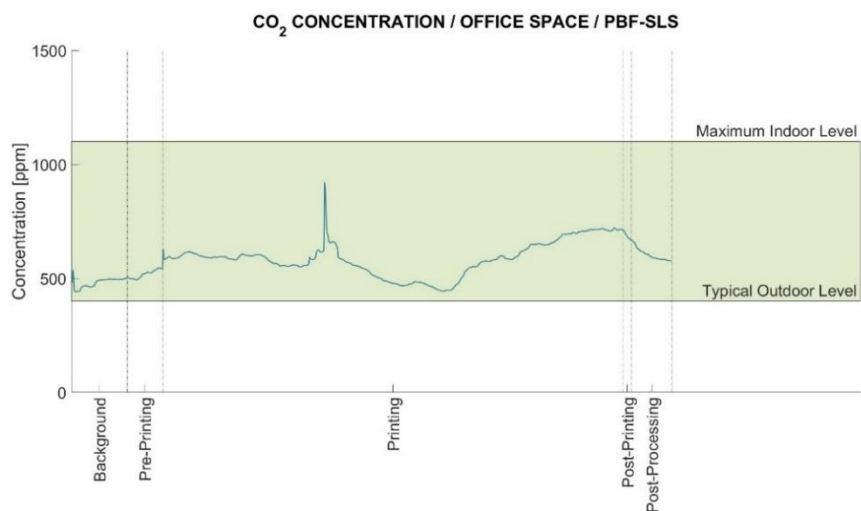


Figure 4.41 CO₂ Concentrations in Office Space during PBF-SLS

An oxygen concentration below 19.5% by volume is classified as deficient in oxygen content. The atmospheric air necessitates oxygen levels ranging from 19.5% to 23.5% at sea level. The volume of oxygen in atmospheric air is typically 20.95% across every elevation (Spelce et al., 2016). Therefore, these values were adopted as threshold values to evaluate O₂ concentration. In Figure 4.42 and Figure 4.43, 19.5% was delineated as the “Minimum Safe Level, while 23.5% was given as the “Maximum Safe Level.” Additionally, 20.95% was depicted as “Typical O₂ Concentration”.

Minimum, maximum, and average O₂ concentrations in the PBF-SLS production space and the office space during PBF-SLS operations, along with the duration of each phase, average temperature, and relative humidity of the space during each phase, are inserted in Table 4.22.

Table 4.22 Descriptive Statistics of O₂ Concentrations during PBF-SLS

		Background	Pre- Printing	Printing	Post- Printing	Post- Processing
PRODUCTION SPACE	Min (%)	20.95	21.09	20.77	21.00	21.00
	Max (%)	21.27	21.36	21.36	21.09	21.36
	Avg (%)	21.08	21.15	21.03	21.05	21.09
	Time (min)	54	33	469	6	154
	Temp (°C)	25.56	26.76	24.17	24.69	25.73
	RH (%)	38.55	35.79	42.29	45.28	44.24
OFFICE SPACE	Min (%)	20.91	21.00	20.95	21.00	20.95
	Max (%)	21.23	21.27	21.36	21.23	21.32
	Avg (%)	21.03	21.08	21.08	21.04	21.05
	Time (min)	39	25	321	6	28
	Temp (°C)	25.06	25.77	26.24	26.25	26.13
	RH (%)	49.53	48.17	45.88	45.42	44.53

The results of O₂ concentrations in the PBF-SLS production space during PBF-SLS operations pointed out that O₂ concentrations remained stable and maintained within safe limits throughout all phases, indistinguishable from background levels. While the minimum recorded concentration was 20.77%, the maximum concentration was 21.36%. Therefore, it can be concluded that PBF-SLS operations did not influence O₂ concentration in the related production space. O₂ concentrations in this production space during PBF-SLS operations are provided in Figure 4.42.

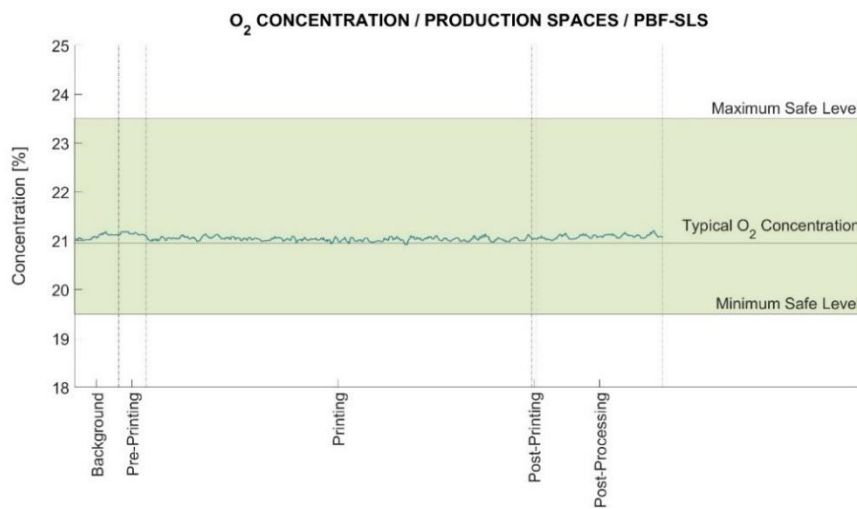


Figure 4.42 O₂ Concentrations in Related Production Space during PBF-SLS

The results of O₂ concentrations in the office space during PBF-SLS operations pointed out that O₂ concentrations remained relatively stable and maintained within safe limits throughout all phases, indistinguishable from background levels. While the minimum recorded concentration was 20.91%, the maximum concentration was 21.36%. Accordingly, it can be concluded that PBF-SLS operations taking place in the related production space did not influence O₂ concentration in the office space. O₂ concentrations in the office space during PBF-SLS operations are given in Figure 4.43.

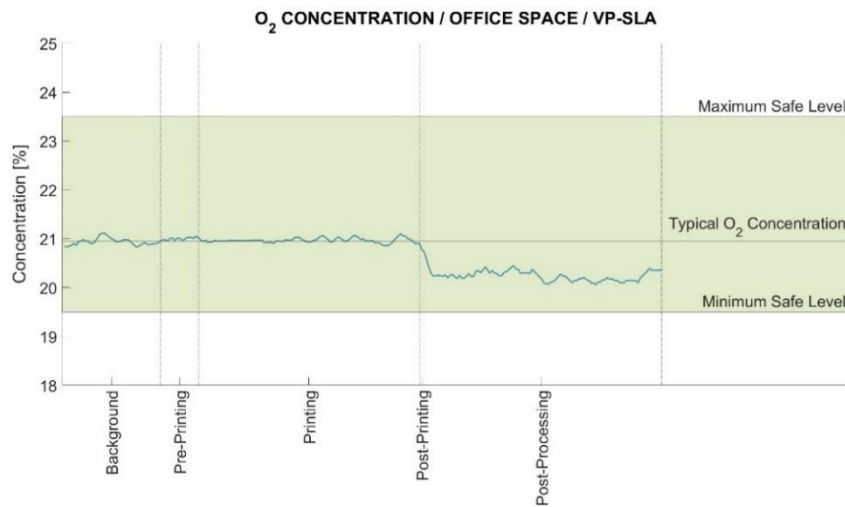


Figure 4.43 O₂ Concentrations in Office Space during PBF-SLS

Employee feedback regarding the perception of IAQ on a scale ranging from very good to very bad, gathered from the Indoor Air Quality Polling Instrument, was quantified using a weighted average method, with the following coefficients assigned to each category: "very bad" (1), "bad" (2), "neutral" (3), "good" (4), and "very good" (5). In Figure 4.44 and Figure 4.45, the categories from very bad to very good were represented by colors ranging from red to green.

The results of employee perception of IAQ in the PBF-SLS production space during PBF-SLS operations indicated that weighted averages of ratings during the background, pre-printing, printing, post-printing, and post-processing phases were 3.33, 3.00, 3.75, 4.00, and 3.25 out of 5.00, respectively. The results suggested that employees perceived the IAQ as above the neutral point during all operational phases. The employee perception of IAQ in the related production space during PBF-SLS operations gathered from the polling instrument is illustrated in Figure 4.44.

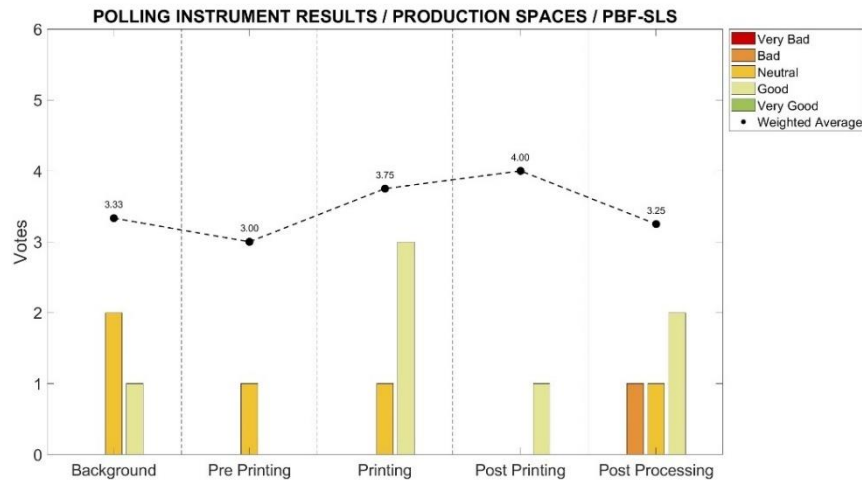


Figure 4.44 Employee Perception of IAQ in Related Production Space during PBF-SLS

The results of INBASE and the polling instrument were considered together to identify potential correlations between IAQ variations due to PBF-SLS operations and the perception of employees within the context of the PBF-SLS production space. The employee feedback, which ranged from neutral to good throughout all phases of PBF-SLS operations, did not exhibit a direct or obvious correlation with any of the specific IAQ parameters measured. However, the consistent feedback ranging from neutral to good suggested that the employees did not perceive any significant deterioration in IAQ that could be directly linked to the parameters measured, as they remained within mainly established thresholds.

The results of employee perception of IAQ in the office space during PBF-SLS operations indicated that weighted averages of ratings during the background, pre-printing, printing, post-printing, and post-processing phases were 4.00, 4.00, 4.00, 4.00, and 3.50 out of 5.00, respectively. The results suggested that the IAQ in office space was generally perceived as good with a saddle variation, close to neutral, during the post-processing phase. The employee perception of IAQ in the office space during PBF-SLS operations gathered from the polling instrument is illustrated in Figure 4.45.

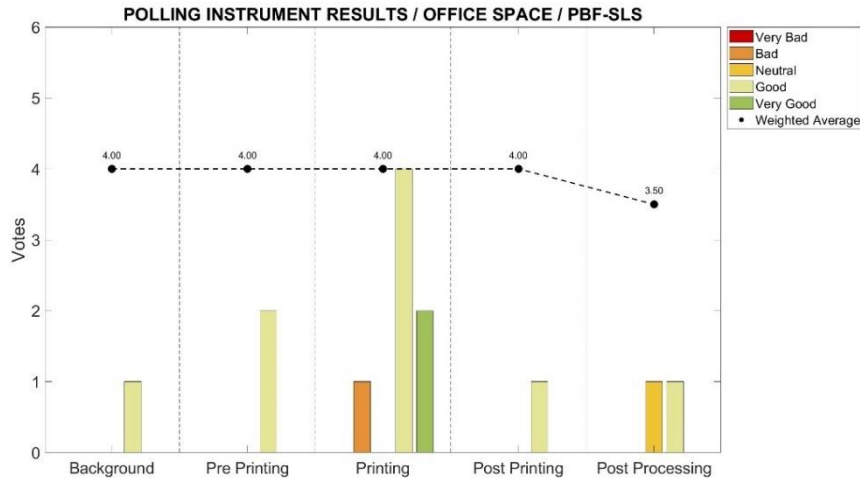


Figure 4.45 Employee Perception of IAQ in Office Space during PBF-SLS

The results of INBASE and the polling instrument were analyzed together to identify potential correlations between IAQ variations due to PBF-SLS operations and the perception of employees within the context of the office space. No apparent correlation between the IAQ perception of employees and the monitored IAQ parameters was identified. The consistent feedback ranging from neutral to good suggested that the employees did not perceive any significant deterioration in IAQ that could be directly linked to the parameters measured, as they remained within mainly established thresholds.

To sum up, based on all these observations, the variations in the ten measured parameters during PBF-SLS operations were presented in both the PBF-SLS production space and the office space. PM values exhibited a fluctuating trend in both production and office spaces. It was observed that this fluctuation was not directly related to the processes. The recorded values remained below the maximum tolerable levels for short-term and long-term exposure. However, PM values in the related production space were generally lower than those in the office space due to the intake and exhaust filters in the SLS printer, the HEPA filter in the SLS powder management station, the constant ventilation in the related production space, and the lack of direct contact with the powder during the feedstock-related

activities. As a result of the TVOC measurements, no critical values were observed in either the production or office spaces, aside from short-term fluctuations. During these short-term fluctuations around level 3, increased ventilation and source investigation, as required by these concentration levels, should be implemented. In both production and office spaces, the values for HCHO remained within the established safe range, and no adverse conditions were detected. The values for C₆H₆ and C₂H₅OH remained below detectable levels throughout the entire production cycle in both production and office spaces. Therefore, these spaces were considered safe with respect to C₆H₆ and C₂H₅OH. NO₂ was detected in the production space. However, due to the value appearing momentarily and then gradually decreasing, its direct connection to the production system remained uncertain. Since the measured values were maintained below the maximum tolerable levels for short-term and long-term exposure, the production space was considered safe with respect to NO₂. In the office space, NO₂ levels remained below detectable limits throughout the entire production process. Therefore, the office space is also deemed safe concerning NO₂. The values for CO₂ and O₂ remained within the established safe range, and no adverse conditions were detected in both production and office spaces. Employee perception of IAQ was maintained within the neutral to good range in both production and office spaces, with the office values being slightly higher. These outcomes demonstrate that PBF-SLS operations did not notably impact IAQ in both production and office spaces due to the SLS equipment having filters and the related spaces being ventilated. Additionally, when the results of INBASE and the polling instrument were analyzed together, a definitive correlation was not captured between IAQ variations due to PBF-SLS operations and the IAQ perception of employees both for production and office spaces. However, it was observed that the variations in IAQ parameters remaining within mostly established thresholds likely contributed to the employees' perception of IAQ above neutral throughout all phases. This suggests that maintaining IAQ within acceptable levels is important in promoting a positive perception of indoor air quality.

4.4 Field Experiments for Vat Photopolymerization - Stereolithography

This section presents the real-time air quality monitoring results obtained from INBASE and employee feedback obtained from the Indoor Air Quality Polling Instrument for the production spaces, including the VP-SLA production space and the post-processing atelier, and the office space during VP-SLA operations. Each parameter, including PM_{1.0}, PM_{2.5}, PM₁₀, TVOC, HCHO, C₆H₆, C₂H₅OH, NO₂, CO₂, and O₂, was evaluated for production and office spaces with respect to the established thresholds based on guidelines and standards provided by certain authorities each of which is detailed in the corresponding parts of the section. The unit conversion was applied when necessary using Equation 4-1, Equation 4-2, Equation 4-3, and Equation 4-4 to align the units of specific sensor outputs to the commonly used units in the guidelines.

Air quality guidelines for PM issued by WHO (2021) do not cover PM_{1.0}. Therefore, no safety limit was indicated in Figure 4.46 and Figure 4.47.

Minimum, maximum, and average PM_{1.0} concentrations in the related production spaces and the office space during VP-SLA operations, along with the duration of each phase, average temperature, and relative humidity of the space during each phase, are given in Table 4.23.

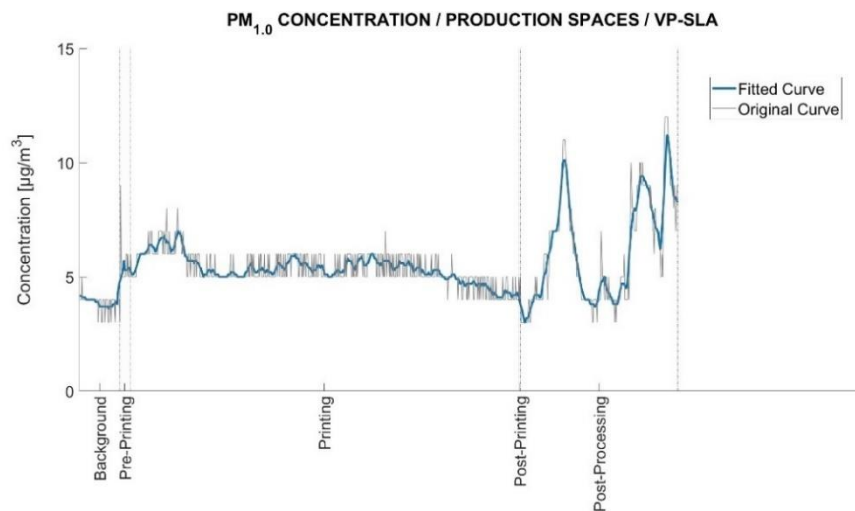
Table 4.23 Descriptive Statistics of PM_{1.0} Concentrations during VP-SLA

PRODUCTION SPACES		Background	Pre- Printing	Printing	Post- Printing	Post- Processing
	Min (µg/m ³)	3.00	5.00	4.00	4.00	3.00
	Max (µg/m ³)	5.00	9.00	8.00	5.00	12.00
	Avg (µg/m ³)	3.87	5.53	5.35	4.50	6.15
	Time (min)	60	15	573	2	232
	Temp (°C)	23.88	24.27	24.29	24.04	22.43
	RH (%)	31.74	30.03	31.13	31.90	39.56

Table 4.23 (continued)

OFFICE SPACE	Min ($\mu\text{g}/\text{m}^3$)	3.00	4.00	3.00	9.00	4.00
	Max ($\mu\text{g}/\text{m}^3$)	5.00	5.00	9.00	9.00	6.00
	Avg ($\mu\text{g}/\text{m}^3$)	4.05	4.63	4.78	9.00	4.70
	Time (min)	42	16	94	2	101
	Temp ($^{\circ}\text{C}$)	23.25	26.46	23.46	27.30	26.24
	RH (%)	27.12	34.35	30.91	29.27	35.26

The results of $\text{PM}_{1.0}$ concentrations in the related production spaces during VP-SLA operations indicated slight variations in $\text{PM}_{1.0}$ concentrations during different phases compared to the background levels. The mean concentrations during the background, pre-printing, printing, post-printing, and post-processing phases were $3.87 \mu\text{g}/\text{m}^3$, $5.53 \mu\text{g}/\text{m}^3$, $5.35 \mu\text{g}/\text{m}^3$, $4.50 \mu\text{g}/\text{m}^3$, and $6.15 \mu\text{g}/\text{m}^3$, respectively. There were $\text{PM}_{1.0}$ emissions associated with each phase, which did not drastically differ from background levels. Hence, it can be concluded that VP-SLA operations did not create significant differences in $\text{PM}_{1.0}$ concentrations in production spaces where these operations took place. $\text{PM}_{1.0}$ concentrations in the production spaces during VP-SLA operations in those spaces are illustrated in Figure 4.46.

Figure 4.46 $\text{PM}_{1.0}$ Concentrations in Related Production Spaces during VP-SLA

The results of PM_{1.0} concentrations in the office space during VP-SLA operations indicated minor variations in PM_{1.0} concentrations during different phases compared to the background levels. The average PM_{1.0} concentration during the background measurements was 4.05 µg/m³, where the measured values varied between 3.00 µg/m³ and 5.00 µg/m³. The average PM_{1.0} concentrations were 4.63 µg/m³, 4.78 µg/m³, 9.00 µg/m³, and 4.70 µg/m³ during pre-printing, printing, post-printing and post-processing, respectively. The concentrations varied between 4.00 µg/m³ and 5.00 µg/m³, 3.00 µg/m³ and 9.00 µg/m³, 9.00 µg/m³ and 9.00 µg/m³, and lastly 4.00 µg/m³ and 6.00 µg/m³ during these phases, respectively. The PM_{1.0} concentration did not differ from background levels except for the post-printing phase and the last segment of the printing phase. However, all these variations in different phases occurred between 3.00 µg/m³ and 9.00 µg/m³. Hence, it can be concluded that VP-SLA operations did not create significant differences in PM_{1.0} concentrations in the office space. PM_{1.0} concentrations in the office space during VP-SLA operations are presented in Figure 4.47.

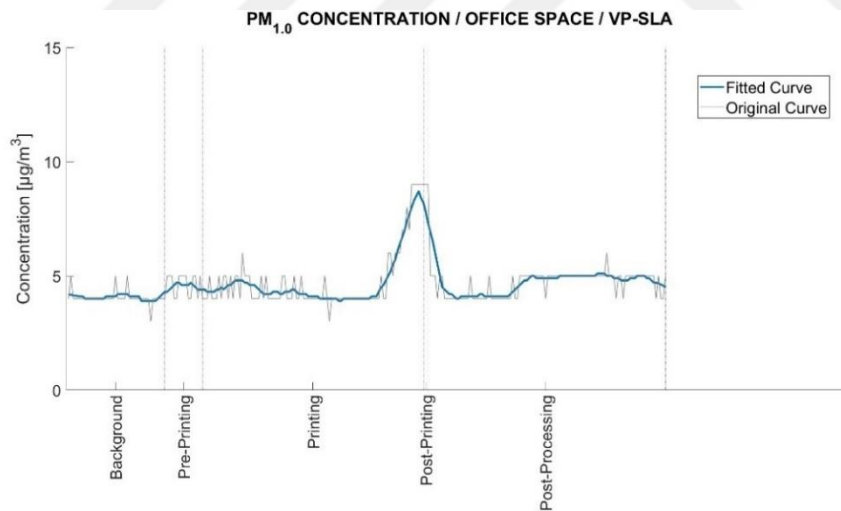


Figure 4.47 PM_{1.0} Concentrations in Office Space during VP-SLA

Air quality guidelines issued by WHO (2021) are used as threshold values to evaluate PM_{2.5} concentrations. The guideline includes four interim target values and one air quality guideline, with values specified for both annual and 24-hour periods. The annual values are 35, 25, 15, 10, and 5 µg/m³, while the 24-hour

values are 75, 50, 37.5, 25, and 15 $\mu\text{g}/\text{m}^3$, respectively (World Health Organization, 2021). In Figure 4.48 and Figure 4.49, the annual interim target 1 of $\text{PM}_{2.5}$ was labeled as the "Maximum Tolerable Level (Annual)," and the annual air quality guideline of $\text{PM}_{2.5}$ was labeled as the "Target Level (Annual)." Similarly, the 24-hour interim target 1 of $\text{PM}_{2.5}$ is labeled as the "Maximum Tolerable Level (24-hour)," and the 24-hour air quality guideline of $\text{PM}_{2.5}$ is labeled as the "Target Level (24-hour)."

Minimum, maximum, and average $\text{PM}_{2.5}$ concentrations in the related production spaces and the office space during VP-SLA operations, along with the duration of each phase, average temperature, and relative humidity of the space during each phase, are tabulated in Table 4.24.

Table 4.24 Descriptive Statistics of $\text{PM}_{2.5}$ Concentrations during VP-SLA

		Background	Pre- Printing	Printing	Post- Printing	Post- Processing
PRODUCTION SPACES	Min ($\mu\text{g}/\text{m}^3$)	4.00	7.00	5.00	5.00	4.00
	Max ($\mu\text{g}/\text{m}^3$)	7.00	13.00	11.00	7.00	17.00
	Avg ($\mu\text{g}/\text{m}^3$)	5.03	7.67	7.40	6.00	8.61
	Time (min)	60	15	573	2	232
	Temp ($^{\circ}\text{C}$)	23.88	24.27	24.29	24.04	22.43
	RH (%)	31.74	30.03	31.13	31.90	39.56
OFFICE SPACE	Min ($\mu\text{g}/\text{m}^3$)	4.00	5.00	4.00	13.00	5.00
	Max ($\mu\text{g}/\text{m}^3$)	7.00	7.00	13.00	13.00	8.00
	Avg ($\mu\text{g}/\text{m}^3$)	5.40	6.50	6.65	13.00	6.62
	Time (min)	42	16	94	2	101
	Temp ($^{\circ}\text{C}$)	23.25	26.46	23.46	27.30	26.24
	RH (%)	27.12	34.35	30.91	29.27	35.26

The results of $\text{PM}_{2.5}$ concentrations in the related production spaces during VP-SLA operations exhibited minor variations relative to the background levels. Throughout the phases, average $\text{PM}_{2.5}$ concentrations experienced modest increases

compared to the background levels. Pre-printing, printing, post-printing phases, and post-processing average measurements were $7.67 \mu\text{g}/\text{m}^3$, $7.40 \mu\text{g}/\text{m}^3$, $6.00 \mu\text{g}/\text{m}^3$, and $8.61 \mu\text{g}/\text{m}^3$, respectively, where the background level was $5.03 \mu\text{g}/\text{m}^3$. The maximum concentration, $17.00 \mu\text{g}/\text{m}^3$, was recorded during the post-processing phase. These values, when compared to established thresholds, showed that all phases remained below the maximum tolerable levels for both 24-hour and annual exposure. The target level for 24-hour exposure was achieved for all phases except peak points observed during the post-processing phase. The target level for annual exposure was not met at any phase except for background levels. Given that the $\text{PM}_{2.5}$ concentrations at any phase did not notably alter from background levels, it can be concluded that VP-SLA operations did not significantly influence $\text{PM}_{2.5}$ emissions in the production spaces where these operations took place. $\text{PM}_{2.5}$ concentrations in the production spaces during VP-SLA operations are inserted in Figure 4.48.

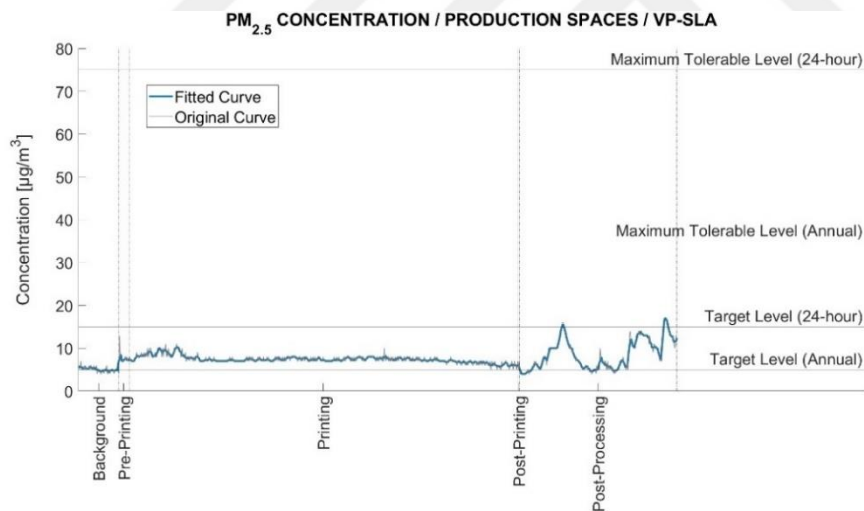


Figure 4.48 $\text{PM}_{2.5}$ Concentrations in Related Production Spaces during VP-SLA

The results of $\text{PM}_{2.5}$ concentrations in the office space during VP-SLA operations exhibited slight variations relative to the background levels. The minimum $\text{PM}_{2.5}$ concentration recorded during the background phase was $4.00 \mu\text{g}/\text{m}^3$, while the maximum reached $7.00 \mu\text{g}/\text{m}^3$, with an average of $5.40 \mu\text{g}/\text{m}^3$. Throughout the pre-printing, printing, post-printing phases, and post-processing, $\text{PM}_{2.5}$ concentrations

experienced slight increases, with average values of $6.50 \mu\text{g}/\text{m}^3$, $6.65 \mu\text{g}/\text{m}^3$, $13.00 \mu\text{g}/\text{m}^3$, and $6.62 \mu\text{g}/\text{m}^3$, respectively. These concentrations, when compared to established thresholds, revealed that all phases remained within the thresholds of maximum tolerable levels for 24-hour and annual exposure durations. However, while the target level for 24-hour exposure was met across all phases, except for intermittent peaks observed during the post-printing phase, attainment of the target level for annual exposure was not achieved across any phase. Given that the $\text{PM}_{2.5}$ concentrations at any phase did not significantly differ from background levels except for intermittent peaks, it can be concluded that VP-SLA operations did not notably influence $\text{PM}_{2.5}$ emissions in the office space. $\text{PM}_{2.5}$ concentrations in the office space during VP-SLA operations are provided in Figure 4.49.

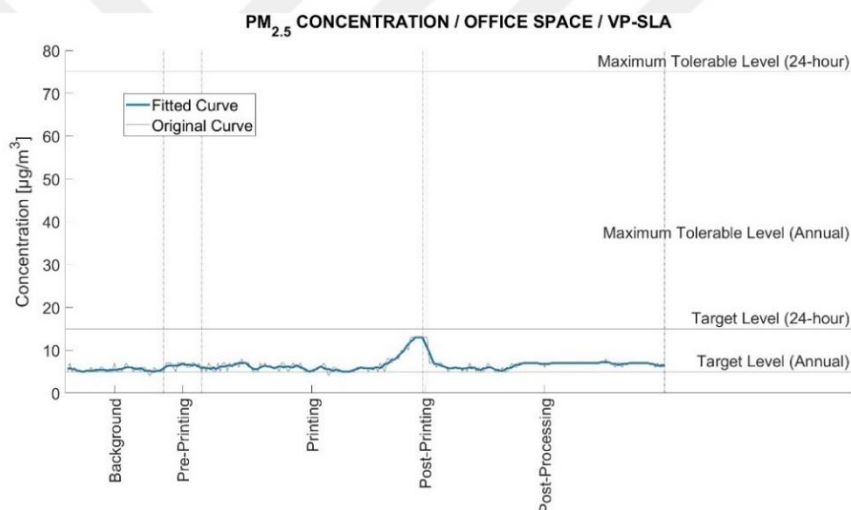


Figure 4.49 $\text{PM}_{2.5}$ Concentrations in Office Space during VP-SLA

Air quality guidelines issued by WHO (2021) are used as threshold values to evaluate PM_{10} concentrations. The annual values are 70, 50, 30, 20, and $15 \mu\text{g}/\text{m}^3$, and the 24-hour values are 150, 100, 75, 50, and $45 \mu\text{g}/\text{m}^3$, respectively (World Health Organization, 2021). In Figure 4.50 and Figure 4.51, the annual interim target 1 of PM_{10} was labeled as the "Maximum Tolerable Level (Annual)," and the annual air quality guideline of PM_{10} was labeled as the "Target Value (Annual)." Similarly, the 24-hour interim target 1 of PM_{10} was labeled as the "Maximum

Tolerable Level (24-hour)," and the 24-hour air quality guideline of PM₁₀ was labeled as the "Target Value (24-hour)".

Minimum, maximum, and average PM₁₀ concentrations in the related production spaces and the office space during VP-SLA operations, along with the duration of each phase, average temperature, and relative humidity of the space during each phase, are given in Table 4.25.

Table 4.25 Descriptive Statistics of PM₁₀ Concentrations during VP-SLA

		Background	Pre- Printing	Printing	Post- Printing	Post- Processing
PRODUCTION SPACES	Min (µg/m ³)	4.00	7.00	5.00	5.00	4.00
	Max (µg/m ³)	7.00	13.00	11.00	7.00	20.00
	Avg (µg/m ³)	5.03	7.67	7.40	6.00	8.73
	Time (min)	60	15	573	2	232
	Temp (°C)	23.88	24.27	24.29	24.04	22.43
	RH (%)	31.74	30.03	31.13	31.90	39.56
OFFICE SPACE	Min (µg/m ³)	4.00	5.00	4.00	13.00	5.00
	Max (µg/m ³)	7.00	7.00	13.00	13.00	8.00
	Avg (µg/m ³)	5.40	6.50	6.65	13.00	6.62
	Time (min)	42	16	94	2	101
	Temp (°C)	23.25	26.46	23.46	27.30	26.24
	RH (%)	27.12	34.35	30.91	29.27	35.26

The results of PM₁₀ concentrations in the related production spaces during VP-SLA operations implied slight variations relative to the background levels. The minimum PM₁₀ concentration during the background measurements was 4.00 µg/m³, while the maximum was 7.00 µg/m³, with an average of 5.03 µg/m³. Throughout the pre-printing, printing, post-printing phases, and post-processing, PM₁₀ concentrations experienced modest increases, with average values of 7.67 µg/m³, 7.40 µg/m³, 6.00 µg/m³, and 8.73 µg/m³ respectively. The maximum concentration, 20.00 µg/m³, was recorded during the post-processing phase. These

values, when compared to established thresholds, showed that all phases remained within the thresholds of maximum tolerable levels for 24-hour and annual exposure and target level for 24-hour average exposure. The target level for annual exposure was met across all phases except for intermittent peaks observed during the post-processing phase. Given that the PM₁₀ concentrations at any phase did not notably deviate from background levels, it can be concluded that VP-SLA operations did not significantly influence PM₁₀ emissions in the production spaces where these operations took place. PM₁₀ concentrations in the production spaces during VP-SLA operations are illustrated in Figure 4.50.

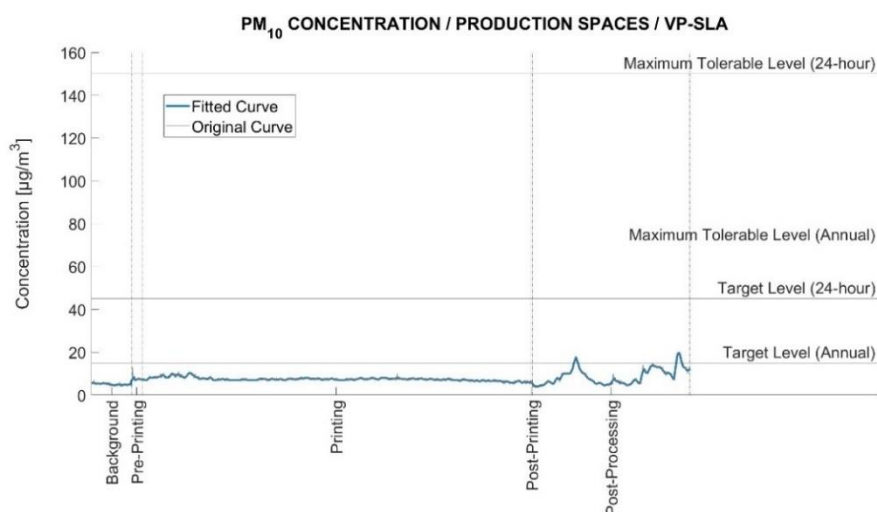


Figure 4.50 PM₁₀ Concentrations in Related Production Spaces during VP-SLA

The results of PM₁₀ concentrations in the office space during VP-SLA operations implied slight variations relative to the background levels. The minimum PM₁₀ concentration during the background measurements was 4.00 µg/m³, while the maximum reached 7.00 µg/m³, with an average of 5.40 µg/m³. Throughout the pre-printing, printing, post-printing phases, and post-processing, PM₁₀ concentrations experienced modest increases, with average values of 6.50 µg/m³, 6.65 µg/m³, 13.00 µg/m³, and 6.62 µg/m³ respectively. The maximum concentration, 20.00 µg/m³, was recorded during the post-processing phase. These values, when compared to established thresholds, showed that all phases remained below all threshold values, including the maximum tolerable levels for 24-hour and annual

exposure and target levels for 24-hour and annual exposure. Given that the PM₁₀ concentrations at any phase did not notably drift from background levels, it can be concluded that VP-SLA operations did not significantly affect PM₁₀ emissions in the office space. PM₁₀ concentrations in the office space during VP-SLA operations are presented in Figure 4.51.

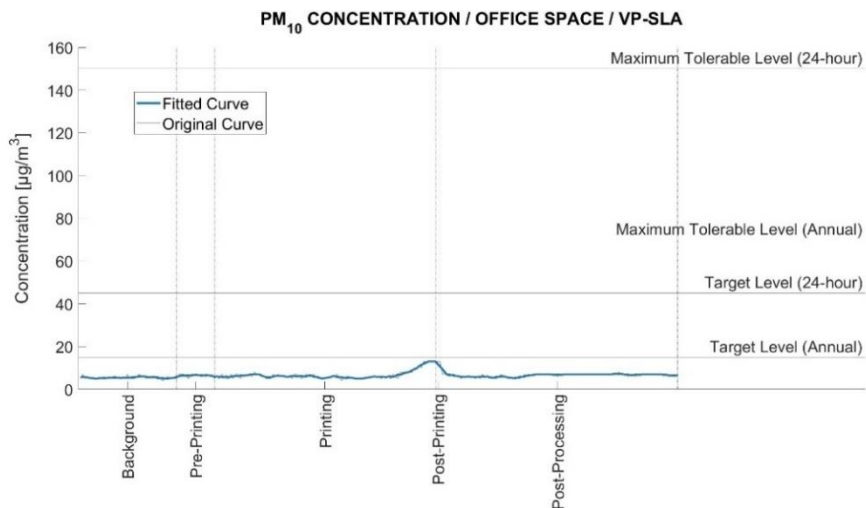


Figure 4.51 PM₁₀ Concentrations in Office Space during VP-SLA

The categorization of TVOC levels issued by the Umweltbundesamt (UBA), the Federal Environmental Agency in Germany (2007), was adopted to evaluate TVOC concentration. Accordingly, in Figure 4.52 and Figure 4.53, delineations were made based on five levels: Level 1 ($< 0.3 \text{ mg/m}^3$), Level 2 ($0.3\text{-}1 \text{ mg/m}^3$), Level 3 ($1\text{-}3 \text{ mg/m}^3$), Level 4 ($3\text{-}10 \text{ mg/m}^3$), and Level 5 ($10\text{-}25 \text{ mg/m}^3$). Level 1 serves as a target value without hygienic concerns. Level 2 does not indicate significant issues but necessitates increased ventilation. At Level 3, hygienic concerns arise, prompting source investigation and increased ventilation, particularly over a maximum duration of 12 months. Level 4 indicates significant concerns, with a maximum toleration duration of a month, necessitating restricted usage and intensified ventilation. Level 5 signifies unacceptable concentrations, permitting usage only if unavoidable and for short durations, with increased ventilation measures (Bekanntmachung des Umweltbundesamtes, 2007).

The commonly used unit and the units specified in this guideline for TVOC concentration are mg/m^3 . Given that the TVOC sensor outputs data in ppb, Equation 4-1 and Equation 4-2 were employed to convert the ppb readings to mg/m^3 . The molecular weight of TVOC is 110 g/mol (Sensirion, 2019).

Minimum, maximum, and average TVOC concentrations in the related production spaces and the office space during VP-SLA operations, along with the duration of each phase, average temperature, and relative humidity of the space during each phase, are tabulated in Table 4.26.

Table 4.26 Descriptive Statistics of TVOC Concentrations during VP-SLA

		Background	Pre- Printing	Printing	Post- Printing	Post- Processing
PRODUCTION SPACES	Min (mg/m^3)	0.00	0.00	0.00	0.44	0.00
	Max (mg/m^3)	0.26	0.27	0.73	0.44	59.21
	Avg (mg/m^3)	0.09	0.10	0.45	0.44	3.26
	Time (min)	60	15	573	2	232
	Temp ($^{\circ}\text{C}$)	23.88	24.27	24.29	24.04	22.43
	RH (%)	31.74	30.03	31.13	31.90	39.56
OFFICE SPACE	Min (mg/m^3)	0.00	0.00	0.00	0.12	0.00
	Max (mg/m^3)	0.16	0.37	0.67	0.22	0.35
	Avg (mg/m^3)	0.06	0.08	0.05	0.17	0.12
	Time (min)	42	16	94	2	101
	Temp ($^{\circ}\text{C}$)	23.25	26.46	23.46	27.30	26.24
	RH (%)	27.12	34.35	30.91	29.27	35.26

The results of TVOC concentrations in the related production spaces during VP-SLA operations suggested notable variations in different phases compared to background levels and established threshold values. The average TVOC concentration during background measurements was $0.09 \text{ mg}/\text{m}^3$, where the measured values varied between $0.00 \text{ mg}/\text{m}^3$ and $0.26 \text{ mg}/\text{m}^3$. Throughout the pre-printing, printing, post-printing, and post-processing phases, TVOC concentrations

remained relatively low, with average values of 0.10 mg/m³, 0.45 mg/m³, 0.44 mg/m³, and 3.26 mg/m³, respectively. The TVOC levels during background measurements and the pre-printing phase remained below level 1, indicating target value without hygienic concerns. On the other hand, the TVOC levels during the printing and post-printing phases fall within levels 1 and 2, necessitating increased ventilation while not indicating significant concerns. The post-processing phase was characterized by the significant elevation in TVOC concentrations, surpassing level 5, corresponding to unacceptable concentrations. Consequently, it can be concluded that VP-SLA operations necessitate effective emission control and ventilation strategies in the production spaces where these operations take place. TVOC concentrations in the production spaces during VP-SLA operations are inserted in Figure 4.52.

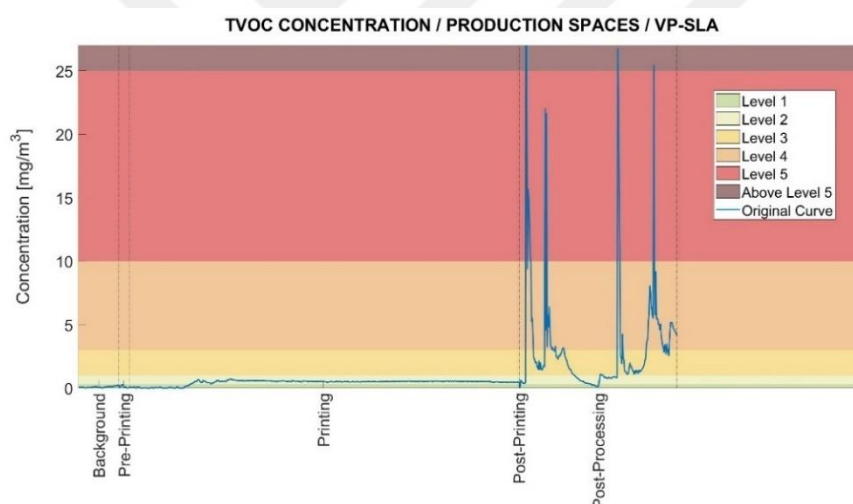


Figure 4.52 TVOC Concentrations in Related Production Spaces during VP-SLA

The results of TVOC concentrations in the office space during VP-SLA operations suggested slight variations in TVOC concentrations during different phases compared to the background levels. The mean of measurements for the pre-printing, printing, post-printing, and post-processing phases were 0.08 mg/m³, 0.05 mg/m³, 0.17 mg/m³, and 0.12 mg/m³, respectively, where the background level was 0.06 mg/m³. Although momentarily increases to level 2 were observed during the pre-printing, printing, and post-processing phases, average concentrations at all

phases remained below level 1, indicating target value without hygienic concerns. It can be concluded that VP-SLA operations occurring in the production spaces did not cause TVOC levels in the office space to diverge from background levels. TVOC concentrations in the office space during VP-SLA operations are provided in Figure 4.53.

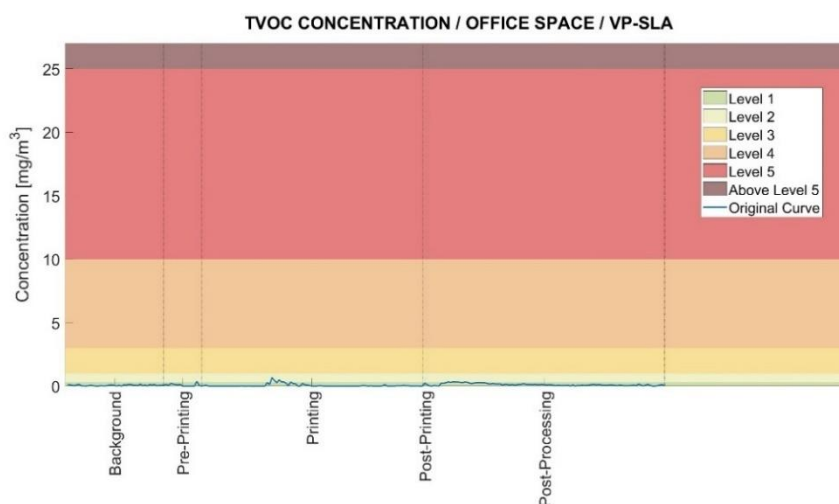


Figure 4.53 TVOC Concentrations in Office Space during VP-SLA

The HCHO guideline value of 0.1 mg/m³ given by WHO (2000) for a 30-minute average is taken as the threshold value. Consequently, in Figure 4.54 and Figure 4.55, 0.1 mg/m³ was delineated as the “Maximum Safe Level (30-minute).”

The commonly used unit and the unit specified in this guideline for HCHO concentration are mg/m³. Given that the HCHO sensor outputs data in ppb, Equation 4-1 and Equation 4-2 were employed to convert the ppb readings to mg/m³. The molecular weight of HCHO is 30.026 g/mol (National Center for Biotechnology Information, 2024b).

Minimum, maximum, and average HCHO concentrations in the related production spaces and the office space during VP-SLA operations, along with the duration of each phase, average temperature, and relative humidity of the space during each phase, are given in Table 4.27.

Table 4.27 Descriptive Statistics of HCHO Concentrations during VP-SLA

		Background	Pre- Printing	Printing	Post- Printing	Post- Processing
PRODUCTION SPACES	Min (mg/m ³)	0.003	0.001	0.003	0.004	0.002
	Max (mg/m ³)	0.004	0.004	0.007	0.004	0.013
	Avg (mg/m ³)	0.003	0.003	0.005	0.004	0.004
	Time (min)	60	15	573	2	232
	Temp (°C)	23.88	24.27	24.29	24.04	22.43
	RH (%)	31.74	30.03	31.13	31.90	39.56
OFFICE SPACE	Min (mg/m ³)	0.002	0.002	0.002	0.002	0.002
	Max (mg/m ³)	0.003	0.003	0.004	0.002	0.004
	Avg (mg/m ³)	0.002	0.003	0.003	0.002	0.003
	Time (min)	42	16	94	2	101
	Temp (°C)	23.25	26.46	23.46	27.30	26.24
	RH (%)	27.12	34.35	30.91	29.27	35.26

The results of HCHO concentrations in the related production spaces during VP-SLA operations indicated almost indistinguishable variations in HCHO concentrations during different phases compared to the background levels. The mean HCHO concentrations during the background, pre-printing, printing, post-printing, and post-processing phases were 0.003 mg/m³, 0.003 mg/m³, 0.005 mg/m³, 0.004 mg/m³, and 0.004 mg/m³. Although there were HCHO emissions associated with each phase, they were way below the 30-minute maximum safety level and indistinguishable from background levels. Accordingly, it can be concluded that VP-SLA operations did not contribute to HCHO concentrations in the production spaces where these operations took place. HCHO concentrations in the production spaces during VP-SLA operations are illustrated in Figure 4.54.

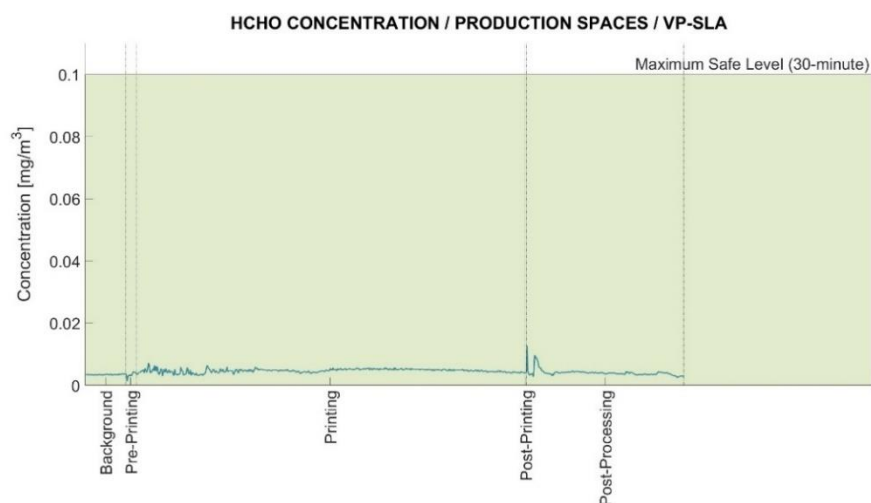


Figure 4.54 HCHO Concentrations in Related Production Spaces during VP-SLA

The results of HCHO concentrations in the office space during VP-SLA operations indicated levels between 0.002 mg/m³ and 0.004 mg/m³ during measurements. As phase measurements did not deviate from background levels and were way below the 30-minute maximum safety level, it can be concluded that VP-SLA operations taking place in the production spaces did not contribute to HCHO concentrations in the office space. HCHO concentrations in the office space during VP-SLA operations are presented in Figure 4.55.

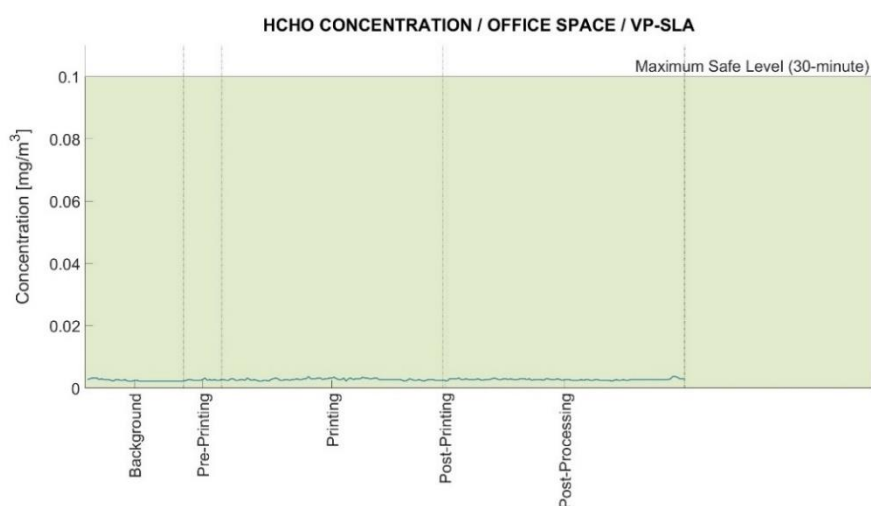


Figure 4.55 HCHO Concentrations in Office Space during VP-SLA

WHO does not state a safe level of exposure for C₆H₆. Thus, no safety limit was indicated in Figure 4.54 and Figure 4.55.

The commonly used unit for C₆H₆ concentration is mg/m³. Given that the C₆H₆ sensor outputs data in ppm, Equation 4-2 and Equation 4-4 were employed to convert the mg/m³ readings to µg/m³. The molecular weight of C₆H₆ is 78.11 g/mol (National Center for Biotechnology Information, 2024a).

Minimum, maximum, and average C₆H₆ concentrations in the related production spaces and the office space during VP-SLA operations, along with the duration of each phase, average temperature, and relative humidity of the space during each phase, are tabulated in Table 4.28.

Table 4.28 Descriptive Statistics of C₆H₆ Concentrations during VP-SLA

		Background	Pre- Printing	Printing	Post- Printing	Post- Processing
PRODUCTION SPACES	Min (mg/m ³)	0.00	0.00	0.00	0.00	0.00
	Max (mg/m ³)	0.00	0.00	0.00	0.00	265.06
	Avg (mg/m ³)	0.00	0.00	0.00	0.00	2.67
	Time (min)	60	15	573	2	232
	Temp (°C)	23.88	24.27	24.29	24.04	22.43
	RH (%)	31.74	30.03	31.13	31.90	39.56
OFFICE SPACE	Min (mg/m ³)	0.00	0.00	0.00	0.00	0.00
	Max (mg/m ³)	0.00	0.00	0.00	0.00	0.00
	Avg (mg/m ³)	0.00	0.00	0.00	0.00	0.00
	Time (min)	42	16	94	2	101
	Temp (°C)	23.25	26.46	23.46	27.30	26.24
	RH (%)	27.12	34.35	30.91	29.27	35.26

The results of C_6H_6 concentrations in the related production spaces during VP-SLA operations revealed that the C_6H_6 concentrations remained at a consistent minimum of 0.00 mg/m^3 during the background, pre-printing, printing, and post-printing phases, indicating no detectable emissions during these periods. However, the post-processing phase witnessed a peak at 265.06 mg/m^3 with an average of 2.67 mg/m^3 . Given that the Multichannel V2 is a qualitative sensor, the quantified values may not represent exact measurements but rather approximate estimates. Thus, it can be concluded that only the post-processing phase of VP-SLA operations emitted C_6H_6 . C_6H_6 concentrations in the production spaces during VP-SLA operations are inserted in Figure 4.56.

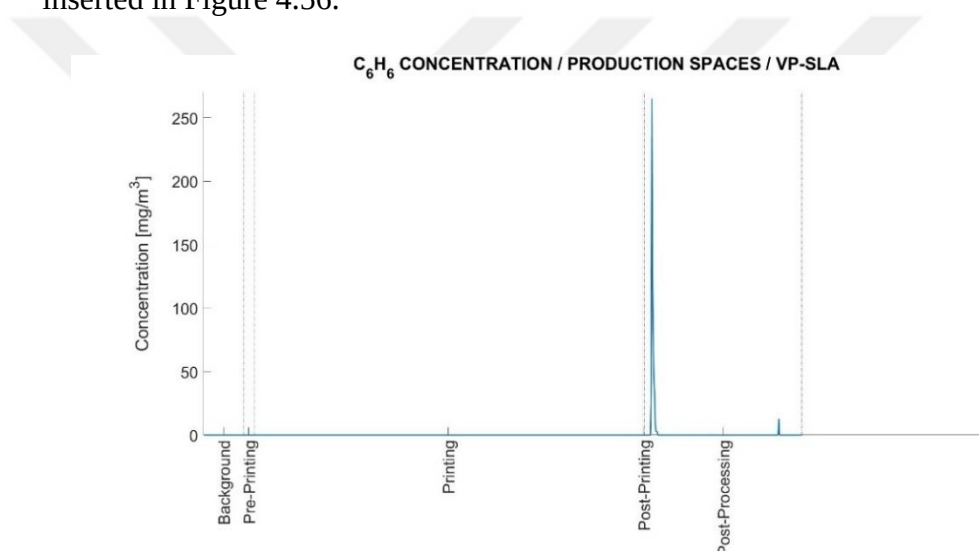


Figure 4.56 C_6H_6 Concentrations in Related Production Spaces during VP-SLA

The results of C_6H_6 concentrations in the office space during VP-SLA operations revealed that C_6H_6 concentrations remained at a consistent minimum of 0.00 mg/m^3 during the background, pre-printing, printing, post-printing, and post-processing phases, indicating no detectable emissions during these periods. Hence, it can be concluded that VP-SLA operations taking place in production spaces did not cause C_6H_6 emissions in the office space. C_6H_6 concentrations in the office space during VP-SLA operations are given in Figure 4.57.

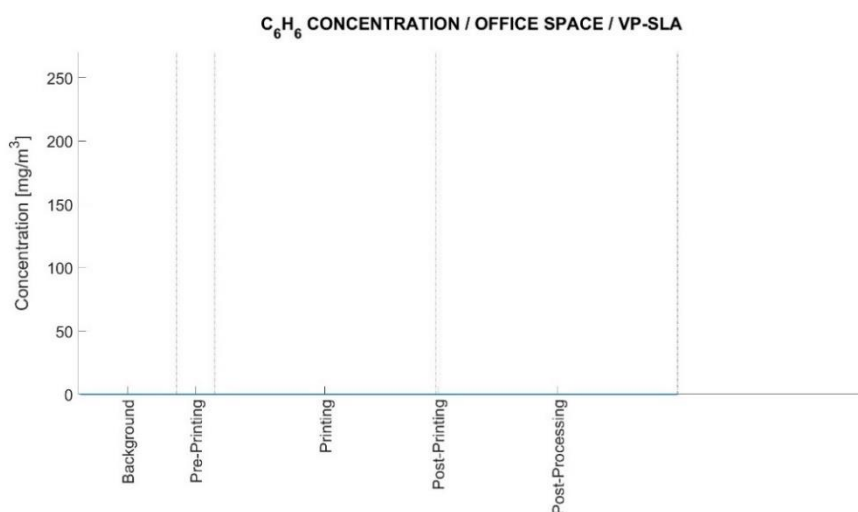


Figure 4.57 C₆H₆ Concentrations in Office Space during VP-SLA

Not being a typical indoor air quality pollutant, OSHA, NIOSH, and ACGIH set the workplace exposure limit to 1000 ppm for an 8-hour permissible exposure limit, 10-hour recommended exposure limit, and short-term threshold limit value (Occupational Safety and Health Administration, n.d.). The odor threshold of C₂H₅OH is 84 ppm (New Jersey Department of Health, 2011). In Figure 4.58 and Figure 4.59, 84 ppm was delineated as the “Odor Threshold.” As the concentrations were below each of these values, the Workplace Exposure Limit of 1000 ppm was not indicated in those figures.

Minimum, maximum, and average C₂H₅OH concentrations in the related production spaces and the office space during VP-SLA operations, along with the duration of each phase, average temperature, and relative humidity of the space during each phase, are illustrated in Table 4.29.

Table 4.29 Descriptive Statistics of C₂H₅OH Concentrations during VP-SLA

		Background	Pre- Printing	Printing	Post- Printing	Post- Processing
PRODUCTION SPACES	Min (ppm)	0.00	0.00	0.00	0.00	0.00
	Max (ppm)	0.00	0.00	0.00	0.00	52.79
	Avg (ppm)	0.00	0.00	0.00	0.00	1.35
	Time (min)	60	15	573	2	232
	Temp (°C)	23.88	24.27	24.29	24.04	22.43
	RH (%)	31.74	30.03	31.13	31.90	39.56
OFFICE SPACE	Min (ppm)	0.00	0.00	0.00	0.00	0.00
	Max (ppm)	0.00	0.00	0.00	0.00	0.00
	Avg (ppm)	0.00	0.00	0.00	0.00	0.00
	Time (min)	42	16	94	2	101
	Temp (°C)	23.25	26.46	23.46	27.30	26.24
	RH (%)	27.12	34.35	30.91	29.27	35.26

The results of C₂H₅OH concentrations in the related production spaces during VP-SLA operations suggested that the C₂H₅OH concentrations remained at a consistent minimum of 0.00 ppm during all the phases, indicating no detectable emissions. However, the post-processing phase witnessed specific peaks, which were at a maximum of 52.79 ppm and an average of 1.35 ppm. These were lower than the odor threshold. Given that the Multichannel V2 is a qualitative sensor, the quantified values may not represent exact measurements but rather approximate estimates. Therefore, it can be concluded that only the post-processing phase of VP-SLA operations involved C₂H₅OH emissions. C₂H₅OH concentrations in the production spaces during VP-SLA operations are inserted in Figure 4.58.

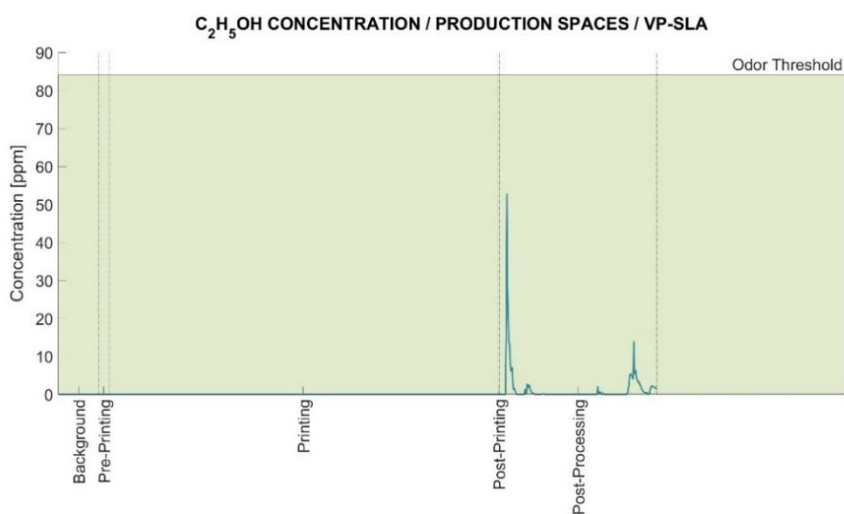


Figure 4.58 C₂H₅OH Concentrations in Related Production Spaces during VP-SLA

The results of C₂H₅OH concentrations in the office space during VP-SLA operations suggested that the C₂H₅OH concentrations remained at a consistent minimum of 0.00 ppm during the background, pre-printing, printing, post-printing, and post-processing phases, indicating no detectable emissions during any of the periods. Consequently, it can be concluded that VP-SLA operations taking place in the production spaces did not cause C₂H₅OH concentrations in the office space. C₂H₅OH concentrations in the office space during VP-SLA operations are given in Figure 4.59.

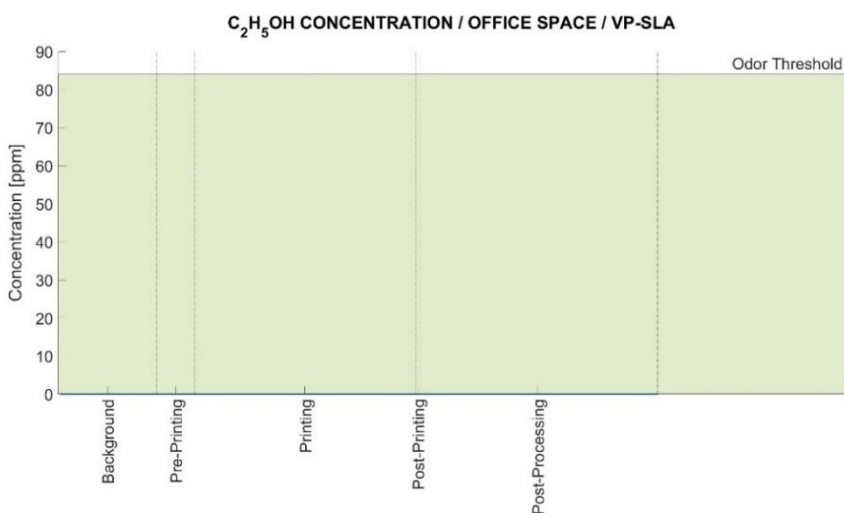


Figure 4.59 C₂H₅OH Concentrations in Office Space during VP-SLA

Air quality guidelines issued by WHO (2021) are used as threshold values to evaluate NO₂ concentrations. The guideline includes three interim target values for annual exposure, one air quality guideline value for annual exposure, two interim target values for 24-hour exposure, and one air quality guideline value for 24-hour exposure. The annual values are 40, 30, 20, and 10 µg/m³, while the 24-hour values are 120, 50, and 25 µg/m³, respectively (World Health Organization, 2021). In Figure 4.60 and Figure 4.61, the annual interim target 1 is labeled as the "Maximum Tolerable Level (Annual)," and the annual air quality guideline value is labeled as the "Target Level (Annual)." Similarly, the 24-hour interim target 1 is labeled as the "Maximum Tolerable Level (24-hour)," and the 24-hour air quality guideline value is labeled as the "Target Level (24-hour)."

The commonly used unit and the units specified in this guideline for NO₂ concentration are µg/m³. Given that the NO₂ sensor outputs data in ppm, Equation 4-2 and Equation 4-4 were employed to convert the mg/m³ readings to µg/m³. The molecular weight of NO₂ is 46.006 g/mol (National Center for Biotechnology Information, 2024c).

Minimum, maximum, and average NO₂ concentrations in the related production spaces and the office space during VP-SLA operations, along with the duration of each phase, average temperature, and relative humidity of the space during each phase, are illustrated in Table 4.30.

Table 4.30 Descriptive Statistics of NO₂ Concentrations during VP-SLA

PRODUCTION SPACES		Background	Pre- Printing	Printing	Post- Printing	Post- Processing
	Min (µg/m ³)	0.00	37.63	0.00	0.00	0.00
	Max (µg/m ³)	0.00	56.45	37.63	0.00	75.27
	Avg (µg/m ³)	0.00	38.89	5.16	0.00	0.49
	Time (min)	60	15	573	2	232
	Temp (°C)	23.88	24.27	24.29	24.04	22.43
	RH (%)	31.74	30.03	31.13	31.90	39.56

Table 4.30 (continued)

OFFICE SPACE	Min ($\mu\text{g}/\text{m}^3$)	0.00	0.00	0.00	0.00	0.00
	Max ($\mu\text{g}/\text{m}^3$)	0.00	0.00	0.00	0.00	0.00
	Avg ($\mu\text{g}/\text{m}^3$)	0.00	0.00	0.00	0.00	0.00
	Time (min)	42	16	94	2	101
	Temp ($^{\circ}\text{C}$)	23.25	26.46	23.46	27.30	26.24
	RH (%)	27.12	34.35	30.91	29.27	35.26

The results of NO_2 concentrations in the related production spaces during VP-SLA operations suggested that the NO_2 concentrations remained at a consistent minimum of $0.00 \mu\text{g}/\text{m}^3$ during the background and post-printing phases, indicating no detectable emissions. However, during the pre-printing phase, NO_2 levels showed a notable increase, with an average concentration of $38.89 \mu\text{g}/\text{m}^3$. Although this was below the maximum tolerable level for annual exposure, it exceeded the target level for annual exposure. During the printing phase, the average NO_2 concentration level, $5.16 \mu\text{g}/\text{m}^3$, was within the target level for annual exposure and the maximum tolerable level for 24-hour exposure. The maximum value in this phase, $37.63 \mu\text{g}/\text{m}^3$, remained below the maximum tolerable annual exposure level but above the target annual exposure level. The post-processing phase revealed minimal NO_2 emissions, with an average concentration of $0.49 \mu\text{g}/\text{m}^3$ and a peak of $75.27 \mu\text{g}/\text{m}^3$. Although the peak value in the post-processing phase exceeded the target level for 24-hour exposure, the average concentration remained below all defined thresholds. Given that the Multichannel V2 is a qualitative sensor, the quantified values may not represent exact measurements but rather approximate estimates. Therefore, there are NO_2 emissions associated with operational phases. While there were some exceedances during specific phases, NO_2 emissions mostly remained within acceptable safety thresholds. NO_2 concentrations in the production spaces during VP-SLA operations are presented in Figure 4.60.

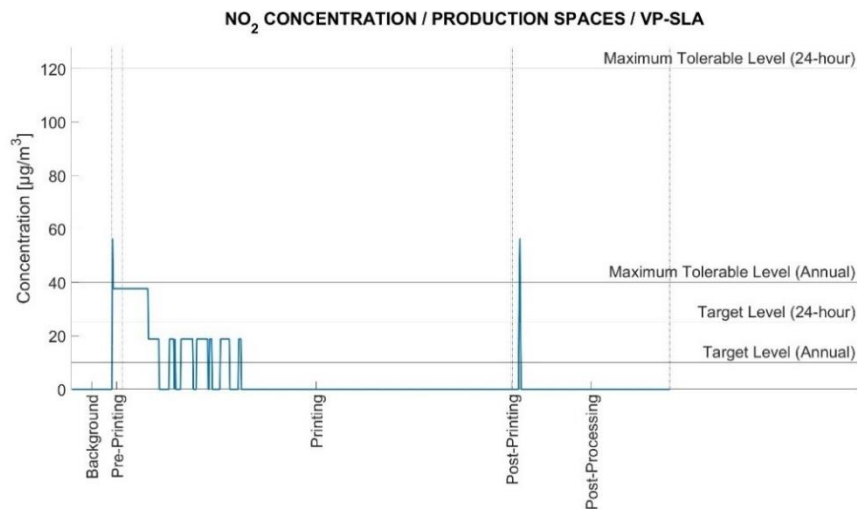


Figure 4.60 NO₂ Concentrations in Related Production Spaces during VP-SLA

The results of NO₂ concentrations in the office space during VP-SLA operations suggested that the NO₂ concentrations remained at 0.00 µg/m³ across the background, printing, post-printing, and post-processing phases, indicating no detectable emissions during these phases. However, the pre-printing phase witnessed a singular peak at 18.82 µg/m³, with the remaining values being 0.00 µg/m³. This anomalous peak was attributed to sensor error; this value was accepted as 0.00 µg/m³. NO₂ concentrations in the office space during VP-SLA operations are tabulated in Figure 4.61.

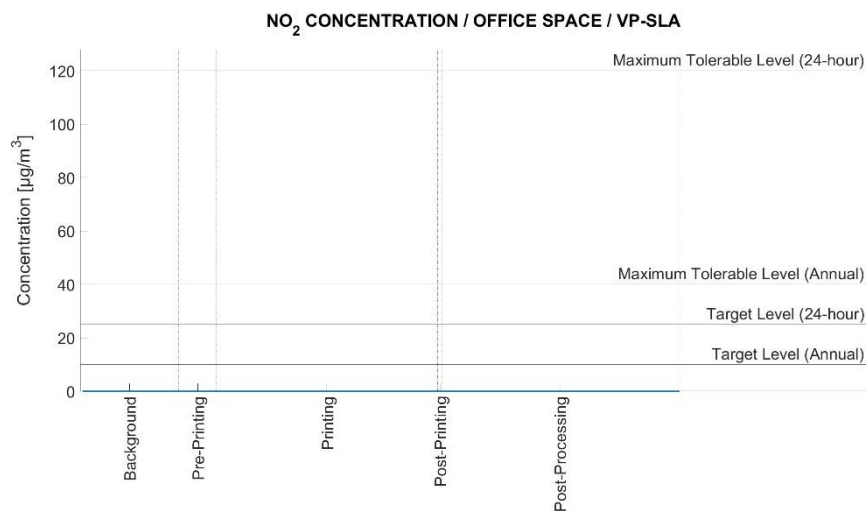


Figure 4.61 NO₂ Concentrations in Office Space during VP-SLA

The typical outdoor CO₂ concentration is 400 ppm. The indoor CO₂ concentration of a poorly ventilated space corresponds to 1100 ppm (López et al., 2023). Hence, these values were taken as threshold values to evaluate CO₂ concentration. In Figure 4.62 and Figure 4.63, 400 ppm was delineated as the “Typical Outdoor Level,” while 1100 ppm was given as the “Maximum Indoor Level.” Consequently, the values between 400-1100 ppm were considered acceptable.

Minimum, maximum, and average CO₂ concentrations in the related production spaces and the office space during VP-SLA operations, along with the duration of each phase, average temperature, and relative humidity of the space during each phase, are illustrated in Table 4.31.

Table 4.31 Descriptive Statistics of CO₂ Concentrations during VP-SLA

		Background	Pre- Printing	Printing	Post- Printing	Post- Processing
PRODUCTION SPACES	Min (ppm)	366.91	638.54	391.93	393.31	530.7
	Max (ppm)	379.9	843.32	646.94	395.32	856.85
	Avg (ppm)	372.96	688.46	512.86	394.32	630.66
	Time (min)	60	15	573	2	232
	Temp (°C)	23.88	24.27	24.29	24.04	22.43
	RH (%)	31.74	30.03	31.13	31.90	39.56
OFFICE SPACE	Min (ppm)	538.87	582.93	551.65	557.10	476.86
	Max (ppm)	724.30	690.71	714.27	561.92	824.37
	Avg (ppm)	608.86	652.75	632.56	559.51	689.07
	Time (min)	42	16	94	2	101
	Temp (°C)	23.25	26.46	23.46	27.30	26.24
	RH (%)	27.12	34.35	30.91	29.27	35.26

According to the results of CO₂ concentrations in the related production spaces during VP-SLA operations, the measured CO₂ concentrations revealed a notable pattern across different phases. During the background phase, the average concentration was 372.96 ppm, which was close to the typical outdoor level of 400

ppm. During pre-printing, there was an increase, with an average of 688.46 ppm, reaching a maximum of 843.32 ppm. The printing phase showed an average concentration of 512.86 ppm. Post-printing levels remained relatively stable, with an average concentration of 394.32 ppm, close to the background level. However, the post-processing phase saw another increase, with an average concentration of 630.66 ppm and a maximum of 856.85 ppm. Despite deviations from background levels in the production spaces caused by VP-SLA operations in those spaces, CO₂ concentrations during all processes, including background, pre-printing, printing, post-printing, and post-processing phases, fell within the acceptable range of 400-1100 ppm. CO₂ concentrations in the production spaces during VP-SLA operations are presented in Figure 4.62.

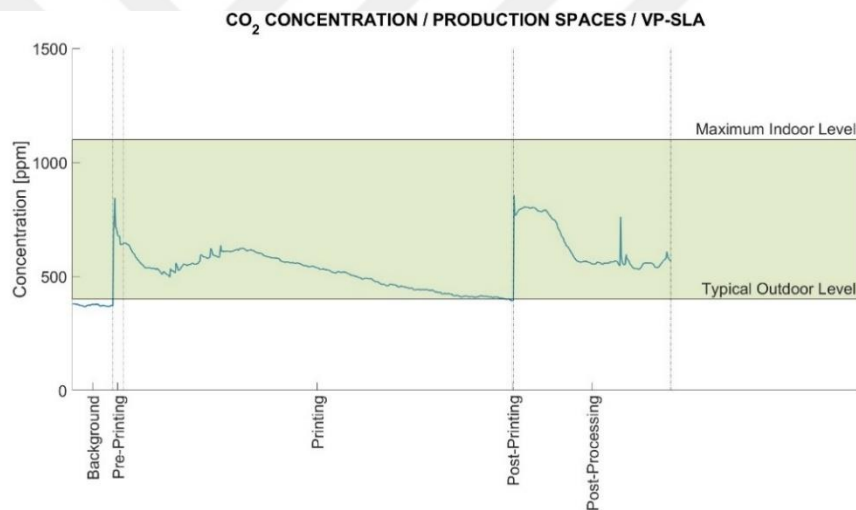


Figure 4.62 CO₂ Concentrations in Related Production Spaces during VP-SLA

According to CO₂ concentrations in the office space during VP-SLA operations, the measured CO₂ concentrations revealed variations between 476.86 ppm and 824.37 ppm. All the recorded values fell within the acceptable range of 400-1100 ppm. CO₂ concentrations in the office space during VP-SLA operations are tabulated in Figure 4.63.

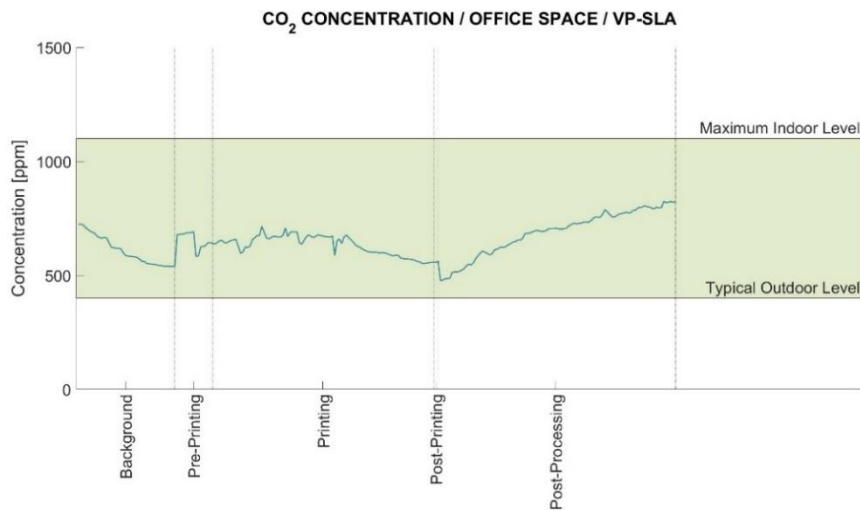


Figure 4.63 CO₂ Concentrations in Office Space during VP-SLA

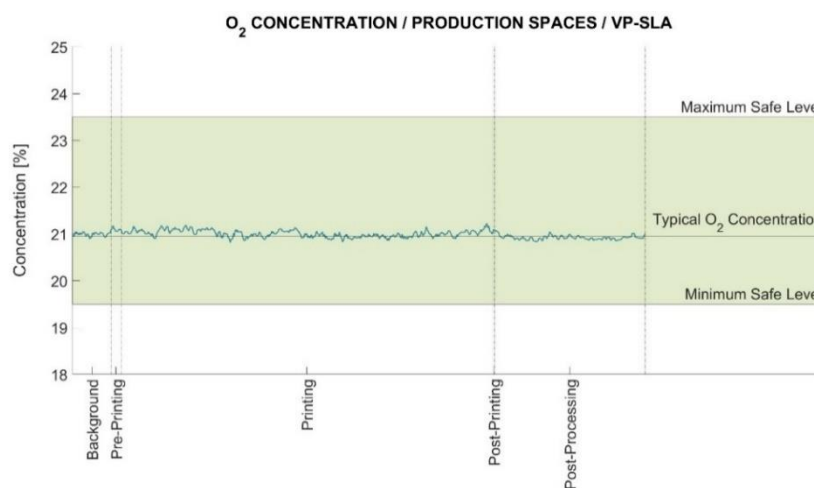
An oxygen concentration below 19.5% by volume is classified as deficient in oxygen content. The atmospheric air necessitates oxygen levels ranging from 19.5% to 23.5% at sea level. The volume of oxygen in atmospheric air is typically 20.95% across every elevation (Spelce et al., 2016). Therefore, these values were adopted as threshold values to evaluate O₂ concentration. In Figure 4.64 and Figure 4.65, 19.5% was delineated as the “Minimum Safe Level, while 23.5% was given as the “Maximum Safe Level.” Additionally, 20.95% was depicted as “Typical O₂ Concentration”.

Minimum, maximum, and average O₂ concentrations in the related production spaces and the office space during VP-SLA operations, along with the duration of each phase, average temperature, and relative humidity of the space during each phase, are inserted in Table 4.32.

Table 4.32 Descriptive Statistics of O₂ Concentrations during VP-SLA

		Background	Pre-Printing	Printing	Post-Printing	Post-Processing
PRODUCTION SPACES	Min (%)	20.77	20.86	20.77	21.05	20.82
	Max (%)	21.27	21.41	21.36	21.27	21.23
	Avg (%)	21.00	21.11	21.01	21.16	20.92
	Time (min)	60	15	573	2	232
	Temp (°C)	23.88	24.27	24.29	24.04	22.43
	RH (%)	31.74	30.03	31.13	31.90	39.56
OFFICE SPACE	Min (%)	20.77	20.86	20.73	20.95	20.05
	Max (%)	21.18	21.18	21.23	20.95	21.00
	Avg (%)	20.94	20.99	20.97	20.98	20.22
	Time (min)	42	16	94	2	101
	Temp (°C)	23.25	26.46	23.46	27.30	26.24
	RH (%)	27.12	34.35	30.91	29.27	35.26

The results of O₂ concentrations in the related production spaces during VP-SLA operations pointed out that O₂ concentrations were maintained within safe limits and around the typical O₂ concentration throughout all phases. O₂ concentrations in production spaces during VP-SLA operations are provided in Figure 4.64.

Figure 4.64 O₂ Concentrations in Related Production Spaces during VP-SLA

The results of O₂ concentrations in the office space during VP-SLA operations pointed out that O₂ concentrations remained relatively stable and maintained within safe limits throughout all phases, including background, pre-printing, printing, post-printing, and post-processing phases. Despite a minor deviation from typical O₂ concentration during the post-processing phase, the values were indistinguishable from background levels. Accordingly, it can be concluded that VP-SLA operations taking place in production spaces did not influence O₂ concentration in the office space. O₂ concentrations in the office space during VP-SLA operations are given in Figure 4.65.

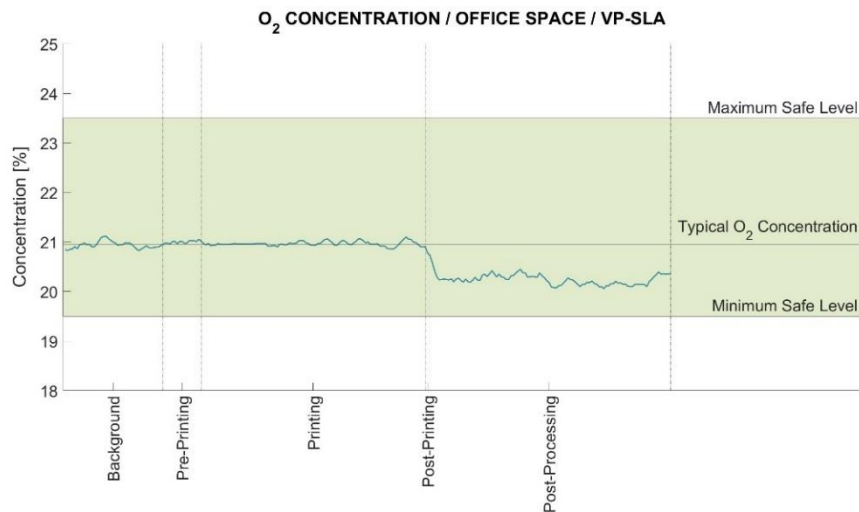


Figure 4.65 O₂ Concentrations in Office Space during VP-SLA

Employee feedback regarding the perception of IAQ on a scale ranging from very good to very bad, gathered from the Indoor Air Quality Polling Instrument, was quantified using a weighted average method, with the following coefficients assigned to each category: "very bad" (1), "bad" (2), "neutral" (3), "good" (4), and "very good" (5). In Figure 4.66 and Figure 4.67, the categories from very bad to very good were represented by colors ranging from red to green.

The results of employee perception of IAQ in the related production spaces during VP-SLA operations indicated that weighted averages of ratings during the background, pre-printing, printing, and post-processing phases were 3.50, 2.00,

2.60, and 2.60 out of 5.00, respectively. The absence of employee feedback during the post-printing phase was attributed to the duration of this phase, two minutes, which was too brief to collect responses. The results suggested that employees perceived the IAQ as below neutral point during all operational phases, except for the background, highlighting the need for improvements in IAQ to enhance employee comfort and satisfaction in the workplace. Specifically, the pre-printing phase received the lowest score, indicating poorer perceived IAQ compared to the other phases. The printing and post-processing phases received slightly higher but still below-average ratings, pointing to ongoing concerns about IAQ during these times. The employee perception of IAQ in production spaces during VP-SLA operations gathered from the polling instrument is illustrated in Figure 4.66.

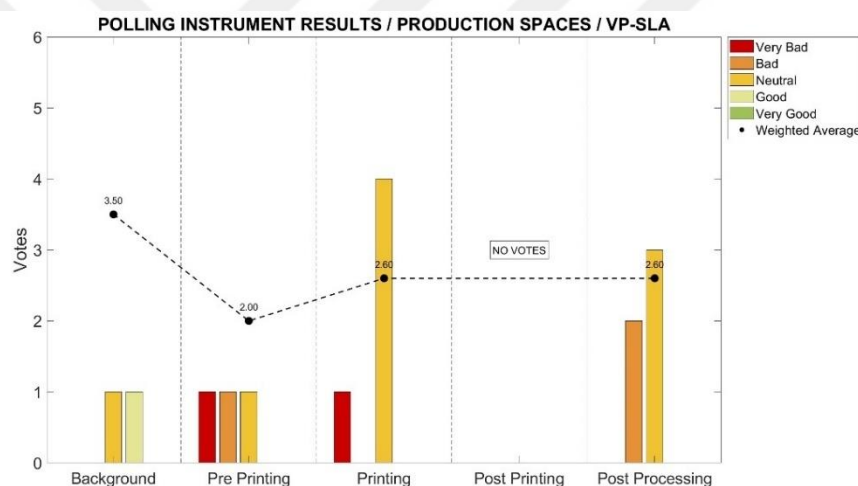


Figure 4.66 Employee Perception of IAQ in Related Production Spaces during VP-SLA

The results of INBASE and the polling instrument were considered together to identify potential correlations between IAQ variations due to VP-SLA operations and the perception of employees within the context of the production spaces, including the VP-SLA production space and the post-processing atelier. The employee feedback indicated a perception of IAQ as below neutral during most phases, except for the background phase. Notably, the pre-printing phase was perceived as having the poorest grade among all phases. When TVOC values were

considered, it was seen that the levels were higher during operational phases compared to the background, causing mild concerns. Although the concentration trend did not directly align with the employee perception of IAQ, the feedback being below neutral during operational phases indicated that TVOC could be a discomfort factor. As HCHO levels were consistently low during all phases, there was no apparent correlation between HCHO concentration and employee perception of IAQ. When C_6H_6 and C_2H_5OH levels were considered, a direct correlation was not observed. However, C_6H_6 and C_2H_5OH levels demonstrating increasing emissions during the post-processing phase could be a factor in IAQ being perceived as below neutral. NO_2 emissions observed during the pre-printing, printing, and post-processing phases could also be a factor in IAQ being perceived as below neutral during these phases. When CO_2 and O_2 concentrations were considered, a correlation was not identified. Therefore, although a definitive correlation was not captured, the potential correlations are linked to TVOC, C_6H_6 , C_2H_5OH , and NO_2 concentrations, suggesting that these parameters may be influential on perceived IAQ in the related production spaces.

The results of employee perception of IAQ in the office space during VP-SLA operations indicated that weighted averages of ratings during the background, pre-printing, printing, and post-processing phases were 3.71, 4.00, 3.67, and 4.00 out of 5.00, respectively. The absence of employee feedback during the post-printing phases was attributed to the duration of this phase, lasting only two minutes, which was too brief to collect responses. The results suggested that the IAQ in the office space was generally perceived as closer to good with saddle variations across different phases. The employee perception of IAQ in the office space during VP-SLA operations gathered from the polling instrument is illustrated in Figure 4.67.

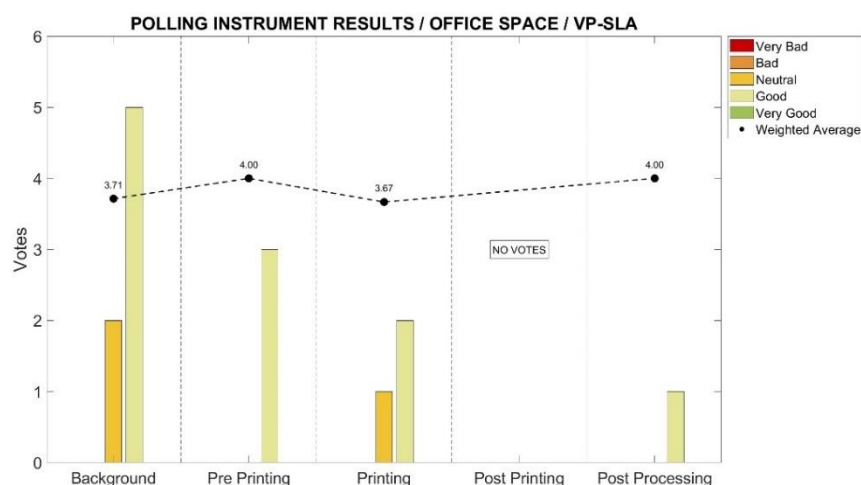


Figure 4.67 Employee Perception of IAQ in Office Space during VP-SLA

The results of INBASE and the polling instrument were considered together to identify potential correlations between IAQ variations due to VP-SLA operations and the perception of employees within the context of the office space. No apparent correlation between the IAQ perception of employees, which was generally positive, and the monitored IAQ parameters was identified. However, the monitored IAQ parameters, which were within acceptable thresholds with slight variations, supported the positive feedback.

To sum up, based on all these observations, the variations in the ten measured parameters during VP-SLA operations were presented in the production spaces, including the VP-SLA production space and the post-processing atelier, and the office space. In the production spaces, it was observed that PM values were influenced by the different phases. A notable increase in PM values was observed during the post-processing phase. Similarly, during the printing phase, average values were found to be higher compared to the background levels. However, the recorded values for PM_{2.5} and PM₁₀ concentrations remained below the maximum tolerable levels for both short-term and long-term exposure. In the office space, an increase was observed in the final segment of the printing phase for all PM values. However, since this trend was not observed in the production spaces, it was revealed that the increase in the office was not production-related, yet was due to a

short-term disturbance in the office space. In production spaces, average TVOC concentration increased during the printing and post-printing stages compared to background levels. Furthermore, hazardous levels were observed in the post-processing phase, exceeding acceptable limits and thereby necessitating effective emission control and urgent ventilation strategies. The TVOC concentration in the office space was maintained below level 2, suggesting the consideration of increased ventilation. The values for HCHO remained within the established safe ranges, and no adverse conditions were identified in production and office spaces. The concentrations of C_6H_6 and C_2H_5OH were below detectable levels except for the post-processing phase in production spaces. This was attributed to the post-processing activities, such as washing and curing performed in the post-processing atelier. Conversely, in the office space, concentrations of C_6H_6 and C_2H_5OH remained below detectable levels throughout the entire production process. Therefore, the office space was deemed safe in terms of C_6H_6 and C_2H_5OH exposure. NO_2 was detected in the production spaces during the printing and post-processing phases. However, as the measured values remained below the maximum tolerable levels for short-term exposure, these spaces were considered safe concerning NO_2 exposure while necessitating precautions against long-term exposure. In the office space, except for a momentary increase, NO_2 concentrations remained below detectable levels throughout the entire production process. Therefore, the office space was considered safe in terms of NO_2 exposure. CO_2 and O_2 levels remained within the established safe ranges, and no adverse conditions were identified in production and office spaces. Employee perception of IAQ in the production spaces ranged between poor and neutral except for the background ratings. Conversely, it was predominantly positive in the office space throughout various phases, revealing that the IAQ perception in the production spaces was poorer compared to IAQ perception in the office space. Additionally, when the results of INBASE and the polling instrument were examined together, no definitive correlation was found between IAQ variations owing to VP-SLA operations and the perception of employees. However, TVOC, C_6H_6 , C_2H_5OH , and

NO₂ concentrations emerged as possible influential factors on perceived IAQ in the related production spaces. In the office space, despite the lack of a clear correlation between IAQ parameter changes and employee perception, the stability and maintenance of IAQ within established thresholds likely contributed to the employees' positive perception.

4.5 Insights into Enhancing Indoor Air Quality in the Case of Additive Manufacturing

The results of the field experiments highlight the need for facility adjustments to address the IAQ challenges associated with AM processes, including powder bed fusion - selective laser melting, powder bed fusion - selective laser sintering, and vat photopolymerization - stereolithography, improve overall workplace safety, and foster a resilient manufacturing ecosystem. The intervention insights gathered as a result of field experiments can be categorized at the design level, organizational level, and equipment level.

At the design level, prevention-through-design concepts can be employed when a workplace engaging in additive manufacturing practices is designed or adjusted. The design should be equipped with considerations for spatial layout and ventilation patterns to minimize the concentration of emissions in occupied spaces and optimize airflow. As the findings of this study revealed that integration of production and office spaces is necessary for the operational dynamics of additive manufacturing activities, the design should integrate production and office spaces in close proximity to enhance operational efficiency. However, the impact of AM operations on IAQ in both production and office spaces necessitates careful consideration. A buffer zone should be established between production and office spaces to mitigate the cross-contamination of pollutants. This can be achieved by implementing separate circulation paths for these spaces, thereby preventing the intermingling of airflows. Additionally, service spaces such as kitchenettes and restrooms should be strategically positioned to minimize unnecessary traffic

through different spaces. For instance, placing these facilities in neutral zones that are easily accessible to employees, without intervening in the circulation of production or office spaces, can reduce pollutant exposure for employees who are not typically present in those spaces. Employing and enhancing ventilation systems, HVAC systems, and local exhaust systems designed for production and office spaces are crucial to effectively capture and remove indoor air pollutants directly at the source of emission. Additionally, regular maintenance of the employed systems is of great significance to ensure optimal functioning.

At the organizational level, operational practices can be optimized to minimize waste and emissions. For instance, scheduling certain operations during off-peak hours can reduce exposure to emissions. Moreover, the integration of real-time air quality monitoring systems that provide continuous data on indoor air pollutant concentrations allows for immediate responses to elevated pollutant levels, such as increasing ventilation or temporarily halting operations. Employee engagement and feedback mechanisms can also be valuable, as employees on the ground can provide insights into practical challenges and effective solutions related to IAQ management. Finally, fostering a culture of continuous improvement through regular training, audits, and updates to safety protocols, such as the use of personal protective equipment (PPE), including respirators, gloves, and protective clothing, can significantly reduce the risk of exposure to indoor air pollutants.

At the equipment level, the proper maintenance of AM equipment, material handling, and equipment and material storage is essential for optimal functioning and to minimize exposure to indoor air pollutants. Therefore, related equipment and materials should be stored in well-ventilated areas with proper procedures in place to prevent spills and leaks. Furthermore, employing emission reduction and emission capture technologies integrated into AM equipment and utilizing post-processing stations tailored for post-processing operations and equipped with filters can further mitigate indoor air pollutants.

CHAPTER 5

CONCLUSION

This chapter is organized into three main sections. Firstly, the summary of the research is outlined. Secondly, the main results and discussions are presented. Thirdly, the limitations of the research are explained, and the future directions are indicated.

5.1 Research Summary

People spend a significant portion of their time indoors (Kosonen & Tan, 2004), particularly in workplaces where they perform physical and mental tasks (Felstead et al., 2003). The developments in technology have transformed workplaces particularly (Rassia, 2017). Technologies such as additive manufacturing brought about certain flexibilities, enabling production activities to occur in smaller spaces as a part of other workplace operations. Therefore, workplaces, where production and office spaces coexist, are increasingly more prevalent as AM becomes widespread across several industries. AM is an emerging manufacturing field that employs 3D printers to fabricate 3D objects through additive processes (Delgado Camacho et al., 2018; Gupta et al., 2019; Kietzmann et al., 2015; Labonnote et al., 2016; Mathur, 2016). There are seven major AM processes with respect to the employed technology (Monzón et al., 2015). These are binder jetting, containing layer-by-layer construction of objects using powdered materials bonded with a liquid binder; directed energy deposition, employing thermal energy sources to melt feedstock material to be deposited onto a build platform; material extrusion, extruding material through a nozzle layer by layer to construct a part; material jetting, dispensing liquid photopolymer resin onto a build platform to be cured by a

UV laser; powder bed fusion, solidifying a powder-based material through a heat source; sheet lamination, laminating sheets using adhesives or ultrasonic welding to form objects; and vat photopolymerization, involving selective curing of liquid photopolymer resin into a solid state in a vat. (Stefaniak et al., 2021; Tofail et al., 2018; Wu et al., 2020). Each of these processes involves pre-printing, printing, post-printing, and post-processing stages that cause certain emissions based on the utilized technology and materials. Therefore, they require concerns for health and safety (Minář et al., 2023), as they directly affect indoor air quality in workplaces. The main risks include particle inhalation, exposure to semi-volatile and volatile organic compounds, and dermal contact with various substances such as powders, binders, resins, solvents, and radiation (Petretta et al., 2019; Roth et al., 2019).

Given that the expansion of AM applications has not been accompanied by comprehensive attention to IAQ, with only a limited number of publications addressing these (Stefaniak et al., 2021), this research explored the complex relationship between AM technologies and indoor air quality. The focus was given to workplaces where production and office spaces were combined. To achieve this, the research utilized semi-structured interviews and field experiments to investigate indoor air quality in the evolving dynamics of workplaces involving additive manufacturing.

The semi-structured interview was designed to gather information regarding the workplace dynamics of the workplace. It contained questions covering the roles and responsibilities of the participants, their perception of integration of production and office spaces, benefits of integration, drawbacks of integration, the impact of integration on communication and collaboration, and the impact of integration on workflow efficiency, IEQ alignments, and conflicts with respect to the integration of production and office spaces and IEQ's impact on comfort and productivity. The semi-structured interviews were conducted with employees in the workplace to gather insights into workplace dynamics.

Two instruments, Indoor Network Based Air Quality Ecosystem (INBASE) and Indoor Air Quality Polling Instrument, were designed for the field experiments. The hardware of the first instrument, INBASE, was developed using a development board, breadboard, base shield, display unit, Wi-Fi module, and sensors sensitive to PM_{1.0}, PM_{2.5}, PM₁₀, TVOC, HCHO, C₆H₆, C₂H₅OH, NO₂, CO₂, and O₂. The software development of INBASE was conducted on Arduino IDE in terms of reading sensor data, formatting it for transmission, and sending it to a server over a TCP connection. The sensors requiring user calibration were subjected to calibration to optimize their response so that the sensor output was proportional to the measured quantity. The hardware of the second instrument, the Indoor Air Quality Polling Instrument, was developed using a development board, breadboard, card shield, display unit, real-time clock, and tact switches. Its software was developed in Arduino IDE for formatting, organizing, recording, and displaying data.

The designed instruments were used for field experiment sessions in a workplace practicing additive manufacturing. The field experiments took place in production and office spaces during the operations of powder bed fusion process - selective laser melting (PBF-SLM) technology, powder bed fusion process - selective laser sintering (PBF-SLS) technology, and vat photopolymerization process - stereolithography (VP-SLA) technology during the pre-printing, printing, post-printing, and post-processing phases. While INBASE acquired real-time data on concentrations of PM_{1.0}, PM_{2.5}, PM₁₀, TVOC, HCHO, C₆H₆, C₂H₅OH, NO₂, CO₂, and O₂ in production and office spaces, the Indoor Air Quality Polling Instrument was used as a feedback mechanism where employees using these spaces in the workplace can rate the space in terms of their perception of indoor air quality using a scale of very good, good, neutral, bad, and very bad. Therefore, the impact of different AM technologies on IAQ parameters and subjective perceptions of IAQ within production and office spaces were captured.

5.2 Main Results and Discussion

The employee interviews highlighted the importance of investigating the impact of AM operations on the IAQ of production and office spaces in workplaces. Critical insights revealed into operational dynamics, environmental and health impacts, and workplace design. The integration of production and office spaces was reported to improve task management, streamline operations, reduce travel time, and enhance communication and collaboration in the context of AM operations. However, challenges were noted regarding indoor air quality and the adequacy of facilities to support the integrated functionality. While the integration offered notable operational and collaborative benefits, it raised indoor air quality concerns, which were investigated by conducting field experiments. Consequently, the research questions were addressed through field experiments, with this chapter organized to present each research question alongside its corresponding answer.

The first research question and the findings answering this question are

- How do different AM processes, including PBF-SLM, PBF-SLS, and VP-SLA that take place in the related production spaces, impact IAQ parameters—such as particulate matter, volatile organic compounds, formaldehyde, benzene, ethanol, nitrogen dioxide, carbon dioxide, and oxygen—in those production spaces during various phases of AM operations?

The results of the field experiments where the PBF-SLM production space was monitored revealed that $PM_{1.0}$, $PM_{2.5}$, and PM_{10} concentrations indicated variations during different phases, such as pre-printing and post-printing, compared to the background levels. Despite these fluctuations, $PM_{2.5}$ and PM_{10} concentrations mainly complied with a majority of established thresholds. TVOC concentrations suggested certain fluctuations in different phases compared to background levels. While the background and pre-printing phases did not indicate any hygienic concerns, the printing and post-printing phases aroused mild concerns. Specific

peaks were observed during the printing phases, necessitating increased ventilation and source investigation. HCHO concentrations indicated almost indistinguishable variations during different phases compared to the background levels. All recorded values complied with the established thresholds. C₆H₆, C₂H₅OH, and NO₂ concentrations remained undetectably low throughout all phases, indicating that PBF-SLM production space was considered safe concerning C₆H₆, C₂H₅OH, and NO₂. Although CO₂ concentrations revealed interesting patterns across different phases, the concentrations mainly stayed within the established thresholds. O₂ remained relatively stable and maintained within safe limits throughout all phases.

The results of the field experiments where the PBF-SLS production space was monitored revealed that PM_{1.0}, PM_{2.5}, and PM₁₀ concentrations indicated slight variations during different phases compared to the background levels. Despite these fluctuations, PM_{2.5} and PM₁₀ concentrations mainly complied with a majority of established thresholds. The powder management station effectively controlled emissions, preventing significant deviations from background levels. TVOC concentrations suggested slight fluctuations in different phases compared to background levels, with no critical values observed. The short-term fluctuations highlighted the necessity of increased ventilation and source investigation, as required by these concentration levels. HCHO concentrations indicated almost indistinguishable variations during different phases compared to the background levels. All recorded values complied with the established thresholds. C₆H₆ and C₂H₅OH remained undetectably low throughout all phases. NO₂ concentrations were negligible during most phases, except for an increase during the printing phase. Since the measured values were maintained below the maximum tolerable levels for short-term and long-term exposure, the PBF-SLS production space was considered safe with respect to NO₂. Although CO₂ concentrations revealed interesting patterns across different phases, the concentrations mainly stayed within the established thresholds. O₂ remained relatively stable and maintained within safe limits throughout all phases.

The results of the field experiments where the production spaces, including the VP-SLA production space and the post-processing atelier, were monitored revealed that $PM_{1.0}$ concentrations indicated slight variations during different phases compared to the background levels. Although $PM_{2.5}$ and PM_{10} concentrations exhibited certain variations during different phases relative to the background levels, they mainly complied with a majority of established thresholds. TVOC concentrations suggested notable fluctuations in different phases compared to the background levels. While the background and pre-printing phases did not indicate any hygienic concerns, the printing and post-printing phases aroused mild concerns. On the other hand, the post-processing phase caused a significant elevation in TVOC concentrations associated with post-processing activities, reaching up to unacceptable concentrations with respect to the established thresholds. HCHO concentrations indicated almost indistinguishable variations during different phases compared to the background levels. The recorded values complied with the established thresholds. C_6H_6 and C_2H_5OH concentrations were negligible during most phases, except for significant peaks observed during the post-processing phase. NO_2 concentrations exhibited specific peaks during the pre-printing and post-processing phases, exceeding long-term thresholds while being maintained within maximum tolerable levels for short-term exposure. As the sensor detecting C_6H_6 , C_2H_5OH , and NO_2 is a qualitative sensor, the quantified peak values may not represent exact measurements but provide approximate estimates with a reliable trend. Consequently, the post-processing phase can be associated with increasing levels of C_6H_6 and C_2H_5OH in the post-processing atelier. Similarly, the printing and post-processing phase can be associated with increasing levels of NO_2 in the VP-SLA production space and post-processing atelier. CO_2 concentrations revealed a notable pattern across different phases. However, the concentrations mainly stayed within the established thresholds. O_2 remained relatively stable and maintained within safe limits throughout all phases.

The second research question and the findings answering this question are

- How do different AM processes, including PBF-SLM, PBF-SLS, and VP-SLA that take place in the related production spaces, impact IAQ parameters—such as particulate matter, volatile organic compounds, formaldehyde, benzene, ethanol, nitrogen dioxide, carbon dioxide, and oxygen—in the office space during various phases of AM operations?

The results of the field experiments, where the office space was monitored when PBF-SLM operations took place in PBF-SLM production space, revealed that PM_{1.0}, PM_{2.5}, and PM₁₀ concentrations exhibited a stable trend with little variations compared to the background levels. Despite slight fluctuations, PM_{2.5} and PM₁₀ concentrations mainly complied with a majority of established thresholds. TVOC concentrations did not indicate hygienic concerns at any phase. It mainly followed a stable trend with indistinguishable variations compared to the background levels. HCHO concentrations indicated almost indistinguishable variations during different phases compared to the background levels. All recorded values complied with the established thresholds. C₆H₆, C₂H₅OH, and NO₂ concentrations remained undetectably low throughout all phases, indicating that the office space was considered safe concerning C₆H₆, C₂H₅OH, and NO₂. Although CO₂ concentrations revealed interesting patterns across different phases, the concentrations mainly stayed within the established thresholds. O₂ remained relatively stable and maintained within safe limits throughout all phases.

The results of the field experiments, where the office space was monitored when PBF-SLS operations took place in PBF-SLS production space, revealed that PM_{1.0}, PM_{2.5}, and PM₁₀ concentrations indicated slight variations during different phases compared to the background levels. Despite these fluctuations, PM_{2.5} and PM₁₀ concentrations mainly complied with a majority of established thresholds. The powder management station effectively controlled emissions, preventing significant deviations from background levels. TVOC concentrations suggested slight fluctuations in different phases compared to background levels; however, no

critical values were observed. The short-term fluctuations highlighted the necessity of increased ventilation and source investigation, as required by these concentration levels. HCHO concentrations indicated almost indistinguishable variations during different phases compared to the background levels. All recorded values complied with the established thresholds. C₆H₆, C₂H₅OH, and NO₂ remained undetectably low throughout all phases, indicating that the office space was considered safe concerning C₆H₆, C₂H₅OH, and NO₂. Although CO₂ concentrations revealed interesting patterns across different phases, the concentrations mainly stayed within the established thresholds. O₂ concentrations remained relatively stable and maintained within safe limits throughout all phases.

The results of the field experiments, where the office space was monitored when VP-SLA operations took place in production spaces, including the VP-SLA production space and post-processing atelier, revealed that PM_{1.0} concentrations indicated slight variations during different phases compared to the background levels. Although PM_{2.5} and PM₁₀ concentrations exhibited certain variations during different phases relative to the background levels, they mainly complied with the established thresholds. TVOC concentrations suggested slight variations during different phases compared to the background levels. While background and post-printing did not reveal any hygienic concerns, the pre-printing, printing, and post-processing phases suggested mild concerns, necessitating increased ventilation. HCHO concentrations indicated almost indistinguishable variations during different phases compared to the background levels. The recorded values complied with the established thresholds. C₆H₆, C₂H₅OH, and NO₂ concentrations remained undetectably low throughout all phases, indicating that the office space was considered safe concerning C₆H₆, C₂H₅OH, and NO₂. CO₂ concentrations revealed a notable pattern across different phases. However, the concentrations mainly stayed within the established thresholds. O₂ remained relatively stable and maintained within safe limits throughout all phases.

The third research question and the findings answering this question are

- How do workplace employees perceive IAQ in the related production spaces in the presence of different AM processes, including PBF-SLM, PBF-SLS, and VP-SLA, that occur in those production spaces?

The results of the polling instrument in the PBF-SLM production space revealed that employee perception of IAQ followed a declining pattern, with the weighted averages of IAQ ratings during operational phases at or below neutral. The findings of the polling instrument in the PBF-SLS production space revealed that the IAQ was perceived above the neutral point overall during PBF-SLS operations. When placed in the VP-SLA production space and post-processing atelier, the polling instrument's outcomes revealed that the IAQ was perceived below the neutral point overall during operational phases.

The fourth research question and the findings answering this question are

- How do workplace employees perceive IAQ in the office space in the presence of different AM processes, including PBF-SLM, PBF-SLS, and VP-SLA, that occur in the related production spaces?

The results of the polling instrument in the office space during PBF-SLM operations taking place in the PBF-SLM production space, PBF-SLS operations taking place in the PBF-SLS production space, and VP-SLA operations taking place in production spaces, including the VP-SLA production space and post-processing atelier, revealed that employee perception of IAQ was positive mainly with weighted averages of employee ratings above neutral throughout all phases of these AM operations.

The fifth research question and the findings answering this question are

- How do variations in monitored IAQ parameters due to different AM processes correlate with IAQ perceptions of employees in the related production spaces?

When the results of INBASE and the polling instrument in the context of PBF-SLM production space during PBF-SLM operations were considered together, no definitive correlation was found between them. However, TVOC concentrations emerged as potentially influential factors in perceived IAQ. Similarly, a definitive correlation was not captured, when the findings of INBASE and the polling instrument in the context of PBF-SLS production space during PBF-SLS operations were considered together. However, variations in IAQ parameters, that are mostly within established thresholds, likely contributed to the employees' perception of being above neutral throughout all phases. Lastly, when the outcomes of INBASE and the polling instrument in the context of production spaces, including the VP-SLA production space and post-processing atelier during VP-SLA operations, were considered together, no direct correlation was found. Nonetheless, TVOC, C₆H₆, C₂H₅OH, and NO₂ concentrations emerged as possible influential factors on perceived IAQ.

The last research question and the findings answering this question are

- How do variations in monitored IAQ parameters due to different AM processes correlate with IAQ perceptions of employees in the office space?

When the results of INBASE and the polling instrument in the context of office space during PBF-SLM operations taking place in PBF-SLM production space were considered together, despite the lack of an apparent correlation between IAQ parameters and employee perception, maintaining IAQ within established thresholds likely contributed to positive employee perceptions. Similarly, when the findings of INBASE and the polling instrument in the context of office space during PBF-SLS operations taking place in PBF-SLS production space were considered together, a definitive correlation was not captured. However, variations in IAQ parameters, that are mostly within established thresholds, likely contributed to the employees' perception of being above neutral throughout all phases. Lastly, when the outcomes of INBASE and the polling instrument in the context of office space during VP-SLA operations taking

place in production spaces, including the VP-SLA production space and post-processing atelier, were considered together, no direct correlation was found. However, maintaining IAQ parameters mainly within established thresholds likely contributed to positive employee feedback in terms of IAQ.

The summary of the results is presented in Table 5.1. For the $PM_{1.0}$ parameter, “monitored levels” indicate observed concentrations, though no specific safety limit is established. Regarding $PM_{2.5}$ and PM_{10} , “safe levels” indicate concentrations remaining below the maximum tolerable limits for 24-hour and annual exposure throughout the production cycle. In the case of TVOC, “safe levels” refer to concentrations below level 1 or within levels 1 and 2, signifying no significant hygienic concerns or only necessitating increased ventilation. “Elevated levels” indicate concentrations reaching level 3, prompting the need for source investigation and increased ventilation. In contrast, “critical levels” pertain to concentrations at or above level 5, which are unacceptable and require usage only if unavoidable, with enhanced ventilation measures. Within the context of the HCHO parameter, “safe levels” denote concentrations that remain below the maximum safe level for a 30-minute average throughout the production cycle. Regarding C_6H_6 , “non-detectable levels” refer to concentrations consistently measured at 0 mg/m³. The term “elevated levels” indicates concentrations that show a significant increase, although no specific safety limit is established. For the C_2H_5OH parameter, “non-detectable levels” refers to concentrations consistently measured at 0 ppm. The term “safe levels” describes concentrations that remain below the workplace exposure limit throughout the production cycle. In the case of NO_2 , “non-detectable levels” refers to concentrations consistently measured at 0 µg/m³. The terms “safe levels” denote concentrations that predominantly, if not entirely, remain below the maximum tolerable levels for 24-hour and annual exposure levels throughout the production cycle. Within the context of the CO_2 parameter, “safe levels” denote concentrations that predominantly, if not entirely, remain within the typical outdoor and maximum indoor level thresholds throughout the production cycle. In terms of O_2 , “safe levels” denote concentrations that

remain within the minimum and maximum safe level thresholds throughout the production cycle. Finally, within the context of IAQ perception, “above neutral” refers to weighted averages of employee ratings exceeding a score of 3, while “below neutral” denotes weighted averages falling below a score of 3.

Table 5.1 Summary of the Results of the Research

	PBF-SLM		PBF-SLS		VP-SLA	
	Production Space	Office Space	Production Space	Office Space	Production Space	Office Space
PM_{1.0}	monitored levels	monitored levels	monitored levels	monitored levels	monitored levels	monitored levels
PM_{2.5}	safe levels	safe levels	safe levels	safe levels	safe levels	safe levels
PM₁₀	safe levels	safe levels	safe levels	safe levels	safe levels	safe levels
TVOC	elevated levels	safe levels	elevated levels	elevated levels	critical levels	elevated levels
HCHO	safe levels	safe levels	safe levels	safe levels	safe levels	safe levels
C₆H₆	non-detectable levels	non-detectable levels	non-detectable levels	non-detectable levels	elevated levels	non-detectable levels
C₂H₅OH	non-detectable levels	non-detectable levels	non-detectable levels	non-detectable levels	safe levels	non-detectable levels
NO₂	non-detectable levels	non-detectable levels	safe levels	non-detectable levels	safe levels	non-detectable levels
CO₂	safe levels	safe levels	safe levels	safe levels	safe levels	safe levels
O₂	safe levels	safe levels	safe levels	safe levels	safe levels	safe levels
IAQ Perception	below neutral	above neutral	above neutral	above neutral	below neutral	above neutral

In brief, these results emphasize the need for facility adjustments at the design, organization, and equipment levels. Therefore, it is crucial to highlight the necessities regarding spatial adjustments with the introduction of buffer zones in between production and office spaces, improved ventilation coupled with localized exhaust systems tailored for these spaces, the use of PPE for the employees working in production spaces, and regular maintenance of equipment to address IAQ challenges in the workplace associated with PBF-SLM, PBF-SLS, and VP-SLA operations, particularly in production spaces, while also being applicable for the office space.

5.3 Limitations and Future Directions

This study, while comprehensive, has certain limitations. Firstly, this study investigates only a limited number of AM processes (PBF-SLM, PBF-SLS, and VP-SLA), and therefore, the findings cannot be generalized to all AM operations. Factors such as the use of different materials and the printing of various designs in the same equipment were not addressed in this study. Secondly, as only one air quality monitor was available for this study, simultaneous monitoring of production and office spaces was not feasible. The monitoring process for production spaces was completed before beginning the monitoring in office spaces. Consequently, it was not possible to capture real-time IAQ data for both environments simultaneously during identical operations, potentially affecting the comparability of the findings. Additionally, the utilized quantitative and qualitative sensors during monitoring processes are commercially available electrochemical sensors whose base measurements are in terms of voltage. This reliance on voltage-based sensors may introduce limitations in accuracy and precision. Thirdly, the temporal aspect of the data collection, confined to singular printing operations, might not capture the complete picture of indoor air quality variations over more extended periods. Lastly, employee feedback on indoor air quality has a subjective nature

owing to being influenced by individual perceptions and experiences. This may lead to potential variability.

Future research should aim to address these limitations by expanding research to include a broader range of AM processes to explore the full spectrum of IAQ impacts associated with different AM technologies, materials, and design complexities. Deploying multiple air quality monitors with high-grade sensors could facilitate the simultaneous collection of real-time IAQ data in both production and office spaces, allowing for increased data collection frequency, more accurate comparison with precise estimates, and a deeper understanding of IAQ dynamics in integrated work environments. Conducting longitudinal studies to monitor IAQ over extended periods would offer a more comprehensive view of the effects of AM operations on indoor air quality over time. Additionally, integrating health and comfort indicators, such as physiological measurements or productivity metrics, alongside subjective employee feedback could provide a more holistic view of the impact of indoor air quality on workplace health and performance. Exploring various mitigation strategies, such as advanced ventilation systems or localized air cleaning technologies, could offer practical solutions to the air quality challenges identified in integrated production and office spaces.

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APPENDICES

A. The Semi-Structured Interview in Turkish

Ofis alanı, bir organizasyon içinde bireylerin işlerinin, görevlerinin ve sorumluluklarının yerine getirildiği, masa, bilgisayar, telefon ve diğer ofis ekipmanları ile donatılmış bir mekandır.

Üretim alanı, bir organizasyon içinde üretim veya imalat süreçlerinin gerçekleştirildiği ve fiziksel ürünlerin üretildiği bir mekandır. Bu mekan, üretim ekipmanları, montaj hatları, depolama alanları ve işleme alanları ile donatılmış olabilir.

Çalışma alanı, işin gerçekleştirildiği fiziksel ortamı ifade eder ve bireylerin veya ekiplerin görevlerini yerine getirmek için kullandığı tüm mekanları, tesisleri ve kaynakları kapsar. Bu, ofis alanları, üretim alanları, laboratuvarlar, stüdyolar, atölyeler ve işle ilgili faaliyetlerin gerçekleştirildiği diğer belirlenmiş mekanları içerir.

X Şirketi, ofis alanları ve üretim alanlarının entegre edildiği bir çalışma alanıdır.

1. Bu çalışma alanındaki rolünüzü ve sorumluluklarınızı tanımlar mısınız?
2. Bu çalışma alanındaki ofis ve üretim alanlarının entegrasyonunu nasıl algılıyorsunuz ve bu entegrasyonun gerekliliği hakkında ne düşünüyorsunuz?
3. Bu çalışma alanında ofis ve üretim alanlarının entegrasyonu ile ilişkili herhangi bir avantaj gözlemlediniz mi? Varsa, bunlar nelerdir?
4. Bu çalışma alanında ofis ve üretim alanlarının entegrasyonu ile ilişkili herhangi bir dezavantaj gözlemlediniz mi? Varsa, bunlar nelerdir?
5. Bu çalışma alanında ofis ve üretim alanlarının entegrasyonu, ekip üyeleri arasındaki iletişimi ve işbirliğini nasıl etkiliyor?
6. Bu çalışma alanında ofis ve üretim alanlarının entegrasyonu, organizasyon içindeki iş akışları ve süreçlerin verimliliğini nasıl etkiliyor?

İç Mekan Çevre Kalitesi, kapalı alanlardaki iç mekanın genel kalitesini ifade eder ve bina sakinlerinin sağlığı, konforu ve verimliliğini etkileyebilecek çeşitli faktörleri kapsar. IEQ, iç hava kalitesi, termal konfor, akustik konfor ve aydınlatma kalitesi gibi birden fazla faktörden etkilenir.

7. Ofis ve üretim alanları tarafından gereksinim duyulan iç mekan çevresel kalite koşullarında herhangi bir uyum veya çatışma gözlemlediniz mi? Varsa, bu gözlemleri detaylandırabilir misiniz?
8. Ofis ve üretim alanları tarafından sağlanan iç mekan çevresel kalite koşullarındaki uyum veya çatışmalar, her iki alanda çalışan çalışanların konforunu ve verimliliğini nasıl etkiliyor?

B. The Semi-Structured Interview in English

Office space refers to the area within an organization where tasks, duties, and responsibilities are performed by individuals in an environment equipped with desks, computers, phones, and other office equipment used for office work.

Production space refers to the space within an organization where production or manufacturing processes are executed, and physical products are manufactured. This area may be equipped with production equipment, assembly lines, storage areas, and processing areas.

Workplace refers to the physical environment where work is conducted, encompassing all areas, facilities, and resources utilized by individuals or teams to perform their tasks and responsibilities. This includes but is not limited to office spaces, production areas, laboratories, studios, workshops, and any other designated areas where work-related activities take place.

Company X is a workplace where office and production spaces are integrated.

1. Can you describe your role and responsibilities within this workplace?
2. How do you perceive the integration of office and production spaces in this workplace, and what do you think about the necessity of this integration?
3. Have you observed any benefits associated with integrating office and production spaces in this workplace? If so, what are they?
4. Have you observed any drawbacks associated with integrating office and production spaces in this workplace? If so, what are they?
5. How does the integration of office and production spaces in this workplace impact communication and collaboration among team members?
6. How does the integration of office and production spaces in this workplace affect the efficiency of workflows and processes within the organization?

Indoor Environmental Quality (IEQ) refers to the overall quality of the indoor environment, encompassing various factors that can affect occupants' health,

comfort, and productivity. It is influenced by multiple factors, including indoor air quality, thermal comfort, acoustic comfort, and lighting quality.

7. Have you observed any alignments or conflicts in the indoor environmental quality conditions required by production and office spaces? If so, could you elaborate on these observations?
8. How do alignments or conflicts in the indoor environmental quality conditions provided by office and production spaces impact the comfort and productivity of employees working in both spaces?

