Air Pollution from High-rise Construction in Rotterdam: Comparison of black carbon (BC), ultrafine (UFP)and particulate matter ($PM_{2.5}$ and PM_{10}) ambient concentrations from conventional and biobased (Cross-Laminated Timber CLT) construction methods

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Thank you to all the people who have supported and motivated me during this period, during the thesis, and during this experience. There are no more words to show my gratitude…

Gabriel

Abstract

Keywords: Air quality, Rotterdam, Amsterdam, Highrise building, Ultrafine particle, Black carbon, Particulate matter, Cross-laminated timber, Emissions, Health, Machinery, biobased materials, construction, climate change.

This research addresses the challenge of climate change and air quality, focusing on the construction industry's impact in the Netherlands. The construction sector, a significant source of air pollution, necessitates sustainable practices for mitigating the effects of climate change and reducing pollutants. The study emphasises the need for stricter local regulations and innovative technologies to curb air emissions within the cities.

Examining air pollutants such as Ultrafine Particles (UFP), Black Carbon (BC), $PM_{2.5}$, and PM_{10}, the research clarifies their role in ambient concentrations. While acknowledging the global nature of air pollution, its impact on health, the economy, and various sectors in the built environment highlights the need for comprehensive measures. The Netherlands' commitment to reducing air pollutant emissions aligns with European agreements and initiatives, emphasising promoting emission-free technologies in construction machinery.

The shift from conventional high-rise construction to bio-based materials, particularly Cross-Laminated Timber (CLT), emerges as a promising solution. Cross-laminated timber is praised for its environmental friendliness, speed of construction, seismic resistance, and ability to resist high temperatures. The study examines the ecological concentrations of UFP, BC, $PM_{2.5}$, and PM_{10} in high-rise buildings constructed using CLT and conventional methods, offering insights into the potential benefits of sustainable construction practices.
Focusing on specific construction sites in Rotterdam and specific urban construction sites like Amsterdam, the research compares ambient concentrations during construction, highlighting the environmental impact of different building methods. The lack of regulations for UFP and BC in the Netherlands underscores the importance of investigating their concentrations to guide future research and regulatory efforts.

The research project aims to inform policymakers, architects, builders, and the community about the environmental and health implications of construction decisions. The study envisions a cleaner, healthier, and more sustainable urban environment in Rotterdam and beyond by fostering awareness and providing a blueprint for future investigations.

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List of Tables, Figures, and Images.

List of abbreviations

BC	Black carbon.
CLT	Cross-laminated timber.
EF	Emission factor.
EU	European Union.
NL	The Netherlands.
PM	Particulate matter.
PM10	Particulate matter with diameter less than 10 micrometres.
PM2.5	Particulate matter with diameter less than 2.5 micrometres.
RIVM	Rijksinstituut voor Volksgezondheid en Milieu.
TNO	Nederlandse Organisatie voor toegepast-natuurwetenschappelijk onderzoek.
UFP	Ultrafine particle.
WHO	World Health Organisation.

"…architecture has taken on an immense disciplinary responsibility towards the solid, the vegetative, and the aqueous rather than towards the aerial of things of a meteorological kind… the air has been unnoticed because it does not show itself…"

French philosopher Luce Irigaray

1. Introduction:

Understanding Ultrafine particles, Black Carbon, and Particulate Matter ($PM_{2.5}$ & PM_{10}).

Climate change and air quality represent pressing global challenges in the 21st century. The construction industry and the logistics that surround it have a direct and indirect impact on the environment. The construction industry is a source of air pollution, noise, dust, and solid waste. In the context of Rotterdam, addressing these issues requires the development of more sustainable construction methods to reduce air pollutants and mitigate the impacts of climate change (International Energy Agency. & Global Alliance for Buildings and Construction., 2019). To reduce air emissions, it is crucial to implement stricter local regulations and adopt innovative technologies that minimise emissions of air pollutants within the city (Arocho Rosa, 2015).

The construction industry, a major contributor to air-polluting emissions such as ultrafine particles, black carbon, and particulate matter 2.5 and 10, plays a significant role in global warming and poses risks to human health (ref). Despite the adverse effects, the global scale of air pollution can dilute the impact of localised concerns (ref). The centralisation of decision-making processes in distant bureaucratic entities further exacerbates the disconnect from the unique local circumstances crucial for enhancing air quality. Recognising the importance of leveraging local knowledge and experiences, it is imperative to develop strategies addressing air pollution challenges, fostering a cleaner and healthier environment for Rotterdam residents and future generations. The profound impact of air pollution on health is evident, causing numerous premature deaths annually in Europe and exerting a substantial economic toll, estimated between 330 and 940 billion euros ((Tasiopoulos, 2020); (EUROPEAN COMMISSION, 2021). Interwoven connections between air pollutant production and diverse economic sectors, including agriculture, industry, transportation, and the built environment, underscore the complexity of the issue. Notably, in the Netherlands, the building construction sector alone contributes to 38% of all air pollutants produced ((I DIRECTIVE 2008/50/EC OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 21 May 2008 on Ambient Air Quality and Cleaner Air for Europe, n.d.)).

Air pollutant emissions result from the energy used by buildings and the processes used in building construction. The Netherlands intends to cut air pollutant emissions countrywide by 55% regarding CO_2 (Hague, 2019) & (EUROPEAN COMMISSION, 2021) under the National Climate Agreement and the "fit-for-55" package announced by the European Commission in 2021. Many agreements, subsidies, programmes, and policies have been developed around these sectors to reduce air-polluting emissions; some examples include the programme for a circular agriculture transition in the case of agriculture and the reduction of "peak polluters" in the case of industry, where the government has introduced subsidies to reduce nitrogen and ammonia deposition. In the built environment, the government will concentrate on emission-free pilot projects of construction machinery in the next three years (Hekma et al., 2021). The government is promoting the change to emission-free cars by 2030 in the transportation sector.

High-rise buildings have traditionally been built using steel and concrete. The use of biobased materials, in this case, the use of cross-laminated timber, known as CLT, in the construction of mid-rise and high-rise, has proven to be a competitive solution with respect to its steel and concrete counterparts. Cross-laminated construction (CLT) is presented as a more environmentally friendly, faster, lighter (up to 6 times lighter than concrete, seismic resistance, which has the ability to resist high temperatures for a long time without suffering deterioration in its mechanical characteristics (Younis & Dodoo, 2022), (Introduction to New Material-Cross Laminated Timber, n.d.).

Understanding the impact of building practices on air quality is essential for implementing effective measures to reduce emissions. This research aims to measure ambient concentration of Ultrafine particles (UFP), Black Carbon (BC) and particulate matter ($PM_{2.5}$ and PM_{10}) around high-rise buildings construction sites, comparing air pollution at sites using biobased techniques, particularly cross-laminated timber (CLT) versus those using conventional construction (concrete and steel) in Rotterdam and Amsterdam.

1.1 Context of the research.

This research takes place in Rotterdam and Amsterdam in the Netherlands. Amsterdam and Rotterdam, Figure 1., located in the provinces of Noord- and Zuid-Holland, respectively, are the two largest cities in the Netherlands. Rotterdam, the biggest port in Europe, is the Netherlands' major logistic and economic centre, and Amsterdam is the capital of the Netherlands, located in the province of North Holland. Both cities are in constant change and adaptation, implementing different urban and architectural projects. Rotterdam is the city with the most high-rise buildings in the whole of the Netherlands, with 350 high-rises completed, including the tallest tower in the whole of the Netherlands (De Zalmhaven) with a height of 215 meters, completed in 2022 (Council on tall buildings and urban habitat, 2023). It is also home to many of the world's most influential and prestigious architecture offices, such as OMA, MVRDV, Neutelings Riedijk Architects, among others.

Figure 1. Location Rotterdam and Amsterdam.

For this study, it is essential to define what a high-rise building is, what is a conventional construction system and what is a biologically based construction method. According to Kadaster, in the Netherlands, a high-rise building is a building more than 35 meters high or consolidated by ten floors or more (Kadaster: brt: hoogbouw., n.d.). (Bosch & Peine, n.d.)Conventional construction is "that which is based on a non-renewable, fossil-based extractive economy... associated with the linear economic approach to production"; It commonly involves the use of materials such as concrete, steel, aluminium and glass, where concrete and steel are the most used worldwide, for the construction of the structure of a building (slabs, columns, load-bearing walls, etc.), (Keena et al., 2022), Figure 2. A bio-based construction method can be defined as "one based on bio-based materials; these materials come from regenerative crops that ensure the ecological health of the harvest site... made from raw materials from living nature. "raw materials that can then be reusable." in a new building" (Inspiration Book Bio-Based and Nature Inclusive to Build, n.d.). Among the different biobased construction systems, we can name Laminated Veneer Lumber LVL, Glued Laminated Timber GLT, Nail Laminated Timber NLT and Cross Laminated Timber CLT; this thesis will focus on Cross Laminated Timber CLT. CLT or Cross Laminated Timber "consists of several layers (usually 3, 5 or 7 layers) of boards stacked on top of each other, with alternating layers placed at right angles. Layers are glued or mechanically fastened so that" in this way, they form panels that serve as structural elements for load-bearing walls, slabs, beams, etc. (Introduction to New Material-Cross Laminated Timber, n.d.), Figure 3.

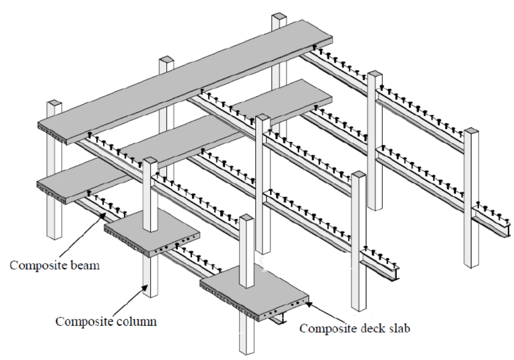

Figure 2. Concrete/Steel Structure.

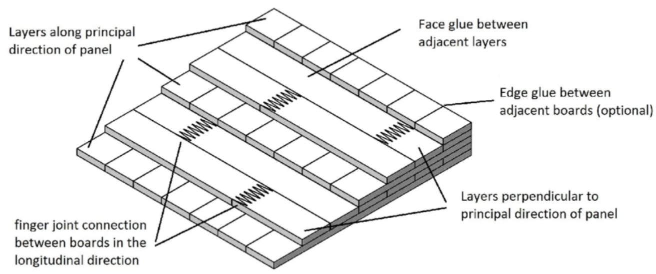

Figure 3. Cross-laminated timber (CLT).

In this study, four construction sites in Rotterdam were initially selected to analyse the ambient concentrations of UFP, BC, $PM_{2.5}$ and PM_{10}. These sites were PostRotterdam, Sawa, Boompjes and Colosseumplot. These sites are currently under construction; PostRotterdam and Boompjes have conventional structures, Colosseumplot is a mix of conventional and CLT structures, and Sawa has a CLT structure. To expand the scope of the research to include an additional biobased project, the Switi project, located in Amsterdam, was added. The final thesis focuses primarily on the most interesting comparisons found, so we primarily analyse Post Rotterdam, Sawa, and Switi. Table1. shows a summary of each project.

The PostRotterdam project is located in the heart of Rotterdam in the Centrum district; the project consists of a high-rise building with a height of 150m, with a mixed-use architectural program, with use of retail, galleries, restaurants, cafes, a 5-star hotel and private housing, the structure of the building made of conventional way with the use of concrete and steel (ODA Architecture, 2019). The Sawa project, located in the Delftshaven district of Rotterdam, consists of a 50-meter-high tower with residential use, consisting of 109 apartments. At Sawa, the construction is entirely made with CLT, making " SAWA the first fully tall wooden residential building in Rotterdam."(Mei architects and planners, 2022). The Boompjes project, also located in the Centrum district in Rotterdam, is a high-rise building with a height of 100m (TEAM V, 2016); like PostRotterdam, the construction is conventional, using concrete and steel, and also mixed-use, with a commercial area and private housing. Finally, the Colosseumplot project, located south of Rotterdam in the Feijenoord district, with a height of 70 m, is a mixed-use project, which includes social and private housing, with social and commercial areas and a social centre. The project is mixed, using conventional concrete and steel as well as CLT (Orange Architects, 2021). Switi is a middle-rise project located in the Zuidoot-Amsterdam district; it consists of housing with a program of 24 ground-level homes and 45 in an 8-story tower; the project's structure is in CLT (HOH Architecten, n.d.).

ID	Project	Location	Structure	GFA(m2)	Height (m)	Company (Arch. firm)
1	Sawa	Rotterdam	CLT	12000	50	Mei Architects
2	PostRotterdam	Rotterdam	Conventional	79000	150	ODA Architecture
3	Colosseumplot	Rotterdam	CLT+Conventional	72000	70	Orange Architects
4	Boompjes	Rotterdam	Conventional	43000	100	Team V
5	Switi	Amsterdam	CLT	12100	27*	HOH Architecten

Table 1. List of sites in Rotterdam and Amsterdam.

Subsequently, the focus was narrowed to three projects, PostRotterdam, Sawa, Figure 4., and Switi Figure 5., excluding Boompjes and Colosseumplot, for further analysis, to focus field measurement efforts on only the most interesting comparisons. This approach allows us to make more measurements at the selected sites to discover more characteristic differences in the environmental conditions and contaminant concentrations associated with the construction systems to be compared. It facilitates a more robust examination of the implications of both conventional and biobased materials (CLT) construction practices within the urban landscapes of Rotterdam and Amsterdam Zuid-Oost.

Figure 4. Rotterdam sampling sites.

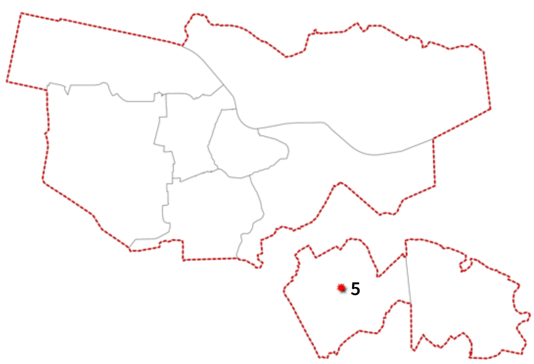

Figure 5. Amsterdam sampling sites.

With the focused comparison of these three sites, we investigate the effectiveness of different construction methods in terms of air quality and environmental sustainability. Ultimately, the knowledge gained from this study will be instrumental in shaping future urban development strategies and promoting a more sustainable and ecologically conscious built environment.

The various stages of the construction of any building impact the generation of air-polluting particles. According to the Ferrovial company (Ferrovial, 2023), the different construction processes are the following: closure of the work, land and foundation, construction of structures, mechanics, electricity and plumbing, insulation and waterproofing and finally, finishes and closures, Figure 6. These stages employ various construction equipment, which is responsible for the emissions of air-polluting particles that put the health of construction workers at risk, as well as public health, especially the inhabitants near a construction site. Emissions from the equipment may belong to road equipment (truck, concrete mixer, etc.) and off-road equipment (excavator, crane, caterpillars, etc.).The gas-phase pollutants generated by this equipment include carbon monoxide (CO), nitrogen oxides (NOx), non-methane hydrocarbons (NMHC), and carbon dioxide (CO_2) (Jung et al., 2020), alongside the particulate air pollutants that are the primary focus of this thesis: ultrafine particles (UFP), black carbon (BC) and Particle Matter ($PM_{2.5}$ and PM_{10}).

Today, air pollutant emissions from construction operations are governed by various regulatory documents. However, civil designers don't always comply with emissions regulations in complete obedience to the construction operation (Azarov et al., 2018). For example, different processes can be carried out at different times; however, the approach cannot work simultaneously. The environmental effect of the building can be accurately evaluated by considering the sequence and simultaneity of the processes. It is especially critical for buildings that are built on urban land. (Azarov et al., 2018). This is because urban areas are often more densely populated and have a higher concentration of pollutants, making it even more important to consider the environmental impact of construction activities. Additionally, evaluating the sequence and simultaneity of processes can help identify opportunities for optimisation and mitigation measures to minimise emissions and reduce the overall environmental footprint of the building.

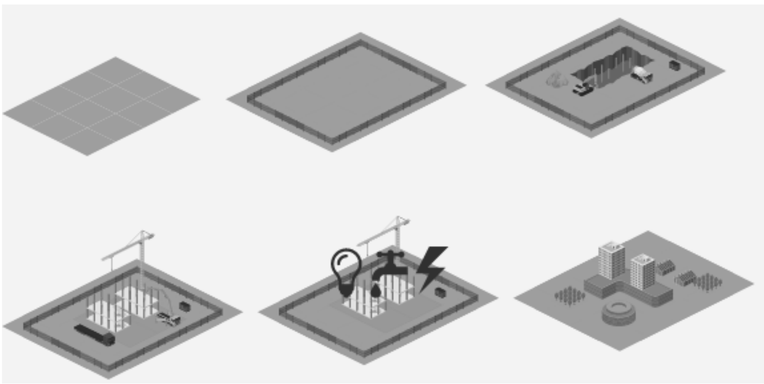

Figure 6. Construction process..

This thesis focuses on measurements of the ambient concentration of UFP, BC, $PM_{2.5}$ and PM_{10} at the Sawa, PostRotterdam and Switi construction sites. Ultrafine particles (UFP) result from the combustion of biomass, fossil fuels, biofuels, landfills, agricultural activities, and gas-phase precursors in the atmosphere (called secondary aerosol formation). They are particles with a diameter of less than 100 nm; due to their size, they have a substantial impact on health since they can penetrate the respiratory tract deep into the lungs, where they can be absorbed by the blood and transported into the bloodstream. According to (Morawska et al., 2008), deposition of these ultrafine particles has been observed in the lungs, liver, kidneys, heart, and brain.

Black carbon (BC) is emitted directly into the atmosphere by the incomplete consumption of fossil fuels (particularly diesel-driven road and non-road vehicles), biomass and biofuels (Lükewille, n.d.-a).According ((Guttikunda & Kopakka, 2014); (Dentener et al., 2006)), BC is likely the second most important contributor to global warming after $C0_2$. Like UFP, BC has adverse health effects; it has been associated with respiratory tract problems and cardiovascular diseases (Reche et al., 2011).

Particulate matter (PM) is a class of pollutants that includes dust, smoke, and other types of solid and liquid pollutants that remain suspended in the air due to their small size (Particulate Matter (PM) Pollution | US EPA, 2023). Dust, dirt, soot, and smoke are examples of the largest particles in this group that can be seen with the naked eye, but fine and ultrafine particles are too small to be visible to the human eye and must be measured by non-optical techniques. The EU's air quality legislation covers two PM size fractions: PM_{10} is particulate matter with an aerodynamic diameter of 10 µm or less, and $PM_{2.5}$ is particulate matter with an aerodynamic diameter of 2.5 µm or less (also termed 'fine PM'(Lükewille, n.d.-b).In Figure 7. it is possible to appreciate a comparison between the different sizes of the studied particles.

1.2 Description of the Problem and a Problem Statement.

The problem revolves around the environmental impact and public health of air pollution due to the release of harmful pollutants from ultrafine particles (UFP), black carbon (BC) and particulate matter (PM), including $PM_{2.5}$ and PM_{10}, produced for the construction of high-rise buildings in Rotterdam and Amsterdam (Keuken et al., 2011). Air quality in the built environment is a major concern, and construction activities contribute substantially to air pollution emissions. The release of air pollutants during construction can pose health risks to construction workers and local people, especially those close to construction sites. These pollutants are released due to various construction activities such as excavation, demolition, and material transportation. The particles can penetrate deep into the respiratory system and have been linked to respiratory and cardiovascular diseases.

Figure 7. Size of particles.

In the Netherlands, regulations and standards exist to mitigate the impact of air pollution from $PM_{2.5}$ and PM_{10} particles, subject to annual average limit values. Municipalities are obliged to demonstrate compliance with these limit values in their decision-making processes, as stated by the Council of State in a ruling of July 2016 (Rijksinstituut voor Volksgezondheid en Milieu, 2016). Also, the World Health Organization (WHO) in 2021 published the recommended values for $PM_{2.5}$ and PM_{10} (World Health Organization, 2021). Contrary to $PM_{2.5}$ and PM_{10} in the Netherlands, there are no regulations or annual average values for UFP and BC; according to RIVM, UFP should be studied independently of PM due to insufficient scientific knowledge to provide advice on safe concentrations in the outdoor air(Ltrafijnstof n Ultrafijn Stof En Gezondheid, n.d.). The absence of regulations or annual average values for UFP and BC in the Netherlands highlights the limited scientific understanding of their potential health effects and safe concentrations in outdoor air (Air Quality Policy in the Netherlands, n.d.).

The growth in construction in Rotterdam and Amsterdam has an environmental impact and highlights the importance of considering more sustainable construction systems and processes. In the case of the use of CLT, it is presented as an opportunity for the construction of buildings with more than ten floors (Yadav & Agarwal, 2021) and reducing air pollutant emissions (Hassan et al., 2019) compared to concrete construction. CLT, or Cross-Laminated Timber, is a sustainable and renewable building material that can help mitigate the environmental impact of construction. By promoting the adoption of CLT in Rotterdam and Amsterdam, cities hope to take a significant step towards more sustainable and eco-friendly construction practices.

1.3 Societal and scientific relevance and potential ethical dilemmas.

This thesis addresses the importance of studying UFP, BC and PM during the construction process of high-rise buildings in Rotterdam and Amsterdam. The social relevance of this research is highlighted by the profound impact of construction-related air pollution and its relationship to public health. However, many urban residents are unaware that pollutants such as UFP, BC and PM can have short- and long-term effects on their health.

Long-term health effects span a spectrum of ailments, including cardiovascular disease, respiratory disease, and even lung cancer (Wieser et al., 2021).Short-term effects can manifest as an increased risk of hospital admissions due to respiratory distress and, in extreme cases, can lead to deaths (Kulshrestha, 2018).When left uncontrolled, these pollutants can further exacerbate health disparities with vulnerable populations such as children, older adults, and people with pre-existing respiratory conditions (Guttikunda & Kopakka, 2014). Additionally, the economic ramifications of addressing health problems resulting from construction-related air pollution can overwhelm health systems and hamper overall development within affected areas (Hague, 2019).

In addition, the health risks construction workers face are especially significant (Araújo et al., 2014). Construction workers are the most affected by health risks due to prolonged exposure to air pollutant emissions, including UFP, BC and PM released by construction works. The very nature of their work requires them to spend long periods close to these pollutants, making them the most vulnerable group. In the Netherlands, the RIVM (Netherlands Institute for Public Health and Environment) monitors particulate matter ($PM_{2.5}$ and PM_{10}) as pollutants that negatively affect urban dwellers' health. However, this monitoring focuses primarily on $PM_{2.5}$ and PM_{10}, leaving out the more harmful BC and UFP pollutants construction equipment emits.

The knowledge gap underscores the importance of investigating BC and UFP contaminant concentrations near construction activities. Understanding these pollutants' sources and dispersion patterns can generate valuable information on urban air quality. This thesis compares the environmental concentrations of UFP, BC and PM at conventional and CLT construction sites. With this study, we seek to raise awareness and interest for further investigation of UFP, BC and PM during the construction processes of high-rise buildings in Rotterdam and Amsterdam and serve as a blueprint for further investigations.

1.4 Aims of the research project.

This research aims to determine the ambient concentrations of UFP, BC, $PM_{2.5}$ and PM10 levels at high-rise construction sites in Rotterdam and Amsterdam during their construction. By understanding the temporal and spatial variations of ambient concentrations of UFP, BC, $PM_{2.5}$ and PM_{10} during construction, the research seeks to identify critical points for emissions mitigation and target effective pollution control measures.

The study will compare the ambient concentrations of UFP, BC, $PM_{2.5}$ and PM_{10} profiles associated with CLT and conventional construction methods and machinery to assess their respective contributions to air pollution by comparing the Sawa, PostRotterdam and Switi construction sites. Additionally, the research will evaluate the potential benefits of promoting CLT in skyscraper construction and its impact on city air quality and overall sustainability goals.

By comparing the environmental concentrations of UFP, BC and PM generated during the construction of biobased materials (CLT) and conventional projects, the research aims to provide information on the environmental impact of different construction methods. This analysis will help identify the most sustainable and environmentally friendly construction approach, guiding future construction practices in a greener direction.

1.5 Research question.

What is the influence of Rotterdam high-rise construction on the generation of ultrafine particulate (UFP), black carbon (BC) and particulate matter ($PM_{2.5}$ and PM_{10}) when traditional construction methods are used, compared to the usage of cross-laminated timber (CLT)?
Sub-questions:

1. What are ambient concentrations of UFP, BC, $PM_{2.5}$ and PM_{10} levels during the construction of high-rises in Rotterdam?
2. How does on- and non-road machinery contribute to UFP, BC, $PM_{2.5}$, and PM_{10} emission pollution levels during high-rise construction in Rotterdam?
3. What can the municipality of Rotterdam do to promote, advise, and influence the construction of high-rises based on cross-laminated timber?

1.6 Reading guide.

Following the introduction, chapter 2 refers to the different methodologies to measure both introduction chapter 2 refers to the different methodologies to measure both concentrations of UFP, BC, $PM_{2.5}$ and $PM_{10.}$ In chapter 3 results, in chapter 3.1 sub-question1 is answered through sampling ambient concentrations in the three construction sites indicated in the introduction, sub-question2 is answered in chapter 3.3 of the chapter results under calculations of BC and PM, and finally sub-question3 is answered in chapter 4 in chapter 4.2 in recommendations. Chapter 4. Discussion deals with the findings, limitations, implications, reflections, and future directions related to this thesis, ending with chapter 5. conclusions.

2. Methods:

Literature review sampling and calculations of Ultrafine particles, Black Carbon, and Particulate Matter ($PM_{2.5}$ & PM_{10}).

This thesis has the primary objective of conducting a comprehensive comparison of ambient concentrations of ultrafine particles (UFP), black carbon (BC), and particulate matter ($PM_{2.5}$ and PM_{10}) between two distinct construction typologies. These typologies are conventional and biobased construction using cross-laminated timber (CLT). To facilitate this comparison, three high-rise building projects have been selected.

To address these research questions is employed:

1. a structured literature review,
2. field sampling of UFP, BC, $PM_{2.5}$ and PM_{10} particles at Sawa, PostRotterdam, and Switi building sites,
3. analysis of these comparisons using the software R (https://www.r-project.org/) and
4. calculations of emissions using the TNO methodology.

Figure 8, provides a graphic summary of the research methods.

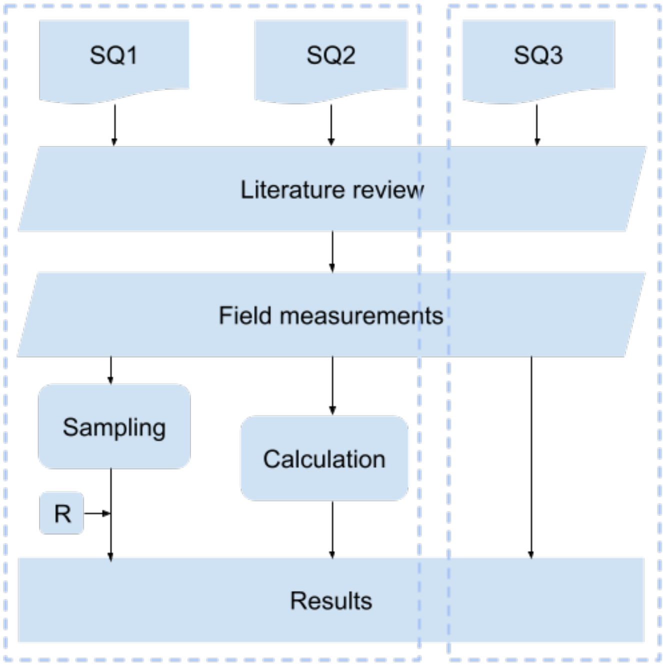

Figure 8. Methodology Diagram

2.1 Literature Review

First, a structured literature review was carried out. Throughout this research, chapters, books, conferences, reports and scientific journals were reviewed, with a total of 95, which were reduced to 54. The structured literature review allows us to highlight the different facets of the construction, its contribution to air pollution and its effects on public health. When reviewing the literature, common themes or topics of interest can be identified:

- Air Pollution and Health: Several references are associated with "Air Pollution" and "Health." This relationship suggests that these references explore the health impacts of air pollution.

- Construction and Air Pollution: Multiple references are linked to "Construction" and "Air Pollution." This relationship indicates that these references may discuss the relationship between construction activities and air pollution.

- Ultrafine Particle and Health: References mentioning "Ultrafine Particle" often have associations with "Health," indicating a focus on the health effects of ultrafine particles, and remains under investigation in relation to construction and the lack of levels related to public health.

- Emissions and Environmental Impact: References associated with "Emissions" often overlap with "Environment," highlighting a connection between emissions and their environmental impact.

- CLT and construction: "Wood" appears in references related to "Construction," suggesting that these references may discuss the use of CLT in construction projects.

In Table 2., shows the trending keywords from the reviewed literature.

Air Pollution	A prevailing keyword indicates the focus on pollution related to construction.	Lu, Yongmei & Fang, Tianfang Bernie (2015), Magdy Hamed, Mohammed et al. (2017), Pearce, John L. et al. (2011), Sun, J. et al. (2019), Wieser, Antonija Ana et al. (2021)
Biobased	Indicates a focus on environmentally friendly construction materials.	Mouton, Lise et al. (2022), Yadav, Madhura & Agarwal, Mahek (2021)
Black Carbon	Another specific pollutant often associated with construction emissions.	Lükewille, Anke (2013), Montagne, Denise R. et al. (2015), Peters, Jan et al. (2014), Reche, C. et al. (2011)
Circular Economy	Represents a growing trend in construction practices emphasising sustainability.	Mostafavi, Fatemeh et al. (2021), Schöggl, Josef Peter et al. (2020), van Stijn, Anne & Gruis, Vincent (2020)
Concrete	A fundamental construction material with implications for construction and air quality.	Ranjbar, Nima et al. (2021), Tangadagi, Ranjitha B et al. (2020), van Stijn, Anne & Gruis, Vincent (2020)
Construction	Appears in various references and seems to be a central topic (e.g., construction activities, Sustainable construction).	Liu, Shao Kun et al. (2016), Lu, Yongmei & Fang, Tianfang Bernie (2015), Magdy Hamed, Mohammed et al. (2017), Montagne, Denise R. et al. (2015), Mostafavi, Fatemeh et al. (2021), Pearce, John L. et al. (2011), Ranjbar, Nima et al. (2021), Rijkeboer, Marlies (2022), Schmitz, Oliver et al. (2019), Seelen, Meinie et al. (2017), Sepasgozar, Samad M.E. & Blair, John (2021), Skullestad, Julie Lyslo et al. (2016), van Dijkhuizen, Martin J. et al. (2021).
Cross-Laminated Timber	A sustainable and innovative construction material.	Skullestad, Julie Lyslo et al. (2016) Slavin, Alexey et al. (2018) Tangadagi, Ranjitha B et al. (2020) van Stijn, A. et al. (2022)
Emissions	Linked to air pollution, emissions are an essential aspect of the research (e.g., construction emissions, black carbon emissions).	Lu, Yongmei & Fang, Tianfang Bernie (2015), Magdy Hamed, Mohammed et al. (2017), Mostafavi, Fatemeh et al. (2021), Peters, Jan et al. (2014), Reche, C. et al. (2011), van Stijn, Anne & Gruis, Vincent (2020). Gangolells et al., (2009) Samarasa, Zissis & Zierock, Karl-Heinz (1995)Transfer Register, (2021)
Health	A prominent keyword that signifies the concern for public health concerning construction and air pollution.	Lu, Yongmei & Fang, Tianfang Bernie (2015), Meng, Junqing et al. (2023), Muñoz, X. et al. (2019), Salma, I. et al. (2014), van Ruijvena, Koen & Tijma, Joep (2022), van Stijn, Anne & Gruis, Vincent (2020).
High-Rise	A specific aspect of construction, possibly linked to urban development and air pollution.	Magdy Hamed, Mohammed et al. (2017), Mostafavi, Fatemeh et al. (2021).
Mapping	May indicate research related to spatial mapping of air pollution.	Wald, Lucien et al. (1998)
Machinery	Indicates the role and impact of machinery in construction activities.	Gangolells et al., (2009) Samarasa, Zissis & Zierock, Karl-Heinz (1995)Transfer Register, (2021)
Netherlands	Appears in several references, suggesting a geographic focus on this region.	Magdy Hamed, Mohammed et al. (2017) Schmitz, Oliver et al. (2019) van Ruijvena, Koen & Tijma, Joep (2022) van Stijn, Anne & Gruis, Vincent (2020)
Off Road	May be connected to off-road construction activities or machinery.	Samarasa, Zissis & Zierock, Karl-Heinz (1995)
On Road	Pertains to construction activities on roads.	Samarasa, Zissis & Zierock, Karl-Heinz (1995)
Particulate Matter (PM)	A specific type of pollutant often discussed in the context of construction-related air pollution.	Meng, Junqing et al. (2023) Muñoz, X. et al. (2019)

		Pearce, John L. et al. (2011) Reche, C. et al. (2011) Smith, Jeremy D. et al. (2019) Tangadagi, Ranjitha B et al. (2020) Vyvyan Howard MB ChB FRCPath. (2009) Yáñez, Marco A. et al. (2017)
Spatial Distribution	Suggests a focus on how pollutants are distributed in space.	Wald, Lucien et al. (1998)
Sustainability	Reflects a growing emphasis on sustainable construction practices	Mostafavi, Fatemeh et al. (2021) Schöggl, Josef Peter et al. (2020) van Stijn, Anne & Gruis, Vincent (2020)
Ultrafine Particle	A specific type of pollutant with potential health implications.	Montagne, Denise R. et al. (2015) Smith, Jeremy D. et al. (2019) Mostafavi, Fatemeh et al. (2021) Traboulsi, Hussein et al. (2017) Viitanen, Anna Kaisa et al. (2017) van Stijn, Anne & Gruis, Vincent (2020)
Urban Areas	Refers to the urban context and how construction and pollution affect urban environments.	Lükewille, Anke (2013) Montagne, Denise R. et al. (2015) Peters, Jan et al. (2014) Reche, C. et al. (2011) Seelen, Meinie et al. (2017) Tangadagi, Ranjitha B et al. (2020)
Wood	Relates to sustainable construction materials and practices including "Cross-Laminated Timber".	Mouton, Lise et al. (2022) Skullestad, Julie Lyslo et al. (2016) Slavin, Alexey et al. (2018)

Table 2. Literature review trend.

Construction and Air Pollution

Dealing with airborne contaminants in the environment is one of the main issues connected to construction activity. The 2015 journal article by Lu and Fang (Lu & Fang, 2015) emphasises how construction activities contribute to air pollution. According to their research, building sites can be essential sources of harmful pollutants such as black carbon and particulate matter (PM). These contaminants may harm human health by significantly influencing air quality. Similarly, Mostafavi et al.'s journal articles from 2021 (Mostafavi et al., 2021) examine the emissions related to building and stress the necessity for more environmentally friendly building techniques to lessen these negative impacts.

Health Impacts

Construction-related air pollution has been linked to many health issues. Research conducted in 2015 by Lu et al. (Lu & Fang, 2015)and in 2023 by Meng et al. (Meng et al., 2023) focuses on the health effects of air pollution linked to buildings. According to their findings, those who live close to construction sites may be more susceptible to heart difficulties, respiratory illnesses, and other health concerns. The study by Muñoz et al. 2019 (Muñoz et al., 2019) highlights the connection between air pollution and construction activities, pointing out that workers in the industry may be more vulnerable to health issues because of their direct exposure to contaminants associated with the job.

Ultrafine Particles and Black Carbon

Particulate matter (PM) is an essential component of construction-related air pollution. Montagne et al.'s 2015 (Montagne et al., 2015) journal articles address the issue of ultrafine particles and black carbon, often present in construction emissions. These tiny particles can penetrate the respiratory system, causing inflammation and exacerbating pre-existing conditions. Further, the study by Peters et al. in 2014 (Peters et al., 2014) connects black carbon emissions from construction to urban areas, suggesting that the effects of construction pollution extend beyond immediate construction sites.

Policy and Mitigation Strategies

Given the severity of the health impacts and the broader environmental implications of construction-related air pollution, exploring potential policy measures and mitigation strategies is essential. Research by Schmitz et al. in 2019 (Schmitz et al., 2019) highlights the need for targeted policies to reduce air pollution in the Netherlands, which includes regulating construction emissions. Additionally, the study by van Stijn and Gruis in 2020 (van Stijn & Gruis, 2020) emphasises the role of circular economy principles in urban construction, which can significantly reduce environmental and health impacts.


THE
POST

2.2 Field measurements: Sampling UFP BC $PM_{2.5}$ and PM_{10} at Sawa, PostRotterdam and Switi.

This study compares ambient concentrations, particularly UFP, BC, and PM ($PM_{2.5}$ and PM_{10}), between these construction typologies, CLT and conventional construction, by analysing ambient concentrations from the Sawa (CLT), PostRotterdam (conventional) and Switi (CLT) projects (see chapter XXX for an overview of the sites). This analysis contributes to understanding the environmental impact of using CLT in construction, thus aiding policymakers and developers in making informed decisions regarding sustainable building practices and reducing air pollution.

The Sawa project serves as a critical reference point for biobased CLT construction. By contrasting its emissions profile with the other two projects, it establishes a baseline for evaluating the potential environmental advantages of CLT over conventional construction materials. These advantages include reduced energy consumption, lower ambient concentrations, and reduced UFP, BC, and PM ambient concentrations, all contributing to improved air quality and overall sustainability.

Finally, based on the TNO methodology, the calculation of UFP, BC, and PM emissions from the on-road and off-road machinery observed at the Sawa, PostRotterdam and Switi construction sites, the table can be observed in Chapter 3.5 Emissions calculations- Black Carbon emissions and Particulate Matter emissions from on-road and off-road machinery, Table 20.

2.2.1 Data collection methodology and steps undertaken.

The data collection process for ambient concentrations of Ultrafine Particles (UFP), Black Carbon (BC), and Particulate Matter ($PM_{2.5}$ and PM_{10}) involved the utilisation of three different portable instruments. These instruments were chosen for their ability to provide specific measurements related to each particle. The primary objective of this data collection work was to assess ambient concentrations resulting from construction activities, particularly those generated by the machinery in operation at the designated construction sites. In addition to the data collection and analysis procedures, the study of the calculations of UFP, BC, $PM_{2.5}$ and PM_{10} emissions from construction machinery (off-road and on-road) provide quantitative emissions estimates.

The first instrument used was the Partector 2 Aerosol Dosimeter, Image 1., designed by NANEOS. This device, recognised as the world's smallest multimetric nanoparticle detector, was used for UFP measurement. Its capabilities include capturing nanoparticles, particle count, and particle diameter (naneos particle solutions gmbh, 2022).

Image 1. Partector 2 Aerosol Dosimeter

The ObservAir DST, Image2., was the second instrument used to measure Black Carbon (BC). This instrument featured an aerosol absorption photometer specifically configured for BC concentration measurement. BC is a component of particulate matter pollution originating from the incomplete combustion of fossil fuels or biomass (Distributed Sensing Technologies, 2023).

Image 2. ObserAir DST

The third instrument used was the CityScanner, Image 3., a low-cost, modular design with Internet of Things capabilities developed by the Senseable City Lab at MIT, employed for quantifying $PM_{2.5}$ and PM_{10} concentrations. It relies on laser technology to count particles within different diameter size bins, thereby providing precise measurements of these particulate matter components (Wang, n.d.).

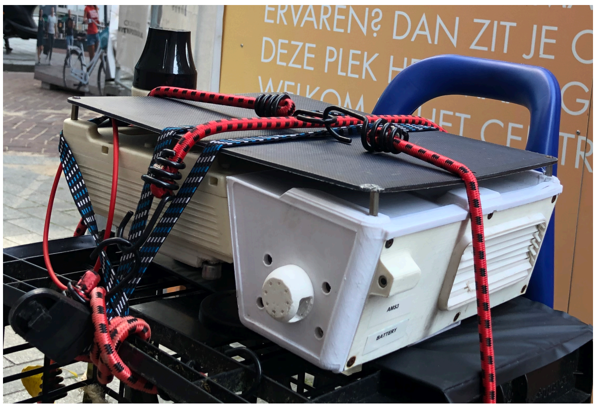

Image 3. CityScanner

A structured data collection approach at each construction site involved the following key steps:

- Identification of Machinery: Initial identification of machinery in operation at the construction site.
- General Survey: A general survey of ongoing construction activities to understand the scope and nature of work.
- Systematic Site Tours: Systematic site tours were conducted following wind direction to ensure comprehensive data collection and account for various sources' emissions.
- Proximity Data Collection: Data was collected from machinery emission sources to assess emissions at close range.
- Duration of Site Visits: Each site visit had a duration of a minimum of one hour to ensure complete data collection and accurate observations.
- Machinery Documentation: The machinery types used were documented to provide additional context to the emissions data.

This structured data collection approach was critical in providing the study's outcomes' validity, reliability, and reproducibility. It allowed for comparing Cross-Laminated Timber (CLT) and Conventional construction method.

Additionally, to pollutant measurements, environmental parameters such as ambient temperature, relative humidity, wind speed, and wind direction were recorded during each visit to the construction sites.

A categorisation strategy was established to capture the variability in construction activity levels. Activity levels were classified as follows: High Activity (involving the concurrent operation of two machines, on-road or off-road, or a combination of both), Medium Activity (involving the operation of a single machine, on-road or off-road), Low Activity (predominantly manual work with hand tools and no machinery in operation), Pause (representing breaks during work, such as lunchtime), and Non-Activity (days barren of construction-related activities, such as holidays or weekends).

The data collection method at each construction site adhered to a structured approach. This entailed initial identification of machinery in operation, a general survey of ongoing construction activities, systematic site tours following wind direction, and proximity data collection from machinery emission sources. Each site visit was maintained for at least one hour to ensure comprehensive data collection and observation accuracy. The structured approach also included documenting the types of machinery being used.

2.2.2 Relevance of the data collection methodology for producing valid reliable and reproducible outcomes.

The data collection methodology for UFP, BC, $PM2_{.5}$, and PM_{10} ambient concentrations at the specified construction sites is relevant and instrumental in producing valid, reliable, and reproducible outcomes. It aligns specific instruments with the characteristics of each pollutant, maintains consistency in instrumentation across construction typologies, and incorporates environmental context, all of which contribute to the quality and trustworthiness of the data collected and the study's findings. This approach allows for a comparison between CLT and Conventional construction methods, aiding in informed decision-making regarding sustainable building practices and air quality improvement. Image 4.

Image 4. Groundwork - Sampling

The data collection methodology employed to gather ambient emission data for Ultrafine Particles (UFP), Black Carbon (BC), and Particulate Matter ($PM_{2.5}$ and PM_{10}) from the Sawa CLT, PostRotterdam Conventional

Construction and Switi CLT construction projects are critically relevant for producing valid, reliable, and reproducible outcomes. For each of these pollutants, we define data as valid and reliable as follows:

- Ultrafine Particles (UFP):
  - Valid Data: Using the Partector 2 Aerosol Dosimeter for UFP measurement ensures the validity of the collected data. This specialised instrument is designed to capture nanoparticles, count particles, and measure particle diameter accurately. Therefore, the methodology aligns well with the specific characteristics of UFP, producing valid data on their emissions.
  - Reliable Data: By consistently employing the same instrument across all three construction typologies (CLT and Conventional), the methodology ensures reliability in data collection. The consistent measurement approach minimises variability due to instrument differences, contributing to the reliability of the outcomes.
- Black Carbon (BC):
  - Valid Data: Using the ObservAir DST, configured for BC concentration measurement, is crucial for valid BC data collection. BC is a component of particulate matter pollution, and this instrument is specifically designed to measure it accurately, ensuring data validity.
  - Reliable Data: Employing the same instrument for BC measurement across all construction sites enhances data reliability. It allows for direct comparisons between the emission levels of BC from CLT and Conventional construction, promoting reliability in assessing the environmental impact.
- Particulate Matter ($PM_{2.5}$ and PM_{10}):
  - Valid Data: The CityScanner instrument, relying on laser technology to count particles within bins with different diameters, is well-suited for $PM_{2.5}$ and PM_{10} concentration measurements. It ensures data validity by offering precise measurements of these particulate matter components.
  - Reliable Data: Consistency in instrument choice for $PM_{2.5}$ and PM_{10} measurement across the construction typologies (CLT and Conventional) contributes to the reliability of data collection. Comparisons between different construction methods are more trustworthy due to this standardised approach.
- Reproducibility:
  - The structured approach ensures reproducibility, including consistent instrumentation and data collection. Other researchers or organisations can follow the same methodology to replicate the study's findings, enhancing the credibility of the outcomes.
  - The categorisation strategy based on construction activity levels (High, Medium, Low, Pause, Non-Activity) adds to reproducibility. It allows for clear definitions of emission scenarios, making it easier for others to apply the same approach in similar studies.
- Environmental Context:
  - Collecting environmental parameters such as ambient temperature, relative humidity, wind speed, and wind direction enhances the validity of the data by providing context. These parameters help in understanding how variations in environmental conditions might influence pollutant emissions.

2.2.3 Data Analysis Procedures.

Once field measurements were collected, data analysis proceeded by the following steps:

- Raw Data Interpretation:
  Tools Used: The raw data collected from the Partector 2 Aerosol Dosimeter, ObservAir DST, and CityScanner instruments are imported into RStudio for interpretation.
  Data Visualization: Graphs, maps, and tables represent the data visually. This includes time series, line plot graphs, violin plots, and density maps to illustrate the distribution of pollutants over time and space.
- General Site Overview:
  Initial Assessment: Each construction site (Sawa CLT, PostRotterdam Conventional Construction, and Switi CLT) is analysed from a general perspective. This overview explains each location's overall concentration patterns and trends.
- Activity Level Comparison:
  Categorisation: The data is categorised based on activity levels, including High, Medium, Low, Pause, and Non-Activity, as defined during data collection.
  Comparative Analysis: A comparative analysis assesses how emission levels vary during different phases of construction activity. This step helps identify any correlation between construction activity and pollutant concentrations.
- Detailed Analysis:
  UFP, BC, PM2.5, and PM10: A more detailed analysis focuses on UFP, BC, $PM_{2.5}$, and PM_{10}. Specific graphs, like line and violin plots, are generated with Rstudio to illustrate the concentration levels of these pollutants during different activities and construction phases.
  Density Maps: Density maps, generated with Rstudio, of ambient concentrations are created to visualise the spatial distribution of pollutants. These maps provide insights into emission hotspots and the impact of machinery on local air quality.
  Machinery Commentary: Alongside the maps and graphs, commentary on the types of machinery in use during specific activities is provided. This commentary helps explain variations in emission levels and sources; furthermore, emissions of BC and PM are calculated.
- Statistical Analysis:
  Wilcoxon Test: To assess the statistical differences between the various activity levels (High, Medium, Low, Pause, Non-Activity), a Wilcoxon test is performed using RStudio. This test is valuable for determining whether observed differences in pollutant emissions are statistically significant.
  Statistical Significance: The results of the Wilcoxon test indicate whether there are significant variations in pollutant levels between different construction activity phases. This statistical analysis adds a quantitative dimension to the findings.

The data analysis procedures in RStudio provide an understanding of pollutant emissions at the construction sites and quantify the significance of these emissions during different phases of construction activity. This analytical approach contributes to the validity, reliability, and reproducibility of the study's outcomes and supports informed decision-making regarding sustainable construction practices and air quality management.

2.3 Emissions calculation BC and PM emissions from observed machinery.

BC and PM emissions calculations from observed machinery.

After visiting the three construction sites, namely, Sawa, PostRotterdam, and Switi, an inventory of the machinery observed at each site was made, categorising them as either on-road or off-road machinery. This inventory forms the foundation for quantifying the estimated black carbon and particulate matter emissions associated with each machine, facilitating a qualitative comparison of the machinery employed across the three construction sites. This qualitative comparison will help identify any potential differences in emissions between the on-road and off-road machinery used at each site. Additionally, it will provide valuable insights into the environmental impact of the construction activities at Sawa, PostRotterdam, and Switi. To calculate emissions of black carbon and particulate matter from both on-road and off-road machinery, the following formula was applied:

Emission = Number of machines x Hours x Load x Power x Emission factor x TAF factor

Where:

- Emission = Emission or fuel consumption (grams).
- Number of machines = the number of machines of a specific year of manufacture with emission factors appropriate to the year of manufacture.
- Hours = the number of hours that this machine type is used on average per year (hours).
- Load = Load the part of the full power of this machine type that is used.
- Power = The average engine power for each machine type (kW).
- Emission factor = the average emission factor or specific fuel use associated with the year of manufacture (emission standard) (g/kW.hour).
- TAF factor = adjustment factor on the average emission factor in connection with the deviation of the average user application from this machine type due to varying (transient) power demand.

It is important to note that the formula was employed for both BC and PM emissions, as BC constitutes a PM component. Emission calculations for UFP were not executed due to the absence of reference values for emission factors.

The column "Number of machines" within the formula was registered based on on-site observations. The column "Hours" was filled in based on the parameters from the "Median Life, Annual Activity, and Load Factor Values for Nonroad Engine Emissions Modelling report" (Epa et al., n.d.).

Concerning the "Load" column, a standard value of 10 tons was adopted for all machines to maintain an overall average. The "Power" column was registered from data from the respective machine model or type websites, providing the mean engine power in kilowatts (kW).

The average emission factor for Stage V diesel machinery was obtained from TNO and utilised in the formula's "Emission factor" column. The lack of knowledge about the year, stage, and kind of diesel gear made this choice necessary. The "Calculation rules and emission factors for determining the emission reduction when using emission-free construction equipment" (Tol et al., 2022)serves as the source for TNO.

The column "TAF factor" was determined utilising the previous TNO reference. In the case of BC emissions, an emission factor value of 1.7 mg km−1 was employed. This choice was made based on the highest value within the range (0.4–1.7 mg km−1), per the reference "Review of black carbon emission factors from different anthropogenic sources" (Rönkkö et al., 2023). This approach was adopted because it was not feasible to categorise machinery as on-road or off-road.

The outcomes of these computations are shown in Table 20., in the thesis's Results Chapter 3.5, and they can be used as a guide to perform a qualitative emissions study. It will also be possible to evaluate the impact of machines on construction activities thanks to this thorough research, regardless of whether cross-laminated timber (CLT) or traditional (steel-concrete) constructions are used. Concerning ambient concentrations and air pollution, this method will provide insightful information on how construction operations at the designated sites affect the environment.

3. Results:

Presentation of sampling UFP BC $PM_{2.5}$ and PM_{10} ambient concentrations at Sawa PostRotterdam and Switi and BC and PM calculations.

This chapter analyses the results obtained from sampling environmental concentrations of UFP, BC, $PM_{2.5}$, and PM_{10} at the construction sites Sawa, PostRotterdam, and Switi, as well as the emissions of BC and PM resulting from the formula explained in Chapter 2 of the methodology.

Sampling was conducted over four months using three monitoring instruments: Partector 2, ObservAir DST, and City Scanner. The sampling results indicate significant levels of environmental concentration (BC, UFP, $PM_{2.5}$, and PM_{10}) at the construction sites under study. These levels pose health risks to workers on-site and nearby residents, highlighting the urgent need for effective pollution control measures at construction sites.

Table 3. summarises the number of visits to each construction site, the particles sampled (UFP, BC, $PM_{2.5}$, and PM_{10}), environmental conditions such as temperature, air velocity, and relative humidity, and the intensity of activities recorded during visits in Sawa, PostRotterdam, and Switi. The intensity of the activities is categorised in four ways:

High activity	Indicates that two or more machines are operating alongside manual activities.
Medium activity	Indicates that there is one machine operating alongside manual activities.
Low activity	Indicate that only manual work is being carried out on the construction site.
Non-activity	Indicates moments when no working machinery or manual labour is present at the construction site.

Table 3. Activity levels.

After the sampling and processing processes were carried out using Rstudio to analyse and compare environmental concentrations, the sampling results are presented in three ways for each of the construction sites: Sawa, PostRotterdam, and Switi. First, an overview is provided, including mean values of UFP, BC, $PM_{2.5}$, and PM_{10}, air velocity and relative humidity values recorded during all visits. This overview is intended to facilitate recognising relationships and patterns between the particles. Table 4.

Second, we compare the mean values of UFP, BC, $PM_{2.5,}$ and PM_{10} across different activities at each site. Airspeed and relative humidity values are omitted in this case.

Third, a more detailed comparison of UFP, BC, $PM_{2.5}$, and PM_{10} ambient concentrations is presented, along with descriptions of working machinery and maps of particle densities. This involves meticulously examining the types of machinery used, their emission characteristics, and associated emission rates. Identifying key sources of emissions provides valuable information on potential areas for pollution control measures.

Regarding BC and PM emissions calculations, the results are shown in a table that summarises the inventory of on-road and off-road machinery observed, along with the emissions values for each of them. This table serves as a reference, and corresponding graphs of BC and PM emissions are also presented to aid in subsequent comparisons. The table not only provides a comprehensive overview of the inventory of on-road and off-road machinery, but it also includes the corresponding emissions values for each category. This allows for a detailed analysis of the contribution of each type of machinery to BC and PM emissions. Additionally, the graphs visually depict the trends and patterns in BC and PM emissions, making it easier to identify any significant variations or similarities between different machinery types.

Legenda	Colour
High activity	
Medium activity	
Low activity	
Non-activity	

Location	Project	Date	Temperature ºC	Wind Speed m/s	Direction	Humidity %	Instrument	Activity
Rotterdam	Sawa	23/03/2023	11,00	5,00	SW	52	BC/UFP	Intense activity in various parts of the site, use of different off-road and on-road machinery//preparing foundation
Rotterdam	Sawa	28/03/2023	6,00	3,00	SW	34	BC/UFP	Intense activity in various parts of the site, use of different off-road and on-road machinery//preparing foundation
Rotterdam	Sawa	05/04/2023	6,00	1,00	E	28	BC/UFP	Intense activity in various parts of the site, use of different off-road and on-road machinery//preparing foundation
Rotterdam	Sawa	11/04/2023	7,00	4,00	NE	42	BC/UFP/PM2.5/PM10	Intense activity hybrid excavator working in site - manual work
Rotterdam	Sawa	18/04/2023	9,00	4,00	NE	43	BC/UFP/PM2.5/PM10	Medium activity, excavator working and manual work
Rotterdam	Sawa	19/04/2023	12,00	4,00	NE	26	BC/UFP/PM2.5/PM10	Low activity mostly manual work
Rotterdam	Sawa	25/04/2023	7,00	3,00	N	34	BC/UFP/PM2.5/PM10	Low activity mostly manual work preparing concrete form and preparing foundation
Rotterdam	Sawa	29/04/2023	12,00	2,00	N	47	BC/UFP/PM2.5/PM10	No activity in the construction site, no manual and no machinery
Rotterdam	Sawa	02/05/2023	10,00	3,00	N	40	BC/UFP/PM2.5/PM10	Medium activity, small excavator working, manual work and electric crane working
Rotterdam	Sawa	04/05/2023	8,00	3,00	E	43	BC/UFP/PM2.5/PM10	Low activity, manual work and use of electric crane
Rotterdam	Sawa	05/05/2023	15,00	3,00	SW	53	BC/UFP/PM2.5/PM10	manual work preparing concrete form, use of a small excavator, and lorry truck transport
Rotterdam	Sawa	25/05/2023	18,00	4,90	SW	39	BC/UFP/PM2.5/PM10	Low activity, manual work and use of electric crane
Rotterdam	Sawa	07/06/2023	21,00	4,30	NE	41	BC/UFP/PM2.5/PM10	Manual work preparing concrete form, and lorry truck transport
Rotterdam	PostRotterdam	16/03/2023	6,00	5,50	W	45	BC/UFP	Mostly manual activity in the site
Rotterdam	PostRotterdam	30/03/2023	11,00	10,00	SW	54	BC/UFP	Low activity, preparing concrete form, manual work
Rotterdam	PostRotterdam	07/04/2023	3,00	3,00	NW	52	BC/UFP/PM2.5/PM10	Low activity diesel crane working
Rotterdam	PostRotterdam	04/05/2023	13,00	3,00	E	41	BC/UFP/PM2.5/PM10	Low activity, manual work and use of electric crane
Rotterdam	PostRotterdam	26/05/2023	11,00	7,50	NE	39	BC/UFP/PM2.5/PM10	Manual work, preparing concrete form, use of machine to move scaffolding
Rotterdam	PostRotterdam	30/05/2023	15,00	3,00	NE	44	BC/UFP/PM2.5/PM10	Pouring concrete and diesel crane working
Rotterdam	PostRotterdam	31/05/2023	11,00	3,00	NE	54	BC/UFP/PM2.5/PM10	Pouring concrete, use of machine to move scaffolding
Rotterdam	PostRotterdam	04/06/2023	11,00	3,50	NE	36	BC/UFP/PM2.5/PM10	Low activity Manual work, preparing concrete form
Rotterdam	PostRotterdam	06/06/2023	16,00	4,40	NE	44	BC/UFP/PM2.5/PM10	Pouring concrete, use of machine to move scaffolding
Rotterdam	PostRotterdam	08/06/2023	24,00	4,90	NE	39	BC/UFP/PM2.5/PM10	Pouring concrete, use of machine to move scaffolding
Amsterdam	Switi	12/07/2023	17,00	6,00	SW	44	BC/UFP/PM2.5/PM10	Medium activity, crane working moving construction elements
Amsterdam	Switi	14/07/2023	15,00	4,00	S	47	BC/UFP	Intense activity, lorry trucks and crane working unloading construction elements and placing in site
Amsterdam	Switi	21/07/2023	13,00	2,00	SW	41	BC/UFP/PM2.5/PM10	Intense activity, working crane
Amsterdam	Switi	11/08/2023	17,00	8,00	S	48	BC/UFP	No activity in the construction site, no manual and no machinery

Table 4. Sampling dates and intensity activities.

3.1Sites.

3.1.1 Project Sawa – Rotterdam Overview.

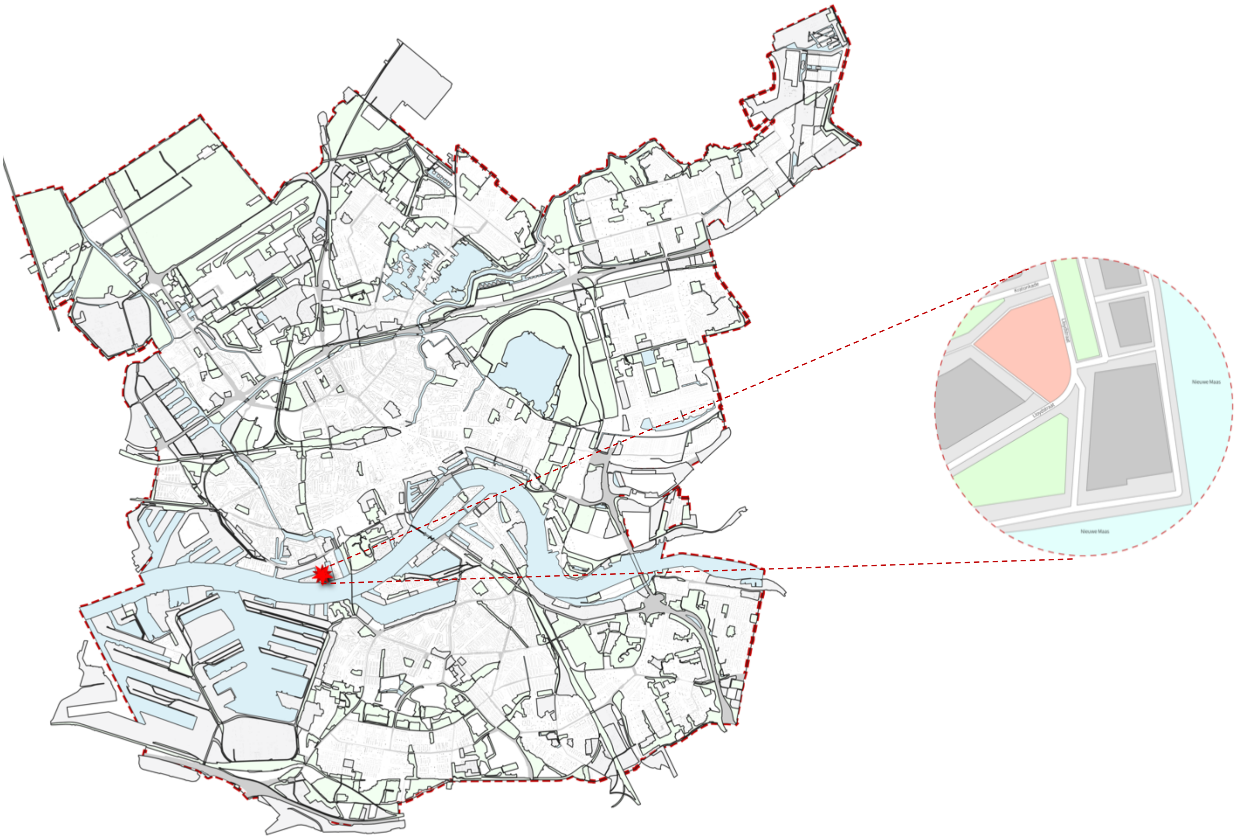

Figure 9. Location site Sawa in Rotterdam.

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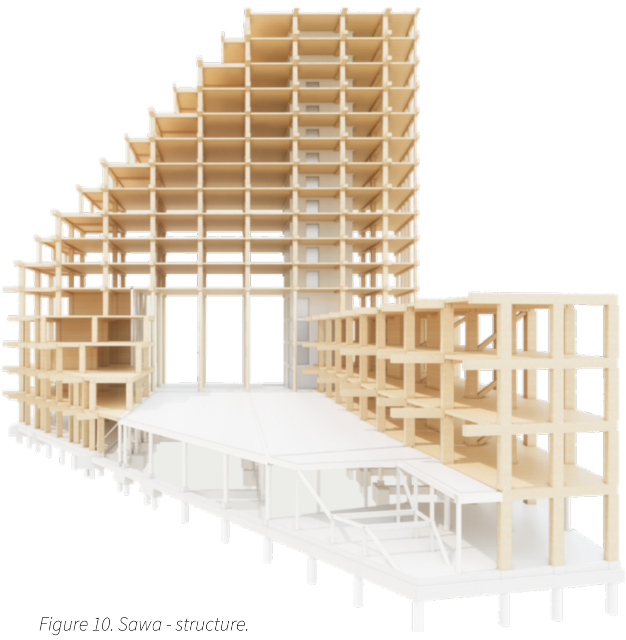


Figure 10. Sawa - structure.
Credit: Mei architects

The Sawa project, located in the Delfthaven area in Rotterdam, is unique in the Netherlands. It is the tallest High-rise building in the country, built entirely in CLT (only the elevator core is made of prefabricated concrete elements); its construction began in the middle of 2022. It is a high-rise building, with a composition of ground floor +14 floors, with a total of 109 homes and 12000m2 GFA. Figures 9 and 10.

We conducted thirteen site visits at the Sawa site in Rotterdam, twelve on working days and one on non-working days. The distribution of activity levels across these days revealed the following: three instances of high activity, two instances of medium activity, seven instances of low activity, and one day with no recorded activity. Table ## presents the mean values of BC (Black Carbon), UFP (Ultrafine Particles), $PM_{2.5}$ (Particulate Matter with a diameter of 2.5 μg/m^3 or smaller), and PM_{10} (Particulate Matter with a diameter of 10 μg/m^{3}or smaller) for each of these days, highlighting discernible variations in pollutant concentrations across different activity levels.

The data in Table 5., elucidates that the means of BC, UFP, and PM_{10} remained relatively stable across the diverse activity days, even in the presence of variations in activity intensity. This consistent trend contrasts with the behaviour of $PM_{2.5}$, where the mean values displayed a contrasting pattern.

It's essential to note that measurements for $PM_{2.5}$ and PM_{10} were unavailable during the first two visits, resulting in a data gap for comparing the averages of these days against those with the highest activity intensity. This data discrepancy underscores the necessity for caution when interpreting and drawing conclusions regarding pollutant concentrations, particularly when comparing days characterised by heightened activity levels.
In conclusion, this comprehensive analysis underscores distinctions in mean pollutant concentrations across days featuring varying activity levels at the Sawa site. While BC, UFP, and PM_{10} exhibit consistent trends concerning activity, $PM_{2.5}$ displays a divergent pattern. The absence of data for initial visits underscores the importance of prudently interpreting and contextualising these averages, especially when assessing pollutant concentrations on days with elevated activity levels.

Table 5. General overview, UFP, BC, PM 2.5 & PM10 – Sawa.

3.1.1.1 Project Sawa - intermediate comparison – Ultrafine Particle.

The result compares ambient Ultrafine Particle (UFP) concentrations contextualised by different activity levels. The data is categorised into five segments, each representing a unique spectrum of activities: High, Medium, Low, Pause, and Non-active days. These categories offer valuable insights into UFP concentrations across different operational scenarios.

Among these categories, days characterised by high levels of activity, primarily driven by machinery operations, exhibit the most pronounced UFP concentration at 22,400 #/cm^3. This distinct elevation in UFP levels on high-activity days underscores the significant impact of machinery-related operations on particle emissions. The over four-fold increase in UFP concentrations from non-active to high-activity days shows that this construction activity contributes about 17,500 #/cm^{3}of of ultrafine particulate matter. To contextualise these findings within a broader framework, a comparison with

In contrast, the lowest UFP concentration is observed on non-active days, registering at 4,800 #/cm^3. This significant contrast emphasises the correlation between heightened activity levels, machinery usage, and elevated UFP concentrations. The data effectively conveys the dynamic relationship between UFP concentrations and distinct activity types, thereby highlighting the importance of comprehending the role of various activities in shaping air quality and potential particle exposure. Figure 11., provides a visual representation of these findings, illustrating the substantial impact of construction activity on UFP concentrations.

A comparison with European mean levels for UFP (Particulate Matter with a diameter of 100 nm or smaller) would be valuable to contextualise these findings within a broader framework. However, the WHO and EU still need targets or regulatory benchmarks for UFP.

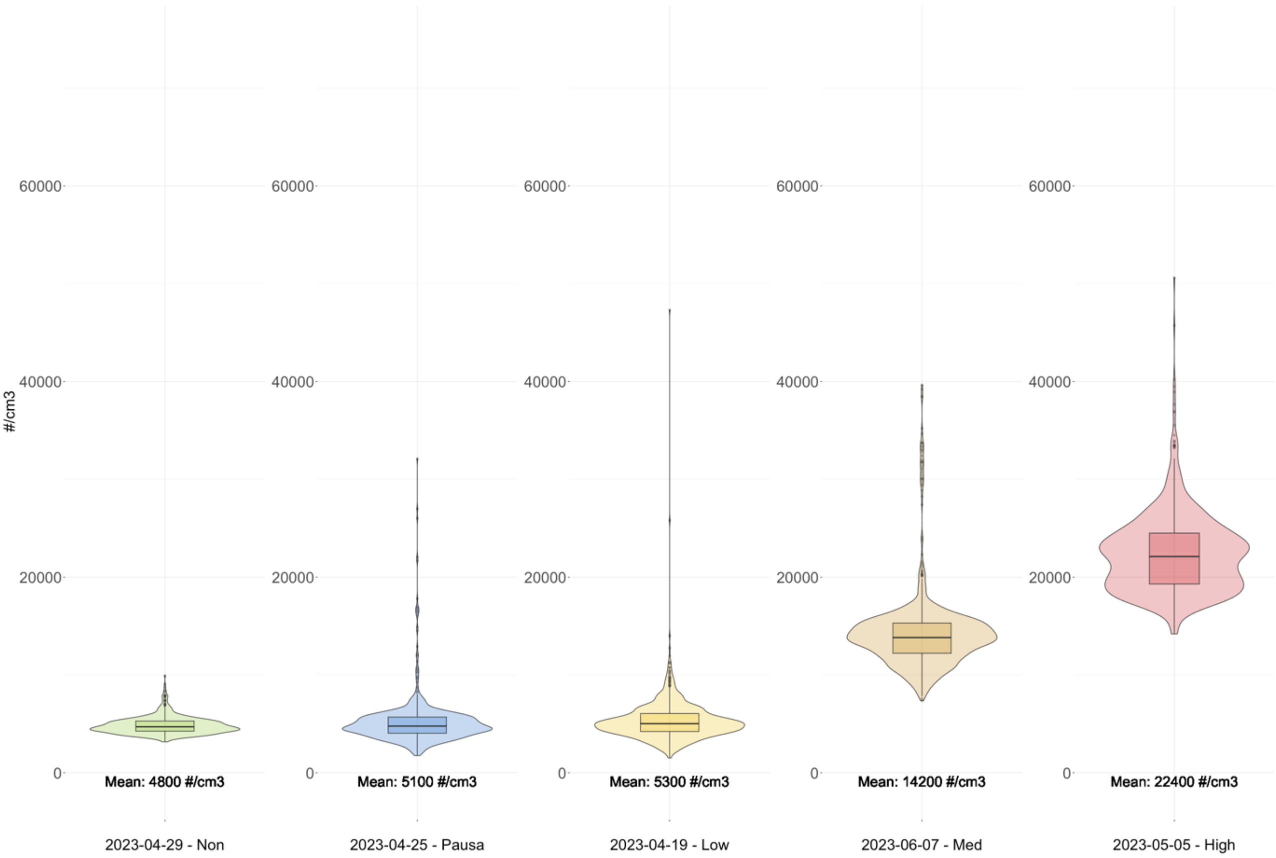


Figure 11. Violin plot – UFP mean values comparison - Sawa.

.y.	group1	group2	n1	n2	statistic	p	p.adj	p.adj.signif
number	High	Low	900	853	766039	4.8e-285	2.4e-284	****
number	High	Med	900	1275	1102254	7.08e-294	4.96e-293	****
number	High	Non	900	750	675000	1.05e-268	4.2e-268	****
number	High	Pause	900	900	806460	2.85e-290	1.71e-289	****
number	Low	Med	853	1275	6372.5	0	0	****
number	Low	Non	853	750	364388.5	1.48e-06	4.44e-06	****
number	Low	Pause	853	900	424350.5	0.000132	0.000264	***
number	Med	Non	1275	750	956066.5	0	0	****
number	Med	Pause	1275	900	1128002	0	0	****
number	Non	Pause	750	900	331099.5	0.507	0.507	ns

Table 6. Wilcoxon signed rank test - UFP - Sawa.

Table 6. The Wilcoxon signed-rank test assessed statistical differences among five activity groups (High, Medium, Low, Pause, and Non-activity) concerning UFP (Ultrafine particle) data. The "Low" group, there is a significant difference between "Low-Med" and "Low-Non" based on the p-values and adjusted p-values. The "Non-Pause" comparison shows a p-value of 0.507, which is not statistically significant (ns).

3.1.1.2 Project Sawa - intermediate comparison – Black Carbon.

In terms of Black Carbon (BC) concentrations, this analysis offers valuable insights into their correlation with distinct activity levels. Again, the dataset is categorised into five discrete classes: High, Medium, Low, Pause, and Non-active days, providing a comprehensive perspective on BC concentrations within varying operational contexts.

Although BC concentrations do not exhibit a consistent range across most categories, with mean values spanning from 0.09 to 0.74 μg/m^3, High-activity days stand out conspicuously with a notably elevated mean concentration of 1.57 μg/m^3. In contrast, Medium-activity days reveal the lowest mean concentration at 0.06 μg/m^3. This observation underscores the multifaceted interplay between activity types and BC concentrations, unveiling the nuanced nature of BC distribution patterns across diverse operational scenarios. See Figure 12.)

Notably, the mean BC concentration on High-activity days exceeds the conventional regulatory threshold established for the protection of public health, which is typically set at 1 μg/m^3or lower, as stipulated by guidelines from the EU Department of Air Health. This observation implies a potential concern regarding heightened BC levels during days characterised by intensive construction activities, thus highlighting the imperative for implementing targeted mitigation strategies in such circumstances.

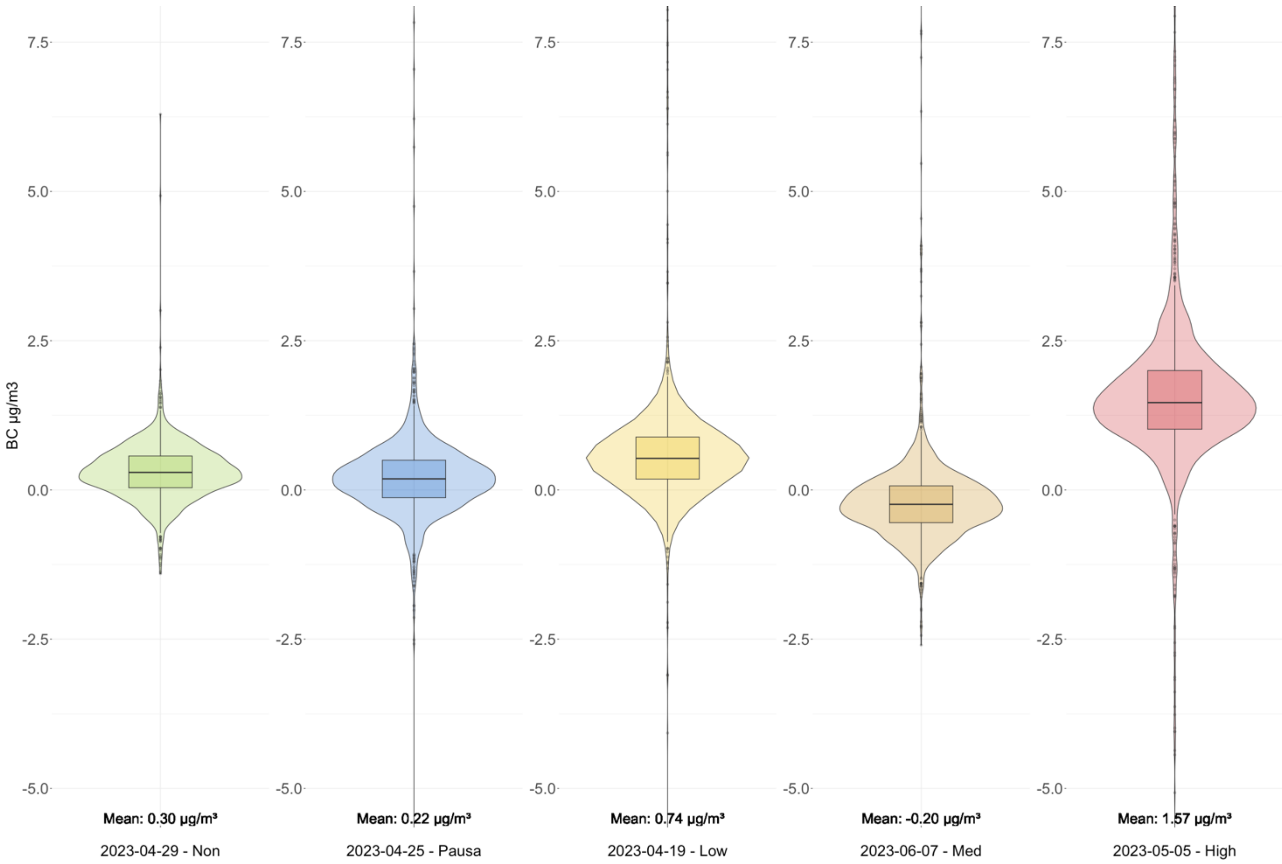


Figure 12. Violin plot – Black carbon mean values comparison - Sawa.

.y.	group1	group2	n1	n2	statistic	p	p.adj	p.adj.signif
BC	High	Low	1786	1710	2529624	1.33e-247	9.30999999999999e-247	****
BC	High	Med	1786	1640	2699084	0	0	****
BC	High	Non	1786	1489	2399636.5	0	0	****
BC	High	Pause	1786	1753	2813121.5	0	0	****
BC	Low	Med	1710	1640	2197958	7.28e-178	4.37e-177	****
BC	Low	Non	1710	1489	1622733	4.74e-41	1.42e-40	****
BC	Low	Pause	1710	1753	2046862.5	1.81e-77	7.24e-77	****
BC	Med	Non	1640	1489	726063.5	1.26e-85	6.3e-85	****
BC	Med	Pause	1640	1753	1100742.5	3.53e-32	7.06e-32	****
BC	Non	Pause	1489	1753	1484111.5	1.59e-11	1.59e-11	****

Table 7. Wilcoxon signed rank test - BC - Sawa.

Table 7. The Wilcoxon signed-rank test assessed statistical differences among five activity groups (High, Medium, Low, Pause, and Non-activity) concerning BC (Black Carbon) data. In the "Low" group, there are significant differences between "Low-Med," "Low-Non," and "Low-Pause" based on the p-values and adjusted p-values. The comparisons between "Med-Non" and "Med-Pause" also show significant differences. The "Non-Pause" comparison indicates a p-value of 1.59e-11, suggesting a highly significant difference.

3.1.1.3 Project Sawa - intermediate comparison – Particulate matter - $PM_{2.5}$

$PM_{2.5}$ (particulate matter with a diameter of 2.5 µm or smaller) concentrations, this investigation reveals their relationships with discrete activity levels. The dataset is stratified into five categories: High, Medium, Low, Pause, and Non-active days. Among these categories, the most evident observation is the nearly unnoticeable mean concentrations observed across a spectrum of activity levels. High-activity days, characterised by a mean concentration of 7 µg/m^3, demonstrate a striking similarity to Low-activity days at 8 µg/m^3, as well as Pause, Medium-activity, and non-active days. This apparent absence of substantial deviations in $PM_{2.5}$ concentrations, even during High-activity days, represents a distinctive feature of this analytical exploration.

The graph illustrates the apparent lack of a correlation between $PM_{2.5}$ concentrations and distinct activity levels. This phenomenon is especially pronounced in the proximity of mean values observed across categories, irrespective of activity intensity. Even on High-activity days, where one might anticipate elevated $PM_{2.5}$ concentrations attributable to machinery operations, the values remain closely aligned with those observed on non-active days. Figure 13. This demonstrates that ambient $PM_{2.5}$ concentrations measured adjacent to this Sawa construction site are dominated by sources other than the construction activity.

Notably, when juxtaposed with WHO $PM_{2.5}$ levels, which typically adhere to a regulatory benchmark of 5 µg/m^3, the observed mean of the ambient concentrations are higher for high, medium, pause and non-activity, only in low activity; the mean value remained below the WHO value. This shows that in a complex urban area, $PM_{2.5}$ concentrations have many contributing factors, making them almost always above WHO benchmark values (World Health Organization, 2021). It is a notable difference compared to the annual levels of the EU with a value of 20 µg/m^3 (Rijksinstituut voor Volksgezondheid en Milieu, 2019), which is above those recommended by WHO.

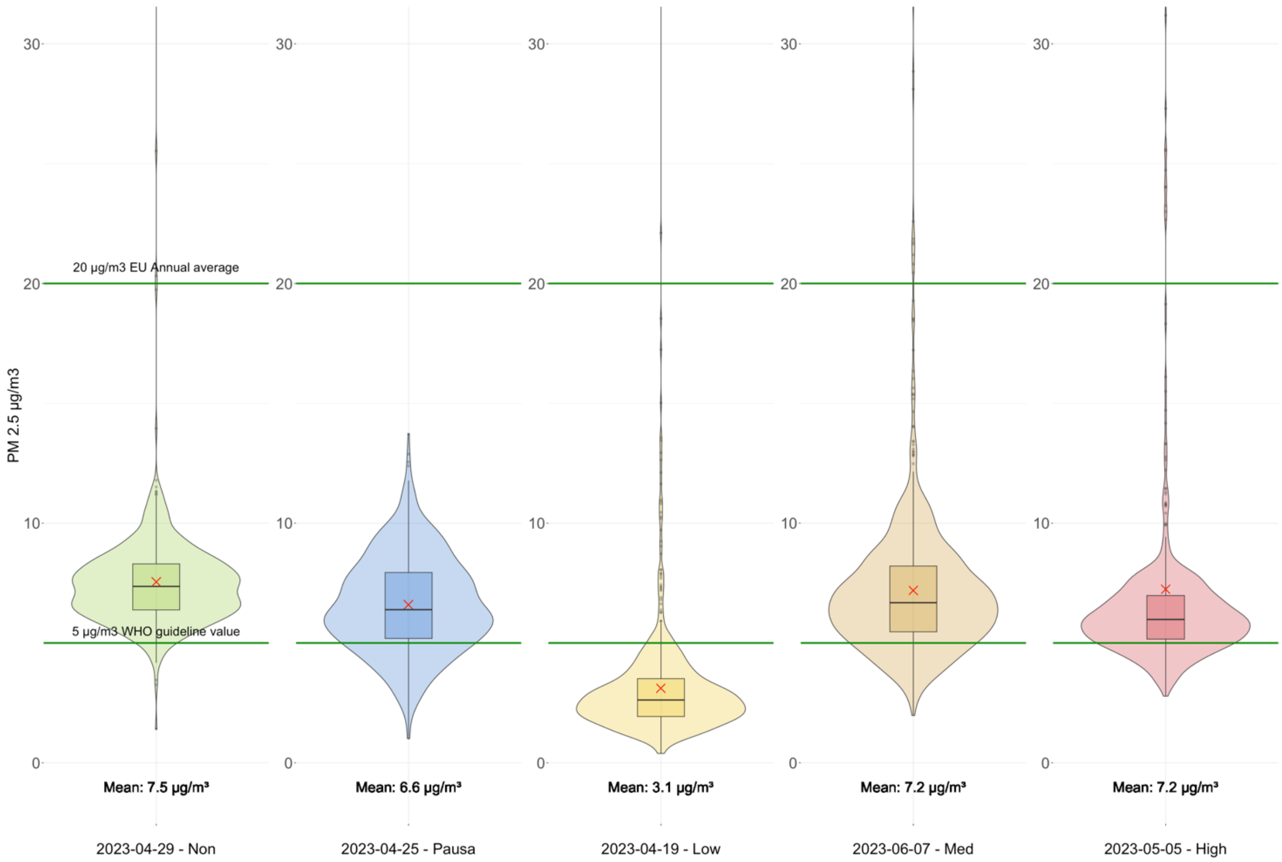


Figure 13. Violin plot – PM2.5 mean values comparison - Sawa.

.y.	group1	group2	n1	n2	statistic	p	p.adj	p.adj.signif
PM25	High	Low	717	744	497480.5	3.41e-180	3.07e-179	****
PM25	High	Med	717	1015	288164.5	1.52e-13	6.08e-13	****
PM25	High	Non	717	559	106677	1.05e-46	6.3e-46	****
PM25	High	Pause	717	705	220795.5	3.69e-05	7.38e-05	****
PM25	Low	Med	744	1015	47795.5	1.5e-215	1.5e-214	****
PM25	Low	Non	744	559	17910.5	8.5e-176	6.8e-175	****
PM25	Low	Pause	744	705	41361.5	1.89e-169	1.32e-168	****
PM25	Med	Non	1015	559	230128	5.4e-10	1.62e-09	****
PM25	Med	Pause	1015	705	386126	0.005	0.005	**
PM25	Non	Pause	559	705	250383	1.29e-16	6.45e-16	****

Table 8. Wilcoxon signed rank test - PM2.5 - Sawa.

Table 8. The Wilcoxon signed-rank test assessed the statistical differences among five activity groups (High, Medium, Low, Pause, and Non-activity) concerning the PM2.5 (Particulate Matter 2.5) data. The "High" group, there are significant differences between all pairwise comparisons ("High-Low," "High-Med," "High-Non," and "High-Pause"). In the "Low" group, there are significant differences between all pairwise comparisons ("Low-Med," "Low-Non," and "Low-Pause"). The "Med-Pause" comparison in the "Med" group is significant with a p-value of 0.005, denoted by "**". The "Non-Pause" comparison in the "Non" group is highly significant with a very low p-value.

3.1.1.4 Project Sawa - intermediate comparison – Particulate matter - PM_{10}

This study explains the concentrations of PM_{10} (particulate matter with a diameter of 10 μg/m^{3}or smaller) and their associations with discrete activity levels. The dataset is meticulously categorised into five segments: High, Medium, Low, Pause, and Non-active days, offering a comprehensive view of the interplay between PM_{10} concentrations and varying operational contexts.

A prominent and unique feature is the proportional relationship between PM_{10} concentrations and the intensity of activity levels. Within these categories, a discernible trend emerges—High-activity days, characterised by a mean concentration of 28 micrograms per cubic meter (μg m^{-3}), unequivocally exhibit the highest levels of PM_{10} concentrations. Following closely, Medium-activity days manifest a mean concentration of 20 μg/m^3, while Low-activity days register a mean concentration of 12 μg/m^3. This ordered progression of mean values from High to Low activity days unequivocally underlines the direct and proportional correlation between activity intensity and PM_{10} concentrations, reflecting the influence of various construction-related activities on particulate emissions. However, it is necessary to note that this clear association does not extend uniformly to the Pause and non-active days within the dataset. The PM_{10} concentration levels during these periods do not conform to the ascending trend observed in the other activity categories. Figure 14.

Notably, when juxtaposed with WHO PM_{10} levels, which typically adhere to a regulatory benchmark of 15 μg/m^3, the observed mean of the ambient concentrations are higher for high, medium, pause and non-activity, only in low activity; the mean value remained below the WHO value. This shows that in a complex urban area, PM_{10} concentrations have many contributing factors, making them almost always above WHO benchmark values (World Health Organization, 2021). It is a notable difference compared to the annual levels of the EU with a value of 40 μg/m^3 (Rijksinstituut voor Volksgezondheid en Milieu, 2019), which is above those recommended by WHO

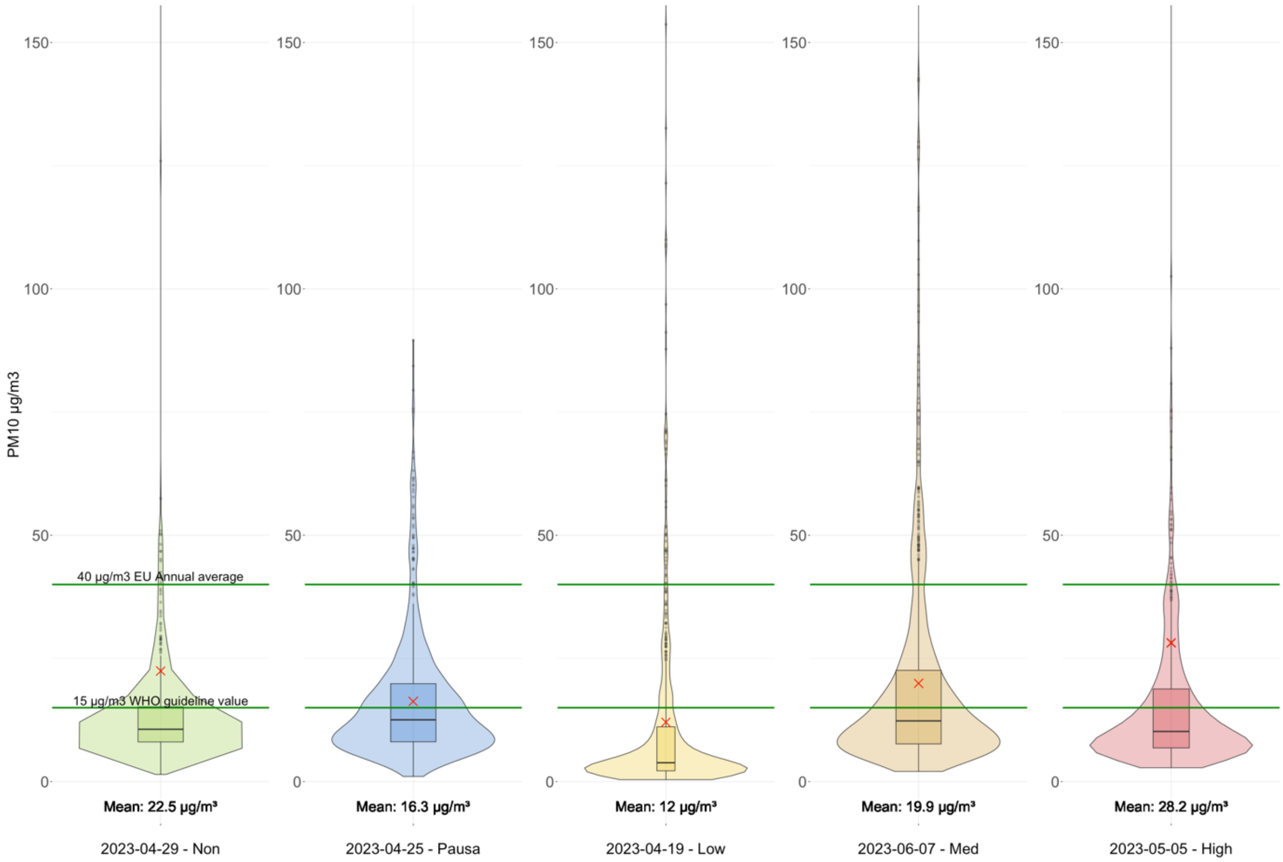


Figure 14. Violin plot – PM10 mean values comparison - Sawa.

.y.	group1	group2	n1	n2	statistic	p	p.adj	p.adj.signif
PM10	High	Low	717	744	397962.5	1.39e-59	1.11e-58	****
PM10	High	Med	717	1015	320845.5	2.7e-05	0.000162	***
PM10	High	Non	717	559	191097.5	0.154	0.308	ns
PM10	High	Pause	717	705	225220.5	0.000378	0.002	**
PM10	Low	Med	744	1015	175774	5.92e-82	5.92e-81	****
PM10	Low	Non	744	559	104288.5	1.21e-53	8.47e-53	****
PM10	Low	Pause	744	705	126268.5	2.02e-65	1.82e-64	****
PM10	Med	Non	1015	559	316185	0.000166	0.00083	***
PM10	Med	Pause	1015	705	366155.5	0.409	0.409	ns
PM10	Non	Pause	559	705	174437	0.000452	0.002	**

Table 9. Wilcoxon signed rank test - PM10 - Sawa.

Table 9. The Wilcoxon signed-rank test evaluated the statistical differences among five activity groups (High, Medium, Low, Pause, and Non-activity) regarding the PM_{10} (Particulate Matter 10) data. The "High" group, there are significant differences between all pairwise comparisons ("High-Low," "High-Med," and "High-Pause"). The comparisons between "Med-Non" and "Med-Pause" in the "Med" group are significant. The "Non-Pause" comparison in the "Non" group is also significant.

3.1.1.5 Project Sawa - detailed comparison – Rotterdam

On May 5, 2023, Figure 15., during one-hour, ambient concentrations of Ultrafine Particles (UFP), Black Carbon (BC), and Particulate Matter (PM2.5 and PM_{10}) were monitored. These emissions are associated with three types of heavy machinery: an excavator (Kubota-KX019-4), a lorry truck (DAF DF), and an electric crane. The figure illustrates the fluctuations in ambient concentrations corresponding to the activities of these machines, with significant peak values indicating moments of heightened emissions. In terms of UFP (Ultrafine Particles), the peak value observed during the lorry truck's activity reached 52,400 #/cm^3, significantly higher than the peak value during the excavator's operational phase, which stood at 35,000 #/cm^3. This distinction suggests that the lorry truck's activity substantially impacted UFP emissions more than the excavator.

For Black Carbon (BC) ambient concentrations, the peak value during the lorry truck's activity was 8.09 μg/m^3, slightly surpassing the peak value during the excavator's activity, which reached 8.05 μg/m^3. Thus, the lorry truck's operations resulted in slightly higher peak BC emissions than the excavator. Regarding Particulate Matter (PM2.5), the lorry truck's activity led to a substantial peak value of 74 μg/m^3. In contrast, during the excavator's activity, the peak value for $PM_{2.5}$ emissions was significantly lower at 16 μg/m^3. This substantial contrast underscores the lorry truck's pronounced contribution to $PM_{2.5}$ emissions during the specified hour.

Regarding Particulate Matter (PM_{10}), the peak value during the lorry truck's activity was 780 μg/m^3, while during the excavator's operations, the peak value for PM_{10} emissions was only 71 μg/m^3. The lorry truck's activity resulted in significantly higher peak values for PM_{10} emissions compared to the excavator. The figure indicates that the lorry truck significantly influenced ambient concentrations of all four particulate matter types (UFP, BC, $PM_{2.5}$, and PM_{10}) during the designated one-hour period. These peak values pinpointed the precise moments when the machinery's operations had the most pronounced impact on ambient concentrations.

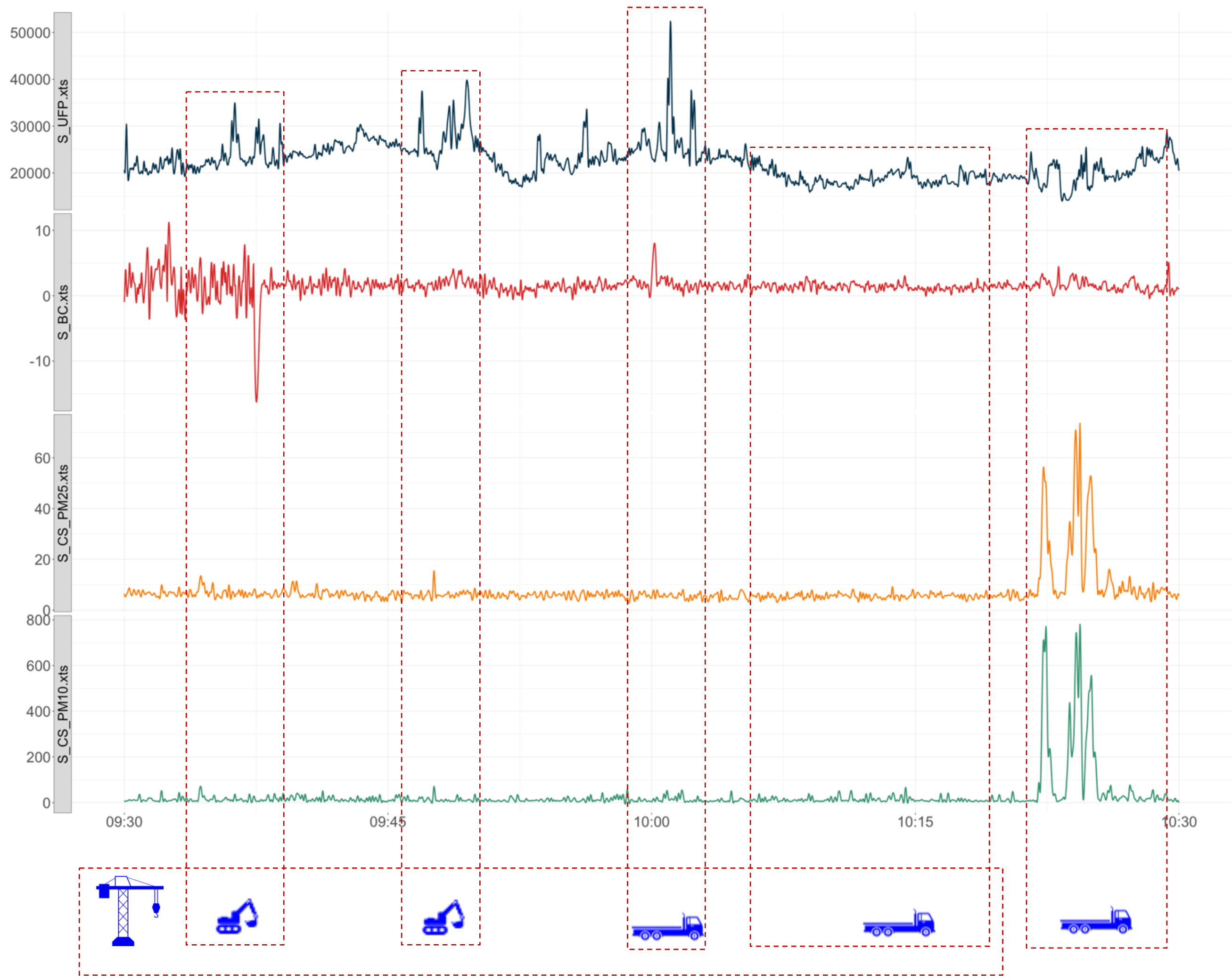
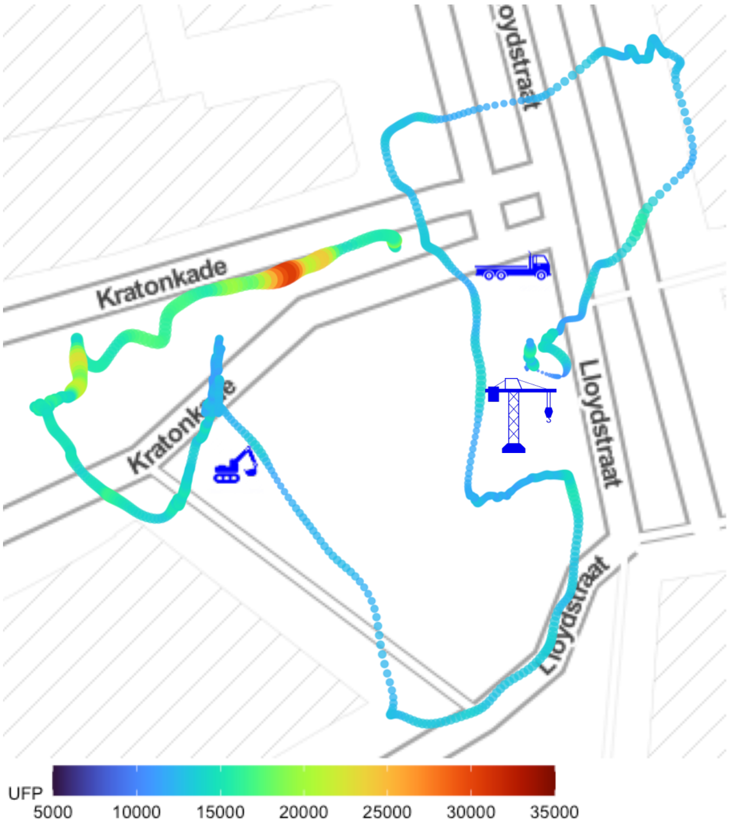


Figure 15. Ambient concentration comparison of UFP, BC, PM2.5 and PM10 from working machinery - Sawa.

Figure 16. UFP density map – Sawa.



Additionally, density maps of UFP, BC, $PM_{2.5}$, and PM_{10} ambient concentrations at the Sawa site in Figures 16, 17, 18, and 19. These maps use colour gradients, where warmer tones denote higher pollution concentrations and cooler tones indicate lower levels. Icons on these maps represent the equipment responsible for ambient concentrations, including the electric crane, lorry truck (DAF DF), and excavator (Kubota-KX019-4). These density maps visually describe the ambient concentrations but also help in locating areas with levels of UFP, BC, $PM_{2.5}$, and PM_{10}. They help identify areas where exposure to these particle contaminants poses a higher health risk.

Figure 17. BC density map – Sawa.

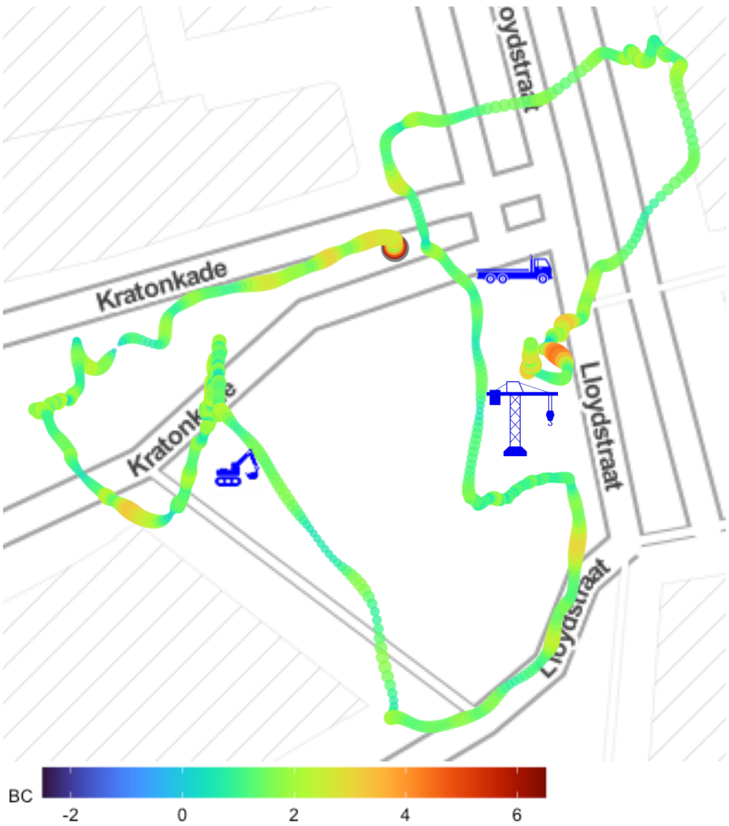


Figure 18. PM2.5 density map – Sawa.

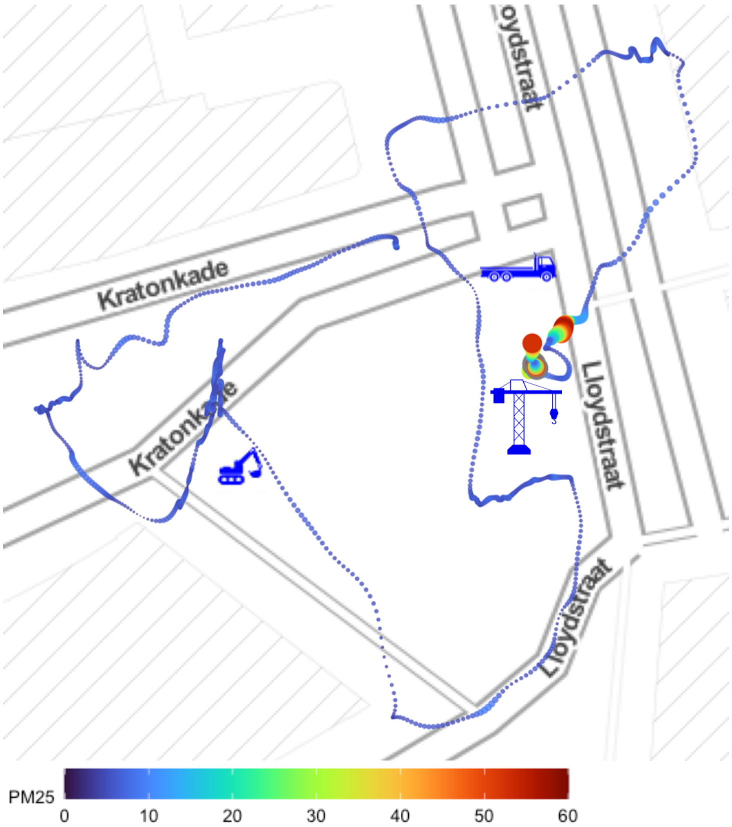
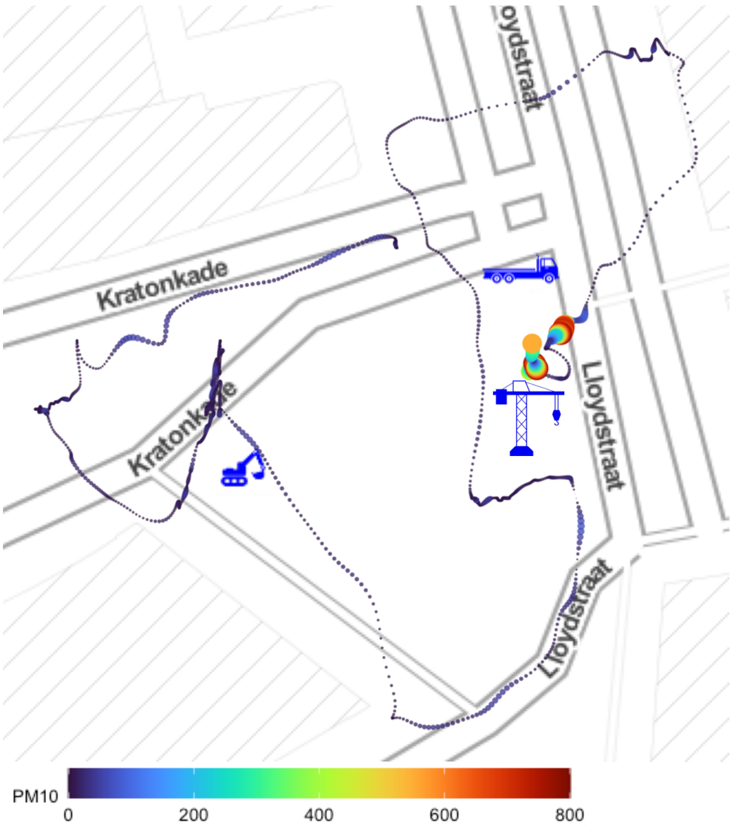


Image 5. Construction process – Sawa.

Figure 19. PM10 density map – Sawa.



3.1.2 Project PostRotterdam – Rotterdam Overview

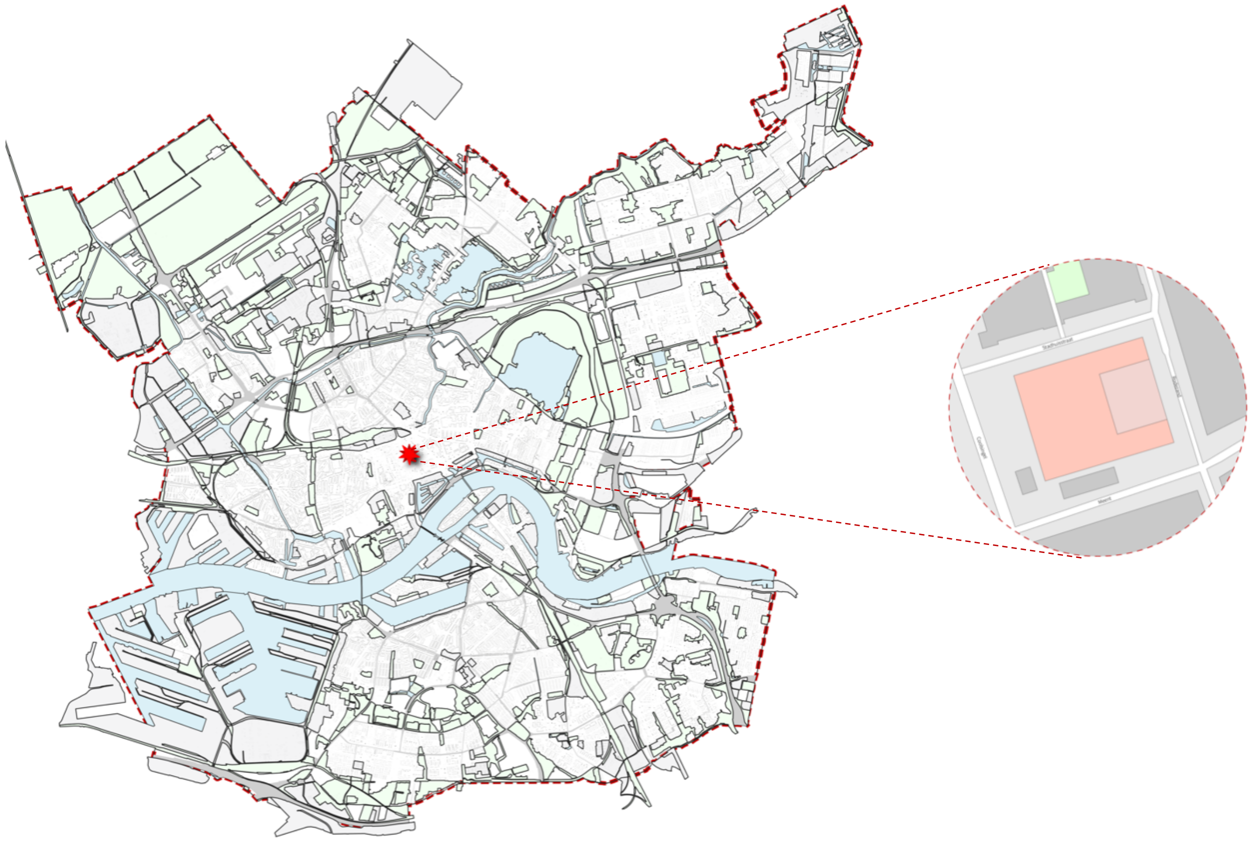


Figure 20. Location site PostRotterdam in Rotterdam.

Figure 21. Render project PostRotterdam. Credit ODA architects

The PostRotterdam project located in the city centre of Rotterdam. It is a mixed high-rise building built with a conventional steel and concrete structure. Its construction began in the middle of 2022, with a GFA of 79000m2 and 150 meters in height. This project comprises galleries, retail, restaurants, cafes, hotel, and private housing. Figures 20 and 21.

We conducted ten visits to the PostRotterdam construction site: two days with high activity, three days with medium activity, four days with low activity, and one with no recorded activity. We examined the daily mean values of pollutants, including BC (Black Carbon), UFP (Ultrafine Particles), $PM_{2.5}$ (Particulate Matter with a diameter of 2.5 µm or smaller), and PM_{10} (Particulate Matter with a diameter of 10 µm or smaller), unveiling intriguing disparities among days characterised by different activity levels.

It is essential that UFP needed to exhibit a clear correlation with the intensity of activity across these days. Similarly, BC did not manifest a distinct pattern that conformed to variations in activity levels. Measurements for $PM_{2.5}$ and PM10 were unavailable during the initial two visits.

Upon scrutinising the data in Table 10, it becomes evident that the mean values of BC, UFP, and PM_{10} displayed inconsistent across days with varying activity levels, including high, medium, and low. This observation contrasts the behaviour of $PM_{2.5}$, which portrayed a different trend in mean values across days characterised by differing activity levels.

The data and observations gathered at the PostRotterdam construction site collectively indicate that UFP and BC did not establish robust correlations with the activity intensity these days. Furthermore, the absence of $PM_{2.5}$ and PM_{10} data during the initial visits underscores the imperative for cautious interpretation when comparing average values with days featuring heightened activity levels.

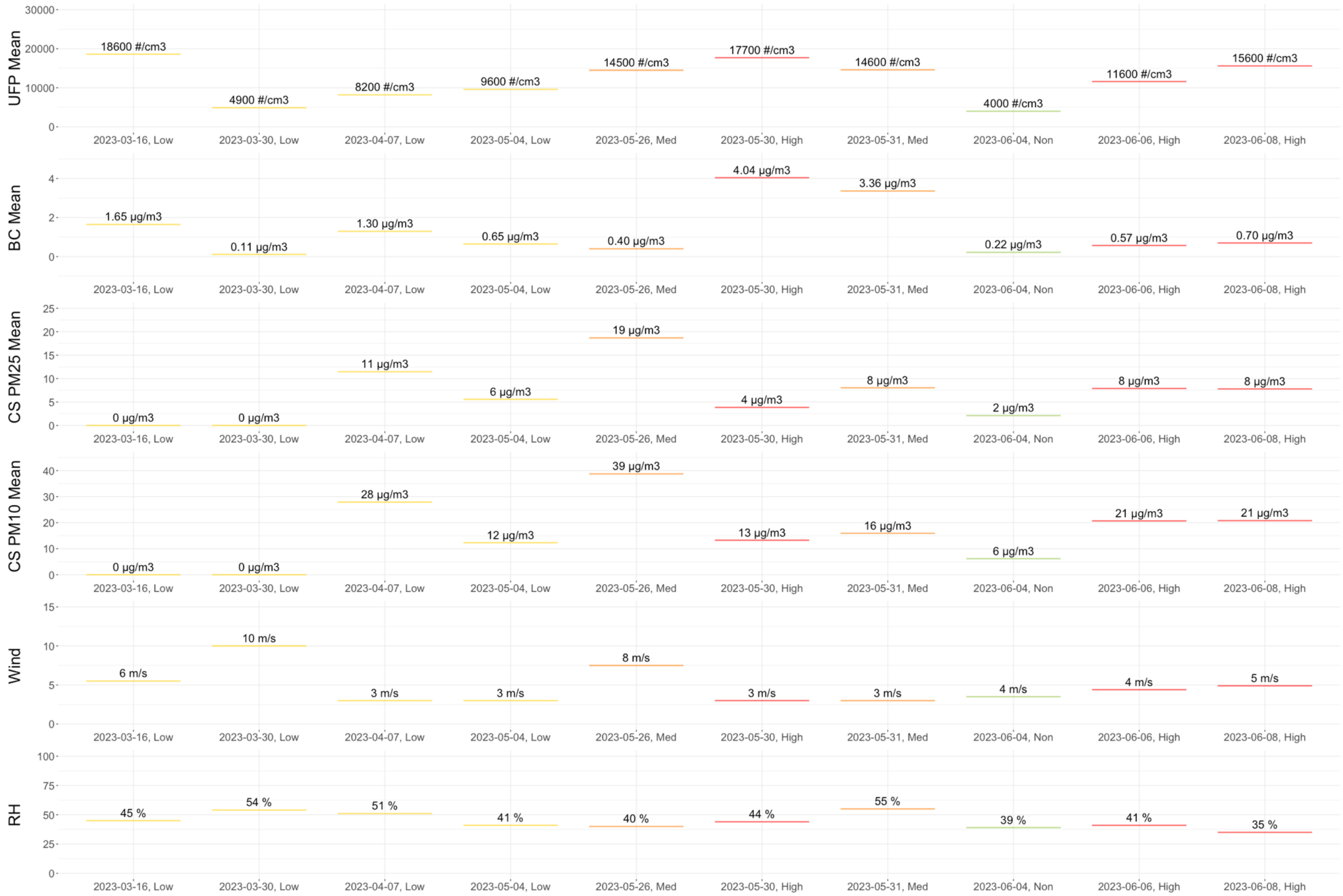


Table 10. General overview, UFP, BC, PM 2.5 & PM10 – PostRotterdam.

.3.1.2.1 Project PostRotterdam - intermediate comparison - Ultrafine Particle

In this analysis, a violin plot presents the mean values of Ultrafine Particle (UFP) emissions originating from the construction site "PostRotterdam." These activities are systematically categorised into five distinct groups: "High," "Medium," "Low," "Pause," and "Non-Activity Day," like the categorisation employed in the Sawa site analysis. A close examination of the plot reveals patterns explaining the correlation between UFP emissions and varying activity levels. Notably, the categories of "High," "Medium," and "Low" exhibit a noticeable progression in their mean UFP emission values. This trend suggests that as activity levels escalate, there is a corresponding increase in mean UFP values, hinting at a plausible association between construction intensity and UFP emissions. Particularly, the "Non-Activity Day" category, indicative of days featuring minimal construction-related work, noticeably stands out with the lowest mean UFP emission value. An interesting observation pertains to the "Pause" category, which unexpectedly displays a notably elevated mean UFP value. Figure 22.

Assessing the mean UFP values across the categories reveals the following descending order: "High Activity" (15,600 #/cm^3), "Medium Activity" (14,600 #/cm^3), "Low Activity" (8,200 #/cm^3), "Pause During Work" (11,100 #/cm^3), and "Non-Activity Day" (4,000 #/cm^3).

A comparison with European mean levels for UFP (Particulate Matter with a diameter of 100 nm or smaller) would be valuable to contextualise these findings within a broader framework. However, the WHO and EU still need targets or regulatory benchmarks for UFP.

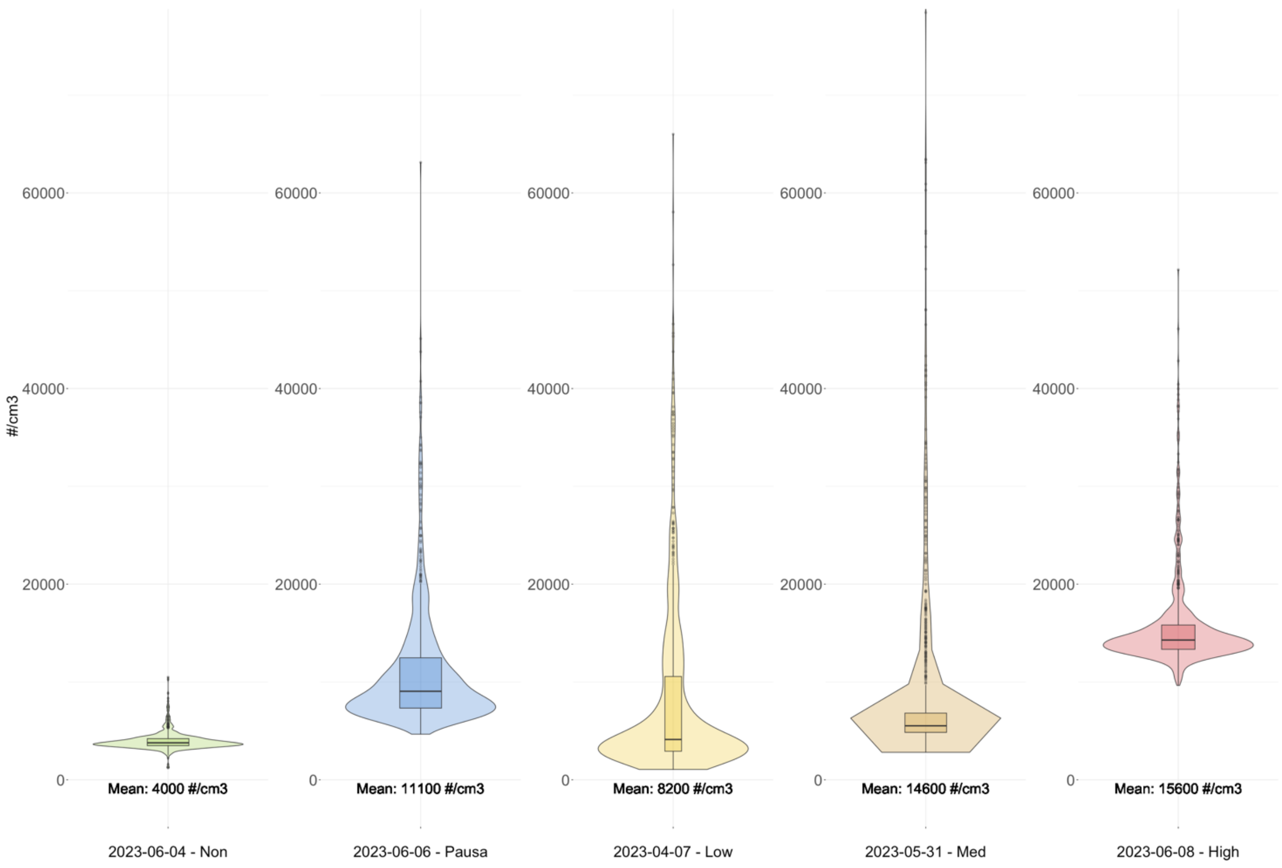


Figure 22. Violin plot – UFP mean values comparison - PostRotterdam.

.y.	group1	group2	n1	n2	statistic	p	p.adj	p.adj.signif
number	High	Low	1186	795	788089	4.82e-142	2.89e-141	****
number	High	Med	1186	1125	1163233	3.22e-210	2.58e-209	****
number	High	Non	1186	748	887110	4.95e-301	4.95e-300	****
number	High	Pause	1186	900	878707.5	1.84e-141	9.2e-141	****
number	Low	Med	795	1125	315878.5	5.1e-28	1.02e-27	****
number	Low	Non	795	748	328288	0.000401	0.000401	***
number	Low	Pause	795	900	182427.5	4.52e-68	1.36e-67	****
number	Med	Non	1125	748	771715.5	7.59e-206	5.31e-205	****
number	Med	Pause	1125	900	198285.5	1.13e-122	4.52e-122	****
number	Non	Pause	748	900	5078	2.39e-260	2.15e-259	****

Table 11. Wilcoxon signed rank test - UFP - PostRotterdam.

Table 11 The Wilcoxon signed-rank test evaluated the statistical differences among five activity groups (High, Medium, Low, Pause, and Non-activity) regarding the UFP (Ultrafine Particles) data with new values. The "High" group, there are significant differences between all pairwise comparisons ("High-Low," "High-Med," "High-Non," and "High-Pause"). The comparisons between "Low-Non," "Low-Pause," "Med-Non," "Med-Pause," and "Non-Pause" are also significant..

3.1.2.2 Project PostRotterdam - intermediate comparison - Black carbon

The presented data elucidates the mean Black Carbon (BC) emission values originating from the construction site "PostRotterdam," measured in units of μg/m^3. There is an absence of any discernible correlation between the mean BC emission values associated with the categories of "High," "Medium," and "Low" construction activity levels. Unlike Ultrafine Particle (UFP) emissions, which exhibit an ascending trend in response to increased construction activity, BC emissions do not manifest a consistent pattern. This divergence may be attributed to the unique and multifaceted characteristics of BC emissions, which are influenced by factors beyond the mere intensity of construction operations.

Notably, a significant correlation emerges when analysing the mean BC emission values within the categories "Pause" and "Non-Activity Day." Both categories display notably lower mean BC values, with "Pause" exhibiting a mean value of 0.62 μg/m^3 and "Non-Activity Day" registering the lowest mean at 0.22 μg/m^3. This concurrent reduction in BC emissions during both pause periods and non-activity days suggests the presence of a common factor contributing to the reduction in emissions. This is likely attributable to the temporary suspension of construction machinery and related activities during these periods. Despite the large variability and scatter in BC data, this also shows that construction significantly contributes to BC levels at these locations. Figure 23.

The hierarchy of mean BC values is as follows: "Medium" 3.36 μg/m^3, "Low" 1.30 μg/m^3, "Pause" 0.62 μg/m^3, "High" 0.70 μg/m^3, and "Non-Activity Day" 0.22 μg/m^3. These values are arranged in descending order. These quantitative statistics carefully illustrate the relative BC emission levels across the different categories. It is important to remember that the European Union (EU) has set acceptable thresholds for BC exposure in the context of European health standards. These regulations usually state that BC levels cannot exceed a specific threshold to maintain healthy air quality. The EU recommendation for healthy BC levels, for example, may be between 0.1 and 1.0 μg/m^3, depending on the precise location and length of exposure.

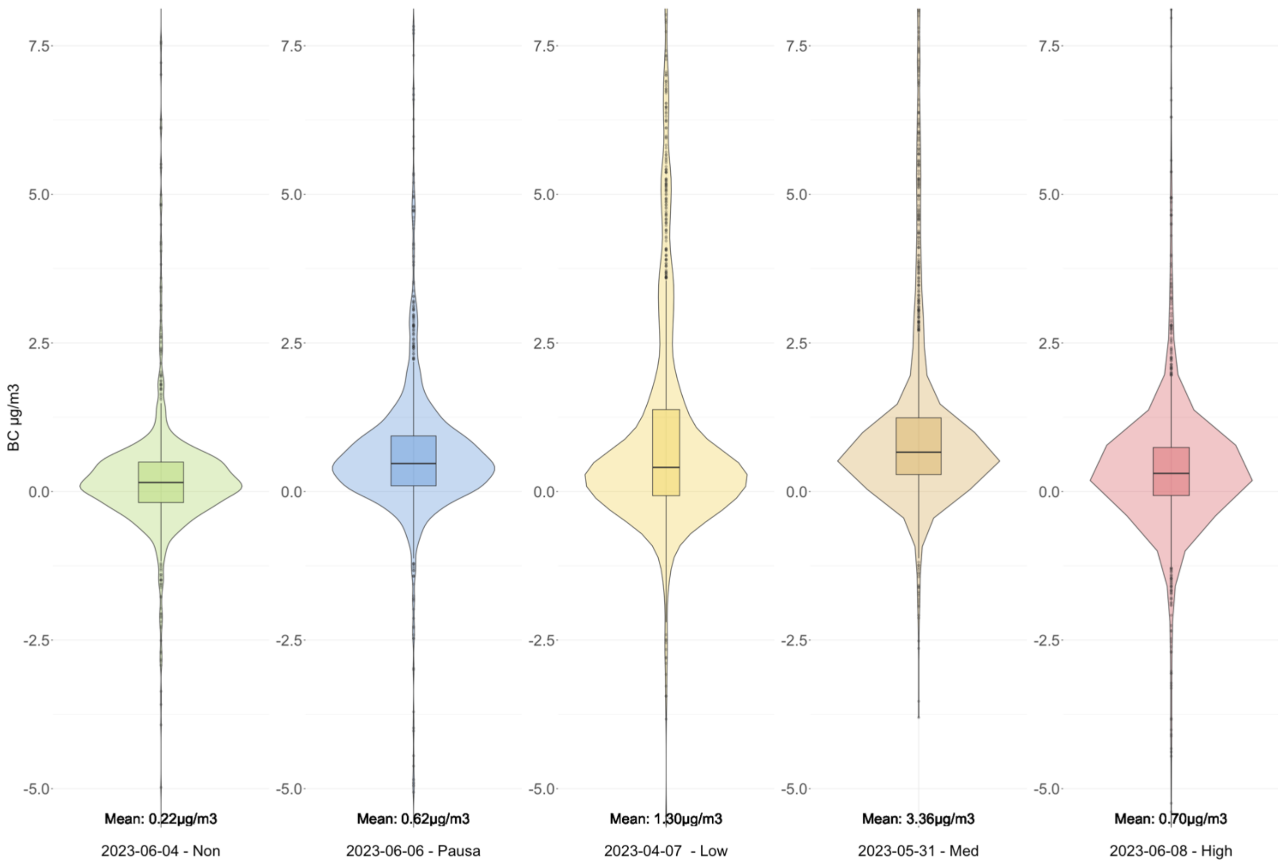


Figure 23. Violin plot – Black carbon mean values comparison - PostRotterdam.

.y.	group1	group2	n1	n2	statistic	p	p.adj	p.adj.signif
BC	High	Low	2346	1574	1625676	2.13e-10	4.26e-10	****
BC	High	Med	2346	2218	1754056	6.29e-81	5.66e-80	****
BC	High	Non	2346	1484	2032558	2.07e-18	8.28e-18	****
BC	High	Pause	2346	1771	1740938.5	5.09e-19	2.55e-18	****
BC	Low	Med	1574	2218	1458152	5.05e-18	1.52e-17	****
BC	Low	Non	1574	1484	1461901.5	1.98e-33	1.39e-32	****
BC	Low	Pause	1574	1771	1379856	0.618	0.618	ns
BC	Med	Non	2218	1484	2460111	5.17e-144	5.17e-143	****
BC	Med	Pause	2218	1771	2322562.5	3.39e-23	2.03e-22	****
BC	Non	Pause	1484	1771	869220.5	2.6e-62	2.08e-61	****

Table 12. Wilcoxon signed rank test - BC - PostRotterdam.

Table 12. The results of the Wilcoxon signed-rank test for Black Carbon (BC) data indicate significant differences among the activity groups (High, Medium, Low, Pause, and Non-activity). The "High" group, there are significant differences between all pairwise comparisons ("High-Low," "High-Med," "High-Non," and "High-Pause"). In the "Low" group, the "Low-Non" and "Low-Med" comparisons are significant. In the "Med" group, the "Med-Non" and "Med-Pause" comparisons are significant. The "Non-Pause" comparison in the "Non" group is significant.

3.1.2.3 Project PostRotterdam - intermediate comparison - Particulate matter - $PM_{2.5}$

The presented analysis pertains to the mean concentrations of $PM_{2.5}$ emissions originating from the construction site known as "PostRotterdam," with the measurements expressed in units of μg/m^3. In contrast to Ultrafine Particle (UFP) emissions, $PM_{2.5}$ values do not manifest a discernible and consistent correlation with varying levels of construction activities. Similarly to UFP emissions, the behaviour of $PM_{2.5}$. This complexity suggests that $PM_{2.5}$ emissions are subject to influences extending beyond construction intensity, thereby rendering them a parameter of greater complexity, necessitating consideration beyond activity-based predictions.

An intriguing observation of note emerges when analysing the mean $PM_{2.5}$ values associated with each distinct category. Notably, the sole category consistently exhibiting lower mean $PM_{2.5}$ values is "Non-Activity Day," with a mean $PM_{2.5}$ concentration of 2 μg/m^3. This discernible trend aligns with the patterns observed in UFP emissions, wherein days devoid of construction-related activities are associated with a substantial reduction in emissions of both PM2.5 and UFP particles. Upon arranging the mean $PM_{2.5}$ values in descending order, the hierarchy unfolds as follows: "Low" 11 μg/m^3, "High" 8 μg/m^3, "Pause" 8 μg/m^3, "Medium" 8 μg/m^3, and "Non-Activity Day" 2 μg/m^3. Figure 24.

Notably, when juxtaposed with WHO $PM_{2.5}$ levels, which typically adhere to a regulatory benchmark of 5 μg/m^3, the observed mean of the ambient concentrations are higher for high, medium, pause and non-activity, only in low activity; the mean value remained below the WHO value. This shows that in a complex urban area, $PM_{2.5}$ concentrations have many contributing factors, making them almost always above WHO benchmark values (World Health Organization, 2021). It is a notable difference compared to the annual levels of the EU with a value of 20 μg/m^3 (Rijksinstituut voor Volksgezondheid en Milieu, 2019), which is above those recommended by WHO.

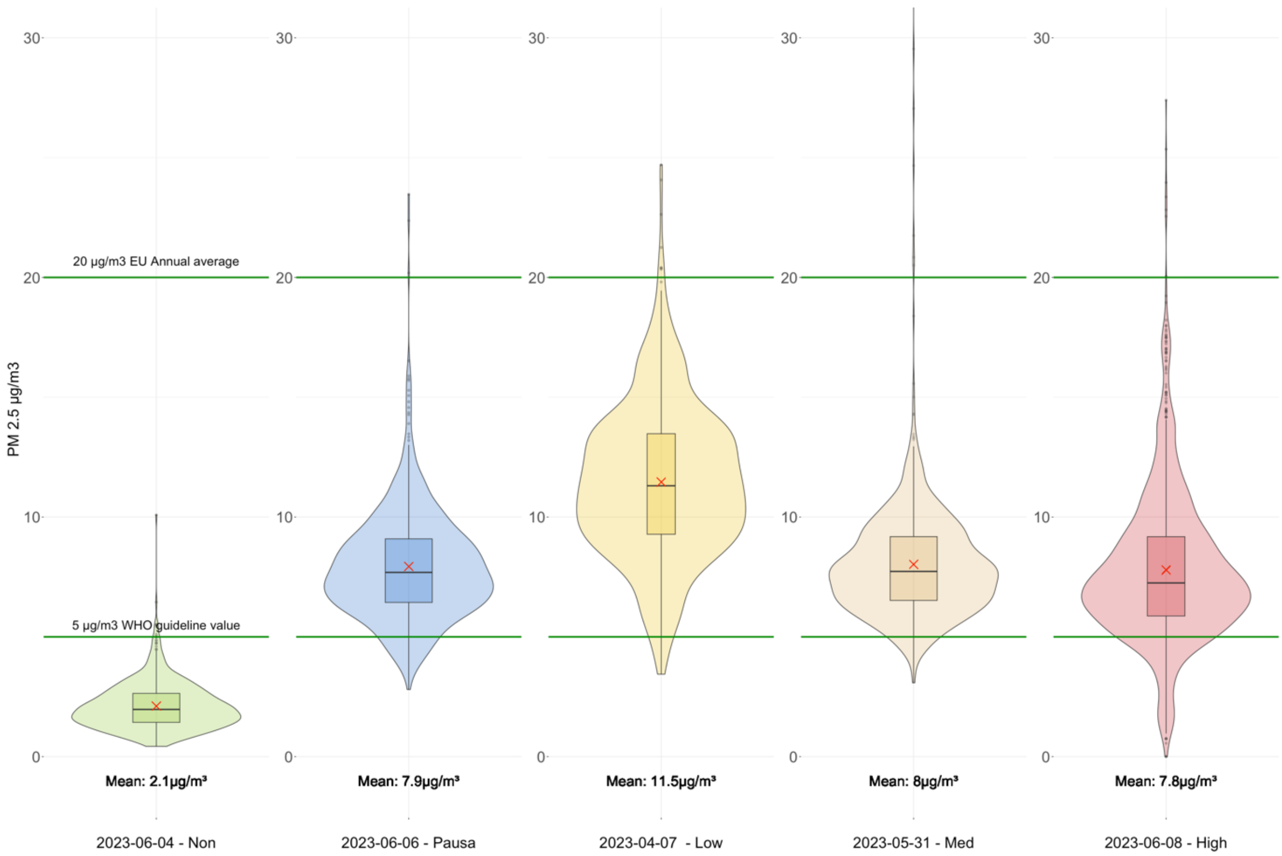


Figure 24. Violin plot – PM2.5 mean values comparison - PostRotterdam.

.y.	group1	group2	n1	n2	statistic	p	p.adj	p.adj.signif
PM25	High	Low	1365	620	158080	4.17e-111	2.5e-110	****
PM25	High	Med	1365	896	548400.5	3.22e-05	9.66e-05	****
PM25	High	Non	1365	586	777694	1.74e-240	1.74e-239	****
PM25	High	Pause	1365	716	447848.5	0.002	0.003	**
PM25	Low	Med	620	896	460715.5	1.15e-105	5.75e-105	****
PM25	Low	Non	620	586	362833.5	2.42e-197	1.69e-196	****
PM25	Low	Pause	620	716	367334.5	6.33e-95	2.53e-94	****
PM25	Med	Non	896	586	523461.5	3.48e-230	3.13e-229	****
PM25	Med	Pause	896	716	326130.5	0.564	0.564	ns
PM25	Non	Pause	586	716	1783.5	1.57e-208	1.26e-207	****

Table 13. Wilcoxon signed rank test - PM2.5 - PostRotterdam.

Table 13. The Wilcoxon signed-rank test results for PM2.5 data showed significant differences among activity groups (High, Medium, Low, Pause, and Non-activity). The "High" group, there are significant differences between all pairwise comparisons ("High-Low," "High-Med," "High-Non," and "High-Pause"). In the "Low" group, the "Low-Non," "Low-Pause," and "Low-Med" comparisons are significant. In the "Med" group, the "Med-Non" comparison is significant. The "Non-Pause" comparison in the "Non" group is significant.

3.1.2.4 Project PostRotterdam - intermediate comparison - Particulate matter - PM_{10}

The mean concentrations of PM_{10} emissions from the construction site "PostRotterdam" do not exhibit a noticeable pattern across the various construction activity levels. Much akin to $PM_{2.5}$, PM_{10} emissions appear subject to many influencing factors extending beyond the mere intensity of construction work, making establishing a direct correlation elusive. Nevertheless, a noteworthy consistency emerges within the category labelled as "Non-Activity Day," consistently maintaining the lowest mean PM_{10} concentration.

When delving into the mean PM10 values associated with each distinct category, the hierarchical arrangement from highest to lowest is as follows: "Low Activity" 28 μg/m^3, "Medium Activity" 21 μg/m^3, "High Activity" 21 μg/m^3, "Pause During Work" 16 μg/m^3, and "Non-Activity Day" 6 μg/m^3. These numerical representations establish a distinctive hierarchy, affording a quantifiable perspective on the comparative levels of PM10 emissions across a spectrum of activity scenarios. Figure 25.

Notably, when juxtaposed with WHO PM_{10} levels, which typically adhere to a regulatory benchmark of 15 μg/m^3, the observed mean of the ambient concentrations are higher for high, medium, pause and non-activity, only in low activity; the mean value remained below the WHO value. This shows that in a complex urban area, PM_{10} concentrations have many contributing factors, making them almost always above WHO benchmark values (World Health Organization, 2021). It is a notable difference compared to the annual levels of the EU with a value of 40 μg/m^3 (Rijksinstituut voor Volksgezondheid en Milieu, 2019), which is above those recommended by WHO.

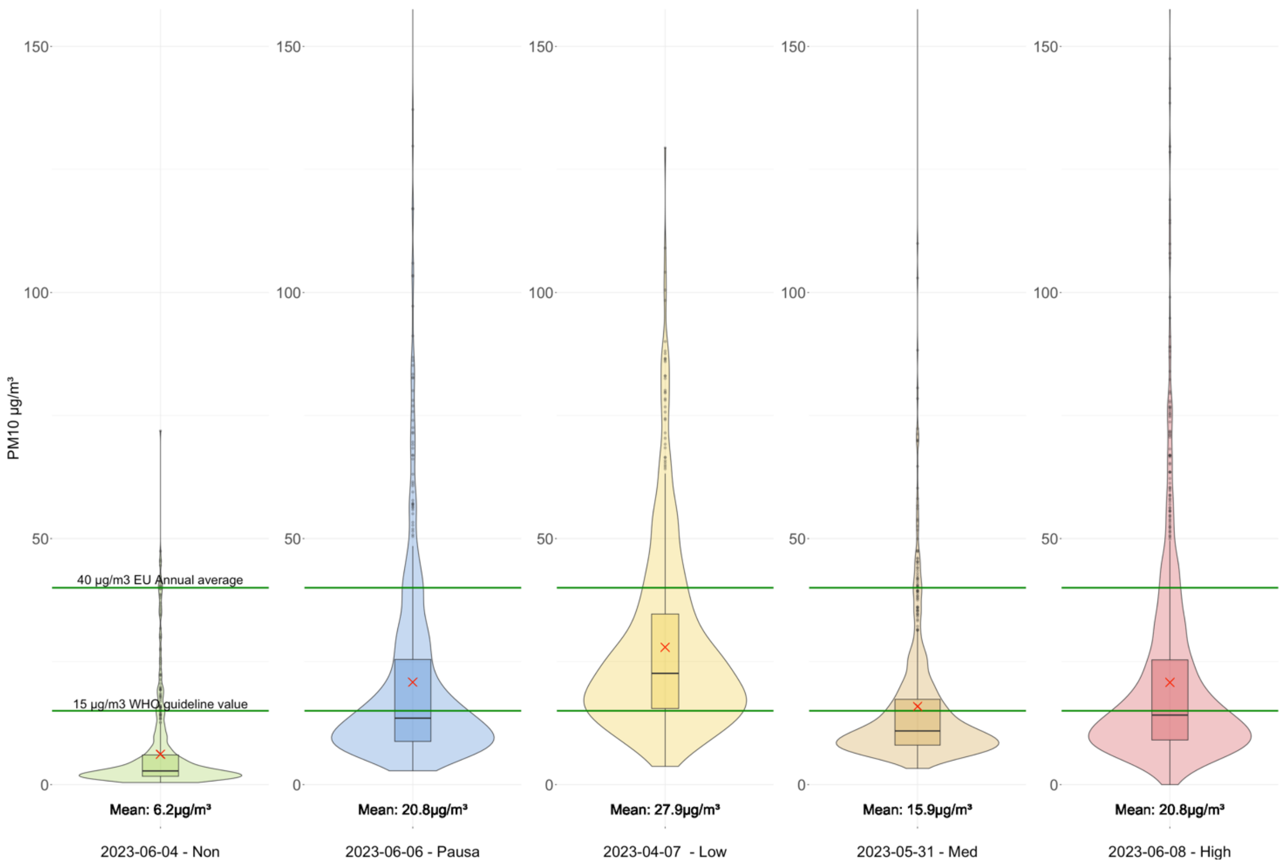


Figure 25. Violin plot – PM10 mean values comparison - PostRotterdam.

.y.	group1	group2	n1	n2	statistic	p	p.adj	p.adj.signif
PM10	High	Low	1365	620	277521.5	8.51e-35	4.26e-34	****
PM10	High	Med	1365	896	727737.5	1.95e-14	5.85e-14	****
PM10	High	Non	1365	586	695486	5.26e-148	5.26e-147	****
PM10	High	Pause	1365	716	495183	0.617	0.617	ns
PM10	Low	Med	620	896	433060.5	1.14e-76	6.84e-76	****
PM10	Low	Non	620	586	337629.5	8.72e-147	7.85e-146	****
PM10	Low	Pause	620	716	302256.5	3.42e-30	1.37e-29	****
PM10	Med	Non	896	586	450164.5	5.17e-120	3.62e-119	****
PM10	Med	Pause	896	716	264003.5	9.79e-10	1.96e-09	****
PM10	Non	Pause	586	716	50710.5	8.23e-123	6.58e-122	****

Table 14. Wilcoxon signed rank test - PM10 - PostRotterdam.

Table 14. The Wilcoxon signed-rank test results for PM10 data show significant differences in particulate matter concentrations among different activity groups (High, Medium, Low, Pause, and Non-activity). The "High" group, there are significant differences between all pairwise comparisons ("High-Low," "High-Med," "High-Non," and "High-Pause"). In the "Low" group, the "Low-Non" and "Low-Med" comparisons are significant. In the "Med" group, the "Med-Non" and "Med-Pause" comparisons are significant. The "Non-Pause" comparison in the "Non" group is significant.

3.1.2.5 Project PostRotterdam – detailed comparison - Rotterdam small

The figure 26 provides a general vision of ambient concentrations of Ultrafine Particles (UFP), Black Carbon (BC), and Particulate Matter ($PM_{2.5}$ and PM_{10}), during a one-hour monitoring period at the PostRotterdam location on June 8, 2023. This monitoring period coincided with the operation of three different types of heavy machinery, each associated with its respective peak emission values. The machinery in operation during this hour included a crane (Minotaur MRT 2150+), a concrete mixer (Man TGS 35.400), and a concrete pump (Cifa K60H), along with an electric crane. The following Figure 26., represent the fluctuations in ambient concentrations corresponding to the activities of these machines.

Specifically, the Crane Minotaur MRT 2150+ operation exhibited the highest peak value for UFP ambient concentrations at 32,844 µ/cm^3. During this machinery's operation, the peak BC ambient emission value was 3.64 µg/m^3, with peak $PM_{2.5}$ and PM_{10} ambient concentrations reaching 23 µg/m^3 and 159 µg/m^3, respectively. The Concrete Mixer Man TGS 35.400, on the other hand, displayed different peak values. Its UFP ambient concentrations peaked at 26,000 #/cm^3, while BC ambient concentrations peaked at 10.05 µg/m^3. Furthermore, peak $PM_{2.5}$ and PM10 ambient concentrations during its operation were observed at 16 µg/m^3 and 89 µg/m^3, respectively.

Similarly, during its operation, the Concrete Pump Cifa K60H showed peak UFP ambient concentrations at 24,700 #/cm^3, with BC ambient concentrations reaching a 14.65 µg/m^3 peak. Peak $PM_{2.5}$ and PM_{10} ambient concentrations were also observed at 28 µg/m^3 and 210 µg/m^3, respectively. The analysis reveals distinct variations in peak ambient emission values for each type of particulate matter among the three different types of machinery. The Crane Minotaur MRT 2150+ exhibited the highest peak values for UFP and $PM_{2.5}$ emissions, while the Concrete Pump Cifa K60H registered the highest peak values for BC and PM10 ambient concentrations. In contrast, the Concrete Mixer Man TGS 35.400 exhibited lower peak values across all four particulate matter categories.

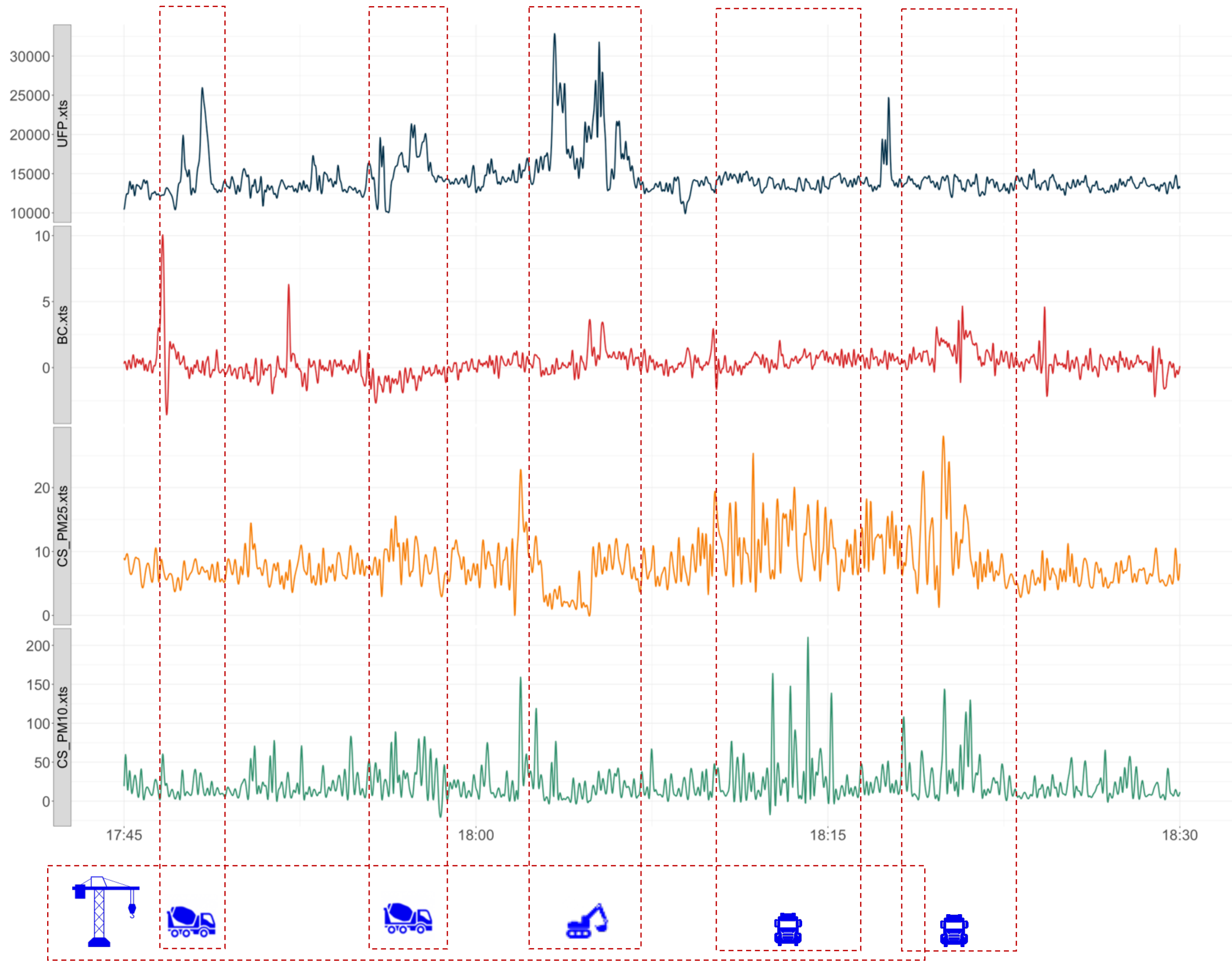
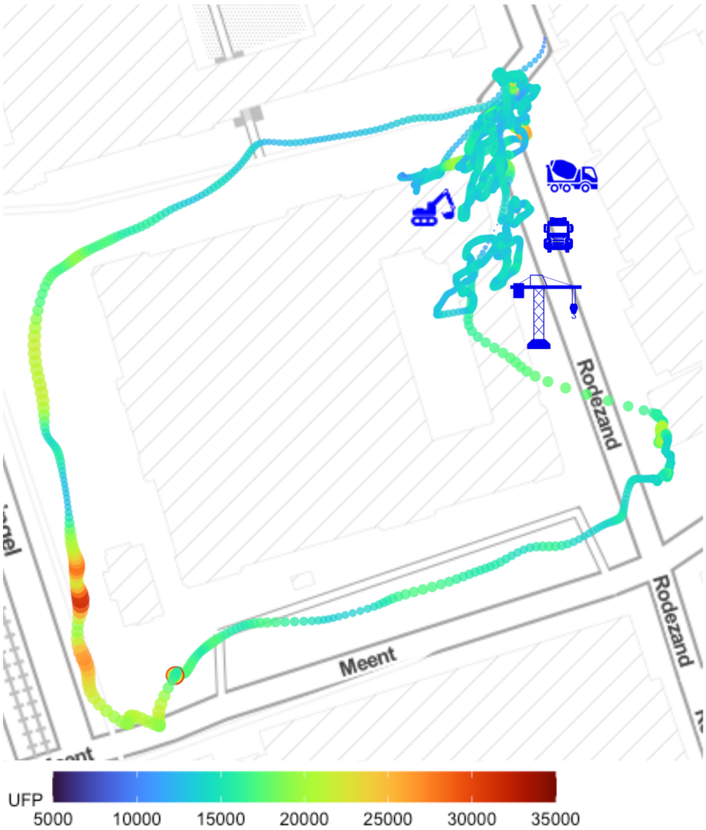


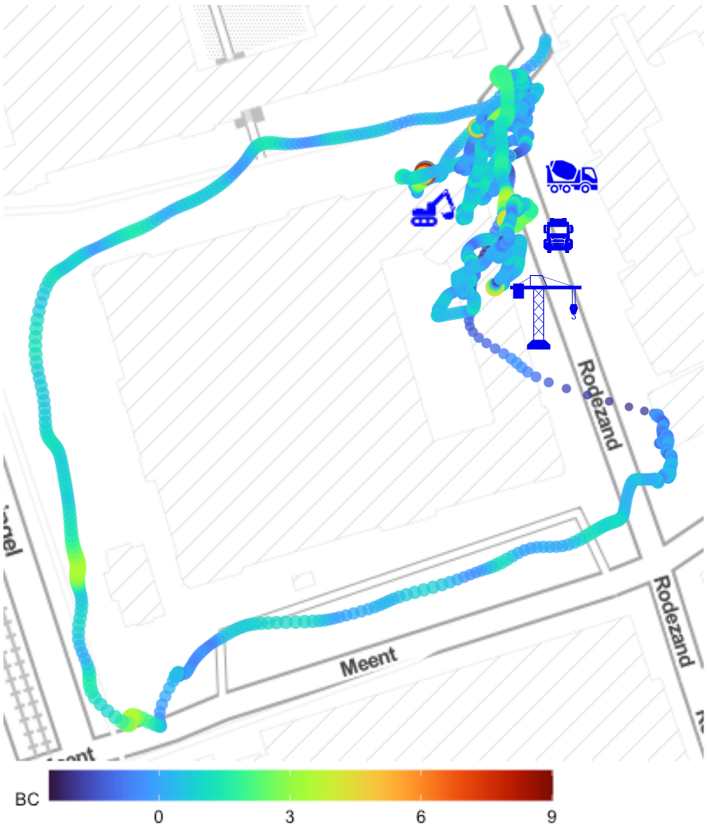
Figure 26. Ambient concentration comparison of UFP, BC, PM2.5 and PM10 from working machinery - PostRotterdam.

Figure 27. UFP density map – PostRotterdam.



Density maps showing ambient concentrations of UFP, BC, PM2.5, and PM_{10} in the PostRotterdam area are presented in Figures 27, 28, 29, and 30. These maps employ a colour gradient, where warmer tones indicate higher pollutant concentrations and cooler tones indicate lower levels. Icons on these maps pinpoint the precise locations of equipment responsible for these ambient concentrations, including the crane (Minotaur MRT 2150+), concrete mixer (Man TGS 35.400), concrete pump (Cifa K60H), and electric crane. These maps help identify areas where exposure to these particle contaminants poses an elevated health risk, enhancing our understanding of the environmental impact of these machinery types during the one-hour monitoring period on June 8, 2023, at the PostRotterdam site.

Figure 28. BC density map –PostRotterdam.



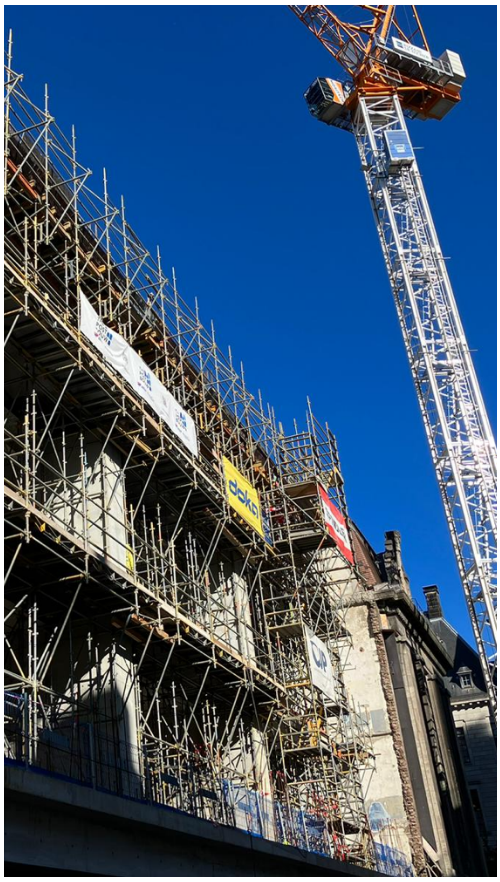


Image 6. Construction process PostRotterdam.

Figure 29. PM2.5 density map – PostRotterdam.

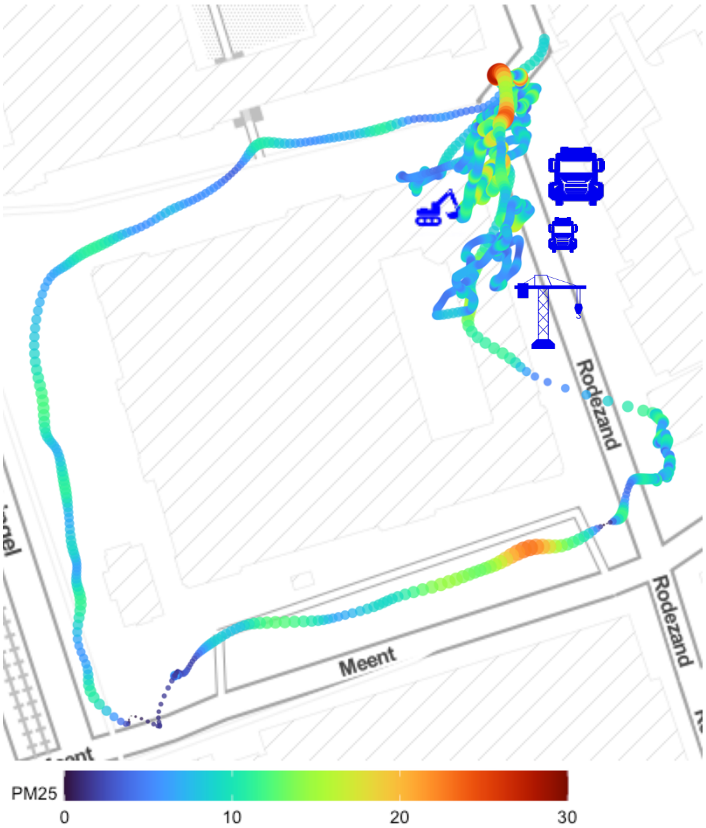
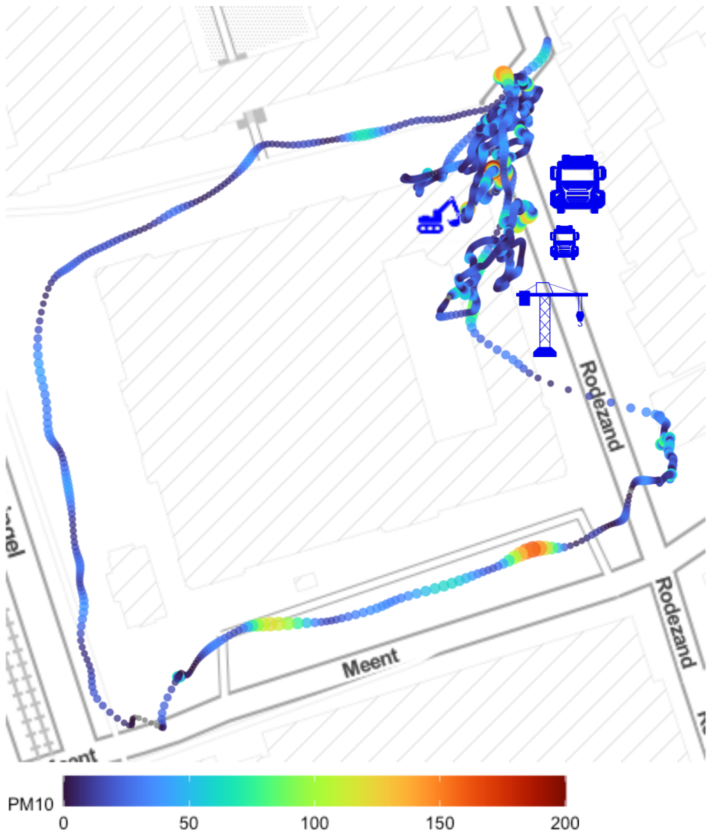


Image 7. Machinery in PostRotterdam.

Figure 30. PM10 density map – PostRotterdam.



3.1.3 Project Switi – Amsterdam Overview

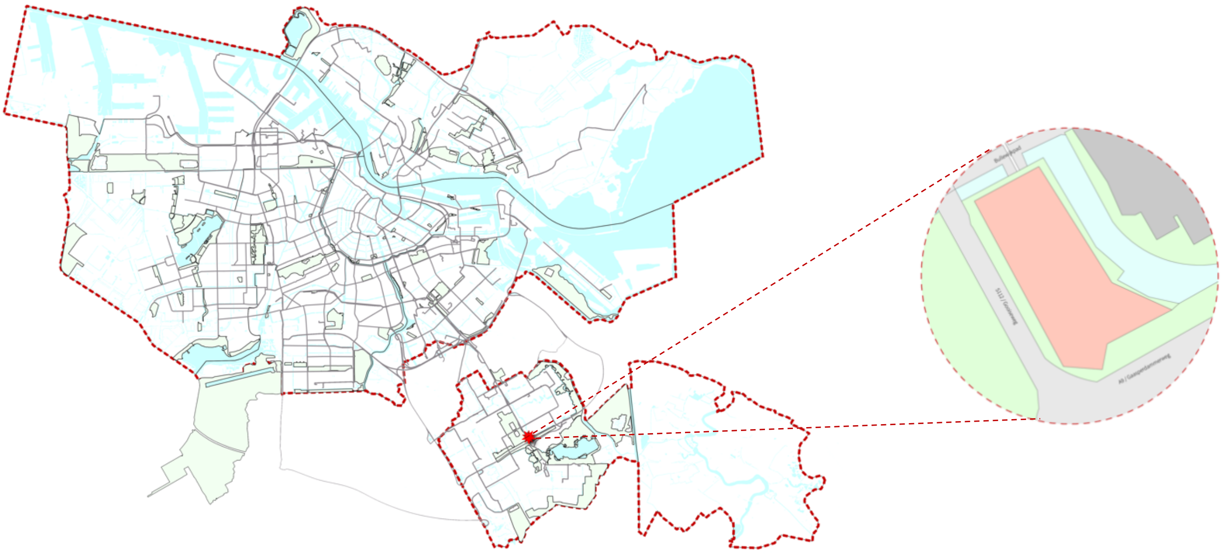


Figure 31. Location site Switi in Amsterdam.

Figure 32. Render project Switi. Credits: HOH architects.

Switi, located in Amsterdam, Zuid-Oost, consists of various single-family homes and apartments: 2 corner houses with a living area of approximately 125 m2, 22 terraced houses with a living area of approximately 125 m2 and 45 apartments with a living area of approximately 60 m2 to 65 m2 t the south-east corner with a height of 8 stories. Switi's structure is entirely CLT. Figures 31 and 32.

The table ## displays a comprehensive overview of the mean concentrations of Ultrafine Particles (UFP), Black Carbon (BC), $PM_{2.5}$, and PM_{10} emissions recorded at the construction site denoted as "Switi," situated in the Amsterdam Zuidoost region. This analysis assumes particular significance due to the distinctive characteristics of the construction project, which notably employs Cross-Laminated Timber (CLT) as its primary construction material. The dataset encompasses four distinct visitation periods associated with specific activity categories. It is worth noting that this classification scheme aligns closely with the categorisations observed in prior studies conducted at the Sawa and PostRotterdam construction projects. Notably, the "Switi" construction site differs from its counterparts in that it consists of only four distinct visits, characterised by three instances of "High Activity" and a single of "Non-Activity".

It is appropriate to highlight specific data limitations inherent in this analysis. Specifically, there is a lack of data for “Medium Activity” and "Low Activity" categories and a lack of data on $PM_{2.5}$ and PM_{10} on some visit days at the "Switi" construction site. This limitation restricts the ability to draw comprehensive comparisons across all activity categories.

The graphical representation, presented Table15., visually delineates the mean concentrations across the four particle emissions—UFP, BC, $PM_{2.5}$, and PM_{10}—providing insight into their dynamics within the context of the "Switi" construction site's various visits. This contextualised evaluation develops an understanding of how these emissions behave within the framework defined by the project's unique attributes and the observed activities.

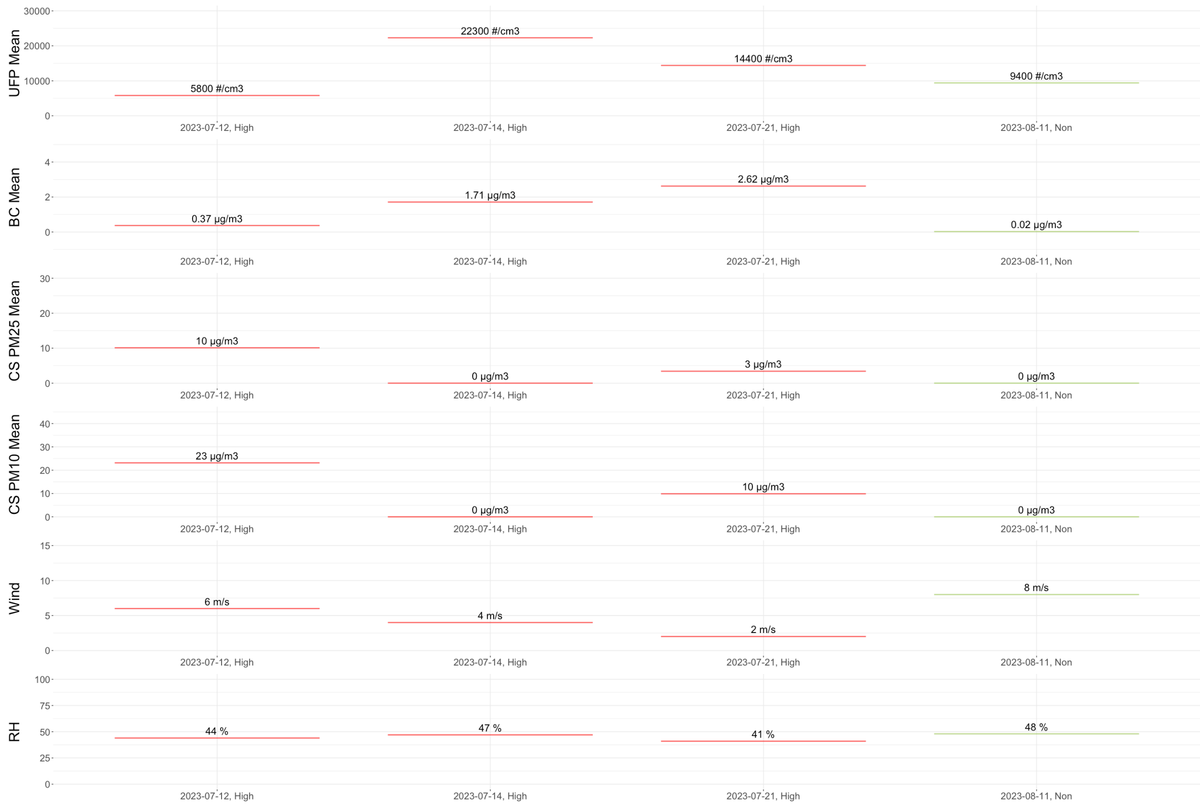


Table 15. General overview, UFP, BC, PM 2.5 & PM10 – Switi.

3.1.3.1 Project Switi- intermediate comparison - Ultrafine Particle

The provided graphical representation offers insight into the mean concentrations of Ultrafine Particles (UFP) ambient concentrations within a construction site context of Switi. In this instance, the dataset is structured around three primary categories: "High,", "Pause", and "Non-working day". It is essential to acknowledge certain data constraints as they pertain to the lack of corresponding data points for analysis within the "Medium" and "Low" categories.

Necessary to this analysis is the observation that the "High" category aligns with expected trends, showcasing mean UFP values of 14,400 #/cm^3. This alignment underscores the consistent and predictable nature of UFP emissions during significant and moderate construction activity periods. However, a counterintuitive observation arises concerning the "Pause" category, which deviates from anticipated trends by exhibiting a mean UFP value of 8,500 #/cm^3. Furthermore, it is worth noting that the "Non-working day" category registers a mean UFP value of 9,400 #/cm^3. Figure 33.

To place these results in a larger context, a comparison with the European mean values for UFP (Particulate Matter with a diameter of 100 nm or less) might be beneficial. Nevertheless, the WHO and EU still require goals or legal standards for UFP.

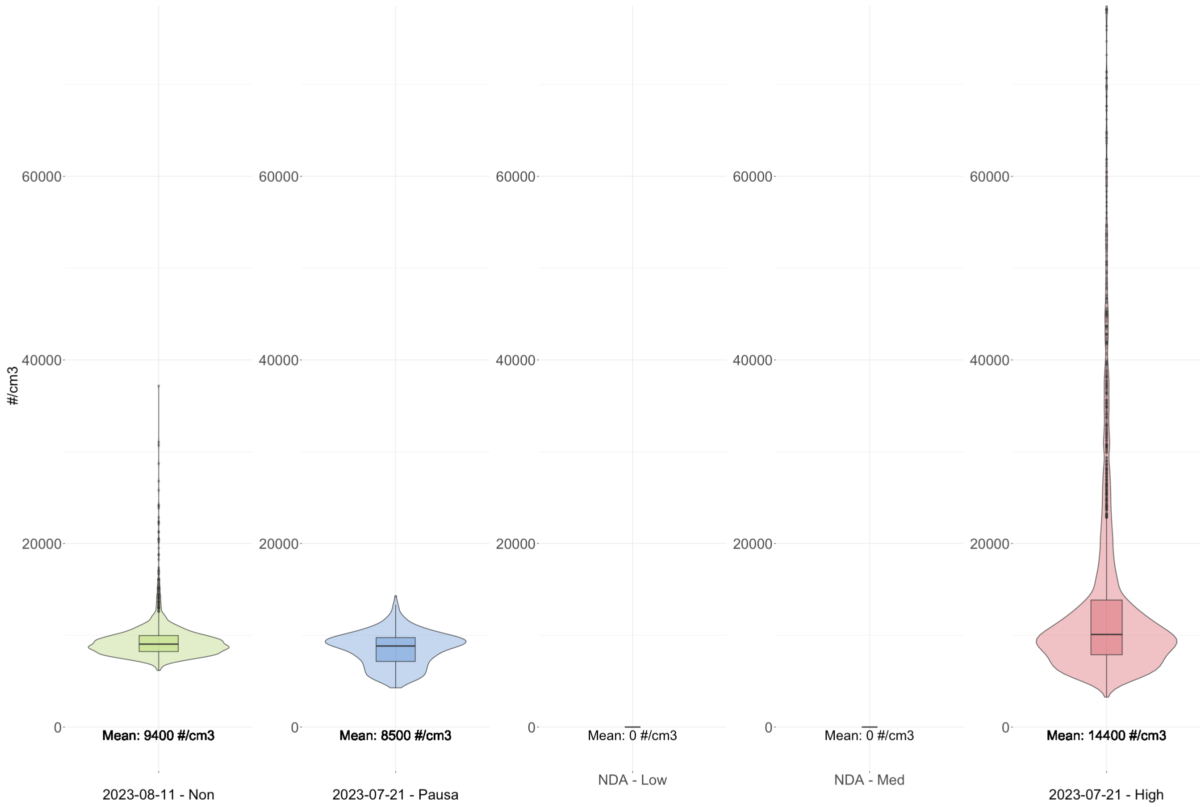


Figure 33. Violin plot – UFP mean values comparison - Switi.

.y.	group1	group2	n1	n2	statistic	p	p.adj	p.adj.signif
number	High	Non	3813	2917	6745638.5	7.95e-51	2.38e-50	****
number	High	Pause	3813	450	1155237.5	2.17e-33	4.34e-33	****
number	Non	Pause	2917	450	776966	3.27e-10	3.27e-10	****

Table 16. Wilcoxon signed rank test - UFP - Switi.

Table 16. The results of the Wilcoxon signed-rank test for UFP (Ultrafine Particles) concentrations show significant differences among various activity groups (High, Pause, and Non-activity). In the "High" group, there are significant differences between both "High-Non" and "High-Pause" comparisons. The "Non-Pause" comparison between the "Non" and "Pause" groups is also significant.

3.1.3.2 Project Switi- intermediate comparison - Black carbon

The provided graphical representation offers insights into the mean concentrations of Black Carbon (BC) ambient concentrations within the context of a construction site of Switi, categorising observations into four primary categories: "High, "Pause," and "Non-working day." It is important to recognise that data constraints exist with absent corresponding data points for other potential categories, similar to prior analyses.

A pattern emerges in the "High" category, which aligns closely with anticipated trends. These categories reveal mean BC emission values of 2.62 μg/m^3 and 0.37 μg/m^3, respectively. This alignment with the mean UFP values suggests a correlation between BC emissions and the intensity of construction activity.

However, a significant departure from expectations becomes apparent within the "Pause" category, where the mean BC emission value stands at 0.69 μg/m^3, exceeding that of the "Non-activity" category with a register of a mean BC emission value of 0.20 μg/m^3, highlighting BC dynamics during periods of minimal or no construction activity. A comparison of these values indicates notably lower BC emissions during non-working days. Figure 34.

To contextualise these findings within a more general framework, comparing them with European Union (EU) recommended BC exposure levels is essential. These European standards can vary depending on regional factors and local regulations. In general, EU guideline values for healthy BC levels may range from 0.1 to 1.0 μg/m^3, contingent upon the specific geographic location and duration of exposure.

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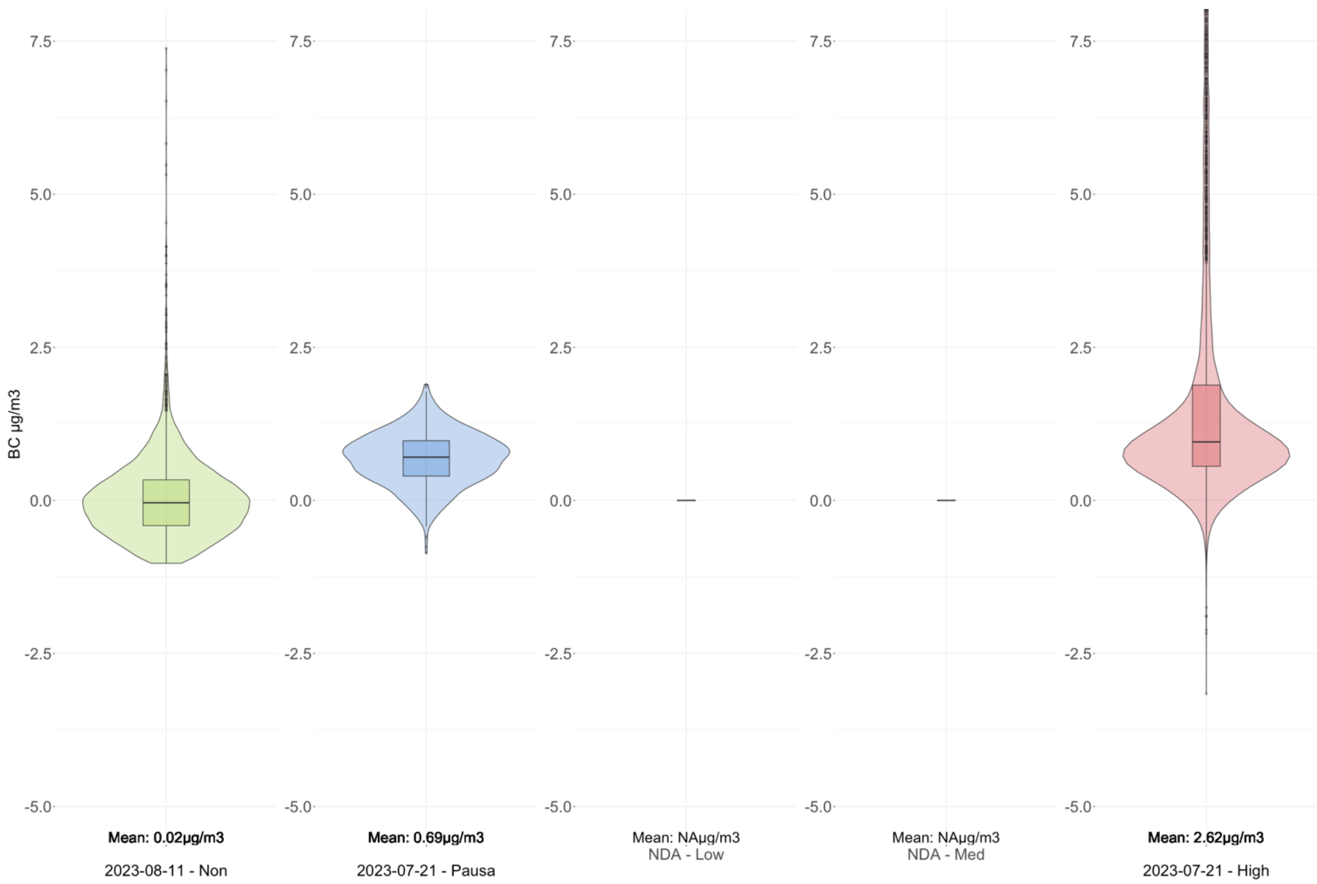


Figure 34. Violin plot –BC mean values comparison - Switi.

.y.	group1	group2	n1	n2	statistic	p	p.adj	p.adj.signif
BC	High	Non	7558	5053	33723963	0	0	****
BC	High	Pause	7558	891	4422781	4.78e-53	4.78e-53	****
BC	Non	Pause	5053	891	764033.5	1.3e-217	2.6e-217	****

Table 17. Wilcoxon signed rank test - BC - Switi.

The table 17., compares the Wilcoxon signed-rank test outcomes for Black Carbon (BC) ambient concentrations, comparing various groups. In the "High" group, there are significant differences between both "High-Non" and "High-Pause" comparisons. The "Non-Pause" comparison between the "Non" and "Pause" groups is also highly significant.

3.1.3.3 Project Switi- intermediate comparison - Particulate matter - $PM_{2.5}$ & PM_{10}

Figures #$PM_{2.5}$ and #PM_{10} in the inquiry provide a comprehensive overview of the mean concentrations for two distinctive air quality parameters, $PM_{2.5}$ and PM_{10}, respectively, within a construction site in Switi. This analysis categorises construction activities into two fundamental classifications: "High" and "Pause." In consonance with previous discussions, it is imperative to acknowledge that data constraints persist, thereby restricting the availability of comprehensive data points.

Initiating the examination with the $PM_{2.5}$ analysis, discernible patterns materialise within the ambit of these two categories; the "High" and "Pause" categories maintain mean $PM_{2.5}$ values of 3 µg/m^3 and four µg/m^3, respectively. This observation imparts insights into the potential influence of varying construction activities on $PM_{2.5}$ emissions. While the "High" and "Pause" categories align with a relatively consistent trend, the unanticipated elevation in $PM_{2.5}$.

Transitioning our focus to PM_{10}, a parallel yet subtly more pronounced pattern surfaces across the categories. The "High" category reports a mean PM_{10} value of 10 µg/m^3, and the "Pause" category exhibits a 14 µg/m^3 value. This consistent order of values reaffirms the earlier findings, underscoring a proportional relationship between construction activity and PM_{10} emissions. Figure 35.

Once overlapping the WHO $PM_{2.5}$ and PM_{10} levels, which typically adhere to a regulatory benchmark of 5 µg/m^3 and 15 µg/m^3 respectively, the observed mean of the ambient concentrations are lower for high and pause activity, in contrast with pause activity where could be expected, high activity wasn't expected, this gives room for further investigation (World Health Organization, 2021). It is a notable difference compared to the annual levels of the EU with a value of 5 µg/m^3 20 µg/m^3 respectively (Rijksinstituut voor Volksgezondheid en Milieu, 2019), which is above those recommended by WHO.

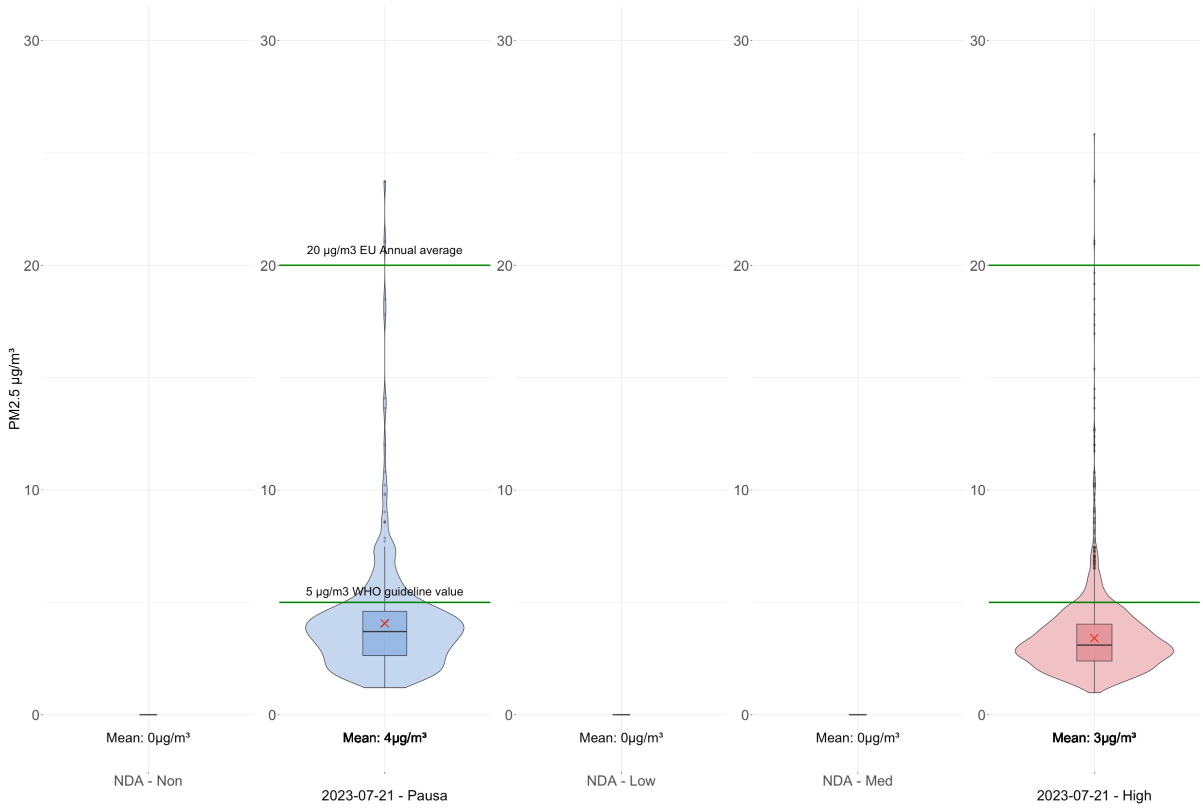


Figure 35. Violin plot – PM2.5 mean values comparison - Switi.

.y.	group1	group2	n1	n2	statistic	p
PM25	High	Pause	3047	360	445858	6.13e-09

Table 18. Wilcoxon signed rank test - PM2.5 - Switi.

The table 18., compares the Wilcoxon signed-rank test outcomes for PM2.5 (Particulate Matter 2.5) ambient concentrations, comparing "High" and "Pause." The low p-value (less than the conventional significance level of 0.05) suggests strong evidence to reject the null hypothesis. The result indicates a statistically significant difference between the "High" and "Pause" groups for the variable "PM25."

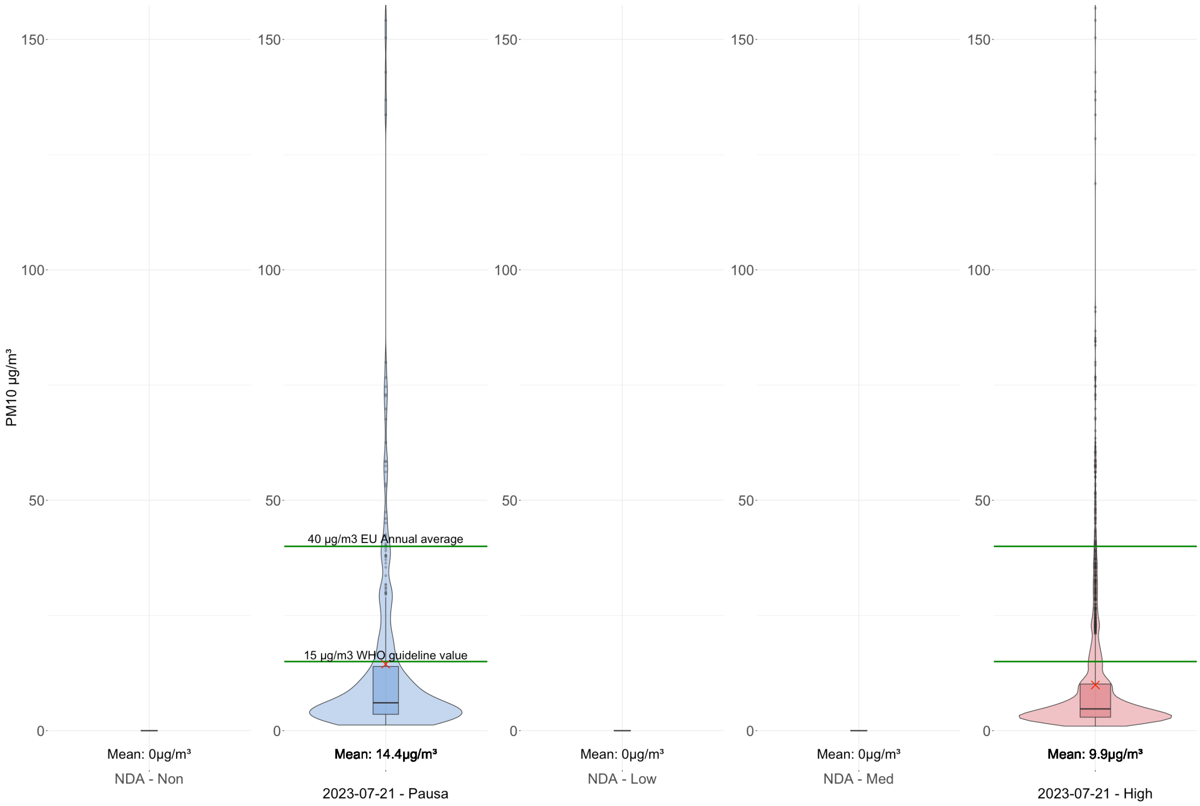


Figure 36. Violin plot – PM10 mean values comparison – Switi.

.y.	group1	group2	n1	n2	statistic	p
PM10	High	Pause	3047	360	465652.5	2.71e-06

Table 19. Wilcoxon signed rank test - PM10 - Switi.

The table 19., compares the Wilcoxon signed-rank test outcomes for PM10 (Particulate Matter 10) ambient concentrations, comparing two groups, "High" and "Pause." The low p-value (less than the conventional significance level of 0.05) suggests strong evidence to reject the null hypothesis. The result indicates a statistically significant difference between the "High" and "Pause" groups for the variable "PM10."

3.1.3.4 Project Switi – detailed comparison

In Figure 37., we present a comprehensive analysis of ambient concentrations, encompassing Ultrafine Particles (UFP), Black Carbon (BC) and Particulate Matter ($PM_{2.5}$ and PM_{10}). This data was collected during a 4-hour monitoring session at the Switi location on July 21, 2023. Throughout this period, two types of heavy machinery were active: a diesel crane (Spierings SK2400-R) and a 100kW diesel generator. The figure offers valuable insights into the correlation between these machinery activities and fluctuations in ambient concentrations, with peak values indicating moments of heightened emissions. During the active work phase, the following peak emission values were recorded when the diesel 100kW generator and the crane Spierings SK2400-R were operational. UFP emissions reached a high value of 219,974 #/cm^3, while BC emissions peaked at 60.76 µg/m^3. $PM_{2.5}$ emissions exhibited their highest concentration at 26 µg/m^3, and PM_{10} emissions registered their peak level at 276 µg/m^3.

Contrarily, the emission values significantly reduced during the pause in activity when the machinery was not operational. UFP emissions decreased to a comparatively low value of 9,910 #/cm^3, BC emissions dropped to a minimal 0.33 µg/m^3, and $PM_{2.5}$ emissions decreased to 6 µg/m^3, with PM_{10} emissions exhibiting a minimal value of 10 µg/m^3. A comparison of these peak values highlights the contrast between ambient concentrations during active work and the emissions during the pause phase. The active work phase, characterised by the operation of the diesel 100kW generator and the Spierings SK2400-R crane, resulted in higher emissions across all four particulate matter categories. In contrast, the pause phase saw emissions reduced to a fraction of their levels during active work, emphasising the direct impact of machinery operation on ambient air quality. These findings underscore the importance of considering machinery and its direct relation to ambient concentrations in environmental assessments and underscore the potential benefits of mitigation strategies during operational phases.

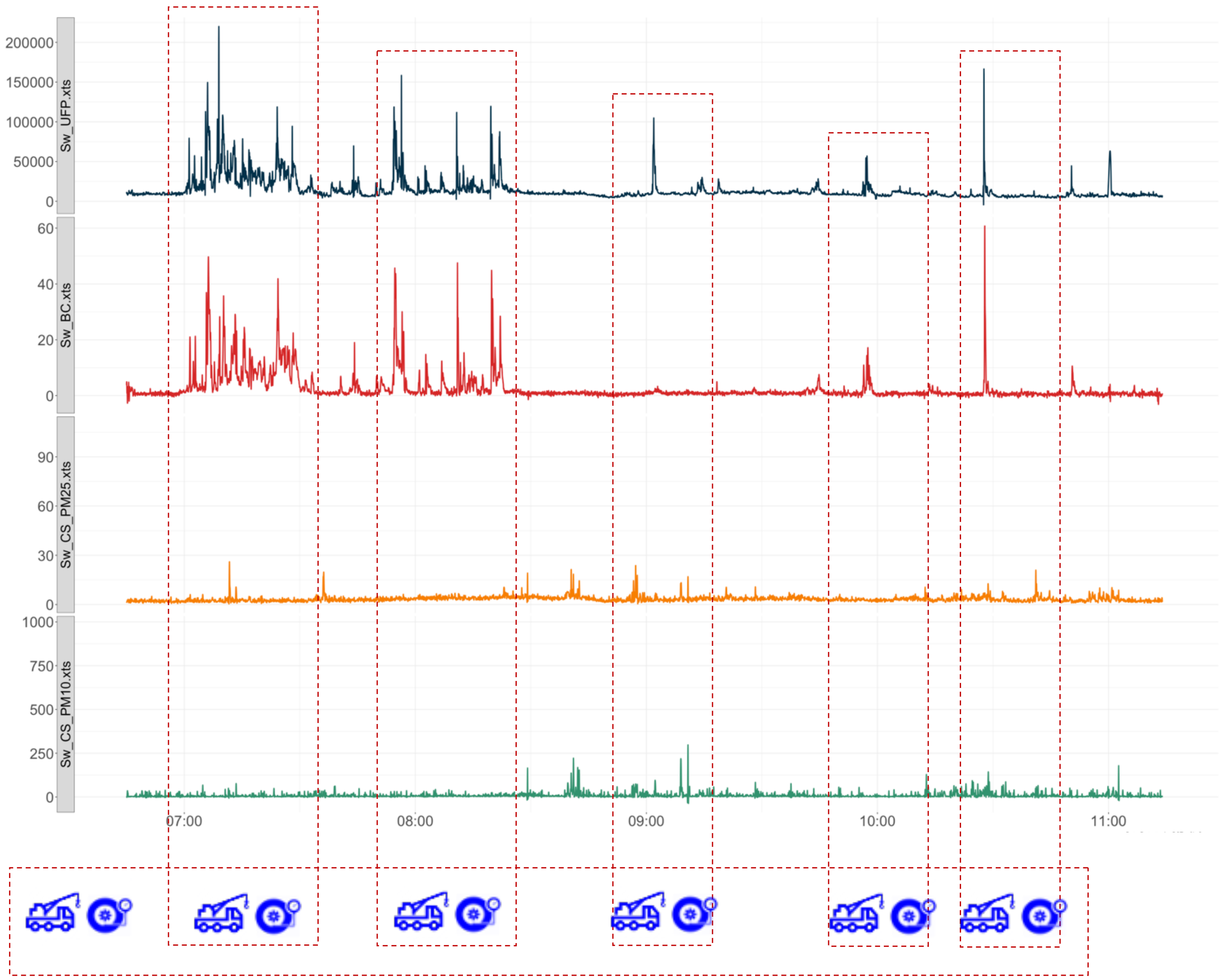
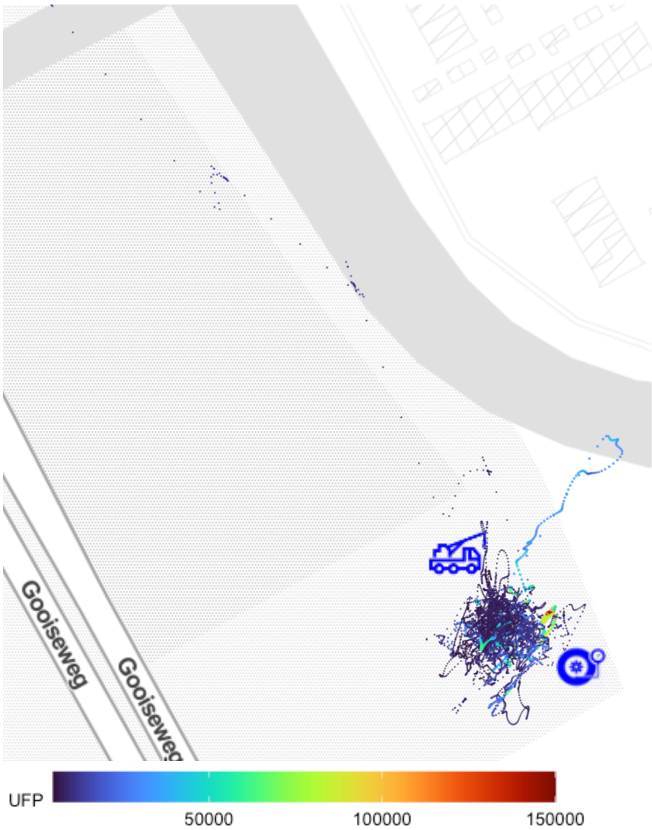


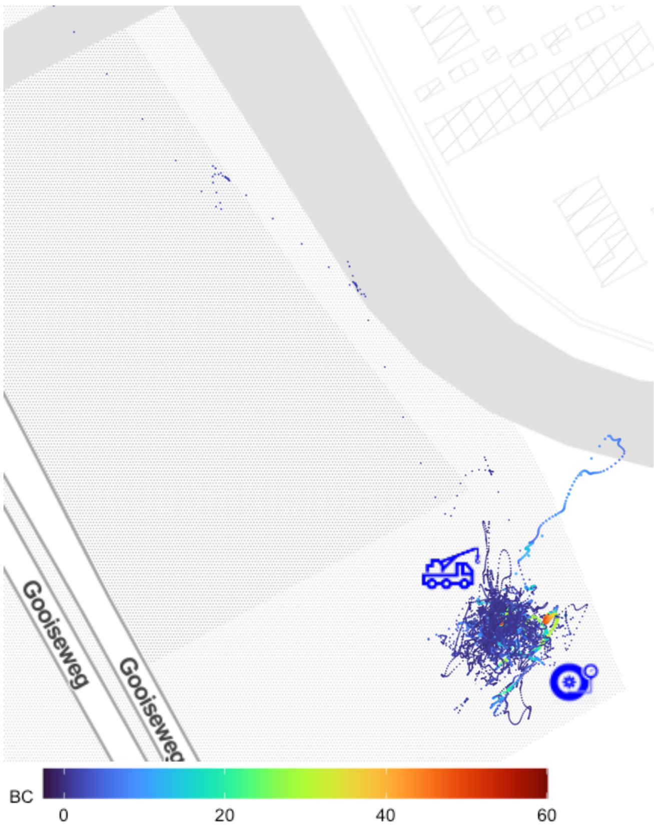
Figure 37. Ambient concentration comparison of UFP, BC, PM2.5 and PM10 from working machinery - Switi.

Figure 38. UFP density map – Switi.



In addition to this analysis, density maps are included in Figures 38, 39, 40, and 41, illustrating ambient concentrations of UFP, BC, $PM_{2.5}$, and PM_{10} in the Switi area. These maps utilize a colour gradient, with warmer hues indicating elevated pollutant concentrations and cooler tones representing reduced levels. Icons on these maps denote the precise locations where machinery operated, contributing to these ambient concentrations. The machinery categories featured include a diesel crane (Spierings SK2400-R) and a 100kW diesel generator, both recognized as sources of the mentioned emissions. These maps assist in identifying areas where exposure to these particle contaminants poses an increased health risk, providing valuable insights into the environmental impact of machinery operation during the four-hour monitoring period on July 21, 2023, at the Switi site.

Figure 39. BC density map – Switi.



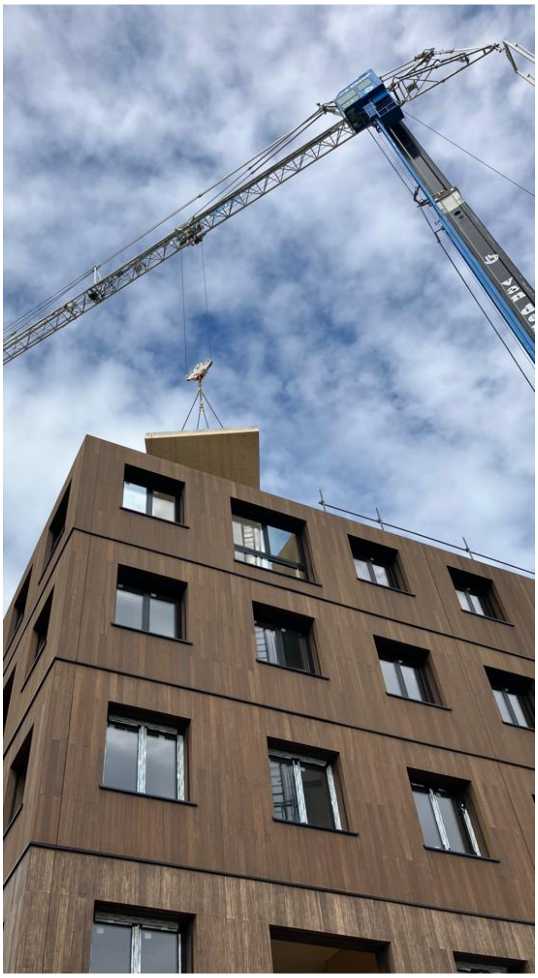


Image 8. Construction process Switi. Credit: Miny Rajiv.

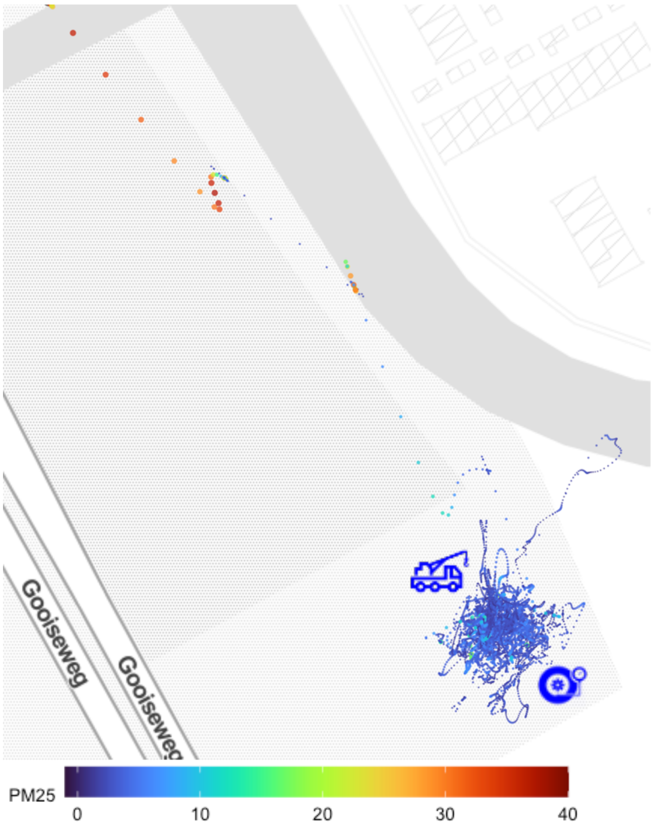


Figure 40. PM2.5 density map – Switi.

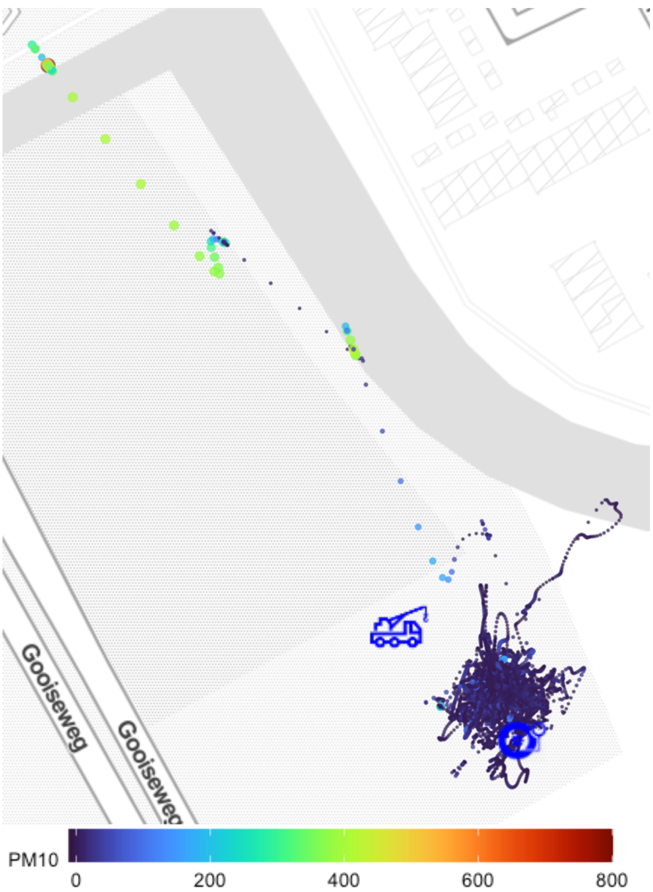


Figure 41. PM10 density map – Switi.

Image 9. Machinery in Switi.

3.2 Comparison across all construction sites (Ultrafine particle, Black Carbon, and Particulate Matter ($PM_{2.5}$ & PM_{10}) Sawa- PostRotterdam-Switi.

3.2.1 Ultrafine Particle.

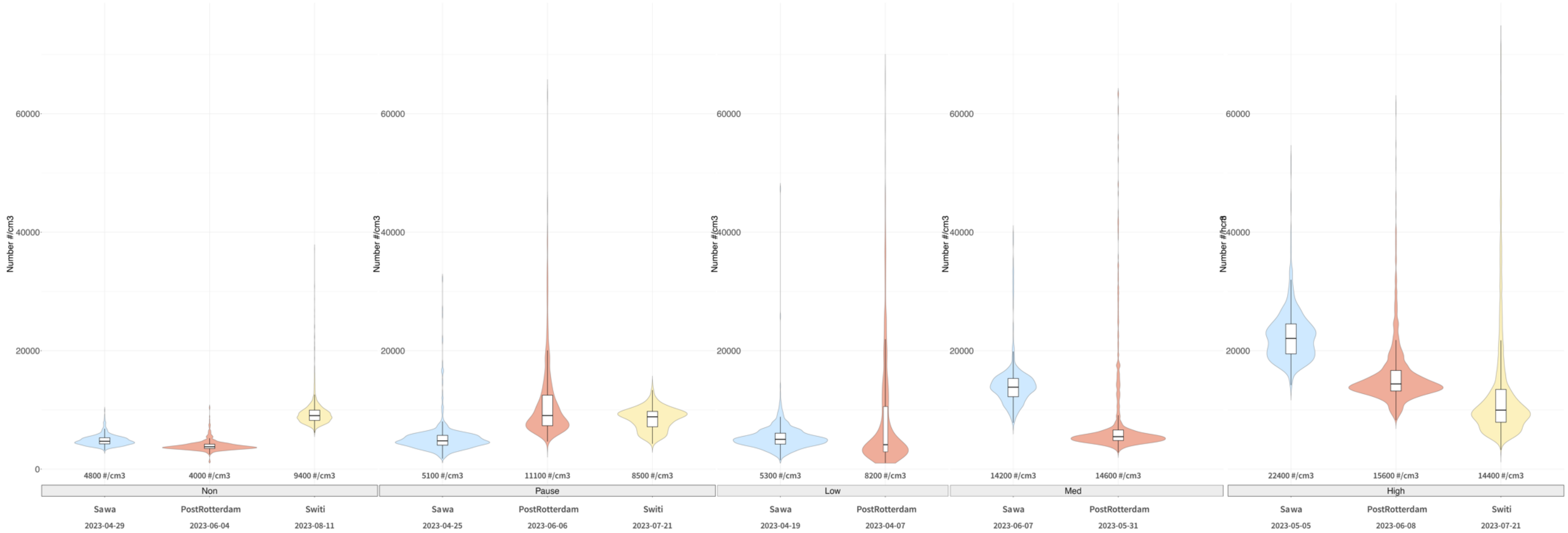


Figure 42. Violin plot comparison of UFP across the three construction sites Sawa, PostRotterdam and Switi.

Figure 42. After reviewing all the mean values across the three construction sites, the results are that Sawa produced the lowest mean UFP ambient concentrations during all five activities, showing its favourable ambient concentrations profile compared to PostRotterdam for all five activities. After comparing Sawa, PostRotterdam, and Siwit focused on high, medium, low and pause activities, Switi produced the lowest mean UFP ambient concentration. This observation emphasises the potential effectiveness of Sawa's and Switi's construction practices, materials, or other site-specific factors in mitigating UFP ambient concentrations despite varying construction scenarios. Further research can explore the mechanisms contributing to these lower emissions at the Sawa construction site.

Sawa, across all five activities (high activity, medium activity, low activity, work pauses, non-working periods), showed the lowest value, 10360 #/cm3 compared with PostRotterdam with a mean value of 10700 #/cm3.

Comparing Sawa, PostRotterdam and Switi, focusing on high, pause and non-active, Switi showed the lowest mean value of 9400 #/cm3, followed by PostRotterdam with the mean value of 11300 #/cm3 and Sawa 11600 #/cm3.

3.2.2 Black Carbon.

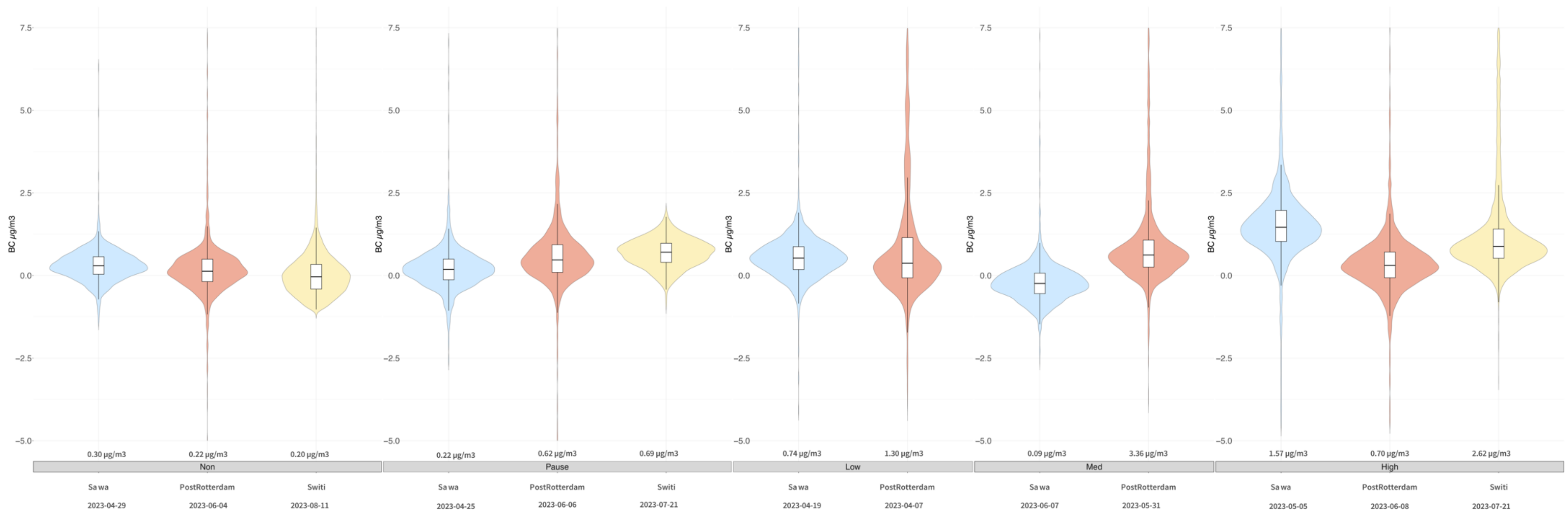


Figure 43. Violin plot comparison of BC across the three construction sites Sawa, PostRotterdam and Switi.

Figure 43. After reviewing all the mean values through the three construction sites, the results are that Sawa produced the lowest mean BC ambient concentrations during all five activities, showing its favourable ambient concentrations profile compared to PostRotterdam for all five activities. After comparing Sawa, PostRotterdam, and Siwit focused on high, low and pause activities, Switi produced the lowest mean BC ambient concentration. This observation emphasises the potential effectiveness of Sawa's and Switi's construction practices, materials, or other site-specific factors in mitigating BC ambient concentrations despite varying construction scenarios. Further research can explore the mechanisms contributing to these lower emissions at the Sawa construction site.

Sawa, across all five activities (high activityactivity, low activity, work pauses, non-working periods), showed the lowest value, 0.54 µg/ m^3, compared with PostRotterdam with a mean value of 1.24 µg/ m^3.

Comparing Sawa, PostRotterdam and Switi, focusing on high, pause and non-active, PostRotterdam showed the lowest mean value of 0.50 µg/ m^3, followed by Sawa with the mean value of 0.69 µg/ m^3 and Switi 1.17 µg/ m^3.

After reviewing all the mean values through the three construction sites, PostRotterdam showed the lowest mean black carbon emissions among the three construction sites under consideration, with an overall mean value of 0.50 µg/m^3.

3.4.3 Particulate Matter - $PM_{2.5}$

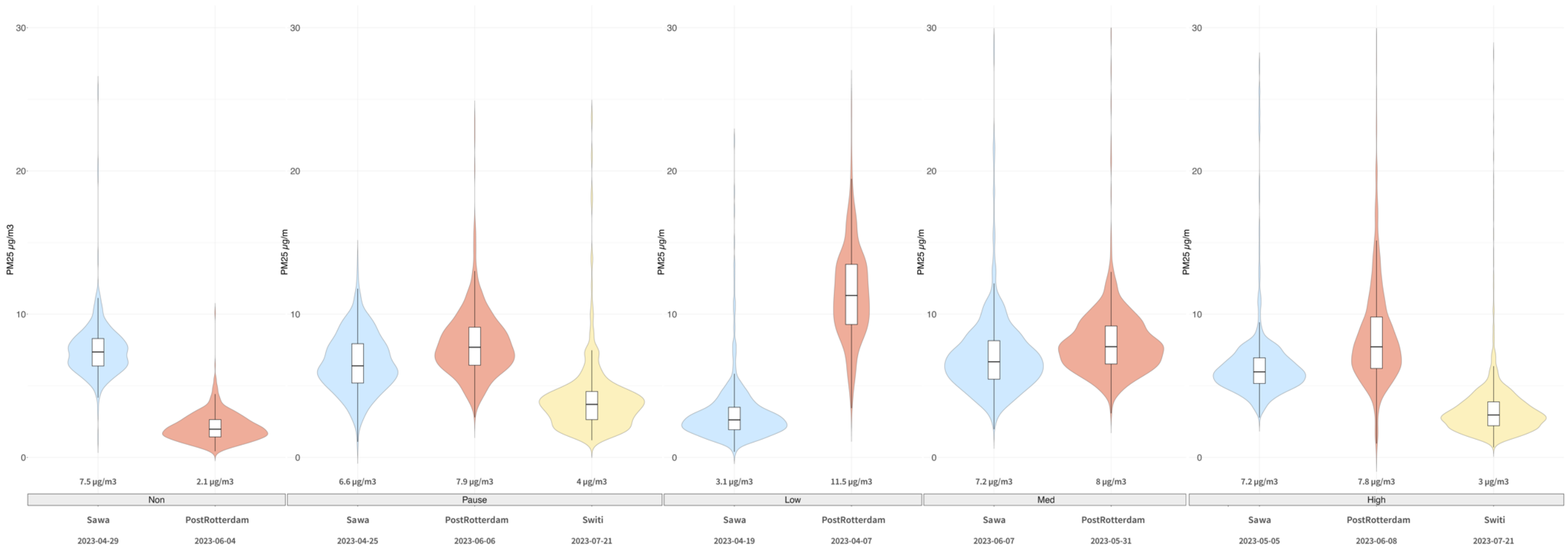


Figure 44. Violin plot comparison of PM2.5 across the three construction sites Sawa, PostRotterdam and Switi.

Figure 44. PostRotterdam consistently demonstrates higher overall mean $PM_{2.5}$ ambient concentrations than Sawa, even when accounting for specific high, medium, and pause activity levels. Switi, on the other hand, exhibits the lowest overall mean $PM_{2.5}$ concentration among these activity levels.

These comparative analyses offer valuable insights into the variations in $PM_{2.5}$ ambient concentrations among these construction sites. PostRotterdam consistently displays elevated mean $PM_{2.5}$ ambient concentrations relative to Sawa and Switi, regardless of the activity grouping.

In the comparison involving all activities at Sawa and PostRotterdam:
For Sawa (All Activities), the overall mean $PM_{2.5}$ ambient concentration results in an overall mean of 6.32 μg/m^3. For PostRotterdam (All Activities), an overall mean $PM_{2.5}$ concentration resulted in an overall mean of 7.44 μg/m^3. The results from this comparison indicate that PostRotterdam consistently exhibits higher overall mean $PM_{2.5}$ concentrations, signifying elevated $PM_{2.5}$ ambient concentrations across all construction activity levels compared to Sawa.

Furthermore, the comparison focused on high, and pause activities for Sawa, PostRotterdam, and Switi:
For Sawa (High, Pause Activities), the overall mean $PM_{2.5}$ ambient concentration resulted in an overall mean of 7.0 μg/m^3. For PostRotterdam (High, and Pause Activities), an overall mean $PM_{2.5}$ ambient concentration resulted in an overall mean of 8 μg/m^3. For Switi (High, and Pause Activities), the overall mean $PM_{2.5}$ ambient concentration resulted in an overall mean of 4 μg/m^3.

3.2.4 Particulate Matter - PM_{10}

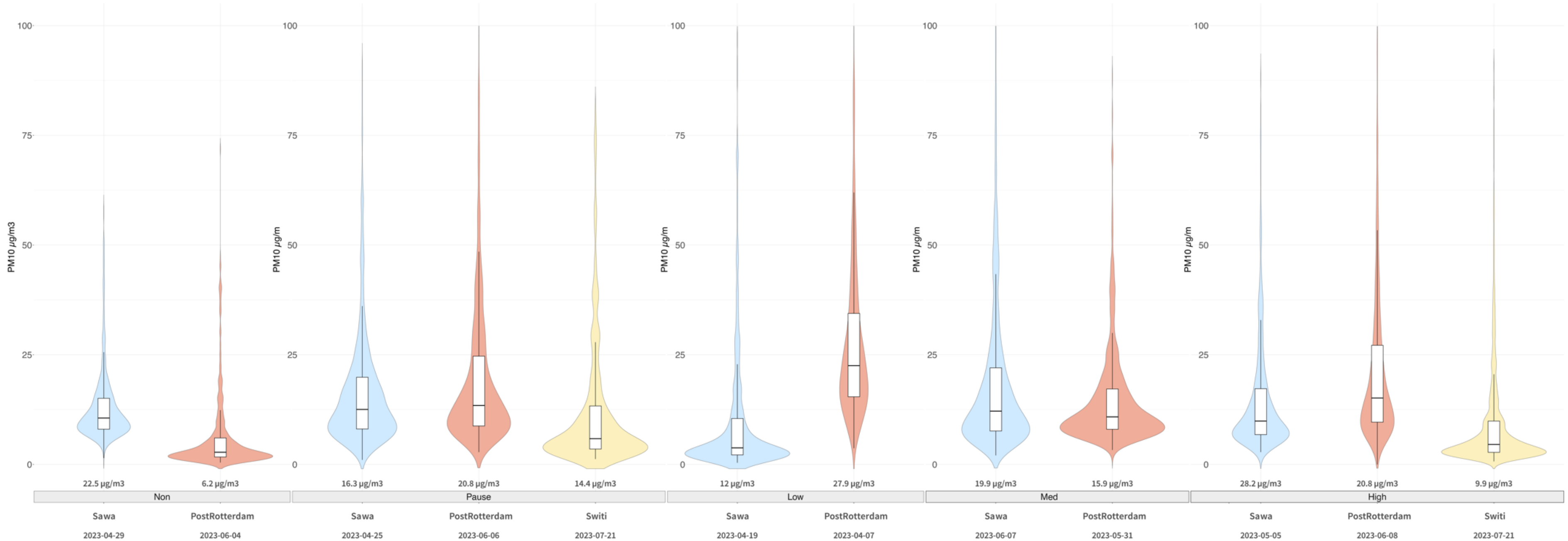


Figure 45. Violin plot comparison of PM10 across the three construction sites Sawa, PostRotterdam and Switi.

Figure 45. Sawa consistently demonstrates higher overall mean PM_{10} ambient concentrations than PostRotterdam, even when accounting for specific high, medium, and non activity levels. Switi, on the other hand, exhibits the lowest overall mean PM_{10} ambient concentration in relation of high activity levels. These comparative analyses offer valuable insights into the variations in PM_{10} ambient concentrations among these construction sites.

In the comparison involving all activities at Sawa and PostRotterdam:
For Sawa (All Activities), the overall mean PM_{10} ambient concentration results in an overall mean of 19.78 µg/m^3. For PostRotterdam (All Activities), an overall mean PM_{10} concentration resulted in an overall mean of 18.32 µg/m^3. The results from this comparison indicate that Sawa consistently exhibits higher overall mean PM_{10} concentrations, signifying elevated PM10 ambient concentrations across all construction activity levels compared to PostRotterdam.

Furthermore, the comparison focused on high, and pause activities for Sawa, PostRotterdam, and Switi:
For Sawa (High, Pause Activities), the overall mean PM_{10} ambient concentration resulted in an overall mean of 22.25 µg/m^3. For PostRotterdam (High, and Pause Activities), an overall mean PM_{10} ambient concentration resulted in an overall mean of 20.8 µg/m^3. For Switi (High, and Pause Activities), the overall mean PM10 ambient concentration resulted in an overall mean of 22.55 µg/m^3.

3.3 Emissions calculations- Black Carbon emissions and Particulate Matter emissions from on-road and off-road machinery.

As mentioned in chapter 2. Methodology, Table.20 shows the result of the emissions calculation for BC and PM from the on-road and off-road machinery observed in the three construction sites, Sawa, PostRotterdam and Switi. The formula results present the emissions per year for BC and PM. To calculate emissions, the following formula was used:
Emission = Number of machines x Hours x Load x Power x Emission factor x TAF factor

Site	Date	Activity	Machinery	Model	No. Machines	Engine(kW)	Hours year	TAF PM	Load (tn)	EF UFP (g/kWh)	EF BC (mg km^{-1})	EF PM(g/kWh)	Emissions UFP (gm)	Emissions BC (gm)	Emissions PM(gm)
	23/03/2023	High activity	Drilling rig	Woltman THW 7528-D	1	562	466	1.2300	10	nda	1.7	15.6	nda	5476162	50251837
	23/03/2023		Excavator	Hitachi EX8	1	6	1135	0.8900	10	nda	1.7	1	nda	103035	60609
	23/03/2023		Excavator	Kobelco hybrid sk 210h	1	112	1092	0.8900	10	nda	1.7	0.3	nda	1850460	326552
	23/03/2023		Concrete mixer	DAF CF FAD mixer	1	330	606	1.9700	10	nda	1.7	1.4	nda	6697330	5515448
	23/03/2023		Concrete pumps	SPTM 2000	1	129.5	606	1.9700	10	nda	1.7	0.3	nda	2628195	463799
	28/03/2023	High activity	Drilling rig	Woltman THW 7528-D	1	562	466	1.2300	10	nda	1.7	17	nda	5476162	54761617
	28/03/2023		Excavator	Kobelco hybrid sk 210h	1	112	1092	0.8900	10	nda	1.7	0.3	nda	10304	326552
	28/03/2023		Crane	Kobelco 7250-2	1	247	990	1.2300	10	nda	1.7	0.5	nda	5113122	1503860
	05/04/2023	High activity	Excavator	Kobelco hybrid sk 210h	1	112	1092	0.8900	10	nda	1.7	0.3	nda	1850460	326552
	05/04/2023		Crane	TADANO ATF 70-4	1	320	990	1.2300	10	nda	1.7	1.4	nda	10304	5455296
	05/04/2023		Truck	Scania p320	1	239	1641	1.2300	10	nda	1.7	0.5	nda	8200881	2412024
	11/04/2023	High activity	Excavator	Kobelco hybrid sk 210h	1	112	1092	0.8900	10	nda	1.7	0.3	nda	1850460	326552
	11/04/2023		Crane	Liebherr LTM 1250	1	400	990	1.2300	10	nda	1.7	1.4	nda	10304	6819120
	18/04/2023	Medium activity	Excavator	Kobelco hybrid sk 210h	1	112	1092	0.8900	10	nda	1.7	0.3	nda	10304	326552
	02/05/2023	Medium activity	Excavator	Kubota - KX019-4	1	11.8	1092	0.8900	10	nda	1.7	1	nda	10304	114682
	05/05/2023	High activity	Lorry Truck	DAF DF lorry	1	239	1641	1.2300	10	nda	1.7	0.5	nda	10304	2412024
	05/05/2023		Excavator	Kubota - KX019-4	1	11.8	1092	0.8900	10	nda	1.7	1	nda	194959	114682
	07/06/2023	Medium activity	Lorry Truck	DAF XF lorry	1	239	1641	1.2300	10	nda	1.7	0.5	nda	8200881	2412024
PostRotterdam	26/05/2023	Medium activity	Crane	Minotaur MRT 2150+	1	115	990	1.2300	10	nda	1.7	0.3	nda	2380604	420107
	30/05/2023	High activity	Crane	Minotaur MRT 2150+	1	115	990	1.2300	10	nda	1.7	0.3	nda	2380604	420107
	30/05/2023		Concrete mixer	Man TGS 35.400	1	294	606	1.9700	10	nda	1.7	0.5	nda	5966712	1754915
										nda	1.7				
	31/05/2023	High activity	Crane	Minotaur MRT 2150+	1	115	990	1.2300	10	nda	1.7	0.3	nda	2380604	420107
	31/05/2023		Concrete mixer	Man TGS 35.400	1	294	606	1.9700	10	nda	1.7	0.3	nda	5966712	1052949
	06/06/2023	High activity	Crane	Minotaur MRT 2150+	1	115	990	1.2300	10	nda	1.7	0.3	nda	2380604	420107
	06/06/2023		Concrete mixer	Man TGS 35.400	1	294	606	1.9700	10	nda	1.7	0.5	nda	5966712	1754915
	06/06/2023		Lorry truck	MAN D3876	1	485	1641	1.2300	10	nda	1.7	1.4	nda	16641955	13705140
	08/06/2023	High activity	Crane	Minotaur MRT 2150+	1	115	990	1.2300	10	nda	1.7	0.3	nda	2380604	420107
	08/06/2023		Concrete mixer	Man TGS 35.400	1	294	606	1.9700	10	nda	1.7	0.5	nda	5966712	1754915
	08/06/2023		Lorry truck	MAN D3876	1	485	1641	1.2300	10	nda	1.7	1.4	nda	16641955	13705140
	08/06/2023		Concrete pump	Cifa k60h	1	375	606	1.9700	10	nda	1.7	1.4	nda	7610603	6267555
Switi	12/07/2023	High activity	Generator	100 kVA generator	1	100	606	1.2300	10	nda	1.7	0.3	nda	1267146	223614
	12/07/2023		Diesel Crane	Spierings SK2400-R	1	187	990	1.2300	10	nda	1.7	0.5	nda	3871068	1138550
	14/07/2023	High activity	Generator	100 kVA generator	1	100	606	1.2300	10	nda	1.7	0.3	nda	1267146	223614
	14/07/2023		Diesel Crane	Spierings SK2400-R	1	187	990	1.2300	10	nda	1.7	0.5	nda	3871068	1138550
	14/07/2023		Lorry Truck	DAF XF lorry	1	390	1641	1.2300	10	nda	1.7	1.4	nda	13382191	11020628
	21/07/2023	High activity	Generator	100 kVA generator	1	100	606	1.2300	10	nda	1.7	0.3	nda	1267146	223614
	21/07/2023		Diesel Crane	Spierings SK2400-R	1	187	990	1.2300	10	nda	1.7	0.5	nda	3871068	1138550

Table 20. Black carbon emissions and particulate matter emissions from machinery. **nda=no data available*

Emission = Emission or fuel consumption (grams).

Number of machines = the number of machines of a specific year of manufacture with emission factors appropriate to the year of manufacture.

Hours = the number of hours that this machine type is used on average per year (hours).

Load = Load the part of the full power of this machine type that is used.

Power = The average engine power for each machine type (kW).

Emission factor = the average emission factor or specific fuel use associated with the year of manufacture (emission standard) (g/kW.hour).

TAF factor = adjustment factor on the average emission factor in connection with the deviation of the average user application from this machine type due to varying (transient) power demand.

.3.3.1 Emissions calculations.

Black Carbon from on-road and off-road machinery

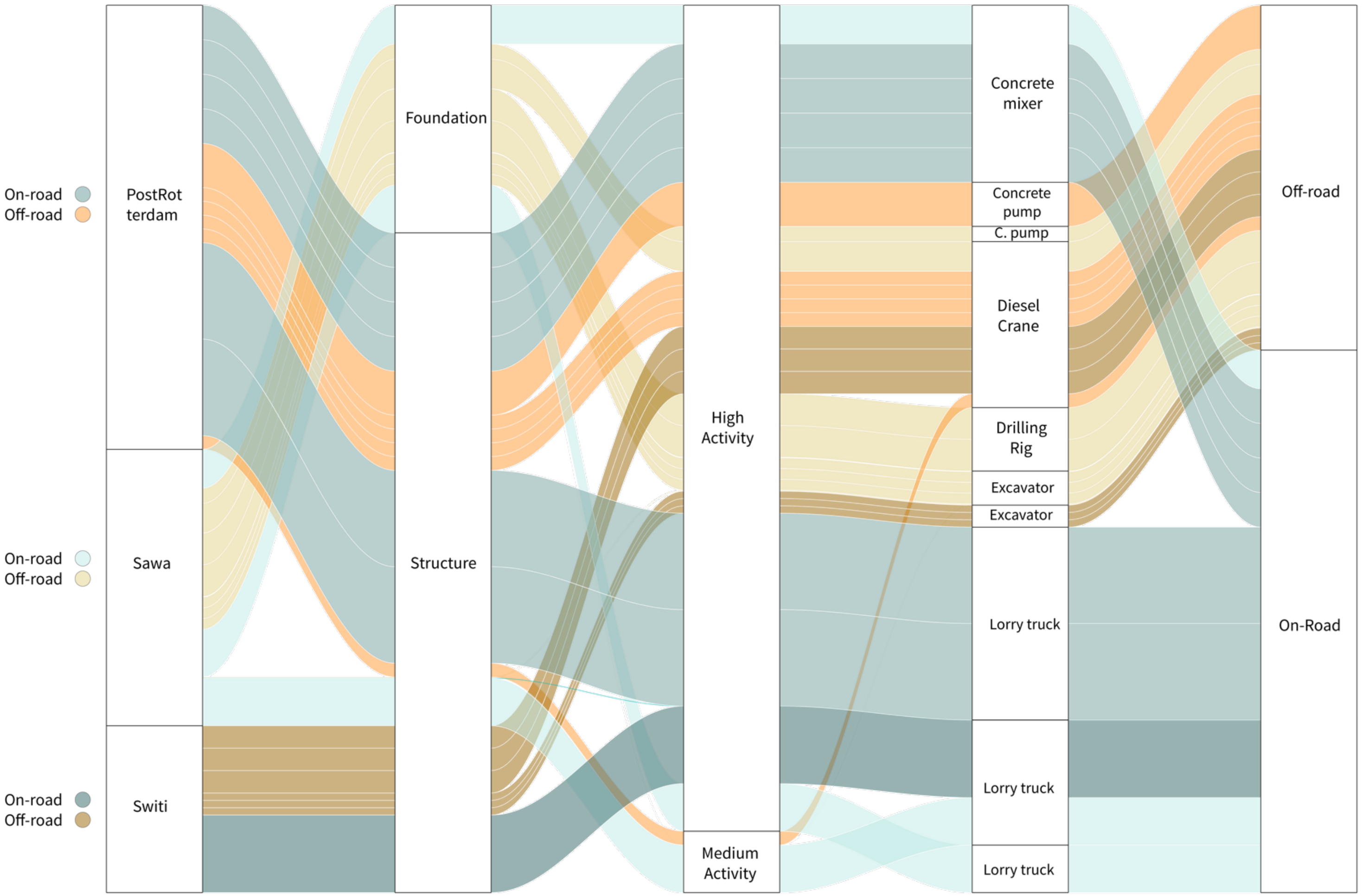


Figure 46. Alluvial diagram shows BC emissions from on-road and off-road machinery.

Figure 46., visualises black carbon emissions from on-road machinery versus off-road machinery across variables such as structure, activity, and type of machinery. This graph illustrates which groups of road and off-road vehicles emit more black carbon particles during foundation and structure activities, where high and medium activities are distinguished, depending on the machinery observed in each work. According to the graph, Structure-activity has a more significant influence on the emission of black carbon particles compared to the foundation and is reflected in road machinery. Compared to the three construction sites, PostRotterdam generates more emissions than Switi and Sawa. Regarding road and off-road machinery, according to the graph, is it possible to observe how off-roading in PostRotterdam has the most influence on black carbon emissions. When it comes to off-road machinery, Switi has more influence on black carbon emissions.

3.3.2 Emissions calculations.

Particulate Matter from on-road and off-road machinery.

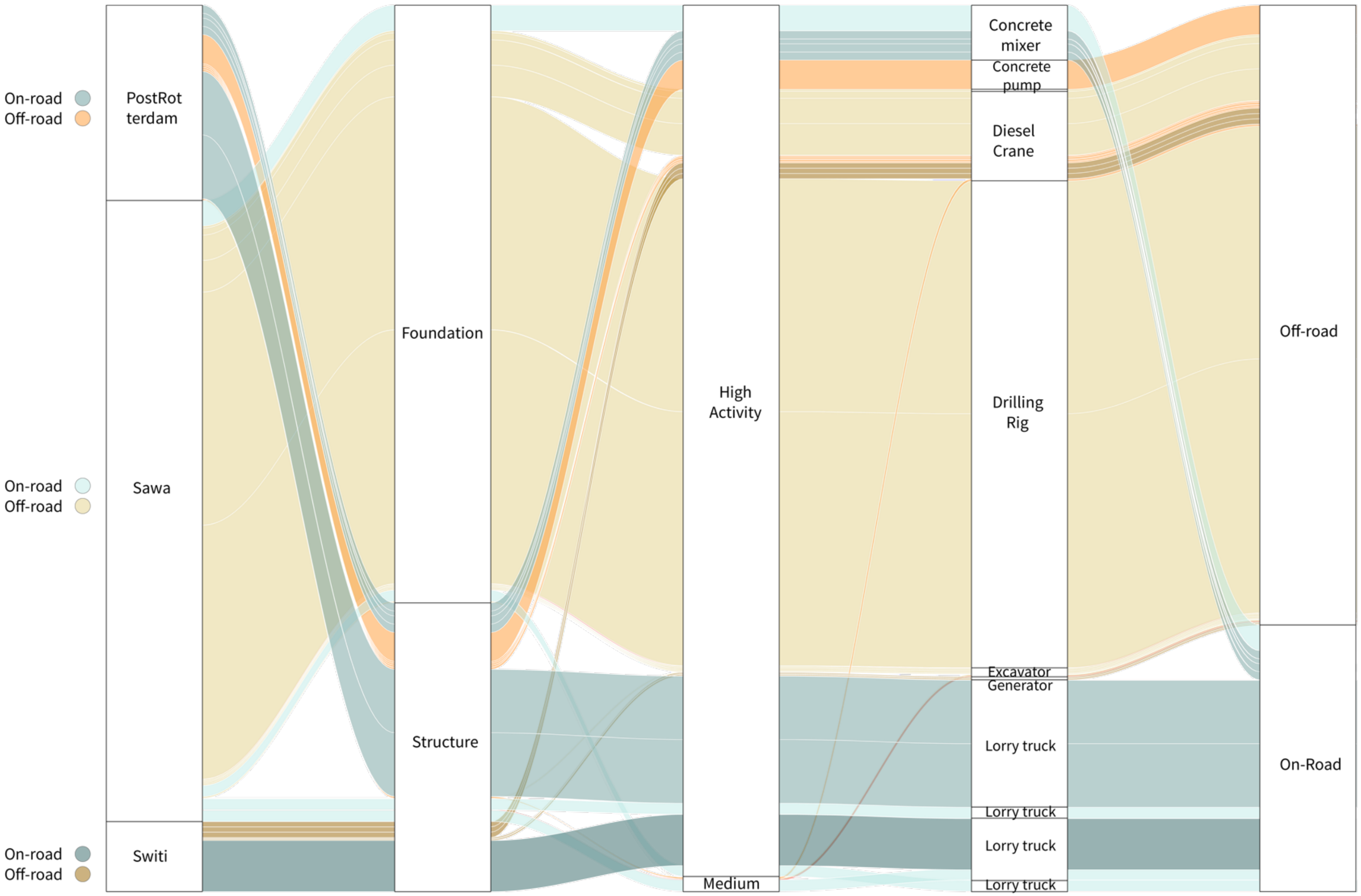


Figure 47. Alluvial diagram shows PM emissions from on-road and off-road machinery.

Figure 47., visualizes particulate emissions from on-road versus off-road machinery across variables such as structure, activity, and type of machinery. This graph illustrates which groups of road and off-road vehicles emit particulate matter particles during foundation and structural activities of high and medium activities, depending on the machinery observed in each work. According to the graph, off-road machinery has a more significant influence on the emission of suspended particles than road machinery. Unlike the three construction sites, Sawa generates more emissions, especially during foundation activities, followed by PostRotterdam and Switi. Regarding on-road machinery, PostRotterdam emits more Particulate matter, compared to the other two construction sites, during structure-activity.Comparing foundation and structure, it is observable that foundation is the process that produces the most emissions of Particulate matter and its influence on off-road machinery; in terms of structure, PostRotterdam has more influence as it is a conventional structure, which is why it requires more on-road machinery than off-road compared to Sawa and Switi.

4. Discussion:

The next chapter dives into the connections, importance, and essential discoveries discovered in this research, taking a closer look at how construction activities, specifically comparing cross-laminated timber to traditional construction methods, relate to the air we breathe and the emissions from on-road and off-road machinery. We note a strong link between construction activities and higher levels of pollutants.

4.1 Main findings

The literature review revealed a lack of regulation for the levels of ultrafine particles (UFP) and black carbon (BC) in the Netherlands, which presents an opportunity to carry out more studies on the distribution of ambient concentrations around construction sites to facilitate the establishment of reasonable maximum ambient pollution levels of UFP and BC arising from on-road and off-road construction machinery. This is essential since, as the literature review has also shown, UFP particles affect public health since, due to their size, they can be absorbed by the blood and transported by the circulatory system, causing problems in the lungs, liver, heart, and brain (Traboulsi et al., 2017). BC particles also contribute to health problems and global warming (Chikri & Wetzels, 2020).

Sampling of ambient concentrations of UFP, BC, $PM_{2.5}$ and PM_{10} at three construction sites (Sawa, PostRotterdam and Switi) allowed a comparison of cross-laminated timber construction and conventional construction, and there was no clear correlation between particulate levels and the type of construction. However, with the indicative calculation of BC and PM emissions, it is possible to identify which machinery is associated with the highest emissions. Firstly, it can be distinguished that the calculation shows that BC emissions are higher in on-road versus off-road machinery, with concrete mixer and lorry trucks the most influential, in the case of PM emissions, off-road compared to on-road, especially during the foundation stage, with the Drilling rig causing the emissions. During the structure stage, diesel cranes and excavators produced more PM emissions.

Sawa (CLT construction) had the lowest mean concentrations of UFP and BC during various activities, followed by PostRotterdam (conventional) and Switi (CLT, with diesel generator for crane). PostRotterdam exhibited the lowest mean BC concentrations but consistently had higher overall mean $PM_{2.5}$ concentrations than Sawa and Switi, most likely due to its location in central Rotterdam with substantial other nearby sources. Sawa had consistently higher overall mean PM_{10} concentrations compared to PostRotterdam, probably at least in part due to the windier conditions next to the Maas River, lofting more dust from the construction site. These findings suggested potentially more effective practices or materials in mitigating particle concentrations at Sawa and Switi than at PostRotterdam. Switi was located at the intersection of two roads, which may provide additional sources of traffic-emitted particulate matter from both roads. Taking these other location and meteorological factors into account, nevertheless, we find that construction sites where CLT is used (Sawa and Switi) have lower ambient concentration levels than conventional construction (PostRotterdam). This suggests that using CLT in construction may reduce air pollution in urban areas. Furthermore, it highlights the importance of considering the specific location and surrounding environment when assessing the impact of construction activities on air quality.

When the estimates of BC and PM emissions from on- and off-road machinery across all sites are compared (Table 20), it provides a comprehensive comparison of black carbon and particulate emissions from both on- and off-road machinery at construction sites. The table illustrates patterns based on structure, activity levels, and machinery types. In particular, the influence of structural activity on black carbon emissions is more pronounced in road machinery, while off-road machinery plays a more significant role in particulate matter emissions. PostRotterdam consistently generates higher emissions than Switi and Sawa, and off-road use in PostRotterdam contributes significantly to high black carbon levels. On the other hand, Sawa outperforms other sites in particulate matter emissions, particularly during foundation activities. Additionally, PostRotterdam exhibits higher emissions from road machinery during structure-related tasks, in line with its conventional construction practices. This integrated analysis provides valuable information on emissions dynamics, facilitating specific strategies to mitigate environmental impacts in construction activities.

After examining the machinery observed at the three construction sites, it is evident that certain types of construction equipment are associated with higher contaminant concentrations. In particular, drilling rigs, excavators, cranes and concrete mixers frequently appear in phases of high activity, contributing to high PM and BC emissions. For example, figures indicate that the Woltman THW 7528-D drilling rig, the Hitachi EX8 excavator, the Kobelco hybrid sk 210h excavator and several cranes consistently generate significant emissions. To address environmental concerns and prioritise cleaner construction practices, it would be recommended to focus on electrifying or employing emissions reduction technologies for types of machinery or similar. At the same time, have initiatives aimed at the electrification of construction sites where possible. An example of the lack of this initiative is in the case of Switi, where it was not electrified and, therefore, used a diesel crane. However, Switi is a CLT-based project where it is shown that it is a more sustainable product to have electrified and be able to have access to an electric crane; it could have a lower impact in terms of the emissions studied. Electrifying construction sites can significantly reduce emissions and create a more sustainable construction industry. By using electric cranes instead of diesel ones, projects like Switi can minimise their environmental impact and promote using renewable energy sources. Additionally, implementing initiatives for the electrification of construction sites can lead to cost savings in the long run by reducing fuel consumption and maintenance costs associated with diesel machinery.

The fact that Sawa and Switi have lower particulate matter levels and employ cross-laminated wood than PostRotterdam indicates that decisions concerning building methods can affect the quality of the surrounding air. Increased awareness of this information might have an impact on Rotterdam's and the Netherlands' building practices, leading to a reassessment of materials and techniques to better promote environmental sustainability and public health.

Socially, the research highlights the potential health risks associated with construction activities, particularly the elevated concentrations of UFP and BC, based on the literature review. Since Sawa and Switi show lower mean concentrations, communities and policymakers have the opportunity to consider taking more effective measures to protect public health. Furthermore, the impact of off-road machinery on BC and PM emissions underlines the need for stricter regulations and environmentally friendly practices in the construction industry. This could lead to a push for more sustainable building practices, simultaneously addressing global warming and public health concerns.

This research has the potential to catalyse changes in the understanding of the scientific community, architects, builders, industrial designers, and politicians, among others, about construction-related air quality problems, influence construction practices on a local and national scale, and guide policymakers toward implementing regulations that prioritise both environmental sustainability and public health.

4.2 Recommendations and Policy Integration.

Air Quality:

To improve air quality standards during construction activities, we propose the implementation of strict emission standards targeting specific equipment commonly used in construction sites. This policy would focus on high-emission sources, for example, drilling rigs, excavators, cranes, and concrete mixers; these machines could set emission limits for ultrafine particles, black carbon, particulate matter, and other pollutants.

These emission standards can function as clear benchmarks, establishing a framework for acceptable pollutant levels and setting explicit expectations for air quality improvement in construction operations.

Regulatory bodies would monitor and enforce compliance to ensure effective implementation. Regular assessments and audits of construction sites would verify adherence to the established emission standards. Non-compliance could result in penalties, fines, or even project shutdowns, creating a strong incentive for construction companies to invest in cleaner technologies.

At the same time, establishing a cap on emissions from construction sites. This approach incentivises construction companies to adopt cleaner technologies and practices throughout their operations throughout a project, fostering a holistic reduction in emissions. This dual-policy framework not only addresses the immediate environmental impact of construction activities but also promotes the long-term sustainability of the construction industry.

Societal Recommendations:
Protect public health during construction, especially in crowded cities such as Rotterdam and Amsterdam. This may include installing air measuring tools, temporary relocation options for residents susceptible to respiratory, heart and cancer conditions, and regular health check-ups for those living near construction sites. Stakeholders should foster collaboration between construction companies, local authorities, and residents. Create spaces where residents can freely share concerns and construction companies can receive feedback to improve.

Technical Recommendations:
Regulatory bodies should establish and enforce standards to regulate UFP and BC levels in the Netherlands, especially in construction zones where emissions are very high. This will contribute to safeguarding public health and reducing environmental impact. Standard monitoring and reporting protocols should be established to ensure construction projects have accurate data. This involves measuring distances, checking the weather, and recording details about machines like maintenance and year made. The use of sustainable materials in construction projects should be promoted. For example, to promote the use of cross-laminated timber (CLT), developers and builders should be offered incentives, subsidies, or tax breaks if they use eco-friendly materials like CLT. This promotes and encourages sustainable construction practices.

Cost-Benefit Analysis for Resource Allocation:
To guide resource allocation effectively, cities should conduct comprehensive cost-benefit analyses. Taking Switi as an example, where construction activities involve generators and cranes, a city could assess the initial investment in electric infrastructure against the long-term benefits. For instance, the 100 kVA generator and Spierings SK2400-R crane in Switi could be evaluated for their emissions and compared to cleaner alternatives. This data-driven approach ensures that policies are strategically implemented, maximising their impact on air quality improvement relative to the invested resources. It encourages a shift towards more sustainable and environmentally conscious construction practices in Switi.

Architectural and Urban Recommendations:
To promote cross-laminated timber (CLT), use mid- and high-rise buildings and add guidelines to architectural design standards. Showcase CLT's positive impact on the environment, including reducing air pollution and supporting sustainable cities. In the case of urban planning, integrating air quality considerations into urban planning processes Assess how construction affects air quality and plan cities to reduce exposure to pollution. Architects must prioritise sustainability and air quality by exploring and implementing innovative construction practices. One way to reduce the environmental impact of construction is by using modular methods and green design features, such as green roofs. As a recommendation at the urban level, the study for pre-electrification of the construction site should be conducted based on the needs and dimensions of the project. This would help minimise the use of fossil fuel-powered machinery and reduce air pollution during the construction phase. Additionally, implementing strict regulations and guidelines for construction sites, such as proper waste management and dust control measures, can further contribute to improving air quality in cities.

Electric Power Infrastructure Provision:
Cities should actively facilitate the transition to cleaner construction practices by strategically investing in infrastructure, focusing on enabling electric cranes. For instance, in Switi, where high-activity structural work involves generators and cranes, a city could collaborate with construction companies to establish dedicated electrical grids or provide temporary power stations. This ensures that machinery like the Spierings SK2400-R crane can access a reliable electrical power supply. Such measures significantly reduce emissions and foster a shift towards sustainable construction practices.

Innovation Recommendations:
Encourage construction companies to use and invest in eco-friendly technologies. Companies that reduce air pollution during construction can get tax credits, subsidies, or grants. Construction companies should work with research institutions to improve construction practices to evaluate and enhance environmental performance. Encourage the sharing of data, research findings, and best practices to drive innovation in the industry.

4.3 Limitations of the research.

This study is subject to several limitations, which are discussed below.

Contextual limitations.

The context and surroundings of the study sites were a limitation to data interpretation. Sawa is located next to Nieuwe River, in a very windy area; PostRottedam is in the city centre, surrounded by an extensive array of activities; and Switi is located next to the intersection of roads S112 and A9 but outside the Amsterdam urban core; these conditions can affect the ambient concentrations of UFP, BC, $PM_{2.5}$ & PM_{10}. The proximity to busy roads and busy areas in the surroundings of the study sites may introduce additional sources of air pollution. Furthermore, the streets' configuration and buildings' height may also influence airflow patterns and contribute to localised variations in pollutant concentrations.

The need for more information regarding machinery maintenance conditions and their manufacture year is a significant limitation of this research. Understanding these details is crucial for accurately calculating emissions and future data validation (UFP, BC, $PM_{2.5}$ and PM_{10}). With this information, it is easier to determine the accuracy and reliability of the estimated emissions, as machinery maintenance and age can significantly impact emission levels. Knowing the manufacture year can help identify older equipment that may be more prone to higher emissions, contributing more to pollution levels. With more detailed knowledge of emissions-relevant characteristics, the emissions estimates shown in Table 20 could be compared to ambient levels measured at each site to check whether the site-specific relative measured ambient concentrations align with the emissions estimates, i.e., the site with the most significant estimated emissions has the higher ambient concentrations. In this way, observations of concentrations can be used to qualitatively evaluate the completeness and accuracy of emissions models.

Distance from emitters plays a critical role in interpreting comparisons of ambient concentrations (UFP, BC, $PM_{2.5}$, PM_{10}). As emissions disperse over distance, their concentration decreases, making it challenging to compare across sites if measurements are made at different distances. Therefore, it is crucial to strategically place monitoring stations at appropriate distances to ensure reliable and comparable data collection. Those who want to use this construction monitoring data must understand that we measure ambient concentrations, not emissions. These concentrations are related to the emissions but also modified by dispersion and background values from other nearby sources of pollutants.

Communication limitations.

Effective communication is essential for planning visits, obtaining insights into machinery work schedules, and conducting structured interactions with contractors. With clear and efficient communication, it becomes easier to coordinate efforts and gather necessary information for emission monitoring. This can lead to delays in data collection and potential inaccuracies in assessing emission levels. Effective communication also allows for disseminating essential findings and recommendations to stakeholders, ensuring appropriate actions can be taken to mitigate emissions.

Meteorological limitations.

Weather conditions, including rain, ambient temperature, and airspeed, impose practical limitations on fieldwork. These environmental variables can restrict the days and hours available for data collection, potentially extending the research timeline. Furthermore, variations in weather conditions can also impact the representativeness of concentration measurements. For example, heavy rain can wash away pollutants, leading to lower observed concentrations from the same level of emissions. Therefore, carefully considering and monitoring weather conditions are crucial for accurate data analysis.

Duration limitations.

The extended duration of construction projects spanning several years is a temporal limitation. Managing resources and maintaining research continuity over such extended periods can be logistically challenging. Changes in technology and regulations over time may also impact the emissions, impacting the concentration measurements collected during long-term construction projects.

4.4 Implications for Research and Society/Relevant Stakeholders.

The study examines the environmental emissions of constructing skyscrapers in Rotterdam and Amsterdam. The sampling results for Ultra Fine Particles (UFP), Black Carbon (BC), $PM_{2.5}$, and PM_{10} from locations such as Sawa, PostRottedam, and Switi offer valuable information for a diverse audience, including construction companies, architects, urban planners, industrial designers, researchers, and policymakers. This research holds significant implications for the research community and societies. It allows construction companies to reassess their methods by highlighting the potential advantages of integrating cross-laminated timber (CLT) and reducing the use of diesel-powered equipment by electrification or emissions scrubbing to mitigate air emissions. Architects and urban planners stand to gain valuable insights into sustainable building materials, influencing their future designs. Policymakers can leverage this information to formulate more stringent regulations for construction machinery and advocate for environmentally friendly practices.

The findings emphasise the necessity of considering the specific location and surrounding environment when evaluating the impact of construction activities on air quality. Ultimately, we hope this research can guide informed decision-making within the construction industry, aligning practices with environmental sustainability and public health.

Moreover, the research highlights the importance of interdisciplinary research in tackling the intricate environmental challenges present in the urban environment. The collective insights from this study contribute to a broader understanding of sustainable construction practices, fostering a holistic approach to addressing environmental concerns in urban development.

4.5 Reflection on the Interdisciplinarity of the Research.

This research points out an interdisciplinary approach spanning environmental science, construction engineering, meteorology, and data science, integrating diverse fields to result in an integral understanding of environmental emissions while constructing high-rise buildings. Such interdisciplinarity sets a precedent for effectively addressing intricate environmental challenges in urban settings, emphasising the importance of collaboration among researchers, construction companies, and government agencies.

This study models how different disciplines can unite to monitor emissions and formulate sustainable construction practices. The collaborative effort showcased in this research demonstrates the significance of interdisciplinary approaches in tackling multifaceted issues and devising comprehensive solutions.

Building on this foundation, future interdisciplinary work can draw inspiration from integrating environmental sciences, construction engineering, meteorology, and data science. This collaborative research can offer an exemplary understanding of environmental emissions and their implications while constructing high-rise buildings in urban centres. Additionally, it can serve as a conduit for combining various techniques and knowledge to effectively monitor Ultra Fine Particles (UFP), Black Carbon (BC), and PM (2.5&10) emissions.

Moreover, the study highlights the necessity for ongoing collaboration between researchers, construction companies, and government agencies to foster the development and implementation of sustainable construction practices. The interplay between these disciplines is vital for steering the complexities of environmental challenges and working towards holistic solutions.

4.6 Future Research Directions.

This research lays a solid foundation for future investigations in several crucial areas. Firstly, there is potential for a long-term, extensive study to monitor environmental emissions while constructing high-rise buildings continuously. This approach would contribute to building a more diverse dataset and creating an inventory of machinery usage, offering a comprehensive understanding of the long-term impact. As mentioned above, the potential to continue studying UFP and BC emissions related to the construction industry and to be able to design models for the development of standard levels is in the case of $PM_{2.5}$ and PM_{10}, not only in terms of environmental concentrations but also in on-road and off-road machinery used in construction.

Secondly, technological advancements present an opportunity for developing a CityScanner version 2.0. This upgraded version could include measurements of additional pollutants such as NO2, expanding the scope of environmental monitoring beyond Ultra Fine Particles (UFP), Black Carbon (BC), and PM (2.5&10). This technological enhancement would provide more information on combustion-related pollution at construction sites.

Thirdly, compared to conventional construction materials, exploring cost-benefit-emission analyses based on biobased materials, including Cross-Laminated Timber (CLT), could offer valuable insights into economic and environmental sustainability. This avenue of research can guide decision-making in construction practices, promoting more eco-friendly choices.

Lastly, future research could examine the evolution of construction techniques within the urban context. This exploration could lead to the creation of new environmental regulations aimed at fostering sustainable and healthier cities. By considering the challenges and opportunities presented by high-rise buildings, this research direction aims to shape the future of construction practices and contribute to ongoing efforts in environmental impact mitigation.

5. Conclusions.

In conclusion, this research questions how Rotterdam's architecture, construction practices and air quality highlight the multifaceted challenges the construction industry poses to the environment and public health. Luce Irigaray's philosophical perspective is an emotional scene, emphasising the need for architectural responsibility towards solid, vegetative, and aqueous elements, especially in climate change and air quality crises.

The direct and indirect impact of the construction industry on air quality, through emissions of Ultrafine Particles (UFP), Black Carbon (BC), $PM_{2.5}$ and PM_{10}, requires a paradigm shift towards sustainable practices. Rotterdam's commitment to reducing air polluting emissions aligns with the urgent global need. The findings accentuate the potential of bio-based materials, particularly cross-laminated timber (CLT), and diesel equipment's electrification or emissions scrubbing to mitigate air pollution associated with high-rise construction.

The research examines the delicate relationship between construction machinery and emissions, distinguishing between on- and off-road sources. Disparities in emissions levels between construction sites highlight the influence of location, traffic, and environmental conditions. The call for stricter regulations and environmentally friendly practices in the construction industry resonates as machinery emerges as a significant contributor to air pollutants.

From the social point of view, the study highlights the health risks related to construction activities, highlighting the need for proactive measures to safeguard workers' health related to the construction industry and public health. The broader implications extend to architects, builders, policymakers, and the community, urging collective efforts to address the environmental and health impacts of construction decisions.

The research outlines avenues for future research, including long-term environmental monitoring, technological advances for comprehensive pollutant measurement, and cost-benefit and emissions analysis of bio-based materials. The exploration of construction techniques in urban contexts aims to shape policies that promote sustainable and healthier cities.

This research catalyses transformative change, driving a revaluation of building practices and their impact on air quality. By considering the contributions of UFP, BC, $PM_{2.5}$, and PM_{10} and the influence of on- and off-road machinery, the study advocates a holistic approach to construction practices. The goal is to create a cleaner, healthier, and more sustainable urban environment in Rotterdam and as a model for construction practices throughout the Netherlands.

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