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Real-time Estimation of Construction Particulate Matter for Advanced Environmental Monitoring

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Real-time Estimation of Construction Particulate Matter for Advanced Environmental Monitoring

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Real-time Estimation of Construction Particulate Matter for Advanced Environmental Monitoring

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ABSTRACT

Real-time Estimation of Construction Particulate Matter for Advanced Environmental Monitoring

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The predicament of excessive dust pollution, otherwise referred to as particulate matter (PM), represents a notable concern within the construction industry, imparting significant detriment to both construction workers and nearby residents. To solve the uprising issues, two main methods have been applied at the sites, PM monitoring with sensors and PM reduction planning. However, the current sensor monitoring method is restricted to only monitoring PM concentrations at limited site locations and the PM mitigation strategies typically involve the deployment of substantial volumes of water, which are employed inefficiently to precipitate the particulates. Likewise, many researches were introduced to improvise the current problems of managing construction site PM.

Many researches focused on developing the sensors, reducing the cost and weight for cost-efficiency and easier installment at the sites. Despite the development of sensors, allowing more sensor installment throughout the site at a cheaper cost, many areas still remained unmeasured when utilizing only sensors. Therefore, researchers also focused on estimating PM concentrations at certain areas using spatial interpolation methods, which enabled to estimate PM of desired region with only few sensor measured values. However, though there exists an array of approaches for large-scale PM estimation, such as city or country levels, the inconsistent behaviors of PM movement present considerable challenges in accurate surveillance and management of PM within relatively smaller scales, like construction sites. The complex characteristics of construction work hinder the real-time monitoring of PM and the determination of specific periods of increased PM dispersion, which are essential for timely preventative measures. Given the complexities, the present research seeks to develop a simple spatial interpolation model explicitly engineered for PM in construction sites. This model merges an innovative weighting system, which takes into consideration both the wind, the main meteorological factor affecting PM, and the proximity to sensors.

To maximize the usability and economic costs, a sensing module was invented, which includes a sufficient low-cost dust sensor to assist the success of this research. Analyzing the characteristics and distributions of PM, the study employs the PM-fit inverse distance weighting (IDW) method, a variant of the IDW approach that accounts for wind direction and speed, to predict PM levels in regions lacking direct sensor measurement. PM-fit also called wind-applied IDW attributes greater weight to regions closer along the windward path, encountering wind speed for specified values. The estimated PM concentrations across the entire site were subsequently visualized in a three-dimensional map, delineating areas that necessitate PM reduction, thus enabling effective reduction planning and real-time diminishment of workers' PM exposure.

The proposed construction PM estimation models were verified in a controlled experiment site, then validated for real-world applicability in three different fields, including road, bridge, and building construction sites. The estimation method and corresponding visualized dust information three-dimensional map provide an advanced environmental monitoring method, in which dust concentrations are automatically estimated and visualized with the usage of few sensors. The visualized map can enact as a guideline for site managers, empowering them to protect against future health and environmental damages associated with PM inside construction sites.

Keywords: Construction management; Smart construction; Construction dust pollution; Particulate matter 2.5; Particulate matter 10; Sensing module; Low cost sensors; Spatial Interpolation; Inverse distance weighting; Three-dimensional maps

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Chapter 1. Introduction

1.1. Research Background

Over recent years, spurred on by urbanization, the world surged in construction activities, which have yielded many employment opportunities and accommodations worldwide. According to a United Nations report, by 2050, 68% of the world's population is estimated to be residing in urban centers (United Nations, 2018). Despite the considerable advantages of urban expansion, the construction industry has yet to adequately address a primary environmental issue: the proliferation of dust pollution emanating from construction sites. In South Korea, for instance, construction sites comprised 82.3% of all business premises responsible for reported dust production in 2018 (Ministry of Environment South Korea, 2018). The excessive dust pollution, also known as particulate matter (PM), has been a serious concern in the construction industry, given its potential to inflict diverse health problems.

According to Health and Safety Executive 2020 research, over 500 construction workers, 10 people a week, in the U.K. are believed to die from lung cancer due to long time exposure to PM (Health and Safety Executive, 2020). In addition, the United States reports an annual mortality rate of 22,000 to 52,000, largely presumed to be construction workers, due to construction PM exposures (Narayanan, 2019). PM emission causes damage to not only workers at the sites but also nearby residents (Azarmi et al., 2016). A large amount of PM from construction activities negatively impacts the life quality of local residents, leading to numerous complaints and possible postponement of construction projects. In fact, the construction field has been attributed to 91% of annual PM-related civil complaints in Korea (Ministry of Environment South Korea, 2016). Thus, since then, the significance of management and assessment of PM have been continuously emphasized in the construction industry.

The types of PM and monitoring methods need to be understood to effectively manage and analyze the PM in construction sites. PM produced in construction sites are typically divided into three categories based on their sizes: total suspended particles (TSP) of 50μm or less; PM10, measuring 10μm or less; and PM2.5, with a size of 2.5μm or less. Monitoring protocols primarily concentrate on PM2.5 and PM10, which are identified as the most harmful particulates (Environmental Protection Agency, 2022).

In current practices, two methods are generally applied for the measurement and monitoring of PM at construction sites. First, sensor-based monitoring methods are commonly used due to their ease of implementation and accurate real-time measurements, the main requirements for rapidly changing construction sites (Cheng & Teizer, 2013; Smaoui et al., 2018; Wu et al., 2016; Yoon et al., 2023). Alternatively, some sites employ manual PM reduction plans, wherein site managers visually inspect the area, adhering to a checklist that includes factors such as field cleanliness and placement of PM reduction equipment (Ministry of Environment South Korea, 2020b). However, both methods present significant limitations. The prohibitive costs of sensors limit the number of sensors usage, resulting in insufficient PM measurements for managing the entire site. Consequently, the few measured sensor values are represented as the PM concentrations of the whole site, providing an inaccurate understanding of the overall PM distribution of the site. The erroneous information of dust distribution can lead to ineffective allocation of PM reduction resources and waste of considerable amounts of water in attempts to control emissions (Choi, 2022). The Manual observation methods, while complementary, may be time-consuming, less efficient, and susceptible to human error or oversights.

Numerous studies have been pursued to address the shortcomings of present particulate matter monitoring methodologies, with a particular emphasis on enhancing sensor performance within construction sites. For instance, Hong et al. (2022) developed an affordable, portable sensor that provides real-time tracking of PM2.5 and PM10, facilitating versatile dust monitoring within construction sites. Similarly, Alshetty and Nagendra (2022) utilized multiple sensors to assess PM in the periphery of construction sites, thereby determining dust distribution patterns linked to construction vehicle movement. Luo et al. (2021a) also employed advanced sensors to conduct an occupational health risk evaluation premised on dust exposure during earthwork construction, demonstrating variances in PM exposure contingent on specific work locations within construction sites. Notwithstanding the advancements and benefits of sensor-based PM monitoring, there persist inherent limitations similar to those found in existing practices, particularly, requiring a multitude of sensors for comprehensive monitoring of PM distribution across the entire site.

In alignment with Luo et al. (2021a) findings on the variable particulate matter (PM) exposure across different construction site locations, numerous studies have been conducted to devise methods for understanding PM distribution and efficiently planning exposure prevention measures. Among the favored methods, spatial interpolation was the most common and straightforward method for real-time application with high precision. For example, Kim and Jo (2012) and Cho and Jeong (2009) employed spatial interpolation methods, mainly Indirect Distance Weighting and Kriging, for

PM distribution estimation in Daegu and Seoul, South Korea, respectively. However, these studies predominantly focused on macro scales such as city or country scales, thereby overlooking the construction site scale where meteorological factors, especially wind, significantly affect PM movement. Thus, for precise real-time PM monitoring in micro scales, like construction sites, the PM affecting factors were examined.

Analyzing the PM characteristics, the 3 factors, wind, the distance from sensors, and measured PM concentrations were utilized to create the construction site PM estimation model. Moreover, the estimated PM results were also visualized on a three-dimensional map enabling easier PM management. The PM estimation results and the visualized PM information map is expected to provide guidelines for identifying high PM concentration areas to devise cost-efficient reduction plans. Moreover, the newly created real-time construction PM estimation model, being the first attempt, can enlighten future research on construction PM.

1.2. Problem Statement

Until today, the lack of adequate real-time PM monitoring methods to understand the actual PM concentration of the entire construction site with accurate consideration of the PM characteristics, specifically wind, resulted in poor dust management at the site, leading to safety and productivity issues: health damage, inefficient reduction plans, and construction delays (Cheriyan & Choi, 2020a).

Addressing the persistent challenges, the necessity of a comprehensive understanding of real-time PM distributions at the construction site is being emphasized in the construction industry. Real-time PM monitoring could foster safer construction environments by continually detecting PM movement, thus minimizing PM exposure (Cheriyan & Choi, 2020b). Additionally, PM monitoring could enhance site productivity by enabling constant observation and management of areas with high PM concentrations, facilitated by immediate feedback. Therefore, the need for a reliable PM monitoring method that provides a detailed real-time PM distribution map of the entire construction site is once again underscored.

1.3. Research Objectives and Scope

This research proposes a real-time PM monitoring method for the entire construction site using construction dust estimation model. The estimation model was created by applying meteorological factors, to a spatial interpolation method that accurately estimates the PM concentrations, specifically for construction site scale, based on actual field data collected during construction. The PM concentrations or movements were visualized through a 3D map of PM concentration, allowing users to accurately locate PM hotspots that need management for cost-efficient reduction plans and exposure avoidance for workers' health.

Ultimately, utilizing the PM monitoring method, Field managers can use time-series PM concentration data in the overall construction site to determine which workers are exposed to excessive PM for a long time and require measures such as wearing masks and taking breaks. In addition, possible civil complaints can be predicted and taken early action by monitoring the current status of PM concentrations at the site.

Among the diverse types of dust pollution in construction sites, the research was focused on observing the PM, which embeds all the different matters or elements, mainly fugitive matter, that can occur during construction. Also, research was conducted based on the most common and harmful PM sizes, PM2.5 and PM10 (Luo et al., 2021a). Besides wind, other minor meteorological factors were neglected as it has hardly any effect on the PM estimation model.

1.4. Research Process

This Research consists of five chapters, and the details of each chapter are as follows.

Chapter 1. Introduction: This chapter introduces the research background, problem statement, research objectives, and research scope to help better understand the motivations and goals of the research.

Chapter 2. Theoretical Background and Related Works: This chapter briefly introduces the characteristics, impacts, and regulations of PM produced in construction works. Also, the current PM monitoring methods are explained along with the PM monitoring related works, including the development of sensor based monitoring researches, PM estimation monitoring methods, and the analysis of construction PM. The limitations of the previous monitoring methods are explained emphasizing the necessity of a new PM monitoring method.

Chapter 3. Development of Construction Particulate Matter Estimation Model: This chapter aims to develop a model that estimates the PM concentration of the construction site by taking the sensing data in some locations and meteorological factors, wind, as input. The data collection process, model development, and model verification are explained in detail. Based on the data collected with the invented sensing model at the experiment site, the spatial interpolation equation was customized for construction site PM. Then, the estimated PM concentrations were mapped, based on the given colors, on a three-dimensional point cloud map for result visualization.

Chapter 4. Results and Discussions: This chapter validates the construction site application results of the PM estimation model. The efficacy of the model was assessed across selected actual construction sites that exhibit varying conditions, including differences in area, types of work, and PM source generated. This evaluation involved contrasting sensor measurements with the model's estimated values. Data were collected from multiple actual construction sites via sensing modules and served as input for the model, thereby affirmatively demonstrating the system's robust applicability under diverse field conditions.

Chapter 5. Conclusions: This chapter summarizes the research outcomes and discusses the key findings, contributions, and future research directions of the research.

Chapter 2. Theoretical Background and Related Works

2.1. Construction Particulate Matter Characteristics

The construction industry significantly impacts natural environmental pollution. Among the various pollutants generated by construction activities, dust or PM stand as the most critical risk to the environment and human health (Li et al., 2019). The complex characteristics of construction sites can generate unexpected dust emissions, due to the exposure to many dust sources, such as construction equipment and dirt mounds. Hence, construction site dust sources needed to be studied before further research.

Construction sites can be divided into types and phases of work. Although dust erosions may vary depending on the types of construction site, including bridge, tunnel, building, and road construction, dust emissions heavily rely on the construction phase and activities (Li et al., 2019; Stacey et al., 2018). The Construction phase can be broken down into three simple terms, pre-construction, also known as the earthwork phase, superstructure, and finishing stages (Araújo et al., 2014). The earthwork phases generally consist of demolition or dirt moving processes and have been known to create the most PM out of all the construction phases, accounting for 96.04% to

98.93% of the total emissions from all construction activities (Muleski et al., 2005; Yoon et al., 2023). The main dust source during earthwork phase are the operations of heavy construction equipment, such as bulldozers, loaders, excavators, scrapers, dump trucks, graders, and rollers (Kim et al., 2020). Therefore, in this research earthwork phase was targeted, focusing on the major dust sources, i.e. construction equipment and dirt piles.

The dust created in construction sites are normally defined as particulate matter (PM). Although there are many types of PM, grouped based on size of the particulate, PM2.5 and PM10 are known to be the most hazardous component sizes in construction sites (Choi et al., 2022). PM2.5, also called fine dust, includes all the particulate matter with a diameter of less than 2.5 µm, whereas PM10 with a diameter of less than 10 µm (Azarmi et al., 2016; Choi et al., 2022). The relatively small-sized PM can reach deep inside the respiratory systems in human bodies causing adverse outcomes both mentally, depression or child's internalizing problems, and physically, silicosis, cardiovascular diseases, chronic obstructive pulmonary diseases, or lung cancers (Hsieh & Liao, 2013; Joo et al., 2021; Wang et al., 2020). Consequently, to prevent dangers in construction sites, many countries around the world provide PM quality standards. According to World Health Organization (WHO), PM average exposure standards for PM10 (annual), PM10 (24 hours), PM2.5 (annual), and PM2.5 (24 hours) are 20, 50, 10, and 25 μg/m^3, respectively (World Health Organization, 2022). Moreover, in South Korea, the regulations were established as average of annual PM10, 50 μg/m^3, 24 hour PM10, 100 μg/m^3, annual PM2.5, 15 μg/m^3, and 24 hours PM2.5, 35 μg/m^3 (Ministry of Environment, South Korea 2022a). Meeting the government and organization guidelines are essential when in construction for safe productive workplaces (Lee et al., 2023). Likewise, PM monitoring methods are currently in practice and are eagerly researched in the construction and environmental industry.

2.2. Current Construction Particulate Matter Monitoring Methods

While there are many methods to measure and monitor PM, in current practices, sensors are typically placed inside the construction sites for PM monitoring method due to the simplicity and accurate real-time measurements, which are two major critical issues to fit in an everyday changing construction sites (Cheng & Teizer, 2013; Smaoui et al., 2018; Wu et al., 2016; Yoon et al., 2023). In other cases, PM reduction plans are conducted manually through eye observations from site managers where the managers scrutinize the site with a PM status checklist, including field cleaning status, PM reduction equipment placements (Ministry of Environment South Korea, 2020b), and many other necessary procedures for minimal PM erosions and emission of workers (Ministry of Environment South Korea, 2023). However, lots of limitations exist in current PM monitoring methods. Due to the high costs of sensors, only a few sensors are used to represent the PM value of the entire site which leads to inaccurate PM estimation of the overall site. Not being able to accurately locate high concentration areas, requires using PM reduction equipment everywhere that might cause PM without knowing the exact amount of PM erosion in each location (Yu et al., 2004). Therefore, a massive amount of water is used inefficiently to reduce PM emissions (Choi, 2022). Moreover, manual eye observations and checklist method are even more time consuming and inefficient than the sensor method, also creating the possibility of missing spots due to human error or mistakes. As a result, more developed and innovative monitoring methods have been desired for healthier construction sites

2.3. Related Works

2.3.1. Development of Sensor Monitoring Methods

Many researches were conducted to overcome the limitations of current PM monitoring methods. To maximize the sensor performance in construction sites, PM sensor development researches were vigorously studied. Hong et al. (2022) developed a portable environmental low-cost sensor that monitors PM2.5 and PM10 in real-time for more flexible dust monitoring inside construction sites, improvement in usability allowing sensors to be installed near construction activities. More recently, Alshetty and Nagendra (2022) measured the PM in the outer surrounding environments of the construction sites using numerous sensors identifying the dust distribution due to the movement of construction vehicles. Similarly, using developed sensors, Luo et al. (2021a) conducted an occupational health risk assessment based on dust exposure during earthwork construction. By installing a sensor in each worker's location, Luo et al. indicated the differences in PM exposure according to working locations inside the construction site. Despite the development and benefits of sensor-based PM monitoring, many limitations, similar to the current practice limitations, exist when only using sensors, such as only providing PM measurements of the sensor placed locations, which require numerous sensors to monitor the overall PM distribution of the entire site.

2.3.2. Particulate Matter Estimation Methods

Aligning with Luo et al. (2021a) findings, since PM exposures are different in every location of the site, understanding the overall distribution of PM is crucial for the avoidance of each worker’s exposure and an efficient reduction planning where water or equipment is not wasted. Likewise, many studies on PM estimation methods were conducted to overcome the limitations of sensor usage and acquire knowledge of the actual PM distribution.

The simulation methods (Akhavia & Behzadan, 2015; Giunta, 2020; Tong et al., 2018) or the air pollution diffusion modeling method, which is used to estimate the PM for the weather forecast of Korea, which includes Gaussian diffusion modeling, the Eulerian model, and the Lagrangian model (Ministry of Environment South Korea, 2005) were introduced for future distribution estimation of constriction PM for effective reduction plans. However, due to the inconsistent and complex behaviors of construction works, where schedules and parameters are constantly changed or uncertainties commonly occur, the simulated or diffusion modeling results could be only used as references leaving questionable outcomes. Moreover, the two predictive methods required overwhelming input parameters that cannot be accurately measured in real-time in construction sites. Therefore, for accurate and simpler PM monitoring, many researchers commonly used the spatial interpolation method in various types of research. The spatial interpolation method can instantly estimate accurate PM distributions based on updated actual real-time data of the fields, which is a suitable solution for the rapidly changing conditions of construction sites. The spatial interpolation method is where unknown values of a particular location are estimated using only a few sensor values. Shogrkhodaei et al. (2021) estimated PM2.5 distribution of cities in Iran using a few air pollution monitoring stations of Iran. Kim and Jo (2012) utilized PM monitoring station measurements in Daegu, South Korea, to provide the PM mapping result of the whole city for assessment. They used the two most common spatial interpolation methods for PM, Indirect Distance Weighting (IDW), a distance-based weighting method, and Kriging, a statistical geographical data-based way, to estimate the PM distribution of Daegu. Similarly, Cho and Jeong (2009) compared different spatial interpolation methods, including Kriging and IDW, to find the most appropriate PM estimation method for Seoul, South Korea. Similar approaches of using spatial and temporal patterns of dust emissions to estimate the PM distributions were actively held around the world (Feng et al., 2022; Liang & Yu, 2021; Pradabmook & Laosuwan, 2021). As such, the spatial interpolation method supports the difficulties of understanding the distribution of PM in real-time; however, previous research only focused on macro-scales, including city or country scale, excluding the construction site scale. In large-scale estimation, many meteorological factors were averaged and had minimal affection. The inconsistent behavior of meteorology parameters highly affects PM movement creating massive dilemmas for small-scale PM estimation, specifically at construction sites. Therefore, to accurately estimate and monitor the PM of construction sites in real-time, which has never been approached, meteorology factors needed to be understood and applied (Chae, 2009).

2.3.3. Analysis of Construction Particulate Matter

To apply the PM estimation methods on smaller scales, like construction sites, characteristics and the distribution behaviors of PM, needed to be meticulously scrutinized. Likewise, many researchers have studied the correlations of construction PM affecting factors, including wind direction and speed, humidity, temperature, and seasons. Luo et al. (2021b) noted that the earth excavation area had the highest PM dispersion with higher concentrations when closer to the working area. Moreover, Luo et al. observed the correlations between PM and wind by placing a weather station and dust sensors at the construction site. The sensors were placed in various locations on the earthwork site for 4 days. The acceleration of wind likely facilitated the dispersal of pollutants, leading to an earlier escalation of pollution levels. In fact, according to the research result, under static wind conditions, the dust retention rate was higher inside the construction site, whereas with the influence of the wind, dust was dispersed. Meanwhile, Luo et al. (2021b) state that minimal correlations were shown for other meteorological factors such as temperature, humidity, and atmospheric pressure. Chae (2009) also stated that wind speed and direction are the major factors to emphasize in the affection of PM, as wind allow farther travel distances. Similarly, many other construction dust related researches define and focus on the effect of wind direction and speed as it is the main parameter that needs to be considered when monitoring PM (Xie et al., 2019; Yan et al., 2023). Accordingly, Wind was noted as the most critical meteorological factor that needed to be implemented when creating the construction PM estimation model.

2.4. Summary

Construction activities produce significant dust, primarily from equipment and dirt piles, with the greatest amount of particulate matter (PM) generated during the earthwork phase. The PM types most relevant to construction sites are PM2.5 and PM10, small-sized particles that pose a significant health risk (Choi et al., 2022; Hsieh & Liao, 2013; Joo et al., 2021; Wang et al., 2020). The World Health Organization and individual countries have established quality standards for PM to protect workers and the environment (World Health Organization, 2022). To ease the dust pollution problems, significant interest in researching and implementing PM monitoring methods have been continuously conducted in the construction industry.

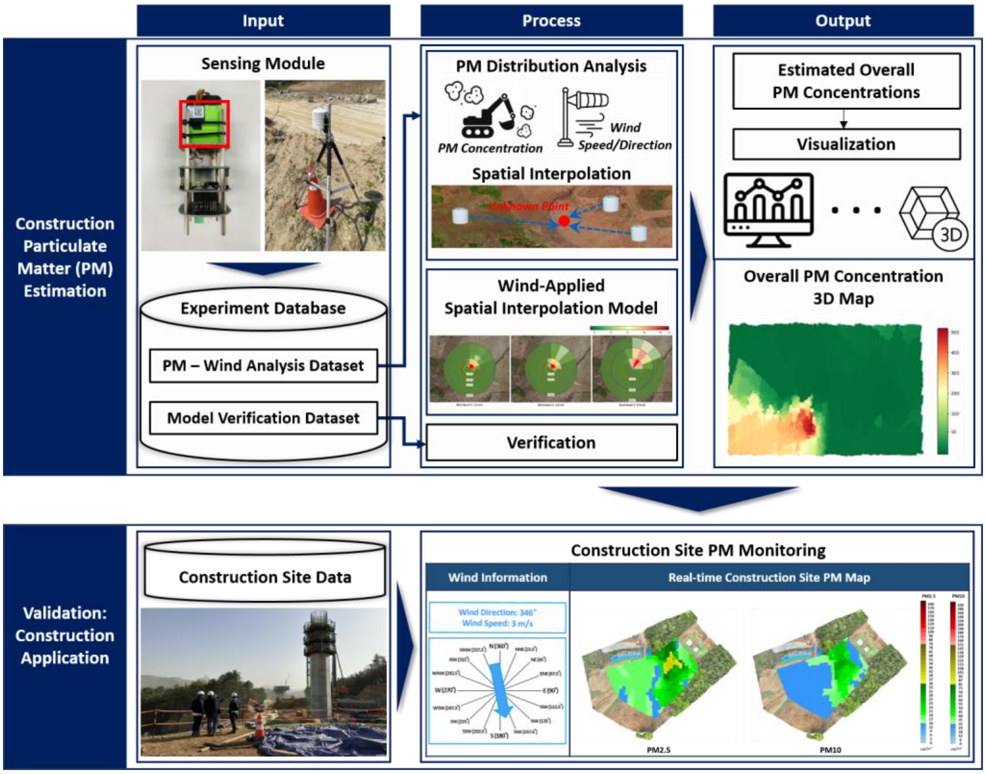
For safer construction sites, sensors and manual monitoring are currently the main methods used to monitor PM at construction sites. Sensors provide real-time measurements, while manual monitoring involves site managers using a PM status checklist to evaluate various site conditions (Cheng & Teizer, 2013; Ministry of Environment South Korea, 2020b; Smaoui et al., 2018; Wu et al., 2016; Yoon et al., 2023). However, both methods have limitations. Sensors are expensive and may not provide a complete picture of the site's PM levels. Manual monitoring is time-consuming and can lead to missed areas due to human error.

To overcome the limitations, researchers are working to improve PM monitoring methods, with some focusing on the development of more effective sensors (Alshetty & Nagendra, 2022; Hong et al., 2022; Luo et al., 2021a) and others on diffusion modeling (Ministry of Environment South Korea, 2005) or simulations (Akhavia & Behzadan, 2015; Giunta, 2020; Tong et al., 2018) of dust distribution. Despite the advancements, limitations still exist. For instance, sensors can only provide PM measurements at their locations and may not give a comprehensive view of PM levels across the entire site. Meanwhile, Diffusion models or simulation does not fit for real-time small scale estimation method due to the requirement of overwhelming parameter, which may not always be provided or accurate in the unpredictable nature of construction activities. Since studies have shown that understanding the distribution of PM across the site is crucial to protect workers and plan efficient dust reduction methods (Luo et al., 2021a). Spatial interpolation methods, which estimate unknown values at certain locations based on a few known sensor values, have been used to address current issues (Cho & Jeong, 2009; Feng et al., 2022; Kim & Jo, 2012; Liang & Yu, 2021; Pradabmook & Laosuwan, 2021; Shogrkhodaei et al., 2021). However, these methods have so far mainly been applied on larger scales and not in the context of individual construction sites, where meteorological factors can greatly affect PM distribution. In addition to enhancing the monitoring techniques, studies have also investigated the relationship between PM distribution and factors with wind being identified as the most significant influence on PM movement (Chae, 2009; Luo et al., 2021b; Xie et al., 2019; Yan et al., 2023). All the literature review information was utilized as references in the model development processes.

Chapter 3. Development of Construction Particulate Matter Estimation Model

3.1. Overall Research Framework

The research framework is shown in Figure 3.1. First, environmental sensing module was invented to optimize construction site environmental data collection. The invented sensing module enhanced portability and enabled simple installation process anywhere in the site including construction equipment. Moreover, the sensing module is comprised of low-cost sensors contributing economically. After sensing module production, an appropriate area similar to an earthwork phase construction site, the highest dust erosion phase, was selected for the experiment site. Site information, such as GPS, spatial information, and available sensor installment locations, was observed using a point cloud map achieved by an unmanned aerial vehicle (UAV). Secondly, a data collection process was conducted. A controllable dust source creator was selected for PM erosion; then, sensing modules were installed for measurement. Referring to previous researches, wind, distance from the dust source or each sensor, and PM concentrations were the deterministic factors affecting PM dispersion (Alshetty & Nagendra, 2022; Shogrkhodaei et al., 2021; Yan et al., 2019). Therefore, besides PM concentration data, distances of each sensor and meteorological data were collected in a database, MongoDB was used for the research. Then, PM measurement, wind speed and direction, and distance data were used to analyze the PM distribution characteristics. Based on the analysis, PM dispersion patterns were found to correlate with wind and distance, called weight percentage. Utilizing the weight percentage equation and spatial interpolation method, the newly invented construction site PM estimation model was developed. The method was verified with a different site dataset, confirming the model performance. With the support of the point cloud map, estimated PM concentrations were visualized in a 3D map for more effective PM monitoring. Lastly, the construction PM estimation monitoring method was validated through actual construction site application. The method was implied in three different construction site building, bridge, and road construction sites, each exhibiting different characteristics.



3.1 Overall research framework for PM estimation model

3.2. Equipment for Data Collection

Three primary materials were needed to collect data for construction PM estimation model development including, 1) dust sensors for PM concentration data collection, 2) weather station to collect wind direction data for model customization, and 3) a controllable dust source creator for PM distribution in a desired area. Each equipment was selected with a thorough search process, especially for the dust sensor. A sensing module was invented and customized with combination of other environmental sensors for construction-fit and economical purposes.

Sensing Module: Dust sensors

Sensors were highly dependent and the most crucial equipment that needed to be carefully selected for the best performance of the research. Sensors were required to be easily portable and cost-effective for economical use in complex construction sites. Three methods are typically used for PM concentration measurement: Gravimetric, Beta Gauge, and Light Scattering. Although Gravimetric and Beta Gauge method sensors have been used for a long time as the PM measurement instrument in many places, it is critically disadvantageous with the high cost and long measurement periods of more than at least an hour up to 24 hours (Takahashi et al., 2008). Moreover, due to their massive sizes and heavy weights, Gravimetric and Beta sensors are generally used for fixed installment purposes (Triantafyllou et al., 2016). On the other hand, Light Scattering method sensors, light-weighted and small-sized, allow convenient mobility and, most importantly, provide a short-measurement period for real-time sensing (Yang et al., 2019; Wang et al., 2023). Consequently, Light Scattering method sensor was selected as the perfect fit for real-time PM measurement for continuously changing and complex construction.

Among the numerous Light Scattering method sensors developed for years, a low-cost sensor, the SPS30 sensor, manufactured by Sensirion, was selected as the most befitting device with high data credibility. The SPS30 sensor was certified by The Monitoring Certification Scheme (MCERTS), established by the Environment Agency and CSA Group Testing UK Ltd., aligns with International and European standards, i.e. ISO/IEC 17000 series, and aims to regulate industrial emissions. The MCERTS is accredited by the United Kingdom Accreditation Service (UKAS), ensuring impartial, competent, consistent certifications with accurate monitoring data and the quality of related equipment or personnel, meeting European Directives (Sensirion, 2022; CSA Group, 2023).

Moreover, numerous SPS30 sensor embedded Korean air purifiers and air quality measurement products have been certified as class 1, the highest rank, by Korea Testing and Research Institute, the main accredited certification and testing organization supported by the Korean government and the International Commission on the Rules for the Approval of Electrical Equipment (Korea Testing & Research Institute, 2023). SPS30 is small enough for simple sensor installment and cheap for multiple purchases. SPS30 has one second response time for real-time PM measurements and provides PM2.5, PM10 measurements in a unit of $\mu g/m^3$ (Sensirion, 2020).

After a suitable sensor selection, for economical and optimal sensor usability in construction sites, the author invented a sensing module, where selected SPS30 sensor was inserted inside one sensor protector with other low-cost environmental sensors that are also required for measurement at the site. The added environmental sensors include noise, vibration, temperature, and humidity. Also GPS modem, with an error below 2.5 meters, was implemented in the sensing module to accurately allocate the sensor locations along with the PM concentrations. The invention of the sensing module allowed convenient installation of the sensors, reducing the difficulty of having to install each environmental sensor individually. Furthermore, having to buy one collaborated sensor for all the required environment measurements, more sensors can be bought at a cheaper cost. Sensing modules are used with a sensor protector for protection from water or other obstacles that might damage the sensors and for a steady PM flow rate to avoid unexpected overload errors. The invented sensing module and site installment example are shown in Figure 3.2. Specifications and the database of the sensing module are demonstrated in Appendix A. Sensors were installed at 1.5m height using a tripod to meet a similar height as a human's face.

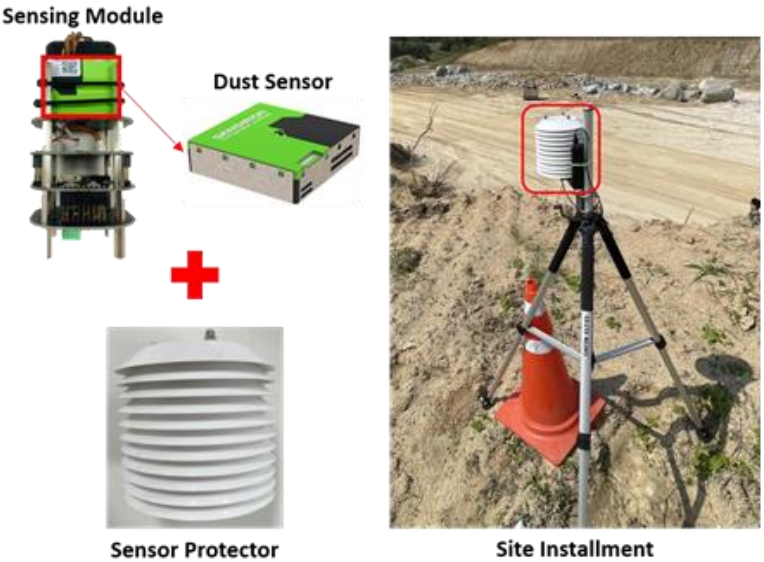


Figure 3.2: Sensing module and site installment example

Mobile GPS locators were used to spot the locations of sensor installation and the distances between each sensor. The mobile GPS locator provided an error below 4 meters, which was within the acceptable range.

Weather Station

Among the many selections of weather stations, the WH-2300S weather station, the most cost-efficient and fitting well to Korean weather manufactured by Chanju Technology (Chanju Technology, 2022), was selected for wind data collection. WH-2300S weather station is certified by the South Korea Public Procurement Service, a government organization in South Korea managing all the materials required for major building works (Public Procurement Service, 2019), that provides credible quality data. WH-2300S weather station measures wind direction from 0 to 360 degree angles divided into 16 azimuths, each 22.5 degrees apart, and wind speed in all ranges. Other meteorological factors were collected through the weather stations: humidity from 1 to 99 percent, and temperature from -30 to 65 degrees (Chanju Technology, 2022). All weather data were collected in one minute intervals for real-time analysis. The weather station was installed and placed near the site where PM sensor measurements were not disturbed.

Dust Source

Requiring dust erosion at a wanted time, the dust source needed to be somewhat controllable in the experimental setting creating enough PM for analysis. Big automobiles were capable of imitating the dust created by construction vehicles, the major dust applicant in construction sites, and used for dust source creators. Dust source was created by driving large automobiles in circles with an approximate radius of 7m, successfully creating copious dust throughout the experimental site.

3.3. Model Development

3.3.1. Spatial Interpolation Methods

Briefly mentioned in the previous chapters, spatial interpolations are widely and mainly utilized methods for real-time construction site environment monitoring, in which values of the known points are used to estimate the values of the unknown points (Lee et al. 2023; Hwang et al., 2022). Among the various interpolation methods, Kriging and IDW were two majorly used methods for dust estimation that showed remarkable outcomes in various researches (Cho & Jeong, 2009; Hwang et al., 2022). Therefore, the two methods were compared for PM-fitting method selection. Kriging, also known as the Gaussian process regression, is a spatial interpolation technique based on the Gaussian process governed by prior covariance. Kriging is highly dependent on statistical data along with the tendency of spatial information. In large scales, cities and country sizes, PM tends to be, hypothetically, evenly scattered showing strong data or spatial correlations between nearby locations within the cities (Montero et al. 2010). For example, when monitoring PM of South Korea, each city may show different PM concentrations but does not show dramatic PM contradictions between different parts of Seoul due to strong spatial and data correlations between areas inside Seoul. Likewise, when estimating large areas, where countless data and strong spatial correlations exist, Kriging would be a more popular and advantageous selection with high estimation accuracy (Cho & Jeong, 2009). However, small-scale and continuously changing construction sites, where PM can differ markedly within few meters depending on wind, even in areas near the dust source, barely show spatial relevance between nearby measurements, resulting in low performance of the Kriging method. In contrast, IDW is a comparably clearer method solely based on distances, where more weights are given to closer points than further ones (Kim & Jo 2012; Li & Heap 2011). While PM is heavily dependent on wind and distance when estimating PM in construction sites, IDW already includes one of the key factors, distance, which is idealized for PM-fit interpolation with minimal deformation. Although IDW also shows comparably high relevance between nearby measurements, IDW is formed with a simple and straightforward weighting system that allows easy customization for wind application, overcoming its deficiency. Thus, IDW was selected as the proper spatial interpolation method to be customized for the dust estimation model.

3.3.2. Particulate Matter Distribution Analysis

The movement and characteristics of PM needed to be carefully examined for accurate construction PM estimation model development. For successful experiments of the PM distribution analysis, site selection was one of the most important steps. The experimental site needed to fulfill three requirements. First, the site needed to be similar to the earthwork construction phase, where an adequate amount of PM erosion was attainable for analysis. Another essential aspect was to find an open dirt field where no nearby residents or areas were harmed by the PM created by the experiment. Lastly, the site needed to be a safe area for UAV photography, which was later used for point cloud map creation to obtain site information and visualization. Through a rigorous investigation, Survey of Construction (SOC) Demonstration Research Center, located in Yeoncheon County, Gyeonggi Province in Korea, was selected as the experiment site. An initial field survey was necessary to determine the various information, including coordinate information for spatial interpolation methods and constraint information such as bumpy dust piles or cliffs for safe sensor installment. An unmanned Aerial Vehicle (UAV) was used to scan the coordinate information of the site. Using a Pix4D application, photographs and coordinate information were combined to create a point cloud map. Through the site's point cloud map examination, a suitable open-flat area with abundant dust, yet free from nearby harm and safe for sensor installation, was found for the two PM distribution analysis experiments, as marked in a white box in Figure 3.3.

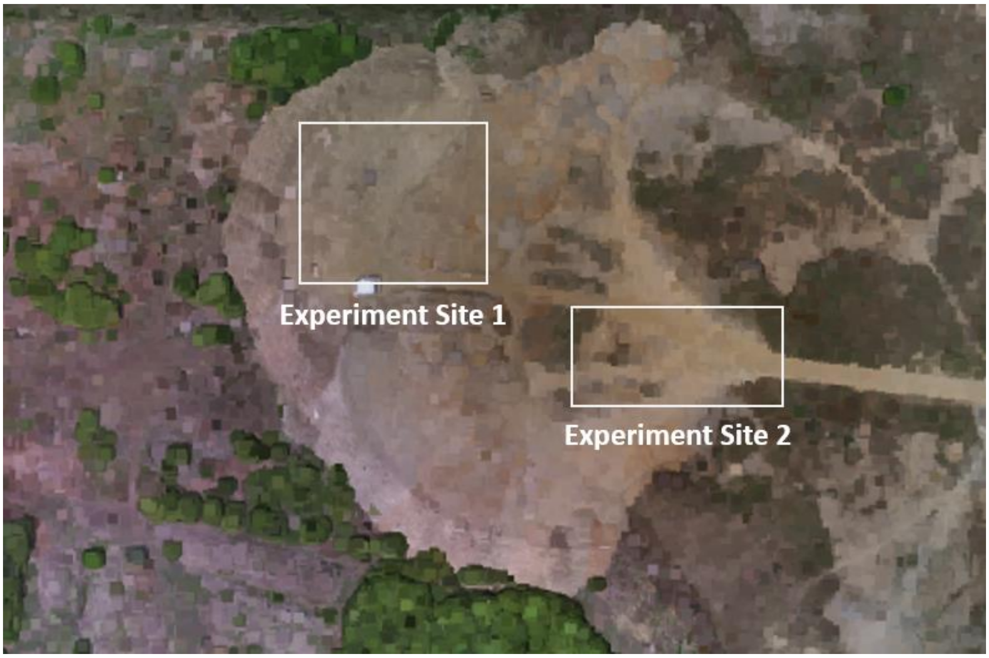


Figure 3.3: Point cloud map of the selected experiment sites

After the site selection and observation, dust data were collected in the database and utilized for PM distribution analysis to analyze how wind affects PM dispersion according to the distance near the dust source. Luo et al. (2021b) mentioned that a dust source in the construction site could seriously pollute an area up to radius of 25m and possibly create cautious areas up to

50m. Thus, two data collection process was conducted as shown in Figure 3.4(a) and Figure 3.4(b). For Figure 3.4(a), sensors were narrowly placed near the dust source, where every angle direction and distance point were measured using 37 sensor installment locations inside the approximately 50m x 50m experimental site. Also, for the cautious area measurements, areas further than radius of 25m, seven sensors were installed in the wind pathway. Additionally, for more precise examination of wind and PM correlation, as shown in Figure 3.4(b), 25 sensors were placed throughout the 60 meter areas in the wind direction. More sensors were installed at wider angles for the areas closer to the dust source, where areas were divided approximately in 10 meter intervals from the source. Figure 3.4(b) experiment design enabled to scrutinize the effects of different wind speeds. All the sensors were installed at a 1.5m height, similar to the height of a human (Lee et al., 2023).

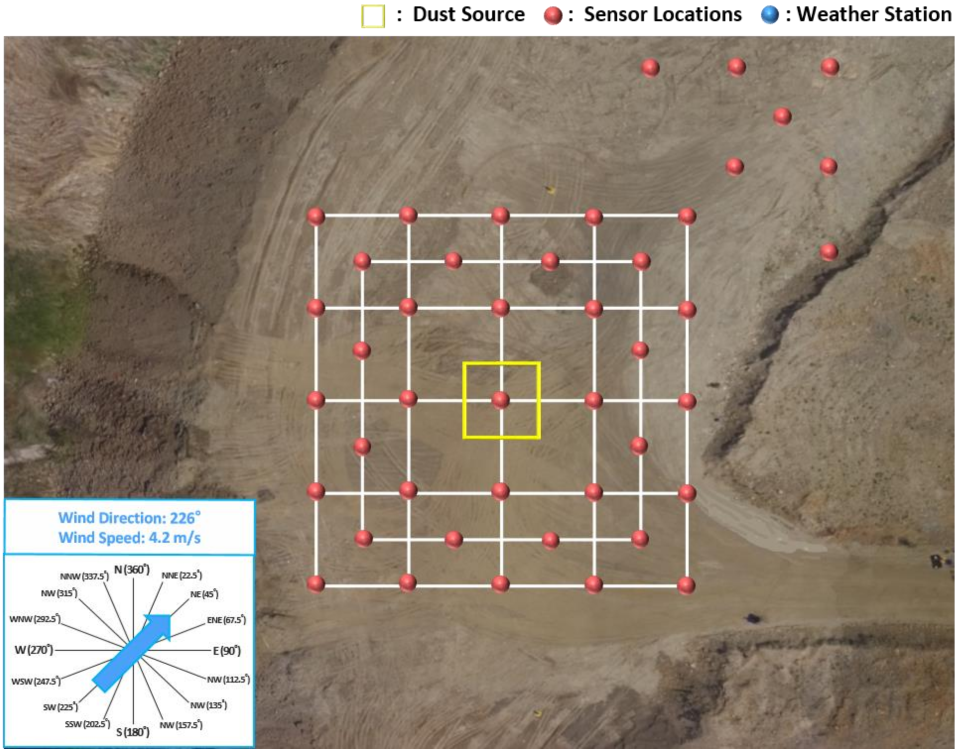


Figure 3.4(a): Sensor locations for PM distribution data collection 1

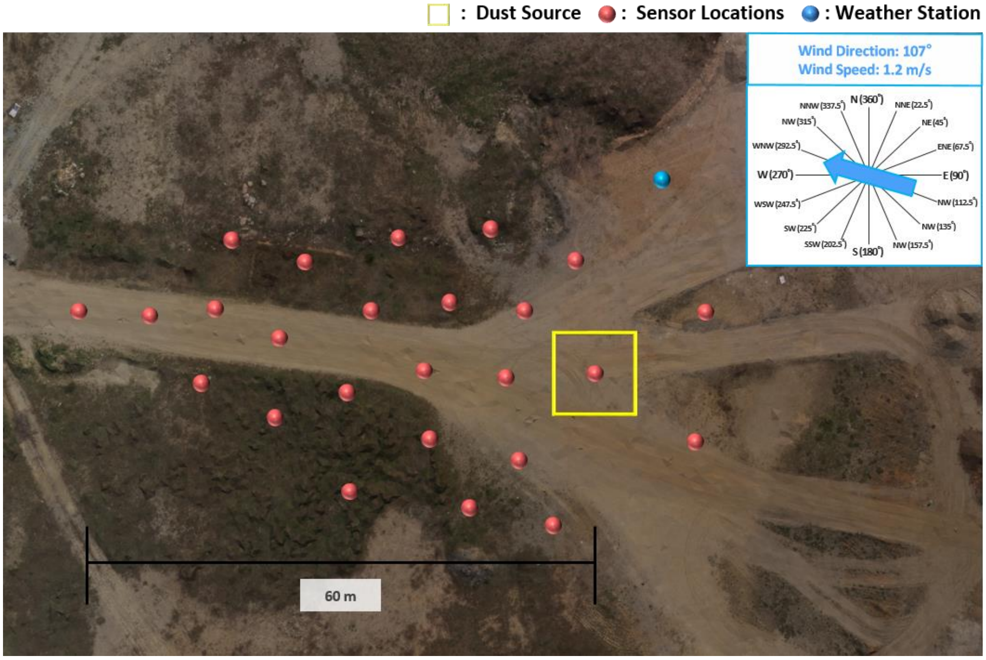


Figure 3.4(b): Sensor locations for PM distribution data collection 2

Dust was generated with the two dust creators, huge automobiles, for data collection as shown in Figure 3.5. Both data collection processes were attempted numerously, more than 15 times, for long periods where a decent amount of dust data in every location and different meteorological, including wind, humidity, and temperature, were collected for analysis. The dust erosion was successful measuring a maximum of 525 μg/m^3 for PM2.5 and 819 μg/m^3 for PM10.

Figure 3.5: Dust erosion from the dust creators

Analyzing the data, PM dispersion patterns were found based on wind direction and wind speed, overall PM showed wide to narrow distribution or fading away distribution in increments of approximately 10m, more if farther apart, and different PM concentration distributions every 22.5 degrees for the areas in the wind direction. Moreover, PM distribution was also distinctive based on wind speed. The examples of PM distribution analysis process are shown in Figure 3.6. If an area was within the distance of 0 to 10m from the dust source and within 22.5 degrees from the wind direction, then the area was 100% affected by the measured PM value of the dust source. However, if far from the dust source, between 20 to 50 meters and not within the wind direction path, then 0% was affected by the dust source. In similar process, all sensor locations, both data collection 1 and 2, were analyzed for various wind directions and speed.

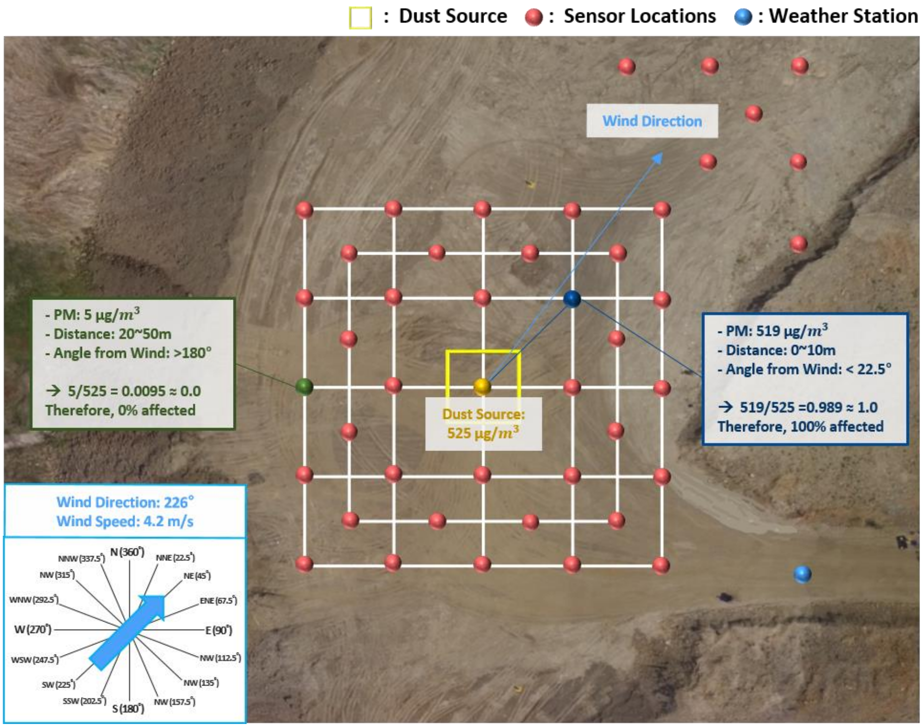


Figure 3.6: Example of PM distribution analysis

3.3.3. Particulate Matter Estimation Model

Based on the patterns observed from PM distribution analysis, the weight percentage equation, an appropriate PM distribution percentile based on wind, was determined. The constructed weight percentage, affecting PM percentile, based on wind direction and speed is shown in Equation 3.1 and Equation 3.2, for PM2.5 and PM10, respectively. Equation 3.3, to find the angle between sensors and the wind direction for affection determination, and Equation 3.4, to find the actual wind movement direction, were also used to support the weight percentage equations. The dust estimation model includes many parameters: 1) weight percentage (WP), the key outcome for additional application of wind to the basic IDW method, 2) d, meter distance of sensors and estimated location, 3) sensor wind angle (SWA), the absolute difference of wind direction and sensor angle, to find the actual PM affected angle from the sensor and the estimated location based on wind direction path, 4) wind direction (WD), the actual wind movement direction at the site, i.e., when weather station gives 0 degrees, the actual wind is moving from north to south in 180 degrees, 5) sensor angle (SA), bearing angle from measurement sensor to the estimated point, and 6) weather station wind (wsw), degree value of wind direction measured from the weather station. A weight percentage heatmap was drawn in Figure 3.7(a) and Figure 3.7(b) to visually show PM distribution analysis results. Other meteorological factors such as humidity and temperature were already encountered in the process of sensor concentration measurement. For example, when increase in humidity, the soil wetness was also already increased, creating less PM at the site. Likewise, when increase in temperature, the soil dried out which increased the dust erosion. Therefore, only wind was applied in the weighting system.

$$\boldsymbol{PM2.5\ WP}\ \textbf{for}\ \mathbf{0 < WS \le 2}\ =$$

$$\begin{cases} if\ \ 0 \le d \le 10\text{m and } \begin{cases} SWA \le 11.25, & WP = 1.0 \\ 11.25 < SWA \le 33.75, & WP = 0.95 \\ 33.75 < SWA \le 56.25, & WP = 0.85 \\ 56.25 < SWA \le 78.75, & WP = 0.3 \\ 78.75 < SWA, & WP = 0.02 \end{cases} \\ if\ \ 10 < d \le 20\text{m and } \begin{cases} SWA \le 11.25, & WP = 0.6 \\ 11.25 < SWA \le 33.75, & WP = 0.45 \\ 33.75 < SWA \le 56.25, & WP = 0.2 \\ 56.25 < SWA, & WP = 0.00 \end{cases} \\ if\ \ 20 < d \le 30\text{m and } \begin{cases} SWA \le 11.25 & WP = 0.3 \\ 11.25 < SWA \le 33.75, & WP = 0.2 \\ 33.75 < SWA, & WP = 0.00 \end{cases} \\ if\ \ 30 < d \le 50\text{m and } \begin{cases} SWA \le 11.25 & WP = 0.15 \\ 11.25 < SWA \le 33.75, & WP = 0.1 \\ 33.75 < SWA, & WP = 0.00 \end{cases} \end{cases}$$

$$\boldsymbol{PM2.5\ WP}\ \textbf{for}\ \mathbf{2 < WS \le 6}\ =$$

$$\begin{cases} if\ \ 0 \le d \le 10\text{m and } \begin{cases} SWA \le 11.25, & WP = 1.0 \\ 11.25 < SWA \le 33.75, & WP = 0.9 \\ 33.75 < SWA \le 56.25, & WP = 0.8 \\ 56.25 < SWA \le 78.75, & WP = 0.3 \\ 78.75 < SWA, & WP = 0.02 \end{cases} \\ if\ \ 10 < d \le 20\text{m and } \begin{cases} SWA \le 11.25, & WP = 0.6 \\ 11.25 < SWA \le 33.75, & WP = 0.5 \\ 33.75 < SWA \le 56.25, & WP = 0.3 \\ 56.25 < SWA, & WP = 0.00 \end{cases} \\ if\ \ 20 < d \le 50\text{m and } \begin{cases} SWA \le 11.25 & WP = 0.3 \\ 11.25 < SWA \le 33.75, & WP = 0.2 \\ 33.75 < SWA, & WP = 0.00 \end{cases} \end{cases} \tag{3.1}$$

$$\boldsymbol{PM2.5\ WP\ \text{for}\ 6 < \mathrm{WS} \leq 8}\ =$$

$$\begin{cases} if\ \ 0 \leq d \leq 20\text{m}\ \text{ and } & \begin{cases} SWA \leq 11.25, & WP = 0.85 \\ 11.25 < SWA \leq 33.75, & WP = 0.75 \\ 33.75 < SWA \leq 56.25, & WP = 0.3 \\ 56.25 < SWA \leq 78.75, & WP = 0.1 \\ 78.75 < SWA, & WP = 0.01 \end{cases} \\ if\ \ 20 \leq d \leq 40\text{m}\ \text{ and } & \begin{cases} SWA \leq 11.25, & WP = 0.7 \\ 11.25 < SWA \leq 33.75, & WP = 0.5 \\ 33.75 < SWA \leq 56.25, & WP = 0.2 \\ 56.25 < SWA, & WP = 0.00 \end{cases} \\ if\ \ 40 \leq d \leq 60\text{m}\ \text{ and } & \begin{cases} SWA \leq 11.25 & WP = 0.4 \\ 11.25 < SWA \leq 33.75, & WP = 0.25 \\ 33.75 < SWA, & WP = 0.00 \end{cases} \end{cases}$$

$$\boldsymbol{PM10\ WP\ \text{for}\ 0 < \mathrm{WS} \leq 2}\ =$$

$$\begin{cases} if\ \ 0 \leq d \leq 10\text{m}\ \text{ and } & \begin{cases} SWA \leq 11.25, & WP = 1.0 \\ 11.25 < SWA \leq 33.75, & WP = 0.95 \\ 33.75 < SWA \leq 56.25, & WP = 0.75 \\ 56.25 < SWA \leq 78.75, & WP = 0.2 \\ 78.75 < SWA, & WP = 0.02 \end{cases} \\ if\ \ 10 < d \leq 20\text{m}\ \text{ and } & \begin{cases} SWA \leq 11.25, & WP = 0.6 \\ 11.25 < SWA \leq 33.75, & WP = 0.3 \\ 33.75 < SWA \leq 56.25, & WP = 0.15 \\ 56.25 < SWA, & WP = 0.00 \end{cases} \\ if\ \ 20 < d \leq 30\text{m}\ \text{ and } & \begin{cases} SWA \leq 11.25 & WP = 0.2 \\ 11.25 < SWA \leq 33.75, & WP = 0.1 \\ 33.75 < SWA, & WP = 0.00 \end{cases} \\ if\ \ 30 < d \leq 50\text{m}\ \text{ and } & \begin{cases} SWA \leq 11.25 & WP = 0.1 \\ 11.25 < SWA \leq 33.75, & WP = 0.1 \\ 33.75 < SWA, & WP = 0.00 \end{cases} \end{cases}$$

$$\boldsymbol{PM10\ WP\ \text{for}\ 2 < \mathrm{WS} \leq 6}\ =$$

$$\begin{cases} if\ \ 0 \leq d \leq 10\text{m}\ \text{ and } & \begin{cases} SWA \leq 11.25, & WP = 1.0 \\ 11.25 < SWA \leq 33.75, & WP = 0.9 \\ 33.75 < SWA \leq 56.25, & WP = 0.8 \\ 56.25 < SWA \leq 78.75, & WP = 0.3 \\ 78.75 < SWA, & WP = 0.02 \end{cases} \\ if\ \ 10 < d \leq 20\text{m}\ \text{ and } & \begin{cases} SWA \leq 11.25, & WP = 0.55 \\ 11.25 < SWA \leq 33.75, & WP = 0.4 \\ 33.75 < SWA \leq 56.25, & WP = 0.2 \\ 56.25 < SWA, & WP = 0.00 \end{cases} \\ if\ \ 20 < d \leq 50\text{m}\ \text{ and } & \begin{cases} SWA \leq 11.25 & WP = 0.2 \\ 11.25 < SWA \leq 33.75, & WP = 0.1 \\ 33.75 < SWA, & WP = 0.00 \end{cases} \end{cases} \qquad (3.2)$$

$$\boldsymbol{PM10\ \ WP}\ \ \mathbf{for\ \ 6 < WS \leq 8}\ \ =$$

$$\begin{cases} if\ \ 0 \leq d \leq 20\text{m}\ \ \text{and} & \begin{cases} SWA \leq 11.25, & WP = 0.85 \\ 11.25 < SWA \leq 33.75, & WP = 0.7 \\ 33.75 < SWA \leq 56.25, & WP = 0.2 \\ 56.25 < SWA \leq 78.75, & WP = 0.1 \\ 78.75 < SWA, & WP = 0.01 \end{cases} \\ if\ \ 20 \leq d \leq 40\text{m}\ \ \text{and} & \begin{cases} SWA \leq 11.25, & WP = 0.6 \\ 11.25 < SWA \leq 33.75, & WP = 0.4 \\ 33.75 < SWA \leq 56.25, & WP = 0.1 \\ 56.25 < SWA, & WP = 0.00 \end{cases} \\ if\ \ 40 \leq d \leq 60\text{m}\ \ \text{and} & \begin{cases} SWA \leq 11.25 & WP = 0.3 \\ 11.25 < SWA \leq 33.75, & WP = 0.2 \\ 33.75 < SWA, & WP = 0.00 \end{cases} \end{cases}$$

$$\boldsymbol{Sensor\ \ Wind\ \ Angle}\ \ (\boldsymbol{SWA}) = |WD - SA| \tag{3.3}$$

$$\boldsymbol{Wind\ \ Direction}\ \ (\boldsymbol{WD}) = \begin{cases} 180 + wsw, & wsw < 180 \\ |wsw - 180|, & wsw \geq 180 \end{cases} \tag{3.4}$$

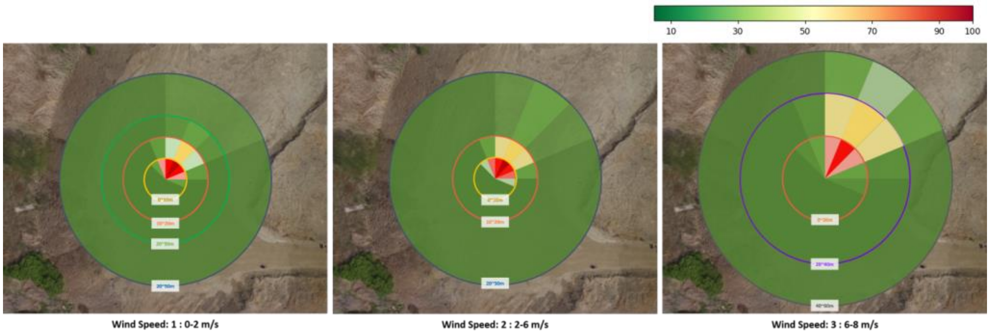


Figure 3.7(a): PM2.5 weighting percentage heatmap

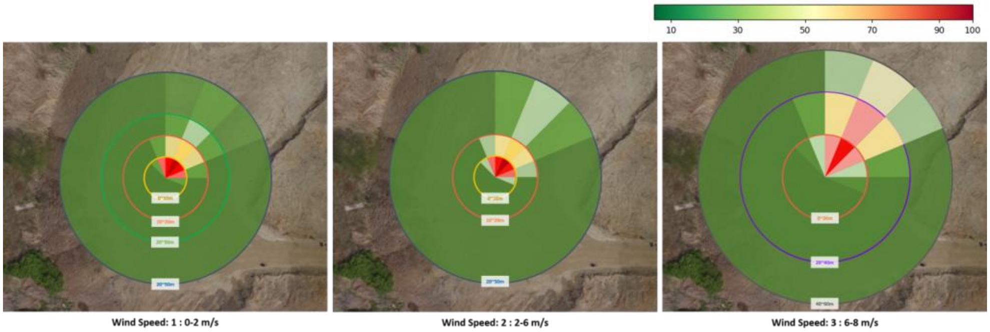


Figure 3.7(b): PM10 weighting percentage heatmap

Weight percentage equations were applied to the basic IDW for PM-fit spatial interpolation method customization. Being aware that weight percentage needed to be proportionally applied to the basic IDW, weight percentage was multiplied in the numerator of the IDW basic weighting system. Correspondingly, Equations 3.5 and 3.6 represent the newly created wind-applied IDW method, or dust estimation model, where x_e, n, x_i, w_i, represent estimated PM concentration for sensor i, number of PM measurement sensors, actual measured PM concentration for sensor i, and weighting for sensor i, respectively.

$$\boldsymbol{x_e} = \sum_{i=1}^{n} \frac{x_i \cdot w_i}{w_i} \tag{3.5}$$

$$\boldsymbol{w_i} = \frac{WP}{(d_i)^2} \tag{3.6}$$

The developed dust, or PM, estimation model was verified using the model verification dataset, where dust data was collected in random locations in the experiment site for model utilization sensor and verification points. For the verification process, the performances of basic IDW and dust estimation model estimation results were compared using the three most common error values, mean absolute error (MAE), mean absolute percentage error (MAPE), and root mean square error (RMSE) (Kang et al., 2021) as shown in Equations 3.7, 3.8 and 3.9, respectively.

$$\boldsymbol{Mean\ \ Absolute\ \ Error\ \ (MAE)} = \frac{1}{n} \times \sum_{i=1}^{n} |x_i - x_e| \tag{3.7}$$

$$\boldsymbol{Mean\ \ Absolute\ \ Percentage\ \ Error\ \ (MAPE)} = \frac{1}{n} \times \sum_{i=1}^{n} \left|\frac{x_i - x_e}{x_i}\right| \tag{3.8}$$

$$\boldsymbol{Root\ \ Mean\ \ Square\ \ Error\ \ (RMSE)} = \sqrt{\frac{1}{n} \times \sum_{i=1}^{n} (x_i - x_e\ )^2} \tag{3.9}$$

3.3.4. Visualization of Particulate Matter Concentrations

The estimated PM concentration results for the entire site were visualized using the Open3D program in Python. Open3D was operated to visualize the consolidated information in a 3D map result through Python, indicating low, medium, and high PM concentrations in colors of green, yellow, and red. The site was mapped and divided into appropriate pixels, where each area was given an appropriate color according to the estimated PM concentrations. In the final result, a 3D map of the site was visualized in the bottom layer and the PM concentration map on the top layer.

3.4. Model Verification

3.4.1. Verification Design

Model verification dataset was accumulated for dust estimation model verification in a 60m x 50m field using 22 sensors. Sensors needed to be placed uniformly, covering both high and low concentration areas for best spatial interpolation performance (Kim and Jo, 2012). Likewise, after random sampling of 1000 combinations of various numbers and placement of sensors, to cover the entire site, about 12 sensors were desirable as input data for spatial interpolation for outstanding estimation results as shown in Figure 3.8. The remaining 10 sensors were used for verification points, comparing estimated values with the actual measured ground truth values. The model verification dataset was collected in different wind directions than the experiment dataset to ease any doubts in the verification process.

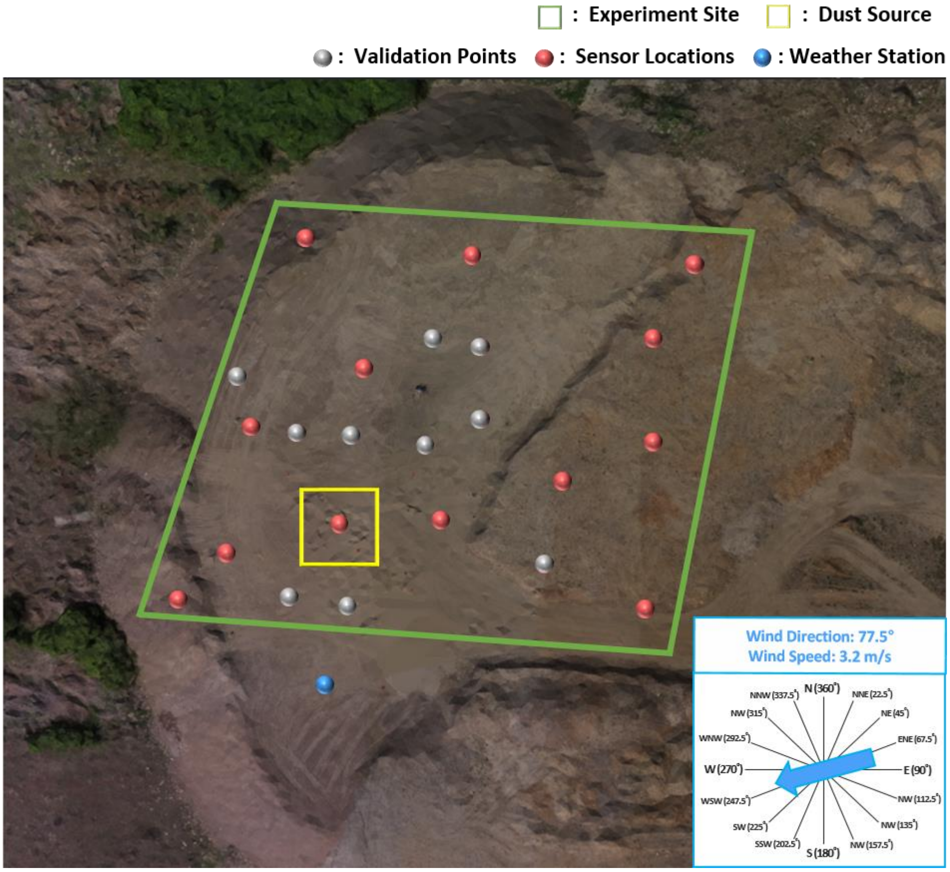


Figure 3.8: Sensor locations for verification data collection

3.4.2. Verification Results and Discussions

The best random sampling results of each number of sensors are demonstrated in Table 3.1(a), PM2.5, and Table 3.1(b), PM10. Briefly mentioned in the verification design part, the estimation result showed best performance when using 12 sensors with the error values.

Table: 3.1(a): Verification results for PM2.5

Number of Sensors	MAE	MAPE	RMSE
8	19.57	2.35	31.81
9	10.79	1.23	19.51
10	6.04	0.85	8.77
11	1.98	0.28	2.51
12	1.62	0.17	2.13
13	1.21	0.14	1.50

Table: 3.1(b): Verification results for PM10

Number of Sensors	MAE	MAPE	RMSE
8	19.16	0.33	41.67
9	7.93	0.3	10.05
10	5.21	0.17	7.22
11	3.68	0.17	4.67
12	3.20	0.14	3.94
13	2.66	0.13	3.20

The PM estimation results of basic IDW, the current methodology for real-time PM estimation (Shogrkhodaei et al. 2021; Kim and Jo 2012; Cho and Jeong 2009), and wind-applied IDW were compared as shown in Table 3.2(a) and Table 3.2(b). For PM2.5 Basic IDW showed pointless application level of performance with an MAE of 21.25, MAPE of 2.77, and RMSE of 24.49, whereas customized wind-applied IDW showed tremendous improvements, MAE of 1.62, MAPE of 0.17, and RMSE of 2.13. Consequently, the error was decreased by more than 91% for all three estimation error results, based on Equation 3.10. PM10 was also enhanced with error decrease percent of more than 92% for all the error values. Error values of PM10 for basic IDW were MAE of 56.98, MAPE of 1.83, and RMSE of 73.99, when wind-applied IDW performed MAE of 3.20, MAPE of 0.14, and RMSE of 3.94. Despite the lower MAPE value, PM10 calculates a higher error value compared to PM2.5 estimation model due to the overall higher PM concentration measurements. Regarding the error values, both PM2.5 and PM10 estimated results satisfied KTR class 1 standard, higher than 80% accuracy, and the MCERTS certificate standards, error less than 5 $\mu g/m^3$ (Korea Testing & Research Institute, 2017; CSA Group, 2023). The estimation results successfully verified the dust estimation model and showed dramatic improvements by simply applying wind to the basic IDW without any other complicated processes.

$$\boldsymbol{Error\ \ Decrease}: \frac{(Basic\ \ IDW\ \ error - Wind{-}applied\ \ IDW\ \ error)}{|Basic\ \ IDW\ \ error|} \times 100 \quad (3.10)$$

Table 3.2(a): IDW estimation result comparison, PM2.5

Method	MAE	MAPE	RMSE
Basic IDW	21.25	2.77	24.49
Wind-applied IDW	1.62	0.17	2.13
Error Decrease (%)	92.4	93.9	91.3

Table 3.2(b): IDW estimation result comparison, PM10

Method	MAE	MAPE	RMSE
Basic IDW	56.98	1.83	73.99
Wind-applied IDW	3.20	0.14	3.94
Error Decrease (%)	94.4	92.3	94.7

Wind blowing from east-northeast to west-southwest, visualized estimated PM concentration results are shown in Figure 4 with two options, side and bird-eye views. The side view provides 3D map in two layers of top, the PM concentration map, and bottom, the point cloud map of the site. Figure 3.9(a) indicates the mapping result for PM2.5 and Figure 3.9(b) demonstrates the mapping result for PM10. Moreover, the mapping results were analyzed in Figure 3.10(a) and Figure 3.10(b).

Examining the PM2.5 mapped results as seen in Figure 3.10(a), actual sensor values measure low PM of 8.20 μg/m^3 and 11.10 μg/m^3 due to the far distance and away from the wind path, as in the green and orange table. For the same area, wind-applied IDW was able to consider the PM characteristics based on distance, estimating within a fair range of 7.15 μg/m3 and 15.58 μg/m3, respectively. Similarly, seen in blue marks, even though near the dust source, with the consideration of the wind, wind-applied IDW estimated low concentration of 9.54 μg/m3, close to the actual concentration of 9.80 μg/m^3. Also in the lower left part of the maps, the model was able to show steadily high PM concentration with the wind effect of distributing PM further than usual in the windward path areas.

Besides the much higher concentration values, PM10 showed similar mapping patterns with PM2.5 mapping results. Wind-applied IDW was able to correctly estimate the PM movement along the wind path. Observing the tables in Figure 10(b), when the actual PM10 concentrations were 28.10 μg/m^3, 19.40 μg/m^3, and 26.10 μg/m^3, reading from the upper table to down, the new estimation model was able to estimate explicit concentrations of 28.88 μg/m^3, 21.86 μg/m^3, and 27.01 μg/m^3, almost identical values with the actual concentration. Overall, analyzing the results, the wind-applied IDW method empowered quantitatively and visually for more accurate PM estimation results.

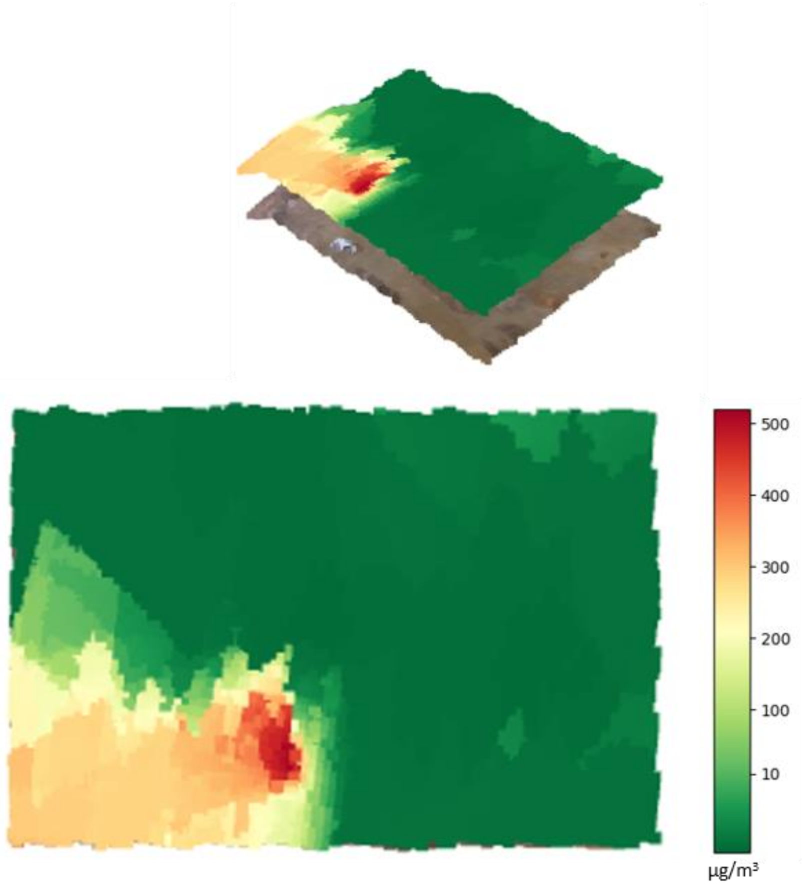


Figure 3.9(a): Wind-applied IDW mapping result, PM2.5

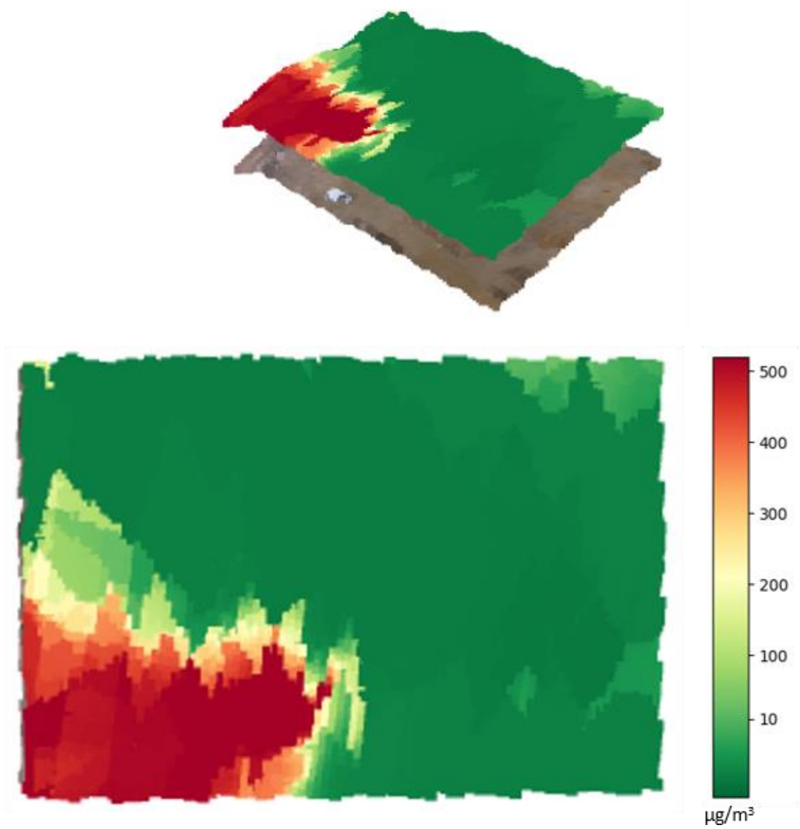
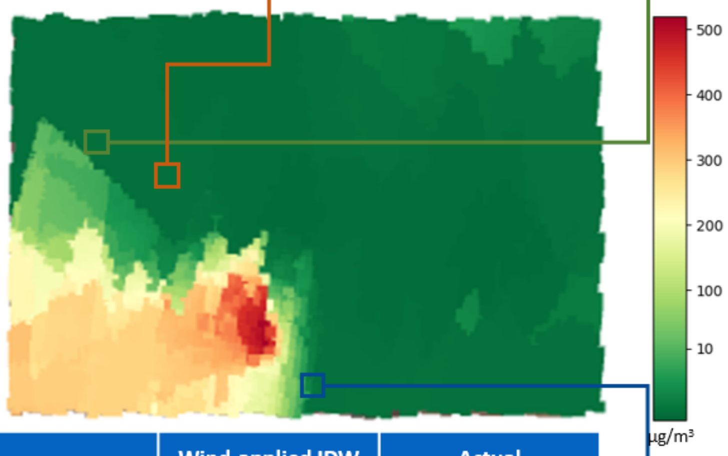


Figure 3.9(b): Wind-applied IDW mapping result, PM10

	Wind-applied IDW	Actual
PM (ug/m3)	7.15	8.20

	Wind-applied IDW	Actual
PM (ug/m3)	15.58	11.10



	Wind-applied IDW	Actual
PM (ug/m3)	9.54	9.80

Figure 3.10(a): PM2.5 mapping result analysis

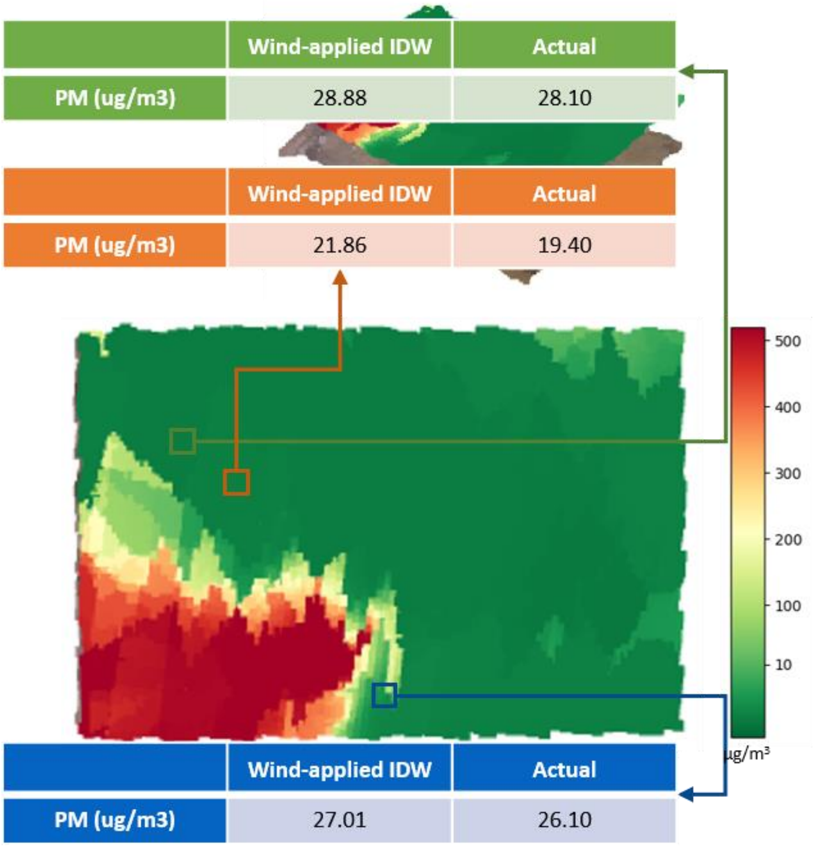


Figure 3.10(b): PM10 mapping result analysis

As verified in the error results and the visualized maps, particle matters being small-size and light-weight were heavily dependent on wind. Likewise, PM movement occurred only in the pathway of the wind direction starting from the dust source; areas outside the direct pathway indicated low PM concentrations, almost similar to the background PM measurement. With the inclusion of wind, wind-applied IDW method implemented the essential characteristics of PM and proficiently estimated the unknown PM values, as seen in the results. Utilizing the invented construction dust estimation model, the constriction dust can be estimated and visualized in real-time with the updated PM concentrations values from the sensors every minute. The results once again proved that the wind-applied IDW method can easily and simply, without other overwhelming parameters, estimate construction PM in real-time for both PM2.5 and PM10.

Chapter 4. Results and Discussions

4.1. Construction Site Application Designs

4.1.1. Construction Site Explanations

The verified dust estimation model was tested in real construction sites for applicability in real-world scenarios. To validate the method in as many situations as possible, three different types of construction sites, road, bridge, and building were selected for field application as explained in Table 4.1. All the construction sites were in the earthwork phase of construction, in which comparably fewer obstacles were placed in the site.

The selected road construction site was located in Jeungpyeong, South Korea with a size of 400 x 40m. Road construction sites are typically long in length, but short in width. Likewise, due to the limited space, only few equipment and workers are sparsely placed for construction work, which also means PM created near the entrance of the site generally does not reach the exit of the site. Therefore, the correlation between PM travel distances and wind speeds can be validated. Three equipment, a breaker, a dump truck, and a water sprinkler truck were operated in the road construction site.

The bridge construction site was located in Sejong, South Korea with a size of 100 x 60m. Although smallest among the three selected sites, bridge site was the most convoluted with diverse equipment. The site being located in the mountain regions; terrains were erratic with different ground heights. Bridge construction sites commonly generate high wind speeds due to the erratic shape of grounds and comprise numerous impediments disturbing the PM distributions. Correspondingly, the applicability of the model can be validated for complex sites, through the selected bridge construction site.

The building construction site, located in Yeoncheon, South Korea, was the same location as the model verification experiment site. Very recently, the Survey of Construction (SOC) Demonstration Research Center went into building construction to expand the facilities at the center. Building sites are generally similar in length and width, which allows evenly PM distribution throughout the site. Very alike to the bridge sites, terrains of the building field were irregular and consisted of many obstacles. The building site allowed comprehensive validation process of both wind direction and speed.

Table 4.1: Specification of the applied construction sites

Type of Site	Location	Size (m)	Experiment Duration	Types of Equipment
Road	Jeungpyeong, South Korea	400x40	1 day (2022.10.20)	Breaker, Dump Truck, and Water Sprinkler Truck
Bridge	Sejong, South Korea	100x60	3 days (2023.4.12 ~ 2023.4.14)	Excavator, Dump Truck, Water Sprinkler Truck, Mixer, and Pile Driver
Building	Yeoncheon, South Korea	120x140	2 days (2023.2.7 ~ 2023.2.8)	Excavator
		220x250	1 Day (2023.02.10)	Excavator and Breaker

4.1.2. Data Collection Design

In the data collection setup process, sensors were installed in appropriate locations for the selected sites. Observed from the model verification results, sensors needed to be placed in the following areas: 1) Dust source, i.e. construction equipment, 2) near major obstacles or hills, where PM movements can be critically affected, 3) outermost edge of the site. Besides the required regions, based on the site characteristics, extra sensors were placed in appropriate locations for dust data collection. Moreover, sensors were placed in random locations, apart from the method utilized sensors, for validation points. All sensor and weather station locations were confirmed by the site managers beforehand and placed where absolutely no interference to the construction works. Figure 4.1 demonstrates the examples of sensor installment on main dust sources, construction equipment, at the construction site.

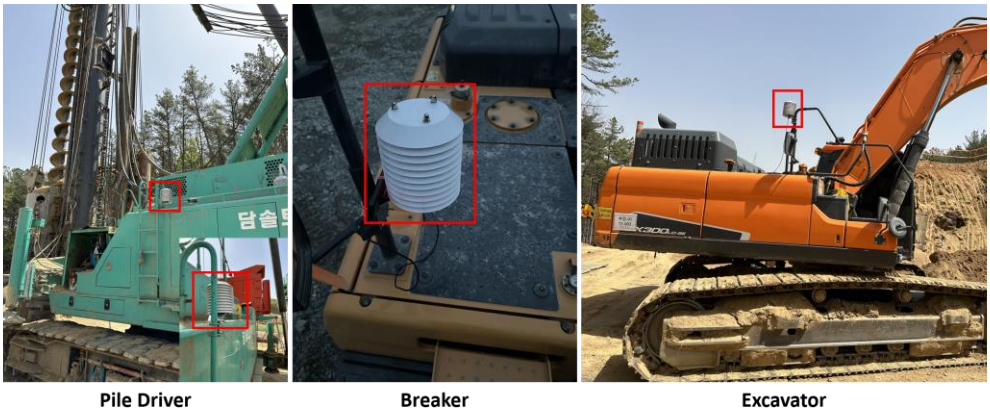


Figure 4.1: Example of sensor installation of construction equipment

Road construction site:

Road construction site was long in length, which required additional sensor installation between the outermost edge and the dust source to detect the whole site. Hence, a total of 17 sensors were used, 8 sensors for PM estimation of the construction site and the remaining 9 for validation points as shown in Figure 4.2. The 8 sensor locations were selected based on the three mandatory areas, one for the construction equipment, an excavator, four on the outer areas, one where pile obstacles are placed next to the dust source, and finally two between the dust source and the outermost sensors. The picture of the data collection setup layout is shown in Figure 4.3. The road construction data was collected for 60 minutes.

Figure 4.2: Data collection setup for road construction site application

Figure 4.3: Road construction site layout

Bridge construction site:

Although the bridge construction site was smallest in size, it embedded the most complex terrain shapes with operation of various construction equipment at the field. Therefore, fulfilling all the required criteria for accurate PM estimation, 10 sensors were used for the estimation model, five for the sidelines of the site, two near hills or obstacles, and total of three sensors for construction equipment, an excavator, a pile driver, and a mixer. In summation, total of 19 sensors were used, where 9 sensors were utilized as validation points. The data collection setup and the picture of the layout are shown in Figure 4.4 and Figure 4.5. A total of 906 minutes of dust data were collected between the 3 experiment days.

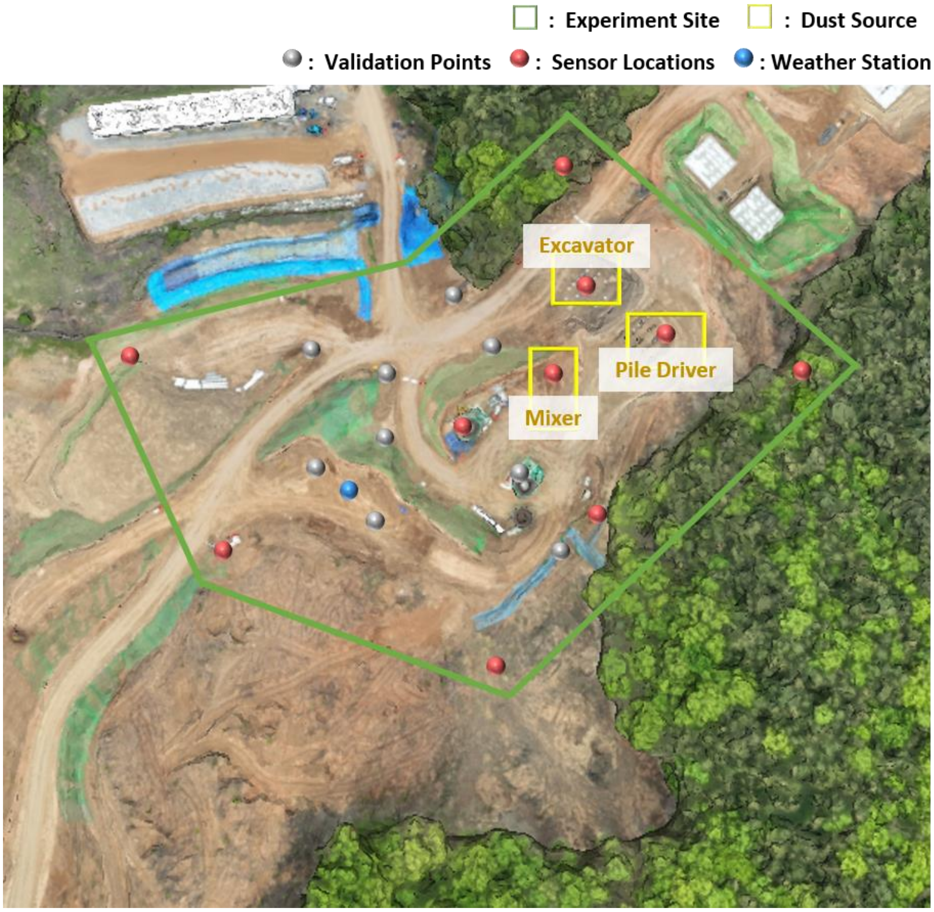


Figure 4.4: Data collection setup for bridge construction site application

Figure 4.5: Bridge construction site layout

Building construction site:

The building construction site applicability was validated in two different areas inside the demonstration center. The size of the first site was 120 x 140m with the operation of one excavator, whereas the second site was conducted in a bigger area of 220 x 250m with an excavator and a breaker. The two sites were utilized in different days where site 1 was measured for 2 days and site 2 for a day. 12 sensors were used for site 1, of which 7 sensors were used for the model and rest for validation points. Other than five sensors for the outer areas and an excavator, two extra sensors were installed near the bumpy dirt mounds as seen in Figure 4.6. The picture of the building site is also shown in Figure 4.7. For site 2, 15 sensors were used for the model sensors and validation spots. 8 sensors were placed for the model usage sensors, one each for the two construction equipment, four in the outskirt areas of the site, and two for the dirt mounds at the site as presented in Figure 4.8 and Figure 4.9. For the first day, dust data was collected for 181 minutes at a 120 x 40m site with one excavator in operation. The second experiment was held in 220 x 250m site for 168 minutes with an excavator and a breaker.

Figure 4.6: Data collection setup for building construction site 1

Figure 4.7: Building construction site 1 layout

Figure 4.8: Data collection setup for building construction site 2

Figure 4.9: Building construction site 2 layout

4.2. Application Results and Discussions

All of the construction site performance were also expressed in the most three common errors MAE, MAPE, and RMSE. Each error value was expressed in one average value of all the error results for the data collection period. Furthermore, a new discrete color bar was used for easier differentiation of PM concentrations. The color ranges are mainly divided into four colors following the standard defined by the Ministry of Environment, South Korea (2020a), which also referred to the color bar from Air Korea, a forecasting website for air quality in Korea (Air Korea 2023). Blue indicates a good atmosphere, green as moderate, yellow as bad, and red as very bad.

4.2.1. Road Construction Site

The estimation result of the road construction site for both PM2.5 and PM10 are shown in Table 4.2. The performance of the estimation result was fairly good, meeting the accuracies of both MCERTS and KTR standards (Korea Testing & Research Institute, 2017; CSA Group, 2023). PM2.5 showed excellent performance, MAE of 3.56, MAPE of 0.09, and RMSE of 4.22. Also, PM10 was able to meet MAE of 4.04, MAPE of 0.09, and RMSE of 5.09. Despite the fewer sensors used than at the experiment site, the model was able to estimate in acceptable range.

Table 4.2: Road construction site estimation results

Type of PM	MAE	MAPE	RMSE
PM2.5	3.56	0.09	4.22
PM10	4.05	0.09	5.09

The examples of the mapping results are shown in Figure 4.10. Looking at the map result, the dust source location can be easily found as it shows the darkest color on the map. Regarding the characteristics of a breaker, in which rocks or possibly particulates are continuously broken down into smaller pieces, PM2.5 concentrations were very high, whereas PM sizes larger than 2.5 seems inconspicuous. Also analyzing the map as seen in Figure 4.11, although there were no defined dust sources at the end of the site, estimation model was able to detect the fugitive dust of PM2.5 that may have aroused due to wind. Although wind direction was from right to left, as seen in Figure 4.11, due to the lengthy characteristics of the road construction site and the effect of low wind speed, PM concentrations created from the construction equipment or the fugitive dust took a long time to travel throughout the site leaving gaps between the sites. PM10 is marked with larger gaps since it takes even more travel time, one of the characteristics of heavier and bigger particulate.

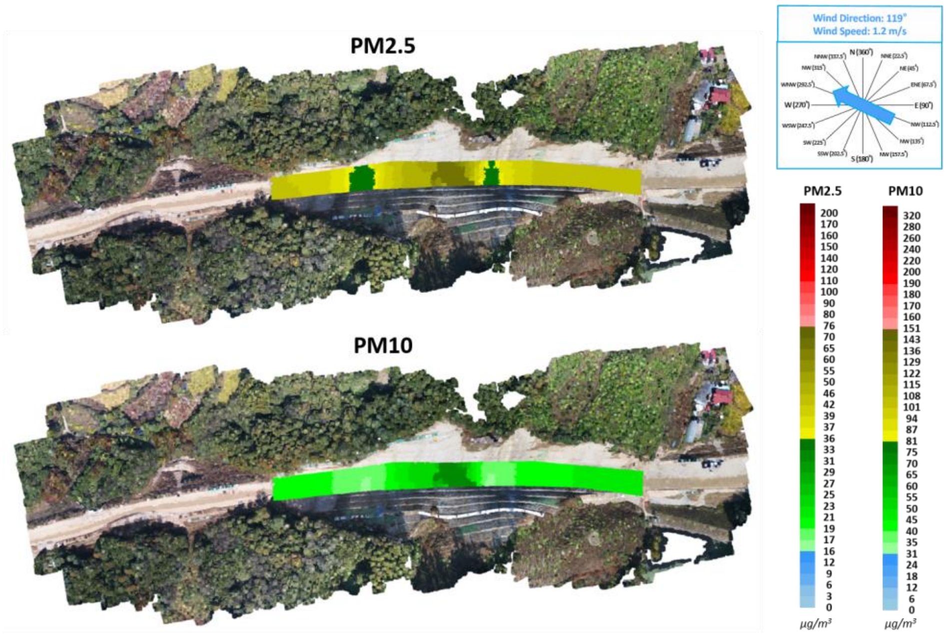


Figure 4.10: Mapping result of road construction site

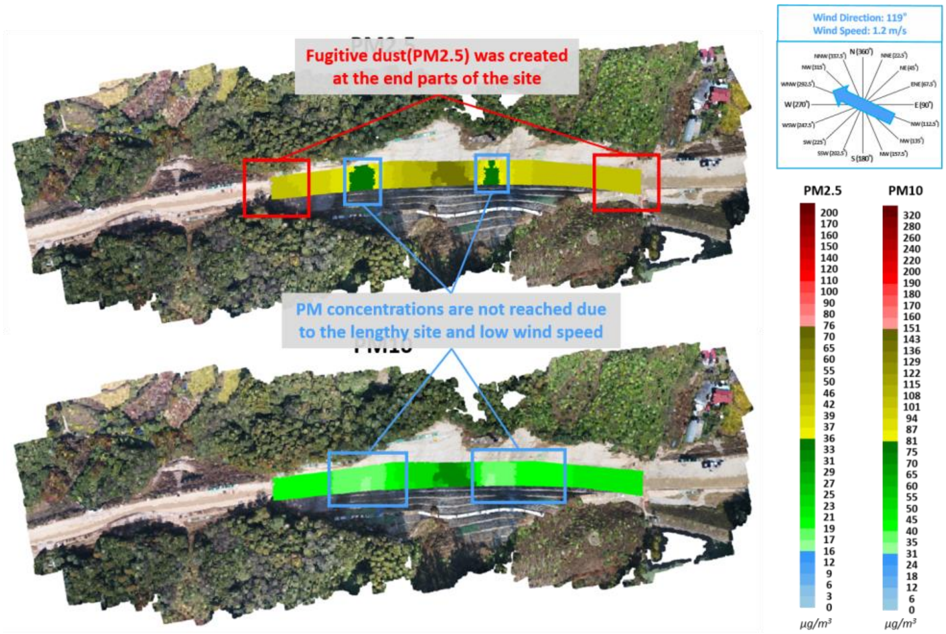


Figure 4.11: Analysis of mapping result of road construction site

Another key factor is the effect of water sprinkler truck. While PM10 barely had any effect due to the already low concentrations, PM2.5 had a dramatic decrease with the effect of the water sprinkler truck as seen in Figure 4.12. Correspondingly, using the construction dust estimation mapping result, the manager can easily and instantly realize when and where the reduction equipment is needed as well as the effects, allowing efficient reduction plans for the site. Overall, the estimation model was able to display the exact situations of the site in real-time, once again evidently explaining the benefits of the model.

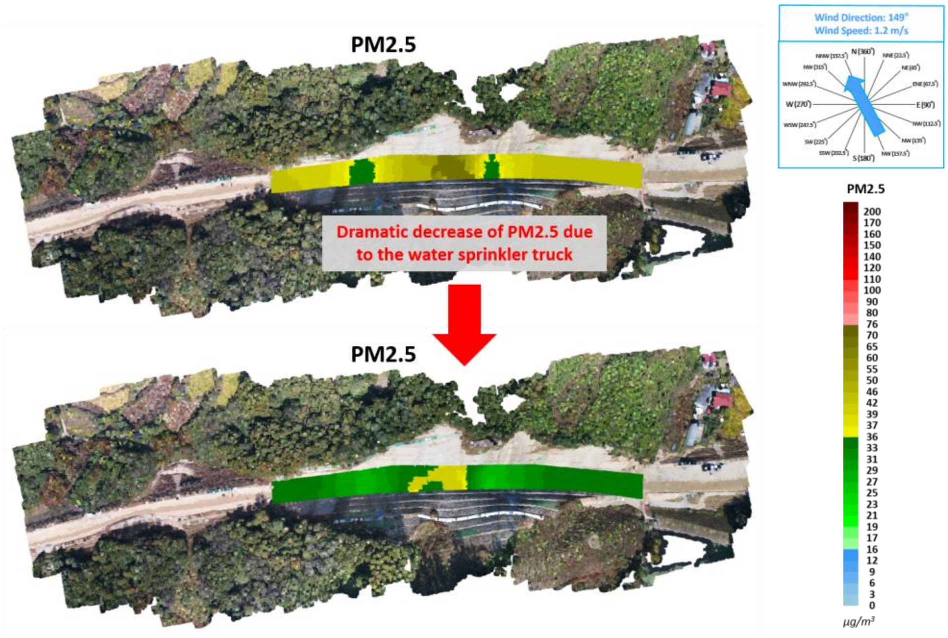


Figure 4.12: Effect of water sprinkler truck on PM2.5

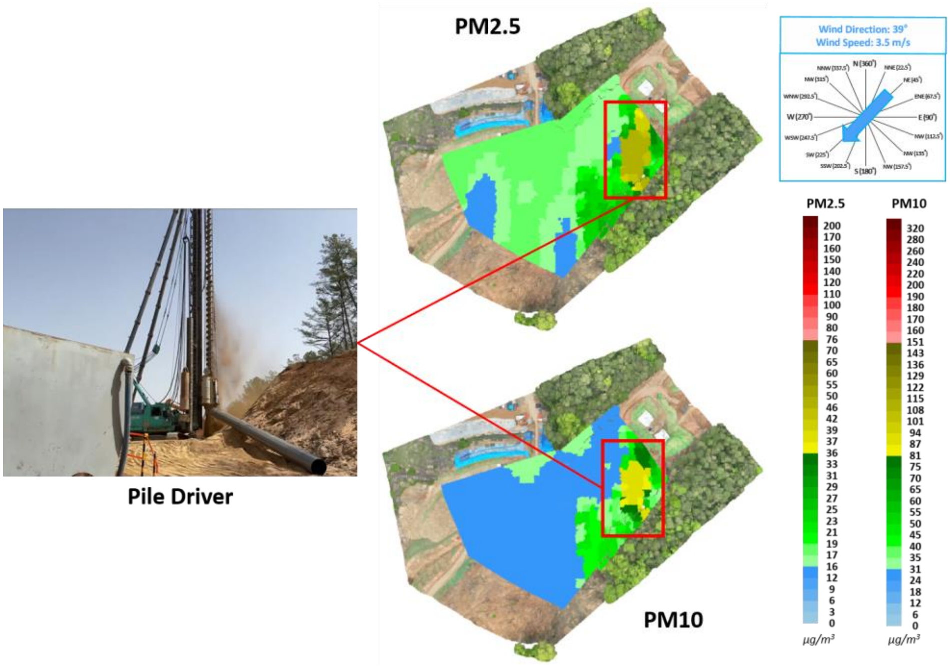
4.2.2. Bridge Construction Site

The bridge construction site being more complex in terrain and diverse in usage of construction equipment, estimation error results were slightly higher than the road construction site. As written in Table 4.3, PM2.5 showed the error values of MAE, 3.08, MAPE, 0.17, and RMSE, 4.72, while PM10 showed a higher MAE of 5.29, same MAPE of 0.17, and also higher RMSE of 8.30. Regardless of the same MAPE values, PM10 shows higher error values because of the higher concentration. For example, when 5 percent error occurs for PM2.5, the error value was 1.85 $\mu g/m^3$ calculated from a max concentration of 37 $\mu g/m^3$, while for the same percent error, PM10 showed 2.75 $\mu g/m^3$ being out of maximum concentration of 55 $\mu g/m^3$. Overall, the error value was sufficient to satisfy the desired accuracy of KTR (Korea Testing & Research Institute, 2017).

Table 4.3: Bridge construction site estimation results

Type of PM	MAE	MAPE	RMSE
PM2.5	3.08	0.17	4.72
PM10	5.29	0.17	8.30

The mapping results during construction equipment operations for the building site are shown in Figure 4.13. Total of three equipment were used in the bridge site, where pile driver accounted for the most PM emission. Mixer and excavator were generally operated at the same time acting as a massive PM source. Also aligning with the road construction site, the PM diminishing effect of the water sprinkler trucks were monitored in the mapping results. However, the sprinkler was not able to lessen the PM created from the mixer, due to the gaseous characteristics of dispersing before reaching the wet ground. Overall, as seen in the figures, the created model allowed accurate mapping results of PM distribution of the construction site based on equipment operations.



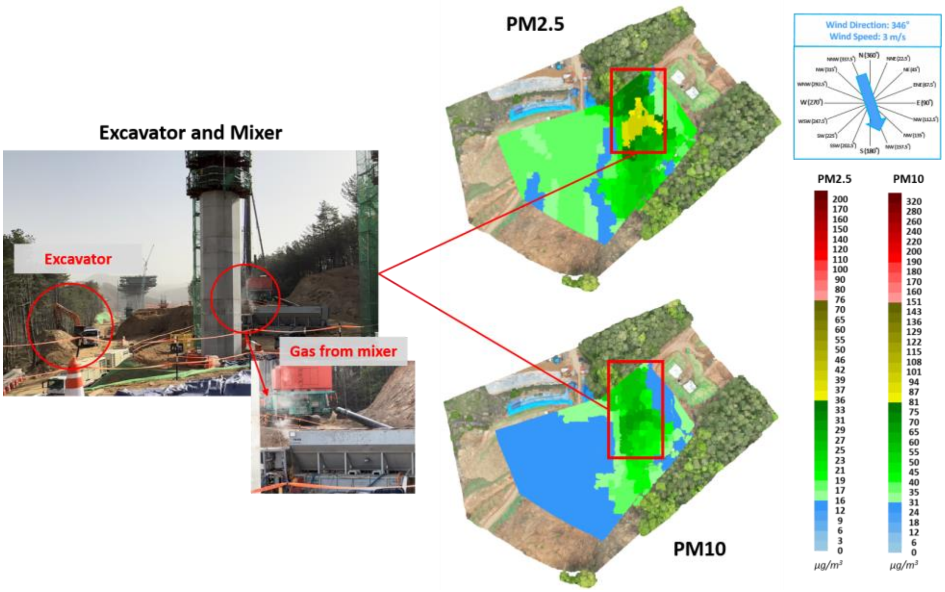


Figure 4.13: Mapping results during construction equipment operations

Although the model showed great performance, examining each error value for all the collected data, improvement aspects were identified for future application. From the error values, approximately 6 cases were identified to result in high errors; PM2.5, over 20 for RMSE, and PM10, 40 for the RMSE value. Two possibilities were discovered for such phenomenon. The substantial error can be attributed to a discrepancy of approximately 2.5 meters in the sensor's Global Positioning System (GPS) values or an error within the point cloud coordinate data. Consequently, the discrepancy resulted in the model inaccurately assuming a distance of 11.3 meters when the actual distance was 7 meters as shown in Figure 4.14, thereby leading to an underestimation of PM estimation value. The observation implies an area of potential improvement: the model's performance might be significantly enhanced by minimizing GPS errors or acquiring more precise point cloud data. Another error may have occurred due to the sensing module blockage of newly entered moving obstacles or new dust erosion from a new PM source as shown in Figure 4.15. For example, if a vehicle or a truck is stationed in front of the validation sensor, most of the PM can be stopped by the new distractor resulting in lower concentration in the validation sensor. The estimation process will be unaffected with an input sensor is nearby, but if the validation sensor stands alone, the calibration is unachievable; therefore, high error value due to the mismatch of high estimated value and low validation value. Similarly, the truck can also act as a new dust source causing fugitive PM only near the validation sensor causing high concentration values while the input sensor not being able to consider the new dust source, estimates low PM for the validation areas. The following miscalculation can be easily solved if a sensing module can be mounted onto the newly entered vehicles. When excluding the two situations, the performance of the PM estimation model is predicted to provide superb results of PM2.5, 2,40, 0.17, and 2.95, while for PM10, 3.95, 0.16, and 4.89, in orders of MAE, MAPE, and RMSE, respectively.

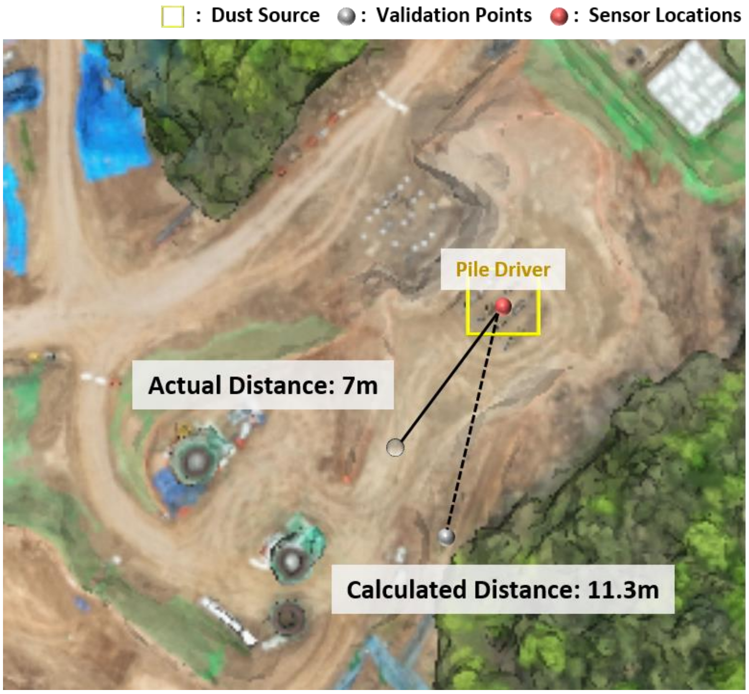


Figure 4.14: GPS error example

Figure 4.15: Example of a new dust source or an obstacle

4.2.3. Building Construction Site

The building construction site was large in size, with many dirt mounds as the building was in the very beginning of the earthwork phase. As mentioned in the previous data collection section, the building construction site was subdivided into two construction sites.

Building construction site 1

The estimation results for the first building construction site are shown in Table 4.4. Building site 1 showed a unique estimation result than the other sites. PM10 error values, MAE of 2.46, MAPE of 0.04, and RMSE of 3.36, were lower than the values of PM2.5, MAE of 2.90, MAPE of 0.05, and RMSE of 3.96.

Table 4.4: Building construction site 1 estimation results

Type of PM	MAE	MAPE	RMSE
PM2.5	2.90	0.05	3.96
PM10	2.46	0.04	3.36

Observing the error results, the concentrations of PM2.5 and PM10 were almost identical, in which very minimal, almost none, dust was created from the defined dust source, the excavator. Both PM2.5 and PM10 had the average background PM concentration of 64 μg/m^3 and 68 μg/m^3, which means most particulate in the atmosphere was sized diameter below 2.5 μm. Analyzing the actual construction site, the author was able to witness the high moisture ground condition as shown in Figure 4.16. Consequently, dust production was significantly mitigated. Through these conditions, the author was able to deduce that the sensor could achieve reasonably high accuracy in mapping, irrespective of additional parameterization, contingent upon soil conditions. This finding substantiates the superiority of sensor measurement in contrast to diffusion or simulation methods, where all the parameters need to be observed and provided as input.

Figure 4.16: Moisturized ground condition of building site 1

Another interesting inspection made in the building construction site was the effect of the noise barrier wall, which in this case also acted as a dust collector. As shown in Figure 4.17, the congestion of PM concentrations was seen in the right sides, where noise barriers are installed. Although the wall may be a positive component for stopping the leakage of PM in the surrounding areas, but can also act as a hazardous area for the construction workers. Therefore, constant monitoring needs to be conducted for safer construction sites.

The sensors were able to consider the conditions of the soil by collecting the dust data in real-time. Accordingly, both results showed excellent outcomes with accurate estimations of dust emission. The results also met all the requirements for MCERTS and KTR standards (Korea Testing & Research Institute, 2017; CSA Group, 2023).

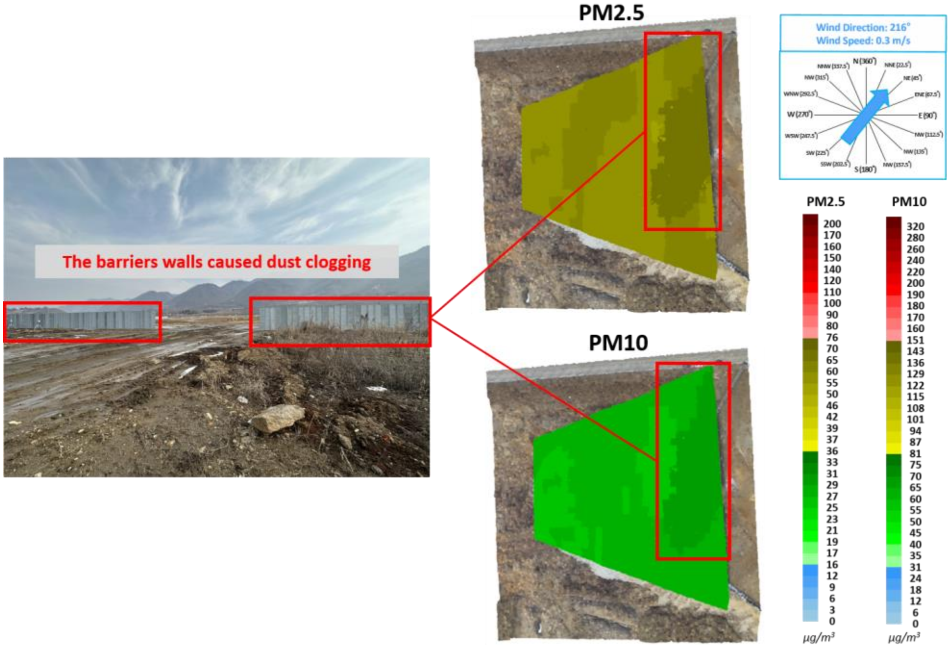


Figure 4.17: The mapping result of the barrier wall effect

Building construction site 2

Building construction site 2 was setup for data collection as mentioned in the previous section. However, within few minutes of the data collection process, the site started raining. Most of the collected data in all the locations were between 10 to 20 μg/m^3, the background PM at the site. Not able to collect adequate dust data for analysis, the building construction site 2 data were neglected for further analysis.

4.2.4. Summary

In this chapter, the dust estimation model, the wind-applied spatial interpolation method, was applied in actual construction sites for validation. The applicability was validated in three different sites, road, bridge, and building sites. Overall, the model showed magnificent performance, enough to meet the required standard values of KTR and MCERTS (Korea Testing & Research Institute, 2017; CSA Group, 2023). Also observing the mapping results, PM10 was fairly managed with low concentrations in most cases; however, in most of the situations, PM2.5 showed high concentration and vigorous dispersion. The estimation model and the visualized mapping result were able to detect the overall PM dispersion of the entire construction site as well as demonstrate the effect of the mitigation equipment after use. In summation, the necessity and effectiveness of the monitoring method were emphasized.

Although many approaches were suggested to monitor PM, this is the first actual construction site based and wind considered PM estimation method to the best of the authors' knowledge that provides a visual PM monitoring method fitted for the entire construction site in real-time. The new micro-scale and real-time PM estimation method can significantly protect workers' health and help construct effective PM reduction plans without waste by providing them with instant feedback about polluted areas.

Chapter 5. Conclusions

5.1. Summary and Contributions

This research proposed a revolutionary dust estimation method for real-time monitoring of construction site PM. First, PM dispersion characteristics were analyzed, which strong correlations were found between PM dispersion, wind, and distance. Applying wind to the basic IDW, the model allowed analysis and update of more accurate movements of PM in construction sites. As a result, the wind-applied IDW method successfully estimated PM concentrations in every location of the entire construction site in real-time. The developed dust estimation model was verified, in an experiment site, and validated in three different real-world construction sites, road, bridge, and building.

The success of the construction site applicability allowed more discrete outcomes of the research result and contributions in the construction related research realm. This research can contribute in many ways. Academically, Real-time particulate matter (PM) data plays a fundamental role in constructing a dynamic and responsive digital twin for construction site operations. This digitally replicated model, fueled by the influx of live PM data, renders an accurate simulation of the construction site, thereby forming a basis for data-driven decision making and strategic planning. Most importantly, the overwhelming amount of experiments and real construction dust data can be provided for future researches.

The effective management of PM in construction sites necessitates the identification of high PM concentration areas to devise cost-efficient reduction plans, alongside continuous surveillance of workers' PM exposure for creating safer workplaces. Leveraging advanced monitoring methods and data analysis, managers can pinpoint PM hotspots and accordingly, formulate targeted reduction strategies. The PM mapping results can display the effects of the reduction strategies, showing exactly how the reduction equipment are utilized. Moreover, managers can announce the PM danger areas to the workers, allowing workers to wear appropriate PM protection gears, such as masks and goggles, before entering the hotspots. Simultaneously, real-time PM exposure data helps to maintain health and safety standards for workers. Successful implementation not only mitigates potential civil complaints but also ensures preparedness to address such issues, thereby reinforcing the site's commitment to environmental responsibility and worker wellbeing.

5.2. Improvement Opportunities and Future Research

Despite the fairly successful method, as this was a preliminary approach introduced, few improvements can be made for higher accuracy: 1) mount the sensing module on dump trucks or water sprinkler trucks to minimize the uncertainties to the estimation model, as explained in the bridge construction site application part of the research, 2) higher GPS accuracy to increase in construction PM estimation model performance.

Also, Future research can include, 1) extended research on developing a construction PM estimation method in peripheral areas for preemptive responses to nearby residents' civil complaints, and 2) Short-term health impact of construction PM, such as stress, heartbeat, vital signs, 3) Smart PM mitigation system based on the estimated concentrations.

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Abstract (Korean)

최첨단 환경 모니터링을 위한 실시간 건설현장 미세먼지 추정 기술 개발

황재현

서울대학교 대학원

건설환경공학부

입자상 물질(PM)이라고도 하는 과도한 미세먼지 오염은 건설 업계에서 주목할 만한 문제이며, 건설 근로자와 인근 주민 모두에게 심각한 피해를 입힙니다. 현재 이러한 미세먼지의 피해 완화 전략으로 상당한 물의 양이 비효율적으로 사용되거나 하나의 센서로 건설현장 전체의 미세먼지 농도를 가정하여 모니터링하는 방법들이 사용되고 있습니다. 이러한 한계점들과 문제점들을 해결하기 위해 지금까지 다양한 연구들이 이루어지고 있습니다.

많은 연구가 센서의 비용과 무게를 줄여 비용 효율을 높이고 현장에 쉽게 설치할 수 있도록 개발하는 데 집중했습니다. 센서 개발에 따라 저렴한 비용으로 현장 전체에 더 많은 센서를 설치할 수 있게 되었지만, 센서만의 활용 방법은 여전히 측정되지 않는 지역이 많았습니다. 이에 많은 연구들이 소수의 센서 측정값만으로 원하는 지역의 미세먼지 농도를 추정할 수 있는 공간 보간법을 이용해 특정 지역의 미세먼지 농도를 추정할 수 있는 연구들이 소개되었습니다. 추정 방법은 도시 또는 국가 단위와 같은 대규모 미세먼지 추정을 위한 다양한 접근 방식이 존재하지만, 건설 현장과 같이 상대적으로 작은 규모의 미세먼지 이동은 일관되지 않은 행동으로 인해 정확한 감시 및 관리에 상당한 어려움이 있습니다. 건설 작업의 복잡한 특성은 적시에 예방 조치를 취하는 데 필수적인 미세먼지의 실시간 모니터링을 전혀 하지 못하고 있습니다. 이러한 문제점들을 극복하고 대안을 마련하기 위해 본 연구에서는 건설현장의 미세먼지를 실시간으로 정확하게 파악할 수 있는 미세먼지 추정 기술을 개발하고자 합니다. 이 모델은 미세먼지에 영향을 미치는 주요 기상 요인인 바람과 센서와의 근접성을 모두 고려하는 혁신적인 미세먼지 추정 기술입니다.

사용성과 경제성을 극대화하기 위해 저가의 먼지 센서가 포함된 센싱 모듈을 개발하여 이 연구의 성공을 지원했습니다. 이 연구는 미세먼지의 특성과 분포를 분석하여 그 중 미세먼지에 가장 많은 영향을 주는 풍향과 풍속을 역거리 가중치(IDW)에

적용하여 건설현장 미세먼지 맞춤 역거리 가중치를 개발했습니다. 새로 개발된 모델은 바람이 부는 경로를 따라 더 가까운 지역에 더 큰 가중치를 부여하고 풍속까지, 즉 미세먼지가 이동할 수 있는 거리, 고려하여 가중치를 부여하게 됩니다. 이후 전체 현장의 미세먼지 농도를 3 차원 지도로 시각화하여 미세먼지 저감이 필요한 지역을 보여줌으로써 효과적인 저감 계획을 수립하고 작업자의 미세먼지 노출을 실시간으로 줄일 수 있습니다.

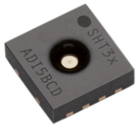
제안한 건설 먼지 추정 모델은 통제된 실험 현장에서 검증한 후 도로, 교량, 건축 공사장 등 세 가지 분야에서 실제 적용 가능성을 검증했습니다. 제안한 추정 방법과 이에 따라 시각화된 먼지 정보 3 차원 지도는 적은 수의 센서를 사용하여 먼지 농도를 자동으로 추정하고 시각화하는 스마트 환경 모니터링 방법을 제공합니다. 시각화된 지도는 현장 관리자에게 가이드라인으로 활용되어 향후 건설 현장 내 미세먼지로 인한 건강 및 환경 피해를 예방할 수 있습니다.

주요어: 건설 관리; 스마트 건설; 건설현장 미세먼지; PM2.5; PM10; 환경정보 센싱모듈; 저가 센서; 공간 보간법; 역거리 가중치 계산법; 3 차원 맵핑

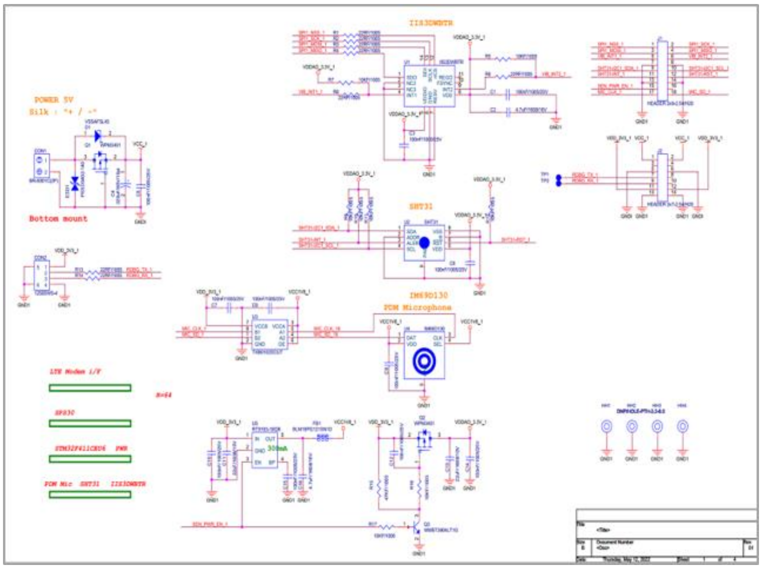
학번: 2021-24837

Appendix A. Sensing Module Development

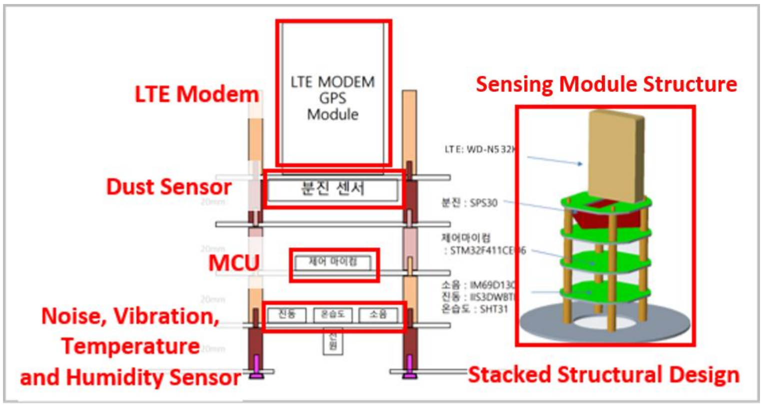
A.1. Other Environmental Sensor Specifications

Category	Specifications		
Noise	Model Name	IM69D130V01XTSA1	
	Manufacturer	Infineon Technologies	
	Measurement Unit	dBA	
Vibration	Model Name	LSM6DS3	
	Manufacturer	STMicroelectronics	
	Measurement Unit	m/s^2	
Dust	Model Name	SPS30	
	Manufacturer	Sensirion	
	Measurement Unit	$\mu g/m^3$ (PM2.5,10)	
Temperature & Humidity	Model Name	SHT31	
	Manufacturer	Sensirion	
	Measurement Unit	℃ (Temperature), % (Humidity)	
LTE Modem (& GPS Module)	Model Name	WD-N532K	
	Manufacturer	Woorinet	
	Communication Network	KT (Network: LTE Cat.M1)	
MCU	Model Name	STM32F411CEU6	
	Manufacturer	STMicroelectronics	
	Processor	ARM Cortex-M4	

A.2. Design of the Sensing Module



PCB design



Hardware Design