Monitoring, Visualization and Assessment of Air Pollutant Emissions on Construction Sites

Xiaoning Ren

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______________________________________ Chair
Dr. Leila Kosseim

______________________________________ External Examiner
Dr. Zhaoheng Liu

______________________________________ External to Program
Dr. Amin Hammad

______________________________________ Examiner
Dr. Osama Moselhi

______________________________________ Examiner
Dr. Chunjiang An

______________________________________ Thesis Co-Supervisor
Dr. Zhi Chen

______________________________________ Thesis Co-Supervisor
Dr. Zhenhua Zhu

Approved by____
Dr. Fariborz Haghighat, Graduate Program Director

November 30, 2018 ______________________________________
Dr. Amir Asif, Dean
Gina Cody School of Engineering and Computer Science

ABSTRACT

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Xiaoning Ren, Ph.D.
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The construction industry is always ranked as one of the largest emission contributors of air pollutants including nitrogen oxides (NO_x), carbon oxides (CO), volatile organic compounds (VOCs), and sulfur oxides (SO_x), which accounts for approximate 23% of the global air pollutions each year. These pollutants are detrimental to the ambient air quality and the health and safety of construction practitioners. The high pollutant emission level has attracted the government's interests to release regulations and initiatives to reduce the air pollutant emissions of construction projects. Also, construction practitioners and researchers are encouraged to mitigate the environmental impacts during the construction process. So far, most of the mitigation efforts have been placed on pre-assessing the environmental impacts of construction activities in the planning stage using emission estimation models. The emission estimation models were developed based on the emission rate analysis of the uninstalled engines in the laboratory environment. Therefore, the estimation models are not able to reflect the real-world emission rates, especially the emission rates of different working modes. In addition, the Portable Emissions Measurement System (PEMS) is employed to monitor the air pollutant emissions of the operating equipment in the construction stage. However, the costly expenses and the particular precautions when using the PEMS to monitor the air pollutant emissions significantly impede the utilization of PEMS. Also, it is impossible to install PEMS to each piece of construction equipment for the air pollutant emission monitoring of the whole construction projects.

The main objective of this research is to develop a set of tools to monitor and visualize the air pollutant emission on construction sites in the real-time and automatic manner. Towards this objective, an Internet of Things (IoT)-based system is created with the integration of microcontrollers, microsensors, and high-definition (HD) cameras. Specifically, the system can be employed to: 1) monitor the onsite air pollutant emissions during construction operations in an automatic and real-time manner; 2) dynamically and

continuously visualize the air pollutant emission; 3) automatically trigger alarms when the air pollutant emissions violate the standards; and 4) quantitatively assess the potential impacts on ambient air quality and the health of workforces. The system has been tested on real construction sites. The results indicated that the system could assist construction practitioners in the monitoring and visualization of the air pollutants produced from construction operations. Also, the results are able to facilitate decision-making on reducing the air pollutant emissions and promote the sustainability of construction operations.

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To My Beloved Family

For all your support, motivation and inspiration

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CHAPTER 1: INTRODUCTION

This research seeks to demonstrate that the technologies in the area of Internet of Things (IoT) with the integration of microcontrollers and microsensors can be used to monitor and visualize the air pollutant emissions on construction sites. This information can be further employed for the rapid assessment of the potential environmental impacts on the ambient air quality and the health of workforces and the automated generation of warning notifications when the onsite pollutant emissions violate the air quality standards. The following sections in this chapter introduce the research motivation, objectives, methodology, contributions, and the organization of this dissertation.

1.1. Problem Statement and Motivation

In recent years, there is a dramatic increase of environmental concerns throughout the world, since global climate change becomes a disturbing issue due to the excessive emission of Greenhouse Gas (GHG). In 2010, there were 30.6 Gt of carbon dioxides emitted into the atmosphere, which reached the highest level (Wong et al. 2013). According to U.S. Environmental Protection Agency (EPA), the breath air of most urban areas where the American live did not meet the National Ambient Air Quality Standards (NAAQS) (Government Printing Office 2007) because of the high emission level of ozone and particulate matters (Rasdorf et. al 2010).

According to the U.S. Environment Protection Agency, the construction industry sector was ranked as the third largest GHG emission contributor (behind the oil and gas sector and the chemical manufacturing sector), which accounted for 6% of the total GHG emissions among all industrial sectors in US (U.S. EPA 2008). In 2005, the annual GHG emissions of the Canadian building and construction industry were 80 million tons. In addition, the construction industry is a major source of criteria air pollutants (CAPs), especially referring to nitrogen oxides (NO_x), particulate matter (PM), carbon monoxide (CO), volatile organic compounds (VOCs), lead, and sulfur oxides (SO_x). The air quality study of UK revealed the construction sector is responsible for approximate 8% of NO_x

emissions every year (The Guardian 2017). Also, 8% of large particle emissions PM_{10} and 14.5% of emissions of the most dangerous fine particles $PM_{2.5}$ are produced from the construction projects (Environment and Climate Chang Canada 2017). The CAPs are detrimental to the ambient air quality and can induce immediate or/and chronic damage to human beings and the ecosystem (EPA Clean Air Act Advisory Committee 2006). Therefore, it is necessary and pressing to control and reduce air pollutant emissions generated from the construction industry.

Figure 1 Air pollution issues on construction sites (magicbricks.com)

Currently, a plethora of government regulations and initiatives has been released in order to reduce the air pollutant emissions generated in the construction industry. For example, the UK government called upon major contractors to take effective actions to cut the GHG emissions. Likewise, U.S. EPA introduced regulations for diesel-based construction equipment to control the construction emissions (U.S. EPA 2004). Moreover, a comprehensive national program was developed to reduce emissions from non-road diesel-based engines (U.S. EPA 2013), where urges engine manufacturers to produce new engines with advanced emission control technologies. The United States Green Building Council (U.S. GBC) developed the program of the Leadership in Energy and Environmental Design (LEED) to facilitate the sustainability of building and construction projects, which highlights the significant impacts of pollutants generated during construction operations. The task of preventing the pollutions from construction activities has been considered as the prerequisite for evaluating the overall environmental performance of construction projects (U.S. GBC 2014). Also, LEED takes into account the pollutions produced from the conventional fuel-based automobiles by recommending the adoption of alternative fuels-powered equipment as well as the reduction of equipment idling (U.S. GBC 2014).

In addition to the governmental regulations and policies, a plethora of research efforts has been mainly placed on the estimation of the potential air pollutant emissions in the planning phase based on the emission estimation models. U.S. EPA developed an emission estimation model, NONROAD, to quantify the typical pollutants, such as CO_x and NO_x, from the non-road construction equipment through the estimation of the fuel consumptions with the predefined pollutant emission rates. Similarly, the Urban Emissions Model (URBEMIS) is presented to estimate air pollutant emissions, which is mainly focused on the land use and development projects. So far, government and authorities have employed the models to facilitate the non-road equipment engine analysis (Beardsley and Lindhjem 1998) and evaluate the environmental performance of government-sponsored land use projects (Litman and Steel 2008). Nonetheless, the biggest drawback of the estimation models is the accuracy of the emission rates. The emission rates were investigated on the uninstalled engines in the laboratory environment (Frey et al. 2007). Therefore, the estimation models are not able to reflect the real-world emission rates, especially the emission rates of different working modes during the real-world construction activities (e.g. idling, traveling and operating). As a result, the emission estimation of the real-world construction activities is significantly underestimated.

In order to investigate the pollutant emissions of the real-world construction activities, researchers have deployed the Portable Emissions Measurement System (PEMS) to monitor the in-use emissions of construction equipment. Generally, PEMS is installed on the operating equipment with the connection to the tailpipe so that the diesel exhaust of the operating equipment can be directly collected. The PEMS is able to measure the mass emissions of NO, CO_x, and PM on a second-by-second basis, which provides a considerably accurate means of monitoring pollutants emitted from diesel-based engines.

North Carolina Department of Transportation and North Carolina State University conducted two field studies to monitor the air pollutant emissions and engine performance of the typical diesel-powered construction equipment (Frey et al. 2007). The selected equipment was prioritized based on the recommendations of the NONORAOD model, including backhoes, off-road trucks, excavators, generators, motor graders and bulldozers. However, the costly expenses, including the purchase cost and maintenance cost, hinder the wide deployment of PEMS, which can be more than 100,000 US dollars (Ren et al. 2018). In hence, it is impractical to install the PEMS onto each piece of construction equipment involved in the construction project. Furthermore, the PEMS is particularly sensitive to the weather and operating conditions. Certain particular precautions and expertise are always necessitated when using the PEMS to monitor the air pollutant emissions from construction equipment.

Alternatively, government and authorities placed the fixed air pollution monitors at the construction jobsites to monitor the real-world air pollutant emission from construction projects. The fixed monitors usually collect the air pollutant data on an hourly basis and transmit the data to the remote server. So far, the fixed monitors-based method has been mainly proposed for the mega construction projects. For example, an air pollutant monitor is placed on the construction site of Champlain Bridge corridor project to continuously monitor the air quality (Infrastructure Canada 2018). The fixed monitor collects the air pollutant data on an hourly basis and transmits the data to the remote office. Four air pollutant monitors were allocated on the four sides of the worksites of Turcot project to monitor the air quality of the construction site and the community (Ville De Montreal 2017). As for the regular construction projects, such as residential and industrial projects, few actions have been taken to monitor the air pollutant emissions and assess the potential environmental impacts. Also, the expense of the monitors is a big concern for the construction practitioners, since the fares of the purchase, operations and maintenance are up to 200,000 dollars (Ren et al. 2018). Moreover, certain expertise is necessitated for the regular calibration and maintenance.

Even though these two monitoring methods have been implemented to monitor the real-time construction activity-related pollutant emissions, the application of these methods for the environmental impacts assessment of the construction activities is still limited. Specifically, the focus of these methods was only placed on the pollutant data collection. No further step was conducted to investigate the potential impacts of the pollutants on the onsite workforces. Consequently, the construction workforces cannot obtain the timely feedback of the air pollution level at the jobsites. They might continue to work in a contaminated environment without any notification, which can cause immediate or chronic health issues. Also, in current practices, no further efforts have been conducted to evaluate the impacts on the proximal areas. Usually, the construction sites are found in both urban and rural areas. As a major pollutant emission source, the construction activities-related pollution might impose significant impacts on the ambient air quality.

1.2. Research Objectives and Scope

The main objective of this research is to investigate whether the air pollutant emissions can be continuously monitored and visualized by the IoT technology with the integration of microcontrollers and microsensors, and whether the monitoring results can be utilized to assess the potential environmental impacts on the ambient air quality and the health of workforces. Towards this objective, specifically, the research effort is divided into the following sub-objectives.

1. Create a smart air quality monitoring system with the integration of microcontrollers, microsensors and HD cameras to monitor and visualize the air pollutant emissions on construction sites. The monitoring system consists of a wireless sensor network, which collects the pollutant data and construction activity videos and transmits data to the remote server in real-time. Then, a user-friendly interface is used to visualize the pollutant data and broadcast the live videos.
2. Develop a proactive alarm system to trigger warnings to construction practitioners when the air pollutant emissions exceed the air quality standards and regulations. The alarm system automatically analyzes the air pollutant concentrations and compares the analysis results with the standards. Air pollution warnings are generated and sent to decision makers by emails when the air pollutant concentrations exceed the standards.

3. Develop an environmental impact assessment system based on the Gaussian Plume-based atmospheric dispersion model to assess the potential impacts of the air pollutant emissions on ambient air quality and examine whether the emissions violate the regulations. With the system, the air pollutant emission quantities in each work zone are obtained to determine the air pollutant concentrations. Then, the Gaussian Plume-based atmospheric dispersion model is adopted to simulate how the air pollutants disperse in the ambient environment under different meteorological conditions. Following that, the environmental impacts caused by the construction operation in each work zone are assessed in comparison with related regulations.

There are different types of construction activities during the construction process (e.g. earthmoving operations, foundation works, etc.). One certain type of construction activities contributes the typical air pollutant emissions. The scope of this research is limited to monitor and visualize the air pollutant emissions produced from the earthmoving operations. The earthmoving operation is one of the major components in a construction project. They heavily depend on the fleets of construction equipment, which could produce a large amount of air pollutants on the construction sites, such as CO, CO_2, NO_x, PM, and so on. CO_2 is always an important air quality indicator, while NO_x and SO_x are two primary causal factors of the acid rain. Also, PM can affect the heart and lungs and cause serious health effects. All the related air pollutants are taken into account in the research. In addition, the construction sector has long been considered as a major source of noise pollution. According to U.S. EPA (U.S. EPA 2018), the noise pollution caused by the construction industry adversely influences the health of millions of people. The noise pollution might cause a variety of problems, such as high blood pressure, speech interference, hearing loss, sleep disruption, and productivity loss. So far, government and authorities have established standards and procedures to reduce the noise levels. However, in current practices, the noise pollution from the construction sector is significantly underestimated. Therefore, the noise pollutions generated from the construction operations are investigated in this research. Besides, the ultraviolet (UV) radiation level at the construction jobsites is taken into account. In the U.S., the diagnosed number of skin cancer is more than that of breast, prostate, lung, and colon cancer combined. Unprotected exposure to the sun's harmful UV radiation is the most contributory risk factor for skin cancer. Considering the construction professionals have to work outdoors for a long time with the over-exposure to the sunlight, the real-time monitoring of the UV radiation can help the onsite workforces better understand the risk and take sensible precautions.

1.3. Contributions

This research is to develop a set of instrumental systems for construction practitioners and decision makers to monitor, visualize and assess the air pollutant emissions of construction operations. The contributions of the IoT-based air quality monitoring system are listed as follows.

1. Monitor the air pollutant emissions produced from construction operations in an automatic, cost-effective and real-time manner without the reliance on the onboard measurement system and the fixed monitors.
2. Dynamically and continuously visualize the air pollutant emissions, which is instrumental for construction practitioners better understanding the pollutant emission trends.
3. Enhance the monitoring interactions by providing a user-friendly interface. The user interface can be used to review the pollutant data, visualize the pollutant emissions and broadcast the live videos.
4. Provide a novel means to analyze the relationship between the air pollutant emissions and the corresponding construction activities based on the pollutant monitoring results and the live construction activity videos.

The contributions of the intelligent alert system are listed as follows.

1. Provide the timely warnings to construction practitioners when the pollutant concentrations exceed the air quality standards. The system automatically analyzes the pollutant monitoring data in comparison with the relevant regulations. Accordingly, warnings are sent to decision makers when the pollutant emissions reach a hazardous level.
2. Facilitate the decision-making process when mitigation plans are needed to alleviate the burdens of air pollutant emissions. The system can identify the specific pollutants when the pollutant concentrations exceed the standards. The detailed

information of the major pollutants is continuously pushed to the server. The decision makers can specify the mitigation plans according to the specific pollutants.

The environmental impacts assessment system can be used to quantitatively assess the potential impacts on the ambient air quality and the health of construction practitioners. The Gaussian Plume-based atmospheric dispersion model incorporated in the system can simulate the dispersion of air pollutants in the ambient environments. Then, the potential impacts due to the pollutant emissions from the construction operations at any downwind location can be estimated.

In addition to the construction-related pollutant monitoring, visualization and assessment, this research can be applied to:

1. Facilitate the monitoring of indoor air quality. Facility managers can employ the proposed system to monitor the real-time indoor air quality to promote occupational comfort. When the indoor air quality is deteriorating, facility managers can distribute the alarms and take actions to mitigate the impacts. Also, facility managers can use the monitoring data to evaluate the efficiency of the Heating, Ventilation and Air Conditioning (HVAC) system.
2. Supplement the sparsity of outdoor air quality monitoring network. The outdoor air quality monitoring network typically consists of numerous fixed air pollution monitors. Due to the pricey expenses and the specific placement locations with continuous power supply, the monitors are sparsely deployed. The cost-effective and portable monitoring system can be employed to supplement the sparsity of the deployment of the existing monitoring network. Also, it can provide more possibilities to explicate the air pollution levels of the area of hot spots for the public.
3. Facilitate the project progress monitoring and documentation. The monitoring system can provide construction managers with the easy-to-access and unlimited construction activity videos based on the low-cost HD camera module. Construction managers can not only monitor the real-time onsite construction activities, but also store the progress-related data instead of the written documentation.

In addition, the ideas or systems proposed in this research can be expanded to other major pollutant-contributory industrial fields, such as the agricultural industry, mining industry, oil and gas industry, and so on. These industrial sectors are heavily dependent on the diesel-based nonroad equipment similar to the construction industry. Take the agricultural industry as an example, 33% of NOx emissions (466,306 tons) and 30% CO2 (43,832,188 tons) were emitted from agricultural non-road equipment in 2008 (Lewis 2009). Meantime, 34% CO (242,770 tons) and 36% PM emissions (48,734 tons) were released to the atmosphere (Lewis 2009). Therefore, the proposed methods with appropriate modifications can be employed to monitor the real-world air pollutants emitted from other industries and assess the potential environmental impacts.

1.4. Dissertation Organization

The motivation, hypothesis, objectives, methodology and results, and contributions behind this research have been introduced. The remaining chapters in the dissertation are organized as follows.

Chapter 2 is a background literature review chapter. It firstly outlines the current practices in the estimation and monitoring of pollutant emissions from construction equipment. This is then followed by the overview of the fundamental IoT technology and previous studies in the field of air quality monitoring using microcontrollers and microsensors, of which this research plans to build on and augment. The chapter ends with an extensive summary on discussing the issues and limitations in current practices.

Chapter 3 delineates the proposed system of this research. The IoT-based system consists of three frameworks, namely air quality monitoring framework, intelligent alert framework, and environmental impact assessment framework. Each framework is illustrated in detail. Chapter 4 describes the implementations of the proposed system and case studies. The conclusions, the research contributions and the recommendations for the future work are summarized in Chapter 5.

CHAPTER 2: LITERATURE REVIEW

This chapter first outlines the current practices in the estimation of air pollutant emissions from construction. Most of the existing practices were performed in the pre-construction stage. Recent research efforts in the monitoring of air pollutant emissions during the construction phase are then presented. These two are followed by an overview of the fundamental knowledge in the field of air quality monitoring based on the IoT technology with the integration of microcontrollers and microsensors which are the ones that this research plans to build on and augment.

2.1 Key Pollutants from Construction Industry

Due to the fuel and diesel-based equipment intensive nature, construction sites are deemed as a significant contributory source of the air pollutants, which mainly include nitrogen oxides (NO_x), sulfur oxides (SO_x) and carbon oxides (CO_x). Figure 2 shows the approximate composition of diesel exhaust gas (Khair and Majerski 2015). Specifically, NO_x accounts for the highest proportion of diesel pollutant emissions with a rate of more than 50%, while CO_x is ranked as the second largest pollutant. In addition, a great number of particulate matters (PM) are emitted from construction activities (e.g. demolition, earthmoving, etc.). Therefore, construction practitioners may expose and work in the contaminated environment in a long time, which could affect the health and safety of the workforces. Also, the long-term construction activities could jeopardize the ambient air quality. Consequently, the potential risks caused by the key pollutants from construction projects are identified and assessed in this study in comparison with the air pollutant regulations shown in Table 1.

Table 1 Local Air Pollutant Regulations in Major Countries (ICAO 2011)

Country/ Organization	Guidelines/Standards	SO_2		NO_2		CO		PM_{10}
		1 H	24 H	1 H	24 H	1 H	8 H	24 H
WHO	WHO Guidelines	-	125	200	-	30	10	50
European Union	Air Quality Framework Directive	350	125	200	-	-	10	50
Australia	National Environmental Protection Measure for Ambient Air Quality	520	200	220	-	-	10	50
Brazil	Air Quality National Standards	-	365	320	-	40	10	150
Canada	Canadian Environmental Protection Act	900	300	400	200	35	15	
China	Ambient Air Quality Regulations	500	150	150	100	10	-	150
India	The Air (Prevention and Control of Pollution) Rules	-	80	-	80	4	2	100
South Africa	SANS 1929 Guidelines	-	125	200	-	30	10	75
Switzerland	Swiss Luftreinhalteve-rordnung	-	100	-	80	-	-	50
U.S.	National Ambient Air Quality Standards		360	-	-	40	10	150

H = hour
Unit: $\mu g/m3$ = micrograms per cubic meter
Time periods given are those over which the average pollutant concentrations are measured

2.2 Estimation of Air Pollutant Emissions in Construction

So far, there are several research efforts that have been conducted to estimate the air pollutant emissions generated from construction operations. In general, these studies can be divided into three levels: 1) at the equipment level; 2) at the operation level; 3) at the project level. The emission estimation methods at three levels are presented in the following section. Then, this is followed by the discussion of the issues and limitations associated with the emission estimation practices.

2.2.1 Emission Estimations at the Equipment Level

The fuel-use and emission rate of construction equipment is considered as a fundamental parameter to predict the emissions from construction equipment. So far, the emission estimation models were developed based on the emission rate inventory to estimate the potential pollutant emissions from each piece of construction equipment involved in the project. These models mainly refer to the OFFROAD, NONROAD, URBEMIS California Emissions Estimator Model (CALEEMod), Road Construction Emission Model (RCEM), and so on. The OFFROAD model was developed by the California Air Resources Board (CARB) to estimate emissions of non-road equipment (CARB 2007), while the CalEEMod model was proposed by the California Air Pollution Control Officers Association (CAPCOA) to quantify emissions from construction operations. The RCEM specializes in estimating emissions for road construction projects. Among those models, NONROAD and URBEMIS are two popular models that have been widely utilized. Specifically, the NONROAD model is a preventative software tool to predict emissions from non-road mobile sources, including construction, mining, industrial equipment and so on (USEPA 2005). There are more than 80 basic and 260 specific types of equipment classified by the engine horsepower in the NONROAD model. The model is capable of estimating the air pollutant emissions, including CO, CO_2, NO_x, PM and SO_x, for a specific equipment type based on the following parameters: engine population (age, fuel type), engine horsepower (hp), load factor (fraction of available power), activity duration (hours / year) and emission factor (grams / hp-hr).

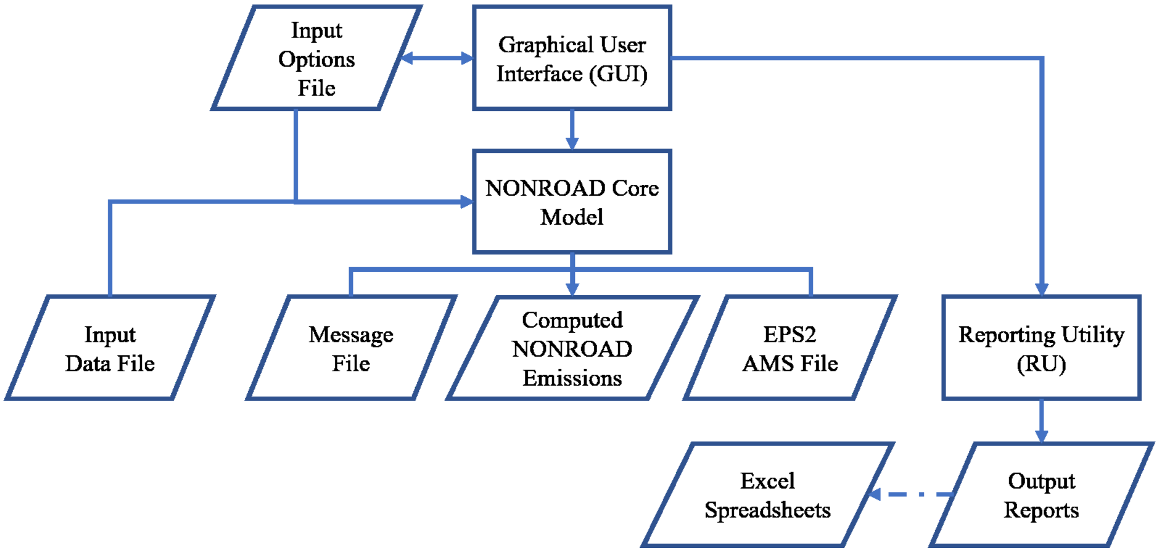


Figure 2 NONROAD model flowchart (USEPA 2005)

The NONROAD model can estimate future year emissions and backcast past year emissions in tons per annum in any geographic area of US. As for estimating future year emissions and backcasting past year emissions, the model takes into account the growth and scrappage rates for the equipment as well as a variety of control program options. In addition, the model can calculate emissions for various time periods, such as any particular month, one of four seasons. As shown in Figure 2, the NONROAD model includes three main components: a graphical user interface, the core model and a reporting utility. Specifically, the user interface provides users with a platform to specify the options for a model. The core model of NONROAD contains all of the algorithms for the calculations of emission estimation. The reporting utility is to produce standardized reports based on the output data generated in the core model. Among all input parameters in the NONROAD model, the load factor is the most essential one, since it describes how the equipment is operated (Lewis 2009). In the construction field, the load factor 0.21 is recommended for backhoes, while 0.59 is designed for dozers, excavators, trucks, and loaders. In hence, the NONROAD model estimates emissions based on an average load factor for a specific type of the construction equipment.

The Urban Emissions Model (URBEMIS) is a comprehensive air pollutant estimation model, which incorporates the California Air Resources Board's Emission Factors (EMFAC) 2007 model for on-road vehicle emissions and the OFFROAD 2007 model for off-road vehicle emissions (URBEMIS 2007). The model allows users to estimate construction project-related emissions, NO_x, CO, PM, CO_2, SO_x, and reactive organic gases (ROG). The amount of the emissions can be calculated on a daily or annual basis. The URBEMIS model can be employed in seven project stages: 1) Demolition; 2) Fine Site Grading; 3) Mass Site Grading; 4) Trenching; 5) Building Construction; 6) Architectural Coating; 7) Paving. The model estimates emissions on a stage basis. Users can decide to estimate emissions for any single stage or a combination of stages. Also, mitigation measures can be specified to analyze the effects of mitigation on emissions. URBEMIS is mainly focused on the land development projects in California. For out-of-state users, vehicle emission outputs should be adjusted to reflect their vehicle fleets. This is because URBEMIS 2007 employs California motor vehicle emission rates which tend to be lower than those in other states due to the strict emission controls in California. Figure 3 illustrates the typical user interface of using the URBEMIS model to conduct the emission estimation. The left side of the interface shows seven steps that can be completed for typical URBEMIS model runs. Users must input specific land use data, gasoline type, and project duration to estimate the emissions produced from the project.

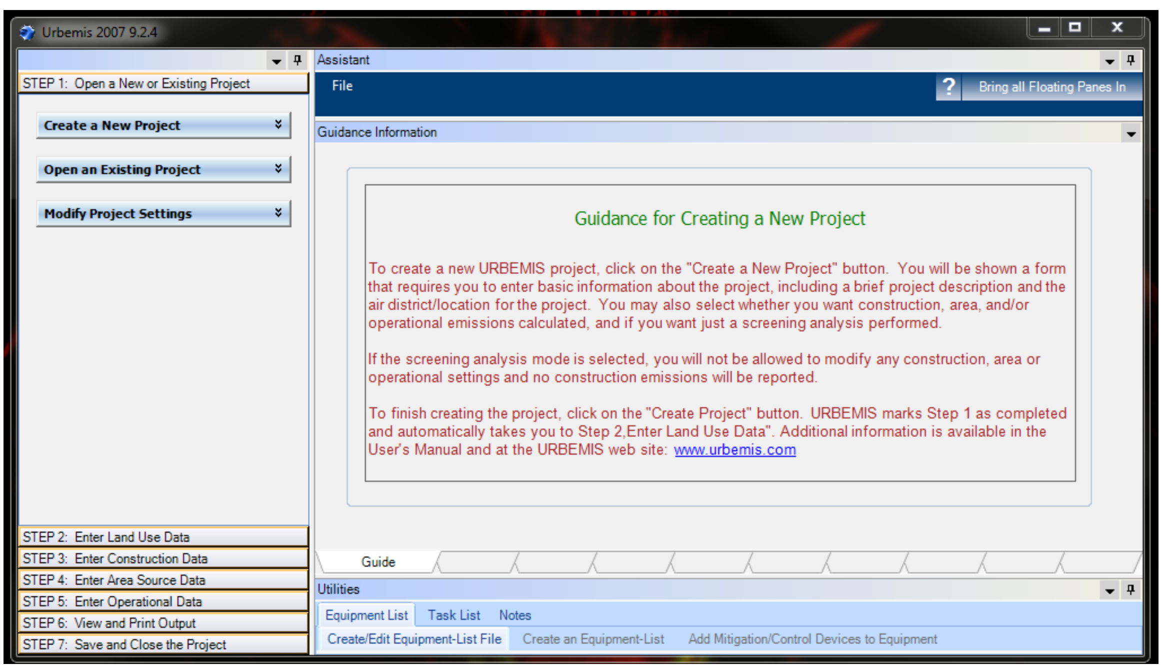


Figure 3 URBEMIS user interface (URBEMIS 2007)

2.2.2 Emission Estimations at the Operation Level

At the operation level, Discrete-event Simulation (DES) model is widely employed to predict emissions during the construction operations in accordance with construction operation plans. Typically, DES models are adopted to simulate the operation of a system as a discrete sequence of events in time so that working durations and fuel consumptions of equipment can be estimated. Within the model, each piece of equipment was represented as resources, while the activity of each equipment (e.g. loading, dumping, hauling, and so on) was represented as a task. The duration of each activity of equipment was observed, and the distribution of each activity was determined by the statistical method. Then, the air pollutant emission is estimated using the NONROAD model.

Ahn and Lee (2013) adopted DES-based models to estimate the carbon emissions of an earthmoving operation, which investigated the tasks of the excavation, hauling and the placement into a stockpile. As illustrated in Figure 4, a DES model was developed to determine the number of dump trucks, the ratio of cycle time and the possible fuel consumptions. Excavators and trucks were represented as resources in the model, and the equipment activity of loading, dumping, exchanging trucks, hauling, and returning was represented as a task. The duration of each activity of equipment was identified and the distribution of each activity was determined as a continuous uniform distribution. Then, the estimation of the potential carbon emissions was completed with the integration of the NONROAD model.

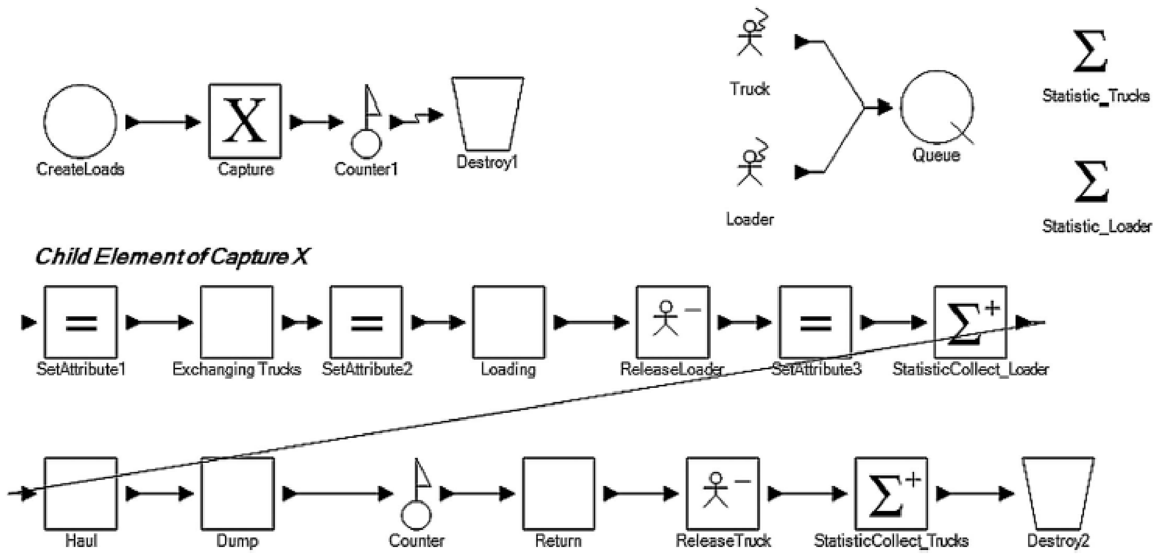


Figure 4 DES-based models for construction operations (Ahn and Lee 2013)

Similarly, Ahn et al. (2010) quantified carbon footprints from the tunneling process based on the discrete-event simulation model. The analysis was focused on Tier 1 and Tier 2 construction equipment involved in the construction operations. According to the estimation results, the major sources of carbon footprints during the tunneling process were the onsite construction operations and the transportations of soil and materials. The emissions of NO_x and PM were taken into account as well as the carbon emissions. Zhang (2014) developed an alternative DES model to predict emissions of two excavators, ten off-road trucks and one dozer in the earthmoving operations. In the study, the load factor concerning the uncertainties and randomness during the earthmoving operations was investigated to improve the emission estimations. Also, an emission calculation model was proposed based on the NONROAD model to estimate pollutant emissions not only from the construction operations but also from other related activities.

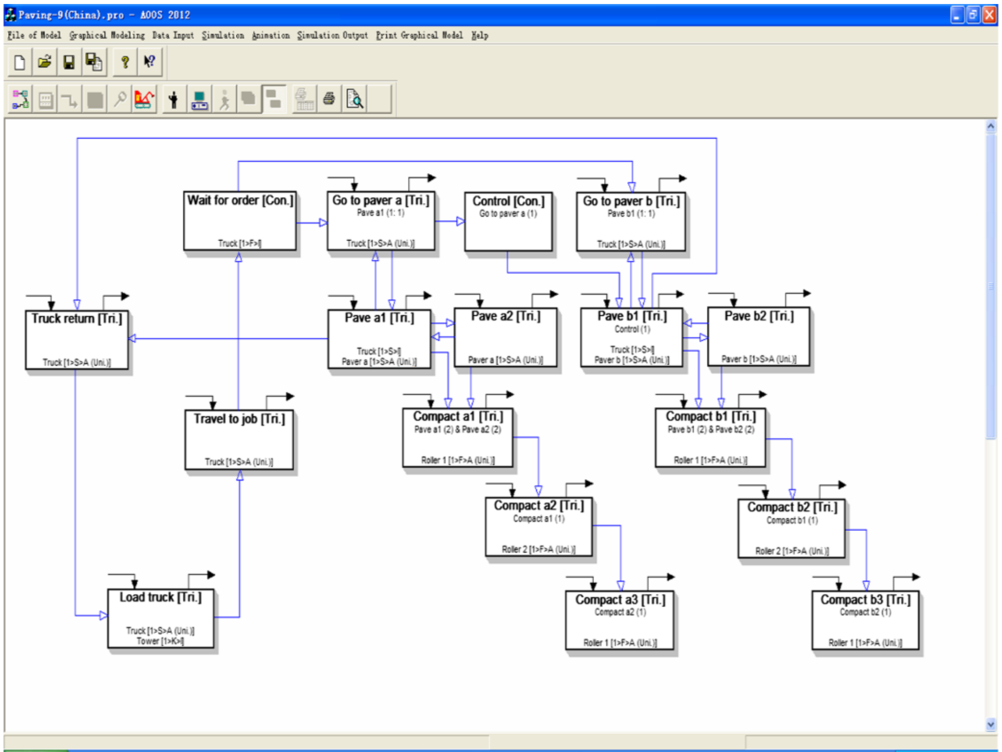


Figure 5 Activity object-oriented simulation model for an asphalt paving operation

Considering the various uncertainties and features in different construction scenarios, Zhang (2015) proposed an improved DES model to estimate fuel consumption and emissions from the asphalt paving operations, as shown in Figure 5. Also, an activity object-oriented simulation (AOOS) platform was developed to simulate the asphalt paving operations, which took into account the particular paving techniques as well as the variations and randomness in the load factors.

2.2.3 Emission Estimations at the Project Level

There are a plethora of research efforts with respect to the environmental impacts assessment of exhaust emissions from non-road equipment and transportation at the project level based on the life-cycle assessment (LCA) approach that has been investigated (Stripple 2000; Mroueh et al. 2001; Treloar et al. 2004). The implementation of LCA is guided by the International Organization for Standardization's (ISO) 14040 series (International Organization for Standardization 2006). Generally, LCA includes four iterative steps, namely goal and scope definition, life-cycle inventory (LCI) analysis, lifecycle impact assessment (LCIA), and interpretation.

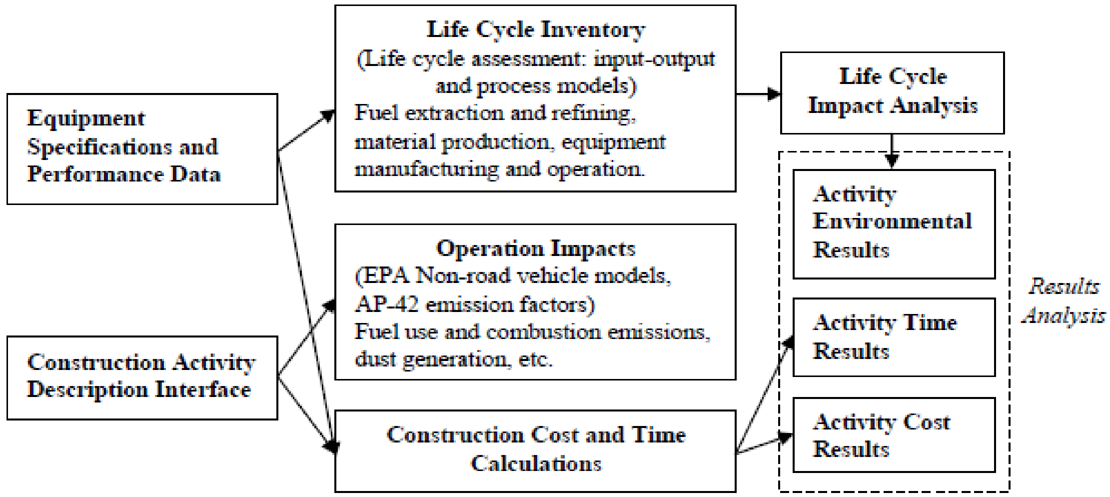


Figure 6 LCA model of heavy construction activities (Ries et al. 2010)

Ries et al. (2010) developed an environmental life cycle model incorporating uncertainties to assess the common non-road diesel-powered construction equipment. The LCA model structure is illustrated in Figure 5. The model mainly consists of three sections: construction equipment specifications and performance data; diesel fuel extraction, refining, and combustion; and estimation of the equipment use, task duration and cost. The energy consumption and the corresponding pollutant emissions of the three sections are investigated and computed. Bilec et al. (2010) conducted a study to holistically analyze and assess the environmental impacts produced from the construction phase of commercial buildings using the LCA model (Figure 6). The proposed model incorporated several data inventories, in term of process, Economic Input Output (EIO) LCA models, and other data into one common LCA framework. Users were required to input the typical process variables, for instance, the dollar value of construction, the quantities of materials, and the duration of the operations. Cass and Mukherjee (2011) employed a hybrid LCA approach to compute the quantities of Greenhouse Gas (GHG) generated from highway construction operations and onsite and to-site transportation. All these research efforts aimed to estimate the potential pollutant emissions and reveal the environmental impacts during the entire life cycle of infrastructures.

Environmental impacts	Data sources
Dust from driving on paved roads	AP-42, Section 13.2.1
Dust from driving on unpaved roads	AP-42, Section 13.2.2
Dust generation during heavy construction operations	AP-42, Section 13.2.3
Welding—hazardous metals and particulates	AP-42, Section 12.9
Surface applications—application of paints, sealants, etc.	User provided information
Construction services—e.g., inspection, architects, engineers, and surveyors	EIO-LCA
Equipment manufacturing	EIO-LCA
Temporary materials	EIO-LCA
Construction equipment—fuel combustion and usage	Nonroad
Construction equipment—extraction and distribution	Franklin; Idemat
Transportation of materials and workers—fuel combustion, extraction, distribution—diesel and gasoline truck, and diesel and gasoline tractor trailer	Franklin
Electricity—on-site usage, generation, distribution	Franklin
Concrete water and wastewater	Independent laboratory results

Figure 7 Hybrid LCA construction model (Bilec et al. 2010)

2.2.4 Issues and Limitations of Emission Estimations

There are several issues or limitations in the practices of the emission estimation no matter at the equipment level, operation level or project level. Firstly, at the equipment level, the emission rates adopted in the NONROAD and URBEMIS emission estimation models are constants, which cannot fully reflect the modes of construction equipment in real-world construction activities. It is mainly because that the experiment of the measurement of the emission rates is conducted on uninstalled engines in a laboratory environment (Frey et al. 2008). On the other hand, the emission rates of the equipment involved in the real-world construction activities are constantly changing in accordance with the equipment mode, in terms of traveling, loading, idling, and so on. In hence, the emission estimation models cannot identify the emission factors of construction equipment in different modes (e.g. idling and operating), which in turn affects the accuracy of emission quantities from equipment.

So far, most of the emission estimation methods at the operation and project level have been developed based on the estimation models. Therefore, they still suffer from the inaccuracies in the quantifications of pollutant emissions. Also, another notorious shortcoming of these methods is that they significantly neglect the possible planning changes during construction operations. Obviously, schedule changes and delays could occur at any time during the construction process. The possible changes would affect the activities of construction equipment (e.g. working durations, working conditions, and so on). When the duration of the construction activities is affected, the corresponding pollutant emission quantities would be influenced. Such way, the estimated emission quantities are not accurate. Therefore, the potential environmental impacts estimated only by the estimation models cannot be fully exposed.

2.3 Monitoring of Pollutant Emissions in Construction

In order to improve the current practices in quantifying the air pollutant emissions from real-world construction operations, researchers and authorities adopted the air pollution monitors to directly measure the air pollutant emissions. Generally, the monitoring practices can be classified into two levels, at the equipment level, and at the project level. At the equipment level, the onboard measurement systems or sensors are installed on the operating equipment to measure the pollutants from the diesel exhausts. The measurement systems or sensors either directly monitor the air pollutant emissions from the construction equipment or estimate the emission amount by identifying the equipment operation durations and the equipment fuel consumptions. On the other hand, the air pollution monitors are allocated at the fixed positions on construction sites to monitor the real-time air pollutant emissions. More details of the related studies could be found as follows.

2.3.1 Emission Monitoring at the Equipment Level

In order to directly monitor the pollutant emissions of operating equipment during the real-world activities, Clean Air Technologies International, Inc. (CATI) conducted onboard in-use emissions measurements by the means of a Portable Emissions Measurement System (PEMS) (May et al. 2002; Gautam et al. 2002; Vojtisek 2003). The PEMS offers a modern and innovative counterpart to check the impact of emissions from combustion engines upon the environment. As shown in Figure X, the PEMS is developed for the emissions regulatory purposes with the integration with advanced gas analyzers, exhaust mass flow meters, weather station, Global Positioning System (GPS) and connection to the vehicle networks. It provides a considerably accurate monitoring of pollutants emitted by engines in a real-time manner (European Commission - Joint Research Centre 2012). The PEMS measures the pollutants of CO_2, CO, and hydrocarbons (HC) based on the non-dispersive infrared (NDIR) detection method, and utilizes electrochemical cells monitors NO_x and O_3. PM is measured by a light-scattering laser photometer detection method (Rasdorf et al. 2010). All diesel exhaust data were recorded on a second by second basis.

Figure 8 Portable emissions measurement system (Tu 2011)

Initially, CATI conducted several experiments to compare the PEMS with the conventional dynamometer measurements at the New York Department of Environmental Conservation (NYDEC) and EPA's National Fuel and Vehicle Emissions Laboratory. The coefficient of determination (R2) values for the comparisons of cyclic emissions were in the range of 0.90–0.99, which indicated the good precision (Abolhasani et al. 2008). Recently, North Carolina State University completed two field studies that quantified the fuel use, emissions, and engine performance data of 39 items of diesel-powered construction equipment (Rasdorf et al. 2010). The equipment includes eight backhoes, one skid-steer loader, three off-road trucks, three track loaders, three excavators, four generators, five-wheel loaders, six motor graders and six bulldozers. The results from the field studies improved the characteristics of the real-world air pollutant emissions of the typical construction equipment. The results can be further used to facilitate the development of the inventories of the real-world fuel consumptions and pollutant emission rates. Also, construction practitioners, such as fleet owners and managers, construction contractors and environmental engineers, can better understand the impacts of emissions from the non-road diesel-based equipment on ambient air quality and the health of the workforces.

Figure 9 Field measurement of in-use activity (Tu 2011)

Alternatively, the micro-electromechanical (MEMS) device, accelerometer, is employed to monitor the equipment utilization and the operating modes for the calculation of pollutant emissions. The MEMS device is designed to measure the acceleration forces on three axes (x, y, and z). Based on the signals on three axes, the information of activity modes (e.g. idling and non-idling) and the operating durations can be extracted. Then, the pollutant emissions generated from the equipment can be computed using the predefined emission factors for idle and non-idle modes of the equipment. For example, Ahn et al. (2013) conducted a study to analyze the pollutant emissions of a medium-sized wheeled excavator. The MEMS sensor embedded in the cell phone was installed on the equipment to monitor the operating modes and durations. The equipment operations, in terms of working, idling and engine-off modes, were classified based on the multiple features extracted from acceleration signals. Then, the potential pollutant emissions were calculated using estimation models.

In order to improve the accuracy of the acceleration signal analysis, Ahn et al. (2015) conducted the experiment to analyze the patterns of the acceleration data from the stationary operating of construction equipment. The statistical significance in differences between the two activity modes was investigated. Then, the MEMS sensors were installed on different excavators to collect the acceleration data during the diverse stationary and non-stationary operations, as shown in Figure 10. Also, a video camera was used to film the construction performance of the equipment for labeling the actual operational modes. Then, the analysis results were compared with the videos to test the accuracy.

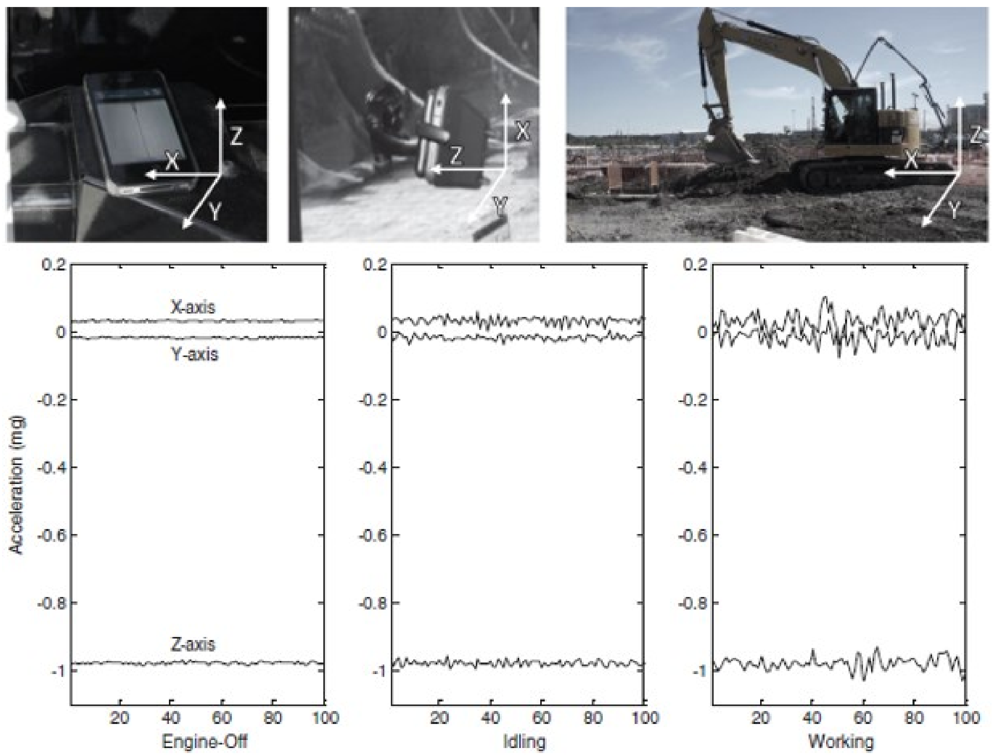


Figure 10 Devices equipped inside an excavator and acceleration signals (Ahn et al. 2015)

2.3.2 Emission Monitoring at the project level

Considering the severe impacts from the construction activity-related pollutions, government and authorities have already taken actions to monitor the air quality at the construction jobsites. Generally, the professional air quality monitors were placed at the fixed positions on/around construction sites to continuously monitor the air pollutant emissions. For example, Infrastructure Canada placed an air pollutant monitor at the construction jobsite of Champlain Bridge corridor project to monitor the major air pollutant emission (Infrastructure Canada 2018). The Champlain Bridge corridor project incorporates the construction of a 3.4-kilometer Champlain Bridge and a 470-meter bridge for L'Île-des-Sœurs, which is one of the largest projects in the past 50 years. The fixed monitor is fixed at the main area of concern based on the planned construction activities, which collects the total PM and PM with a diameter of 2.5 µm or less on an hourly basis and transmits the data to the remote server in real time.

Likewise, Ministère des Transports du Québec launched an air quality monitoring program to monitor the air quality of the worksites of Turcot project. The Turcot project is to reconstruct the largest interchange, Turcot interchange, and redesign the urban landscape of the territory (Ville De Montreal 2017). Considering the complex construction environment and the large scale of the projects, four air monitors were placed on the four sides of the Turcot project worksites to monitor the real-time air quality of the construction site and the nearby communities. The monitors were used to monitor the major air pollutants, such as CO_x, NO_x, PM, on an hourly basis.

Figure 11 Fixed air quality monitors

2.3.3 Issues and Limitations of Monitoring of Pollutant Emissions

Although the pollutant emission monitoring is instrumental for construction practitioners better understanding the impacts caused by the construction operations, there are still several issues or limitations in the current practices that have been identified from previous research studies. Firstly, at the equipment level, the PEMS-based monitoring method is too costly to be widely employed in practice. Specifically, the price of one single piece of the PEMS unit is over 100,000 US dollars (Ren et al. 2018). In addition to the purchase cost, other expenses on the regular calibration and maintenance are necessitated. In hence, it is impractical to install the PEMS onto each piece of construction equipment, especially for the large-scale construction projects where there are tens of construction equipment.

The PEMS is particularly sensitive to the weather conditions. The data collection using PEMS cannot be performed in the rainy or snowy day, since the PEMS is installed on the external surface of the equipment connected with the tailpipe. Furthermore, the suitable range of the working temperature for PEMS is suggested between 32 °F and 90 °F (Rasdorf et al. 2010). Specifically, the moisture would freeze when the temperature is below 32 °F, while the PEMS is intended to overheat when the temperature exceeds 90 °F. Also, the monitoring results from the PEMS are easily affected by the vibration transmitted from the engine and/or the dust and mud existing on construction sites. Vibrations, dust, and mud could cause the malfunctions of PEMS. Therefore, the particular precautions are always needed when using the PEMS to monitor the air pollutant emissions from construction equipment.

As for the monitoring methods using the electromechanical devices, they are more economical and affordable than the PEMS. However, there are still several deficiencies in analyzing the operating modes of construction equipment. First, the feasibility of the accelerometer-based method was tested based on a threshold-based scheme of the acceleration signal energy (Ahn et al. 2015). And the initial determination of threshold values was investigated in the lab environment. During the real-world construction activities, the values would vary in accordance with the different construction scenarios and construction conditions. Even for the same equipment, the threshold value would be different. Therefore, the threshold value of each piece of equipment has to be defined separately. As for the large-scale construction projects where there are tens of construction equipment, the process for the threshold value determination will be labor-intensive and time-consuming. Also, it is impossible to equip accelerators to each piece of equipment, considering the expense of the installations of devices on all onsite equipment would be pricey. For instance, the price of a 3-axis accelerometer is 500 dollars (VECTORNAV 2016). In addition, there is a big challenge to analyze the signal energy captured from the transient mode (e.g. between working and idle modes) due to the uncertainty of the boundary estimation between working and idle modes.

As for the monitoring at the project level, the efforts were primarily advocated by the government and authorities. Contractors and developers of the construction projects hardly conducted the investigation on the air pollutant monitoring, considering the expenses of the fixed monitors. Specifically, the fares spent in the monitor purchase, operations and maintenance can be up to 200,000 Canadian dollars (Ren et al. 2018). Also, certain expertise is required for the regular calibration, operation, and maintenance of the monitor. Furthermore, the specific locations with the continuous power supply for the placement of the fixed monitors need to be well designed. Additionally, the pollutant monitoring results are updated on an hourly basis or even longer, which cannot reflect the real-time air pollutions and provide the timely feedback of the onsite air quality. Last but not the least, the fixed monitors, so far, have been proposed only for the mega projects. For the regular construction projects (e.g. residential and industrial building projects), the government has hardly taken any actions to monitor the pollutant emissions and assess the potential impacts on the ambient air quality and the risks on workers' health. Without the government regulations, it is impossible for the private project developers and contractors to employ the fixed monitors to curb the air pollution issues.

2.4 Internet of Things (IoT)-based Air Quality Monitoring

2.4.1 Definition of IoT Technology

The Internet of Things (IoT) mainly refers to the network of physical devices embedded with electronics, software, sensors, and connectivity which enables the devices to connect and exchange data (Vermesan and Friess 2013). The IoT technology offers opportunities for more direct integration of the physical world into computer-based systems, resulting in efficiency improvements, economic benefits, and reduced human exertions. With the significant development of the related multiple technologies, in terms of real-time analytics, commodity sensors, and embedded systems, the definition of the IoT has evolved. IoT has extended the internet connectivity beyond the standard devices, such as desktops, smartphones, and tablets, to any range of conventionally or non-internet-enabled physical devices or objects (Vermesan and Friess 2013). Embedded with the IoT technology, these devices can communicate and interact over the internet, and they can be remotely monitored and controlled. So far, the IoT technology is extensively applied to the field of consumer, commercial, industrial, and infrastructure spaces.

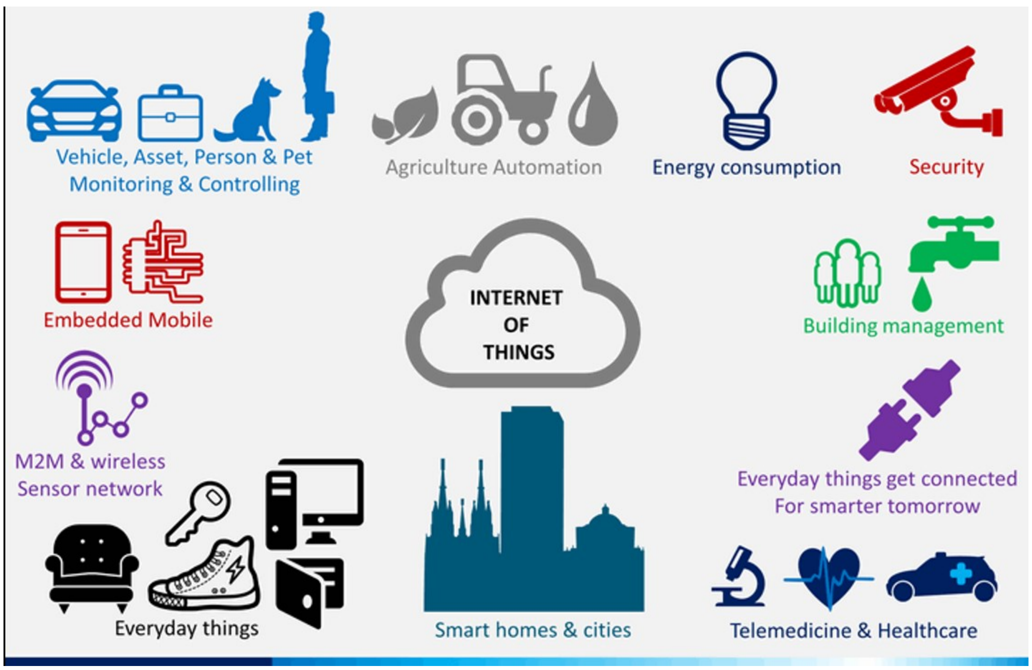


Figure 12 Applications of IoT technology

2.4.2 Air Quality Monitoring System with Microcontrollers and Sensors

In recent years, with the significant development of the sensing technology, cost-effective and portable microcontrollers and microsensors are developed, which gives more possibilities to facilitate the monitoring of air quality. For example, Chaudhry (2013) developed an air quality measurement system to measure the CO concentration. The measurement system incorporates a microcontroller of Arduino Uno and a microsensor MQ-5 gas sensor, which was connected to a computer via the USB cable to transfer the measurement data. The system was allocated in Delhi, India to monitor the concentration of CO in the atmosphere. The measurement data was compared with the data published by the local authorities. Similarly, AL-Haija et al. (2013) developed an air pollution monitoring system to measure the air quality in a university library. The system was developed based on the Arduino microcontroller board and MQ-2 gas sensor (Figure 13 (a)), which was used to measure the concentrations of CO and Liquid Petroleum Gas (LPG). The system was placed in several spots in the library to collect the pollution data. The results were compared with the measurement data collected in the clean air to demonstrate the quality of the intensively-used library.

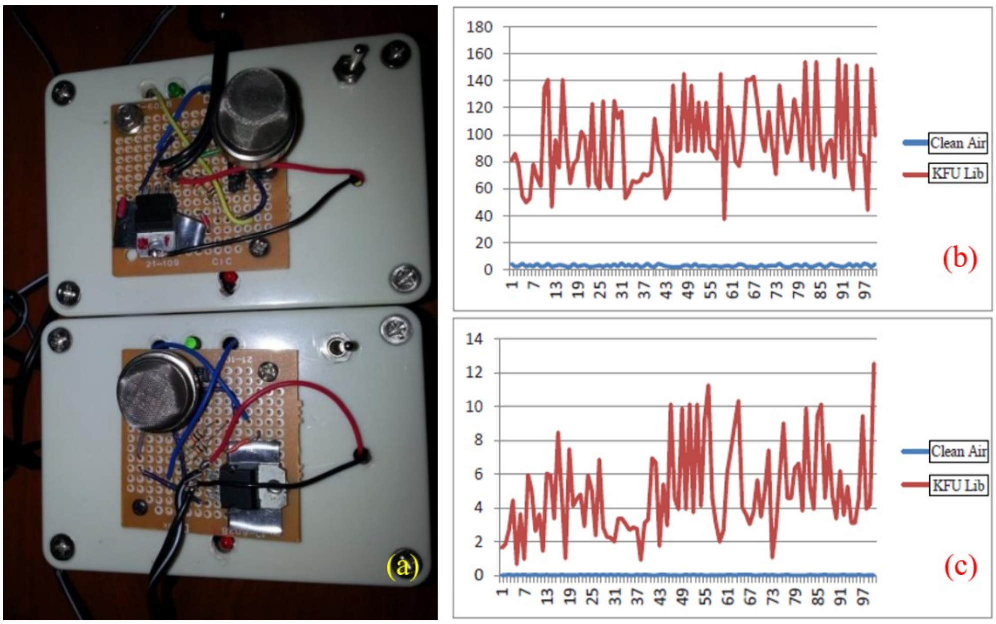


Figure 13 Arduino-based monitoring system (a) Assembled system; (b) LPG concentration comparison; (c) CO concentration comparison

2.4.3 IoT-based Air Quality Monitoring System

With the significant development and the wide spread of IoT technology, the effectiveness and efficiency of the microcontroller-based air quality monitoring system has been significantly improved. The IoT technology is able to connect the microcontroller-based monitoring system with the wireless communication technology. Such way, the monitoring data can be transmitted to the remote server for further analysis in real time other than the reliance on the wired connection. In general, the wireless communication technology mainly refers to Bluetooth, XBee, WiFi, and GSM/GPRS. So far, researchers have developed several IoT-based air quality monitoring systems to monitor the air quality of the indoor and outdoor environments. Detailed descriptions of the related IoT-based monitoring systems are delineated as follow.

2.4.3.1 Bluetooth-based Monitoring System

Bluetooth is a wireless communication technology for the data exchange over a short distance (usually < 10 meters) from devices. So far, several air quality monitoring systems have been developed to monitor the air quality in the indoor and in-car environment based on the Bluetooth communication technology. With the help of the Bluetooth communication technology, these monitoring systems can transfer the real-time data to the smartphone or laptop through the Bluetooth connections. For example, Völgyesi et al. (2008) proposed a mobile in-car air quality monitoring network with the integration of Arduino microcontrollers, microsensors, and the Bluetooth technology. The system was comprised of a number of car-mounted sensors to monitor the concentrations of O_3, CO and NO_2. The monitoring data was transmitted to the laptop inside the car through the Bluetooth-based connection. a mobile monitoring system called MAQS was developed to monitor and control the indoor air quality (Jiang et al. 2011). The system incorporated a network of sensor nodes. As for each sensor node, it consisted of a variety of sensors (e.g. CO2, CO, O3, temperature, and relative humidity sensors) and a Bluetooth link communicating with the smartphone. Similarly, Husain et al. (2016) developed an Arduino-based system with the integration of three air pollutant sensors and an HC-06 Bluetooth module to monitor the real-time air quality of the indoor environment. The sensors of MQ-9, MQ-135 and the optical dust sensor were incorporated to measure the concentrations of CO_x, NO_x, benzene, alcohol and dust particles in the air. An Android mobile cell phone was adopted to receive the pollutant data through the Bluetooth link. The system was deployed and tested in the environments of hospital and building. Suarez et al. (2018) developed a miniaturized wireless sensing module for environmental application and air quality detection, as shown in Figure 14. The sensing module was built based on a high-performance 8-bit microcontroller and air pollutant microsensors, which was focused on the pollutants of VOCs (e.g. acetone, benzene, ethylbenzene, formaldehyde, and dimethylacetamide) and the ambient temperature and humidity. The collected data were transmitted to the smartphone through a Bluetooth communication module.

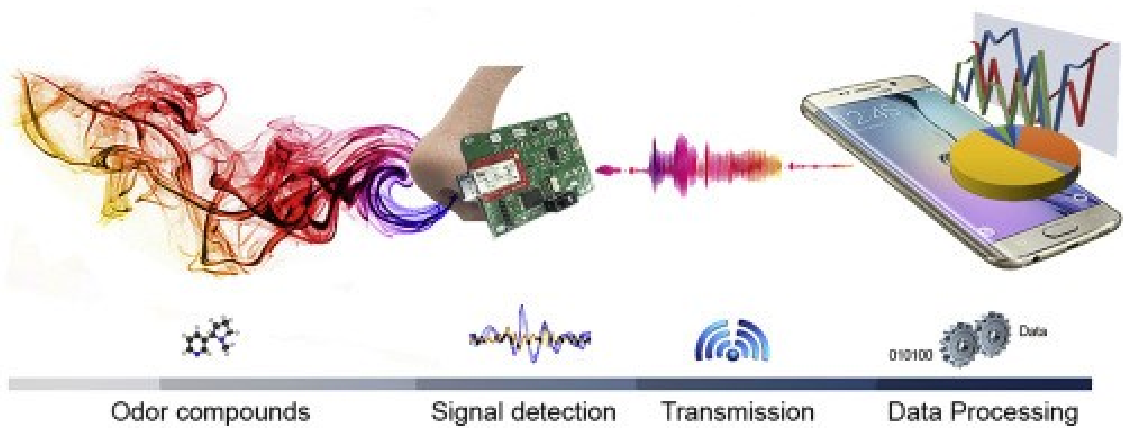


Figure 14 Bluetooth gas sensing module

2.4.3.2 ZigBee-based Monitoring System

ZigBee is an IEEE 802.15.4-based communication protocol used to create the networks with small, low-power digital radios. ZigBee devices can transmit data over long distances through a mesh network. Typically, as shown in Figure 15, the mesh network incorporates three types of ZigBee devices, namely coordinator, router and end device. The coordinator is the most capable device, which is the root of the network. It is able to receive and store the data from the router and end device. The router acts as an intermediate device to receive data from other devices and pass the data to the coordinator and end device, while the end device contains just enough functionality to connect to the parent node of the coordinator or the router.

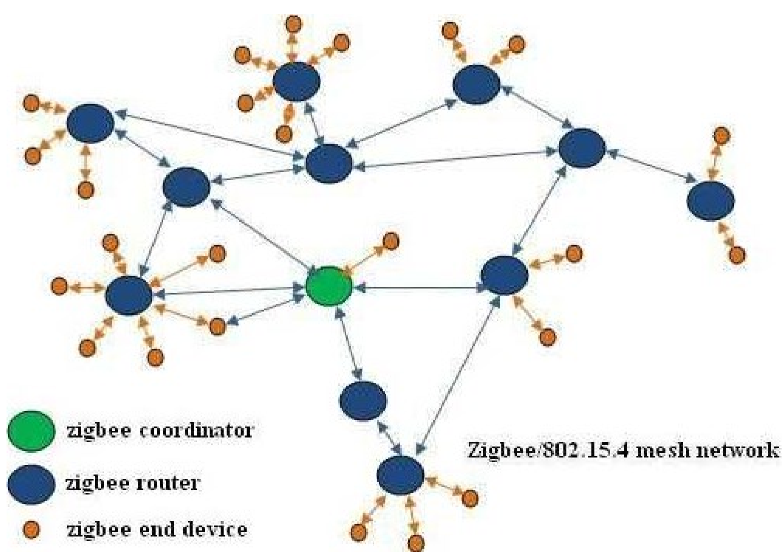


Figure 15 ZigBee mesh network (forum.athom.com)

So far, there are several ZigBee-based monitoring systems have been developed to facilitate the monitoring of air quality in the indoor and outdoor environment. Specifically, in the monitoring of indoor air quality, Abraham and Li (2014) presented wireless indoor air quality sensor network based on the Arduino board, ZigBee modules and gas microsensors. The system was capable of collecting six air quality parameters from different locations simultaneously. Then, a linear least square-based method was used to calibrate the sensors and convert the data values. The efficiency and effectiveness of the system were tested by comparing the results with a professional-grade air quality monitor. Kim et al. (2014) developed a wireless sensor network using the ZigBee modules to monitor the major indoor air pollutants, such as CO_x, NO_x, and PM, in the classroom and church environments. The sensor network, as shown in Figure 16, consisted of several sensor nodes as the data transmitters and a sink node as the data receiver. The sensor nodes were allocated at the target spots to measure the air pollutant data and transmit the data to the sink node, while the receiver was always connected to the server to display the real-time monitoring data.

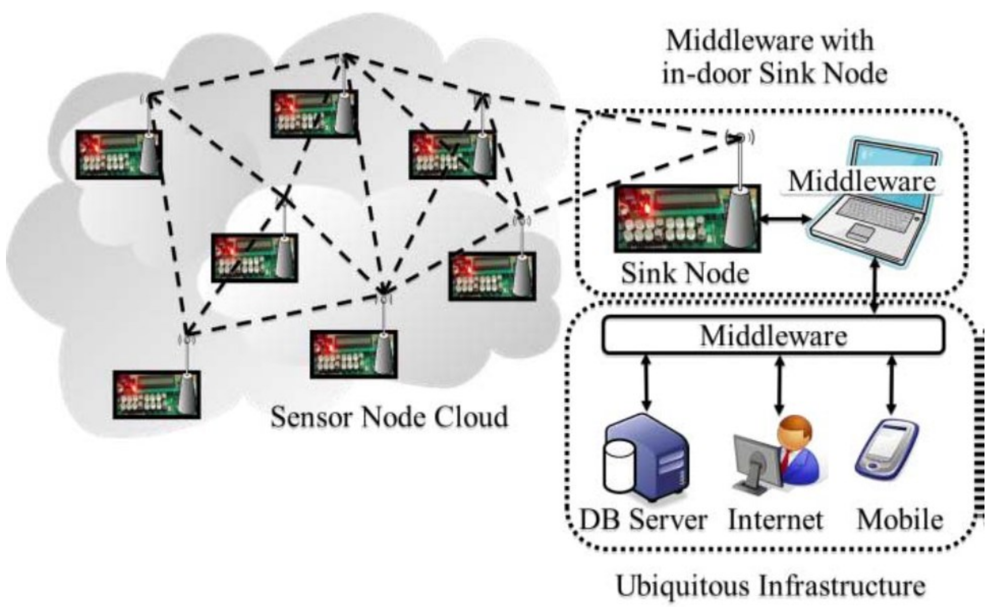


Figure 16 ZigBee network-based air quality monitoring system (Kim et al. 2014)

Likewise, Weekly et al. (2013) developed an air quality monitoring system to continuously measure the PM concentrations within the pedestrian corridor of a heavily-utilized office. At each sensor spot, the microcontroller, integrated with a ZigBee module, read the digital output of the PM sensor and transmitted the readings to the sink node as the data receiver. Based on the monitoring results, facility managers can analyze the local movement of occupants. Also, Kumar and Hanke (2014) presented a smart comfort sensing (SCS) system for the real-time monitoring of thermal comforts based on the ZigBee technology. The thermal comfort is an important factor in the building design to provide a comfortable indoor environment for occupants. The collected data was continuously compared with the ASHRAE55-2013 standard to evaluate the residential building performance. Furthermore, researchers adopted the ZigBee-based monitoring systems to monitor the air quality in the environments of the hospital, library and home (Mujawar et al. 2015; Pitarma et al. 2017). As for the monitoring of the outdoor air quality, Mansour et al. (2014) proposed a simple sensor network-based air quality monitoring system to examine the air quality of the urban and industrial areas. The monitoring system incorporated a set of air pollutant sensors of O3, CO, and NO2, which were placed at the stacks and urban infrastructure. The sensor data was automatically sent to the central server through the ZigBee mesh network.

2.4.3.3 WiFi-based Monitoring System

WiFi is the technology uses the radio frequency signal instead of wires to connect devices within a certain distance of 20 meters indoors and a greater range outdoors. With the help of WiFi communication protocols, Kang and Hwang (2016) developed an integrated system to monitor the real-time air pollutant concentrations of PM and CO as well as the temperature and humidity in each room of a residential building. The monitoring system is mainly comprised of communication interfaces and sensors. The WiFi communication module enables the system to be connected with the network for real-time data transmission, while several sensors were adopted to measure the indoor air pollutant concentrations. Based on the monitoring results, a further experiment was conducted to investigate the indoor air quality level indicators. Similarly, Postolache et al. (2009) devised a real-time monitoring system to measure the levels of methane and alcohol in the residential environment. Each sensor node was installed in the different rooms and connected to the acquisition and control system through the wireless network. Then, the sensor data were published for review in the back-end platform, which is a database controlled by the LabVIEW web server. Folea and Mois (2015) conducted a study to monitor the CO2 level and the absolute pressure in the building. The study provided a possibility to gather and further process the remote data from a bunch of wireless sensors. Furthermore, the proposed system can be employed to facilitate the reduction of the energy consumption of the building.

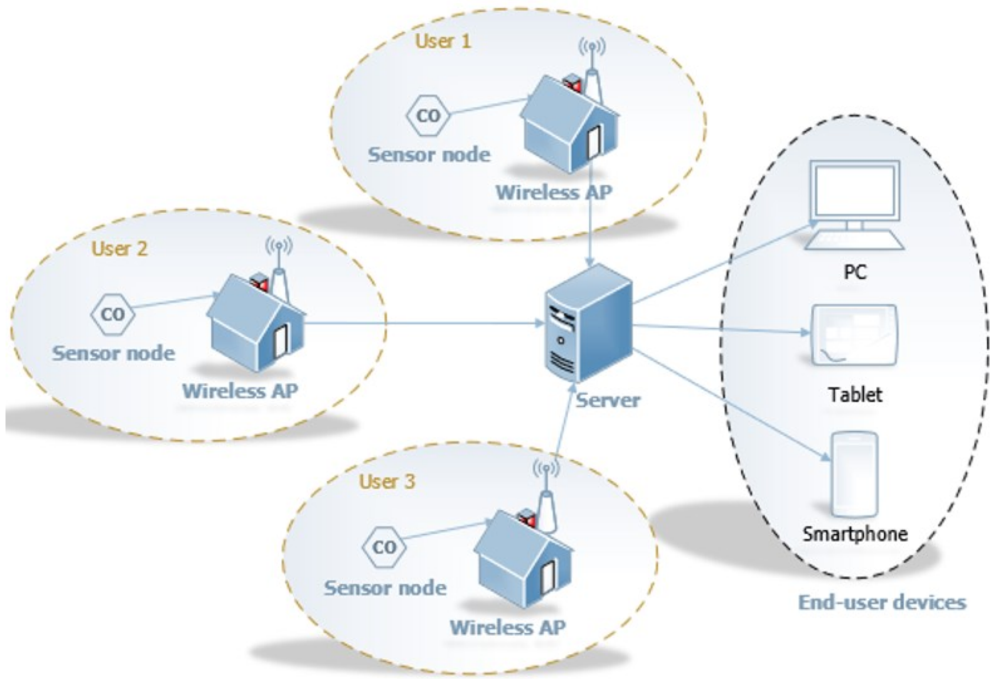


Figure 17 uSense air quality monitoring system (Brienza et al. 2015)

In the monitoring of the outdoor environment, Brienza et al. (2015) developed a low-cost cooperative monitoring system, *uSense* (Figure 17), which broadcasted the pollutant concentrations of CO and NO_2 in a variety of the urban areas. The pollutant data collected at each sensor node was merged to form a packet and transmitted to the server periodically. The web server was developed to dynamically display and store the pollutant data. Similarly, Ahuja et al. (2016) presented a system to measure the alcohol level in industrial areas, recreational areas, and schools. The alcohol concentrations were transmitted to the cloud through the WiFi network for the remote monitoring in real time.

2.4.3.4 GSM Monitoring System

GSM (Global System for Mobile communications) is a standard developed for digital cellular networks used by mobile devices. Subscriber identity module (SIM) cards inserted to the GSM modems are necessitated to enable the devices to connect to the cellular networks for the wireless communications. So far, researchers have conducted the experimental studies using the GSM technology to facilitate the real-time air monitoring. For example, Liu et al. (2011) developed an air quality monitoring system to measure the CO concentration in the urban environment. The monitoring system mainly consisted of two components, including a front-end monitoring system and a back-end database. The front-end monitoring system collected the pollutant data and transmitted the data to the database through the short message service via the GSM technology. Cheng et al. (2014) designed a novel client-could system for the monitoring of PM concentrations in the indoor and outdoor environments (Figure 18). The front-end sensors fixed at the places of interest were connected to the backend via GSM. The real-time PM concentrations at different spots were transmitted to the cloud database for the emission model development. Phala et al. (2016) proposed an air quality monitoring system based on the IEEE/ISO/IEC 21451 standards. The monitoring system adopted the GSM wireless communication module to measure the air polluted gases, such as CO_x, NO_2, and SO_2, and transmit the measurement data to the server for the concentration visualization. Also, an analysis of the control on the cross sensitivity was conducted through the sensor calibration process.

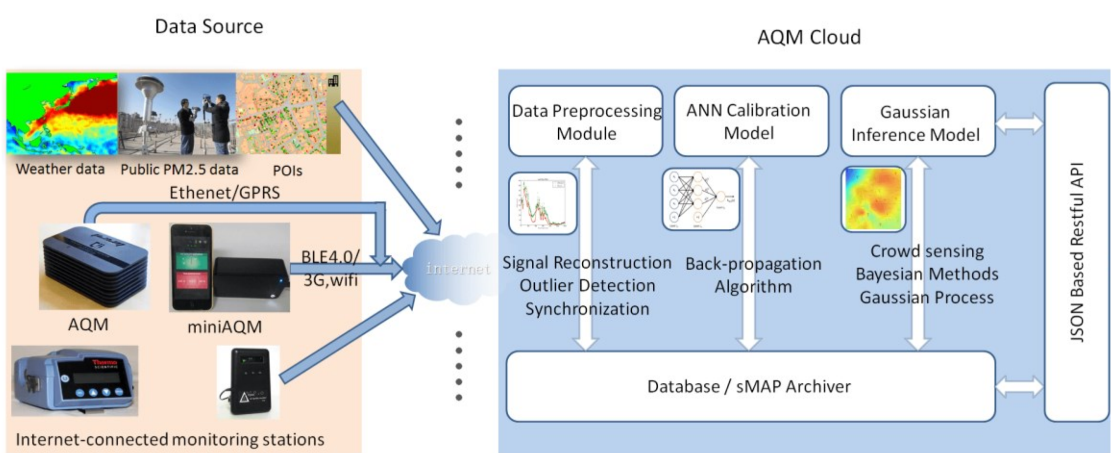


Figure 18 Architecture of the AirCloud system (Cheng et al. 2014)

2.4.4 Issues and Limitations of IoT-based Air Quality Monitoring System

So far, the IoT-based air quality monitoring systems have been developed to measure the air quality of the surroundings in a real-time and automatic manner. The effectiveness and efficiency also have been tested and validated. However, there are still some deficiencies and shortcomings in the air quality monitoring practice that have been identified from the previous research studies. Specifically, the current air quality monitoring systems are mainly limited to monitor the major air pollutants of CO, CO_2, and NO_2 (Brienza et al. 2015; Folea and Mois 2015; Kang and Hwang 2016; Weekly et al. 2013; Kim et al. 2013). As for the air pollutants of NH_3, H_2, and VOCs, and other pollutions, such as noise pollution and ultraviolet radiation, they were not taken into account in the previous studies. Considering the significant impacts of those pollutants on the health of people, it is necessary to monitor the pollutants and evaluate the corresponding impacts on the health of human beings.

The real-time pollutant monitoring data can be used to facilitate the environmental impact assessment and help decision makers take actions to mitigate the impacts. Also, the historical monitoring data is valuable in a variety of applications, such as the pollutant emission model development (Cheng et al. 2014), the building performance evaluation (Kumar and Hanke 2014), and so on. However, in current practices, few research efforts were allocated to archive the real-time monitoring data for further review. Also, in current practices, most research efforts were mainly placed on the hardware development of the monitoring system. In particular, researchers conducted massive studies to improve the monitoring efficiency through the investigations on the integrations of the appropriate communication technology and the cost-effective microcontrollers and microsensors. No further step has been proposed to evaluate the potential impacts on the ambient air quality and the health of human beings. Such way, people might continue to stay in the polluted environment even though they have collected the real-time pollutant concentration data. For example, the construction professionals have successfully collected the real-time pollutant emission data at the jobsite by using the monitoring system. However, they do not clearly understand the meanings of the pollutant concentrations in the ambient environment when the air quality is severely polluted. As a result, the construction professionals cannot distribute the air pollution warnings to the onsite workers and take the prompt actions to mitigate the potential impacts. Therefore, only the reliance on the existing monitoring systems is incapable of the environmental impacts assessment and mitigations.

Furthermore, the monitoring data in the previous studies was mainly pushed to the predefined webpage for the purpose of data display. Few studies have been proposed to quantitatively visualize the pollutant concentrations and statistically analyze the pollutant emission trends. Considering the pollutant emission trends are helpful for decision makers better understand the cumulative impacts of the pollutants, it is vital to continuously visualize the pollutant emissions. In the meantime, the current research studies hardly have developed the user interface to enhance the monitoring interactions and facilitate the data visualization.

The following section detailed discuss the drawbacks of the communication technologies used in the existing IoT-based monitoring systems as follows.

The disadvantages of the Bluetooth-based monitoring system mainly include:

- Interference issues. Bluetooth runs on the low radio frequency, it is potentially subject to interference issues. Provided that several sensor nodes are deployed at the monitoring field, it would cause the data loss during the data transmission;
- Data exchange distance Range. The Bluetooth communication is designed for the close-distance (distance < 10 meters) machine-to-machine communication so that it is only suitable for the communication within a small area.

The shortcomings of the ZigBee-based monitoring system mainly incorporate:

- Incapability to directly store data in the server. The ZigBee technology can be used to create a mesh network for the communication between the ZigBee modules. The coordinator for the data reception has to be connected with the server with wires, since ZigBee modules can only communicate wireless within the mesh network;
- Limited data packet transmission. The ZigBee technology is designed to transmit a small amount of data over a short distance with the average range of 10 to 30 meters. Also, the size of the data packet is proportional to the power consumption to the sensor node. In current practices, researchers intentionally customize the power consumption as the very little mode to prolong the operation time of the

monitoring system as much as possible. Such way, the data packet size is significantly influenced. Moreover, if more parameters/pollutants will be monitored, the data transmission will become a burden for ZigBee-based the monitoring system;

- Cost. Typically, the ZigBee-based mesh network consists of two types of sensor nodes, namely coordinator and endpoint. The cost of each ZigBee module is more than 50 US dollars. If a bunch of spots of interest have to be monitoring, the cost will become a big concern for decision makers;
- Low data transmission speed. Typical, the maximum data transfer speed is 250 Kilo-Bytes Per Second (kbps). The low transmission speed would cause the data transfer lag and data loss, which influences the effectiveness and efficiency of the monitoring performance.

The drawbacks of the GSM-based monitoring system mainly incorporate:

- Pricey cost. Basically, the GSM-based monitoring system requires an expensive GSM module in comparison with other communication technologies. Also, the recurring costs from the cellular carrier are inevitable. Generally, the price of the GSM module is more than 60 US dollars plus the cost of the SIM mobile plan and data plan;
- Excessive power consumption. It is manifest that the GSM technology drains the battery much quicker than other communication technologies. This is one of the main reasons that fewer GSM-based monitoring systems have been employed to facilitate the real-time pollutant monitoring.

2.5 Gaps in Body of Knowledge and Summary

The comprehensive literature was reviewed in the fields pertinent to the estimation and monitoring of air pollutant emissions from construction operations, IoT technology and its applications in the air quality monitoring. After the literature review, the following limitations and gaps are identified accordingly:

- Inability to monitor and quantify the real-world fuel consumptions and air pollutant emissions from construction equipment only based on the estimation models, such as the NONROAD model and URBEMIS model. These models were limited to provide practitioners with a conceptual estimation of the pollutant emissions from construction equipment other than an accurate quantification;

- Simulation-based methods neglected the possible schedule changes and delays occurred during the construction process. Also, the impacts caused from the complexity and uncertainties in the construction environment, such as Ahn and Lee (2013), Ahn et al. (2010), etc., were not taken into account in the previous studies;

- Expensive implementation of the onboard measurement method using PEMS impedes the wide spread of the PEMS-based method. it is impractical to deploy the PEMS to each piece of construction equipment, especially for the large-scale construction projects where there are tens of equipment. Also, the sensitivity to the weather and operating conditions is another concern when employing PEMS to monitor the diesel exhausts from the operating equipment;

- Pricey expense on the purchase, maintenance, and operation of the fixed air monitors is one of the biggest concerns for the private construction related entities, such as contractors and owners. Certain expertise, necessary power supply, and the required placement area also impede the wide employment of the fixed air monitors.

- The Bluetooth-based air quality monitoring systems suffer from the distance limit, since the typical data exchange range of the Bluetooth technology is less than 10 meters. Therefore, the Bluetooth-based monitoring systems are more suitable for the indoor environment;

- The limited data packet and transmission speed influence the efficiency of the ZigBee-based air quality monitoring systems. Also, the cost would be a burden when the ZigBee-based system is employed to monitor a large-scale environment, where consists of numerous endpoints, routers, and coordinators;

- The expense, including the cost of the hardware and the recurring cost from the carrier, is the major concern of the GSM-based monitoring system. Also, the power supply is another issue of the GSM-based systems to accomplish the long-term monitoring goal due to the excessive power consumption;

- Most of the IoT-based monitoring systems were employed to monitor the indoor environment. Few research efforts have been allocated to monitor the air quality of the outdoor environment, especially the complex environment in the industrial fields, such as construction sites, agricultural fields, and mining sites. Therefore, the effectiveness and efficiency of the monitoring performance is not clear;
- Most of the IoT-based monitoring systems were mainly focused on the pollutant data collection. Few systems have been developed to further archive and analyze the pollutant data. Also, few research efforts have been placed on the air quality assessment, the pollutant data visualization, and the warning generation when the pollutant concentrations exceed the air quality standards;
- The monitoring interests, in the previous studies, were mainly placed on the major air pollutants, such as CO_x, NO_x, and PM. As for other pollutants (e.g. VOCs, noise and UV), the potential impacts are significantly neglected.

The literature review confirms that the existing models and methods are deficient in the monitoring, visualization, and assessment of the real-world air pollutant emissions during the construction process. Also, research efforts with respect to the IoT-based monitoring system were mainly placed on the real-time pollutant data collection. Few efforts have been conducted to visualize the pollutant emissions and assess the potential impacts on ambient air quality and the health of workforces. Therefore, there is an urgent need to develop a highly-integrated system, which can be used to collect, archive, visualize and assess the pollutant emissions in a cost-effective, real-time and efficient manner. After analyzing the limitations and gaps in current practices, the present study aims to fill the research gaps by creating a highly-integrated IoT-based monitoring system for the pollutant emission monitoring, the pollutant data storage, the pollutant visualization, and the environmental impacts assessment. The proposed system with the integration of microcontrollers, microsensors, and the IoT technology is able to monitor and archive the pollutant data in the real-time and affordable manner. The pollutant emission visualization and the corresponding impacts assessment help decision makers better understand the environmental performance of the ongoing construction activities. When the pollutant emissions violet the standards, pollution warnings would be distributed to decision-makers, and the decision makers can take prompt actions to mitigate the harmful impacts.

CHAPTER 3: INTERNET OF THINGS (IOT)-BASED MONITORING SYSTEM

3.1 Introduction

This chapter provides a comprehensive description of the proposed system and a detailed explanation of the components required for its development. The system was created to facilitate the monitoring of the real-world air pollutant emissions of the construction operations, in particular, to collect and visualize the air pollutant emissions in real-time, trigger the alarms when the air pollutant emissions exceed the standards and evaluate the environmental performance of the construction operations. The main purpose of the proposed system is to provide construction practitioners and government officers with an effective and efficient tool to mitigate the potential environmental impacts caused by construction operations, including the impacts on the ambient air quality and the health of the workforces. Real-time monitoring and timely feedback of the onsite air pollutions is expected to assist decision makers in the construction site air quality management and the mitigation plans.

The construction project contributes a significant amount of air pollutants during the construction phase where a variety of diesel-based machinery on the construction site is intensively utilized and the construction-related activities are a major source of airborne particles. Researchers and government allocated massive efforts to curb the pollutant emissions in the planning and construction process. In the planning phase, the researchers and construction professionals only estimated the potential pollutant emissions from the construction equipment. However, the pollutions caused by the construction activities are significantly underestimated. Besides, the estimation is difficult to take into account the uncertainties during the construction process, in terms of schedule changes and delays, operating conditions and so on. For example, if the delay occurs in the earthmoving operation, the loader has to wait for the truck more than the scheduled time. Then, the pollutant emissions are underestimated only reliance on the estimations. A further step to investigate the real-world pollutant emissions is to employ onboard exhaust measurement and air pollutant monitors. However, this cannot provide the construction practitioners with a timely feedback of the real-world air quality at the jobsites. And, huge investment and certain expertise are necessitated to implement the monitoring of onsite air pollutions. For those reasons, the following set of characteristics have been identified and deemed as the necessities to make the proposed system more effective and efficient for construction practitioners.

- The system should be cost-effective and efficient in the monitoring of onsite air pollutions;
- The system should be user-friendly without the expertise in the regular operation and maintenance;
- The system should be able to continuously monitor the real-world air pollutant emissions and provide the timely feedback of the onsite air quality;
- The system should be able to continuously visualize the pollutant emissions;
- The system should be able to assist the construction practitioners in the determination of the most pollutant contributory construction activities;
- The system should be able to generate alarms when the air pollutant emissions exceed the air quality standards;
- The system should be able to facilitate the mitigation plans when the air quality is harmful to ambient air quality and the health of workforces.

3.2 Overview of the Proposed System

The proposed IoT-based system mainly includes three sub-systems, as illustrated in Figure 19. First, an air quality monitoring system is developed to automate the monitoring and visualization of the air pollutant emissions on construction sites in a cost-effective and real-time manner. Then, a proactive alarm system is proposed to analyze the monitoring data and trigger alarms when the air pollutant emissions exceed the air quality standards and regulations. Based on the analysis results, the environmental impact assessment system developed based on the Gaussian Plume-based atmospheric dispersion model is used to simulate how the air pollutants disperse in the ambient environment under different meteorological conditions. Such way, the environmental impacts caused by construction operations in each work zone are assessed in comparison with related regulations.

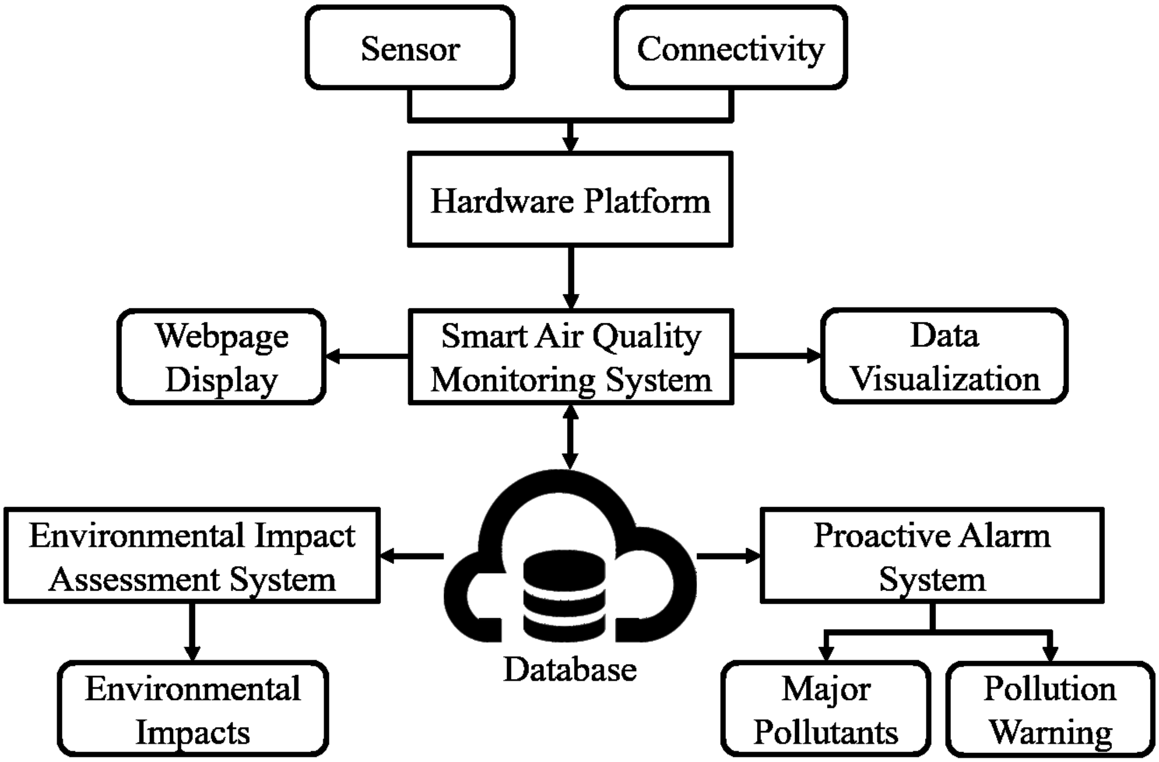


Figure 19 Overall flowchart of the proposed system

3.3 Hardware Platform

The hardware platform is the core component of the monitoring system, which is developed based on the state-of-the-art pollutant sensors and communication technologies. The following section describes the design philosophy and the rapid prototyping of the hardware platform. Specifically, it firstly starts from the comparison and selection of sensor type and communication technology. Then, the rapid prototyping of the platform is described. Following that, the sensor node construction is introduced in detail.

3.3.1 Sensor Type Comparison and Selection

In general, there are three major pollutant sensors in the market, namely semiconductor metal oxide (SMO) sensors, electrochemical sensors and infrared absorption sensors. In order to select the most suitable pollutant sensors of the hardware platform, a set of parameters is employed to evaluate the performance of three types of sensors, including sensitivity, selectivity (Dey 2018), response time (Liu et al. 2012), recovery time (Huang and Wan 2009) and so on. In particular, sensitivity refers to the smallest volume concentration of the target pollutant that can be detected by the sensor. Selectivity represents the ability of the sensor to detect the target pollutant in a mixture of gases. Response time stands for the time the sensor needs to generate a signal in accordance to the pollutant concentration. As an ideal sensor, the sensor should feature in low response time and cost and high sensitivity, selectivity and stability (Bochenkov and Sergeev 2010). As displayed in Table 2, the evaluation and comparison results of different types of sensors are illustrated. It is manifest that the SMO sensors are featuring in the excellent sensitivity and response time to pollutants with good accuracy and stability. In this context, the SMO sensors are more favorable for the real-time monitoring purpose. In addition, in comparison with other sensors, the SMO sensors are perfectly suitable for the portable monitoring systems, which can provide more possibilities in air quality monitoring practices. Moreover, SMO sensors are featured in the excellent affordability and maintenance. Therefore, the SMO sensors are selected to develop the sensor node.

Table 2 Evaluation and comparison of different types of sensors (Dey 2018)

Parameters	Type of Gas Sensors		
	SMO Gas Sensor	Electro Chemical Gas Sensor	Infrared Absorption Gas Sensors
Sensitivity	E	G	E
Accuracy	G	G	E
Selectivity	F	G	E
Response Time	E	F	F
Stability	G	P	G
Durability	G	F	E
Maintenance	E	G	F
Cost	E	G	F
Suitability to portable systems	E	F	P

E: Excellent, G: Good, F: Fair, P: Poor

3.3.2 Communication Technology Comparison and Selection

In current IoT applications, the prevalent communication technologies mainly include four types, namely Bluetooth, ZigBee, GSM/GPRS and WiFi. In order to select the cost-effective and efficient communication technology, a set of criteria is employed to compare the different technologies. As shown in Table 3, the comparison results are described. Bluetooth technology suffers from the limited communication range and extendibility, while ZigBee technology is only able to transmit limited data packet. Both Bluetooth and ZigBee have the data inference issues. Even though the GSM/GPRS is able to transmit the continuous data with low data collision possibility, the cost and the excessive power consumption impede the wide adoption, especially for the long-term monitoring practices. Therefore, WiFi technology is selected to facilitate the hardware platform construction, considering the ability to transmit continuous data with higher signal rate, high extendibility, low data interference and long communication range.

Table 3 Comparison of different types of communication technologies (Singh et al. 2014)

Feature	Communication Technologies			
	Bluetooth	ZigBee	GSM/GPRS	WiFi
Signal Rate	700 kb/s	250 kb/s	2 – 21 Mb/s	11/54 Mb/s
Range (m)	10	10 – 100	1000	100
Data Periodicity	Short bursts of low data	Short bursts of low data	Short bursts of continuous data	Short bursts of continuous data
Data Interference	High	Medium	Low	Low
Extendibility	No	Yes	Yes	Yes
Data Type	Audio, Pictures, Files	Small data Packet	Video, Audio, Pictures, Files	Video, Audio, Pictures, Files
Drawbacks	Short-range; Data Collision; Low extendibility	Incapability to store data in server; Limited data packet; Data Collision	Cost; Excessive power consumption	Moderate power consumption;

3.3.3 Rapid Prototyping

The rapid prototyping indicates the production of a system that describes the essential principles of the early version and operational functions of the final product. The process accelerates the prototype development and allows the system improvement through multiple iterations (Ibrahim and Moselhi 2014). The iterations lead to a more advanced and mature product.

The end users of the prototype are focused on the government officers and construction practitioners. Therefore, it is necessary to make the product more user-friendly, since the end users hardly have the background in electrical engineering and computer science. To achieve the goal, the prototype should have the following characteristics:

- Hardware configuration is easy-to-use to end users with little knowledge in electrical engineering;

- Hardware is ready-to-use to end users with little knowledge in programming;
- Hardware is able to meet the specific monitoring purpose;
- Hardware can be easily adapted to different applications;
- More cost-effective to alternative systems or related products.

On top of the hardware, the prototype is also concerned with the software. The software should share the characteristics of easy-to-use and flexibility (Ibrahim and Moselhi 2014). Therefore, it is desirable to provide the end users with a user-friendly software interface to operate the system.

3.3.4 Sensor Node Construction

In general, the sensor node is constructed with three components, the air pollution monitoring module, the vision-based monitoring module, and the solar photovoltaic power supply module. Specifically, as illustrated in Figure 20, the air pollution monitoring module is used to measure the real-time air pollutant concentrations, while the vision-based monitoring module is structured to capture the videos of the onsite construction activities. The solar photovoltaic power supply module is utilized to provide the electric power to maintain the operations of the sensor node. The following sections elaborate on the three modules in detail.

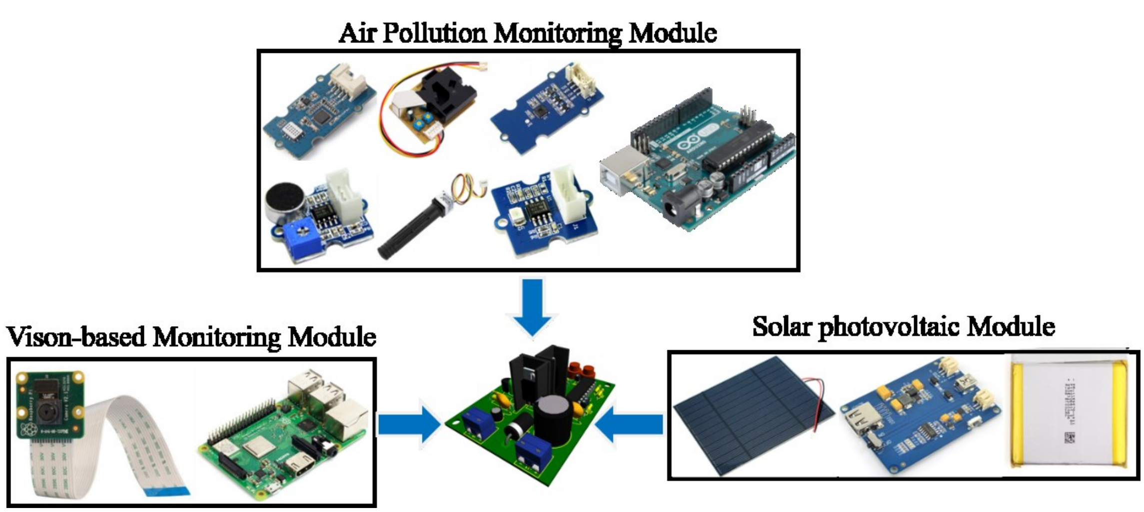


Figure 20 Sensor node construction

3.3.3.1 Air pollution monitoring module

The air pollution monitoring module is composed of a set of microsensors and the microcontroller board, which aims to measure the pollutants concentrations/levels and meteorological parameters. The microcontroller board is the core component of the air pollution monitoring module. In this module, the Arduino UNO R3 microcontroller board is employed, since it is endowed with an effective coding and circuit based on the flexible and easy-to-use hardware and software (How-to Geek 2011). Also, it is featured in the efficient coding and circuit with easy-to-use hardware and software and the excellent compatibility with the microsensors. As displayed in Figure 21 (a), the microcontroller board has 6 analog inputs, 14 digital inputs/outputs, a 16 MHz quartz crystal, Serial Peripheral Interface (SPI) and serial interface. The ESP8266 WiFi shield, as illustrated in Figure 21 (b), is utilized in this study to accomplish the real-time communication. It is an extremely cost-effective board, which is a self-contained system on chip (SOC) with the feature of low power consumption and highly-integrated WiFi solution (Espressif Systems 2017). As for the microsensors, the pollutant sensors adopted in the monitoring module are focused on not only the major air pollutants, such as CO_x, NO_2, PM etc. but also the pollutants of NH_3 and H_2. Besides, the meteorological parameters of temperature and humidity, the UV radiation level and the noise are taken into account in the air pollution monitoring module. Figure 21 (c) illustrates the assorted sensors. The WiFi communication technology is selected to facilitate the real-time communication between the sensor nodes and the remote server. The specifications and characteristics of the sensors are described in Table 4.

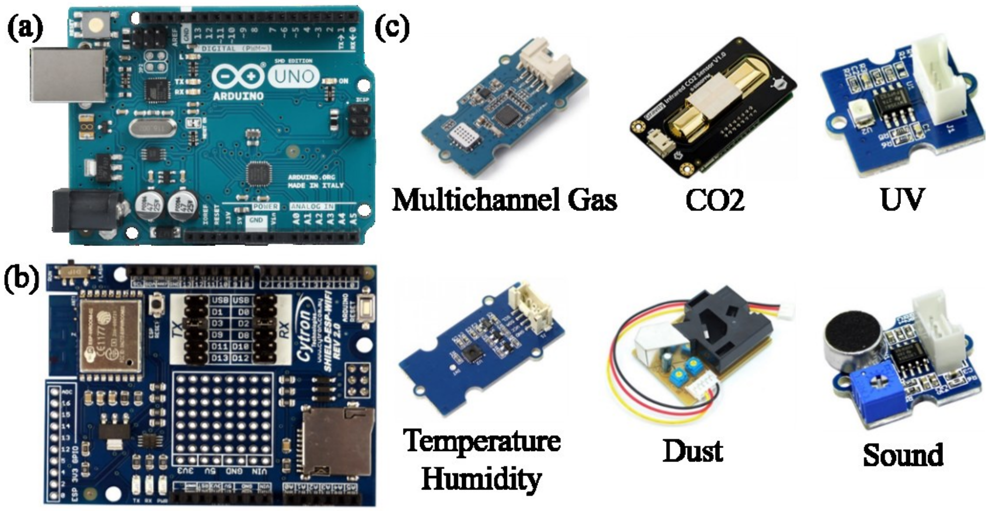


Figure 21 Parts in Air Pollution Monitoring Module

Table 4 Specifications of sensors (Compiled from SeeedStudio.cc)

Sensor	Target	Range	Operating Temperature	Voltage (V)	Price (USD)
CO_2 Sensor	CO_2	0 – 5000 ppm	± (50ppm + 3% reading)	4.5 – 5.5	56.00
UV Sensor	UV	200 – 400 nm	-30 – 85 °C	3.0 – 5.1	9.90
Sound Sensor	Noise	>66 dB	-40 – 125 °C	3.5 – 10	10.00
Dust Sensor	Dust (PM_1)	0 – 28,000 pcs/liter	0 – 45 °C	4.75 – 5.75	11.50
Multichannel Gas Sensor	CO	1 – 1000 ppm	-30 – 85 °C	3.1 – 5.25	39.90
	NO_2	0.05 – 10 ppm			
	NH_3	1 – 500 ppm			
	H_2	1 – 1000 ppm			
	CH_4	> 1000 ppm			
Temperature & Humidity Sensor	Temperature	-40 – 125℃	-40 – 125 ℃	2.4 – 5.5	16.90
	Humidity	0 – 100%			

Multi-channel gas sensor: developed based on the metal oxide sensors of MiCS-6814, which is a robust semiconductor sensor for the pollution detection in the environmental, automotive and industrial applications. The principle of the sensor is that the resistance of the detection layer changes in the presence of the target gases with the wide detection range, high sensitivity and long-life expectancy (SGX sensortech 2018).

UV Sensor: developed based on the sensor GUVA-S12SD, which is a Gallium Nitride material based Schottky-type photodiode. The sensor has a wide spectral range of 200nm-400nm with well visible blindness and high responsivity. The sensor is suitable for the UV index monitoring.

Sound Sensor: designed to detect the sound of surroundings based on the LM2904 amplifier and a built-in microphone. The sensor amplifies and filters the high-frequency signal that received from the microphone, and outputs a positive envelope.

CO_2 sensor: a high-performance sensor with the integration of the mature infrared absorption gas detection and precise optical circuit design. The sensor is featured with high sensitivity and resolution, low power consumption, anti-water vapor interference, no poisoning, high stability, and long cycle life (DFRobot 2018).

Dust sensor: designed to measure the PM (diameter $< 1\mu m$) concentration in the air by counting the low pulse occupancy time (LPO time) in a given time interval. The sensor can provide reliable data for the air purifiers.

Temperature & Humidity sensor: is a highly reliable and accurate sensor with quick response. The sensor is mainly built upon the state-of-the-art CMOSens sensor technology. The sensor is well calibrated and compensated for the digital output (SeeedStudio 2018).

3.3.3.2 Vision-based monitoring module

The vision-based monitoring module is developed to record the construction activities into videos based on the HD camera and microcontroller board. The HD camera, Raspberry Pi Camera, and the microcontroller board, Raspberry Pi 3 Model B+, are adopted in the vision-based monitoring module. As shown in Figure 22 (a), the Raspberry Pi Camera, endowed with a Sony IMX219 8-megapixel sensor, is an ultra-small and lightweight design

(Raspberry Pi Foundation 2018)). It is capable of capturing images with high sensitivity, low crosstalk, and low noise. The image resolution is up to 3280 × 2464. Also, the camera supports the video recording of 1080p30. The Raspberry Pi 3 Model B+ board, displayed in Figure 22 (b), is integrated with a 64-bit quad core processor running at 1.4GHz, dual-band 2.4GHz and 5GHz wireless LAN and PoE capability (Raspberry Pi Foundation 2018). Figure 22 (c) describes the assembled vision-based monitoring module in which the camera is connected to the Raspberry Pi board through the camera serial interface (CSI). Table 5 delineates the specifications of the camera and microcontroller board in detail.

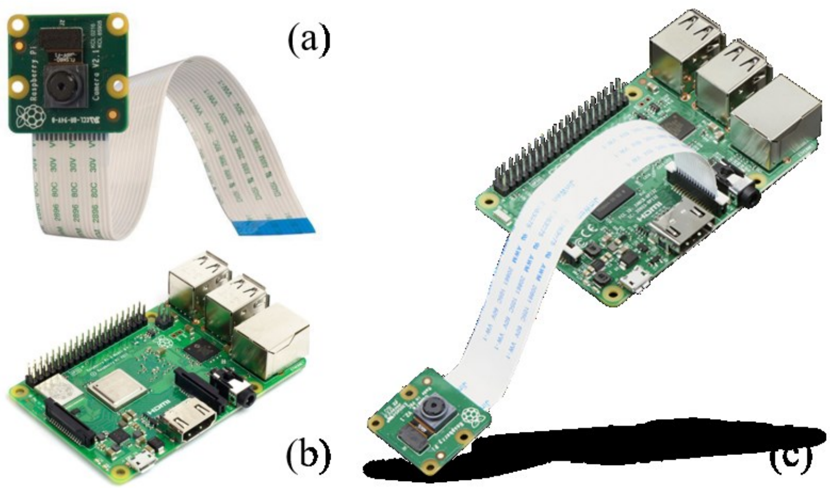


Figure 22 Parts in Vision-based Monitoring Module

Table 5 Specifications of microcontroller and camera (Compiled from raspberrypi.org)

Name	Model	Processor	Memory	Connectivity	Voltage	Multimedia
Pi Board	Raspberry Pi 3 model B+	64-bit SoC @ 1.4GHz	1GB LPDDR2 SDRAM	WLAN Bluetooth Ethernet	5V/2.5A	H.264 encode; OpenGL Graphics
Name	Model	Image sensor	Resolution: Image	Resolution: Video	Lens	Connection
Pi Camera	Raspberry camera V2	Sony IMX 219 CMOS	Max 3280 * 2464	1080p30, 720p60	Fixed 1/4"	Ribbon Cable

3.3.3.3 Solar photovoltaic power supply module

The solar photovoltaic power supply module is devised to complement the electric power from the solar power to run the sensor node. The solar photovoltaic apparatus mainly consists of three components, a solar panel, a LiPo Rider, and a Lithium-ion battery. Specifically, the solar panel, shown in Figure 23 (a), is adopted to perform the high solar energy transformation, which is made of single-crystal materials (SeeedStudio 2018). Typically, the open circuit voltage is around 5V. In the bright summer days, the voltage can rush up to 10V. As illustrated in Figure 23 (b), the LiPo Rider is employed to ride the solar wave to run the sensor node, which is an ideal green power solution for the outdoor sensor system (SeeedStudio 2018). The sensor node can excellently run on the solar power without the extra power supply when the solar power is sufficient. The Lithium-ion battery (Figure 23 (c)) is utilized to store the electrical charge. In case the solar power is insufficient, the sensor node will be powered by the Lithium-ion battery. Figure 23 (d) illustrates the assembled solar photovoltaic power supply module.

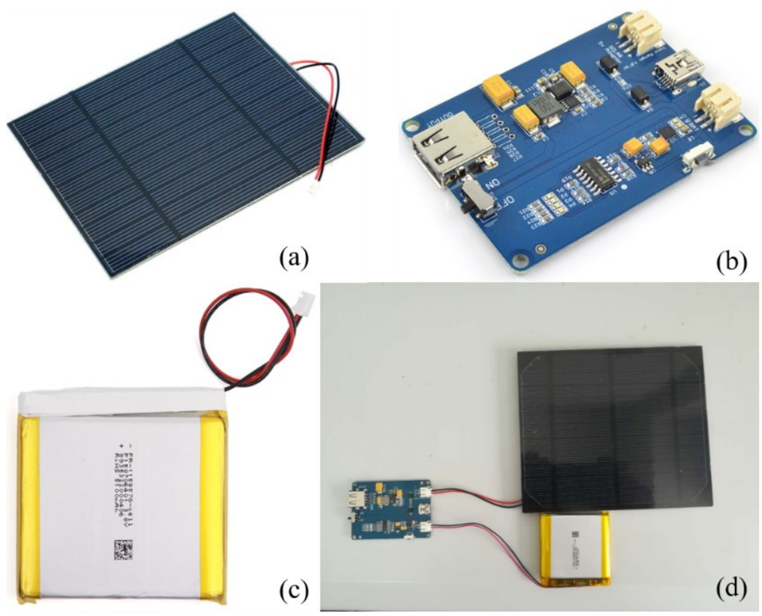


Figure 23 Parts in Solar Photovoltaic Power Supply Module

3.3.3.4 Considerations of practical issues

One challenging issue of the SMO sensors is drift rate and cross-sensitivity. In order to alleviate the potential impacts on the accuracy of the monitoring performance, it is suggested to optimize the operating temperature of SMO sensors, which is 20 °C to 25 °C. Consequently, at each sensor node of the proposed system, adequate ventilation holes in the envelope and heating pads are incorporated to maintain the optimal operating temperature, as shown in Figure 24.

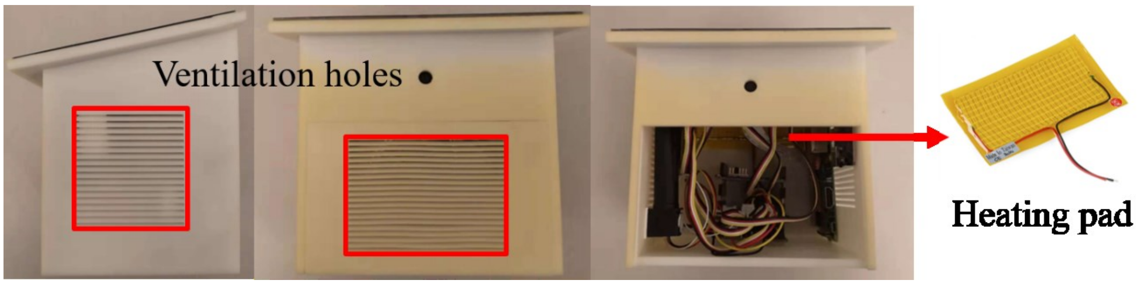


Figure 24 Consideration of ventilation and heating in sensor node construction

3.4 Smart Air Quality Monitoring System

The objective of this sub-system is to develop a cost-effective and efficient tool which can be used to monitor and visualize the air pollutant emissions from construction operations in a real-time manner. The air quality monitoring system mainly consists of a wireless sensor network. The overall architecture of the system is illustrated in Figure 25. The system simultaneously gleans the sensor data and construction activity videos from each sensor node at the measurement spot of interest. At each sensor node, the sensor data and videos are collected and transmitted to the remote server through the local wireless network in real time. Meantime, the sensor data is automatically documented in the database, while the videos are archived in the server. A user-friendly interface is devised to visualize the sensor data and broadcast the live videos. The following sections expound upon data storage process and the graphical user interface.

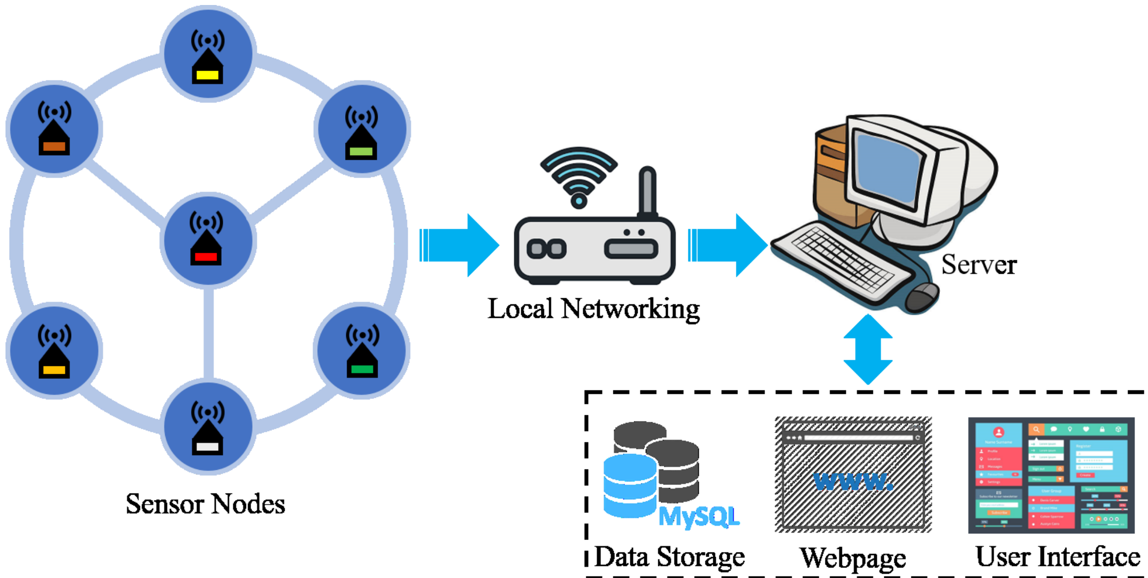


Figure 25 Architecture of smart air quality monitoring system

3.4.1 Data Storage

Once the sensor data and videos are transmitted to the server through the wireless networking, the sensor data and videos will be automatically archived. Such way, not only the real-time sensor data can be monitored, but also the historical pollution records can be further reviewed to assist the decision makers in the development of mitigation plans. Also, not only the live videos are of help for construction professionals to monitor the onsite activities, but also the archived videos can be used for the post-project analysis and planning.

The MySQL database is utilized in the study to archive the sensor data. The MySQL database is an advanced and comprehensive tool featured with high levels of scalability, security, reliability, and uptime (Oracle 2018). As shown in Figure 26, the process of the sensor data documentation is illustrated. For starters, the sensor node is activated to connect to the local wireless network. If the connection is successful, the sensor node is to collect the real-time pollutant data and push the sensor data over the network to a dedicated webpage via the wireless connection. Then, the sensor data is archived into the customized MySQL database via PHP scripts. Also, the air pollutant data is continuously updated and cached on the webpage.

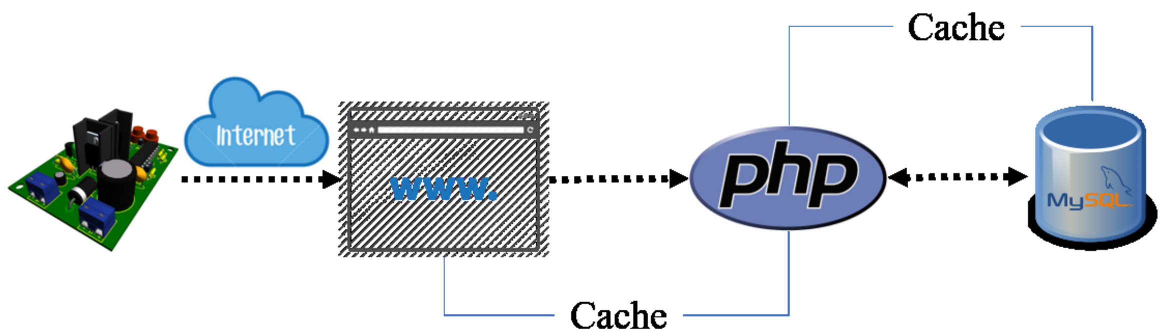


Figure 26 Sensor data storage process

3.4.2 Graphical User Interface

The graphical user interface (GUI) is developed in Visual Studio C# environment to visualize the sensor data and broadcast the live videos, as shown in Figure 27. When the GUI is activated, users are firstly required to identify the sensor node of interest in Box A and the pollutants/parameters of interest to be monitored and visualized in Box B. In the air quality monitoring practices, the primary standards are to calculate the average pollutant concentrations in the certain time interval, such as 1-hour basis, 8-hour basis, and 24-hour basis. The monitoring time interval in accordance with the standards, or even shorter than the standards according to the decision makers' preference, can be selected in Box C. Based on the selection, the mean values of the pollutants/parameters of interest are automatically computed and displayed in Box D. Also, the computation results are continuously updated according to the selected monitoring interval. Correspondingly, the concentration/level trends of the pollutant/parameters are continuously visualized and updated in Box E. The detailed calculation report can be loaded in Box F and exported as an Excel report for the further review. Meantime, construction professionals are able to load and review the entire sensor data in the MySQL database in Box G. The Box H is used to load the live videos from the sensor node of interest by specifying the Uniform Resource Locator (URL) of the camera module.

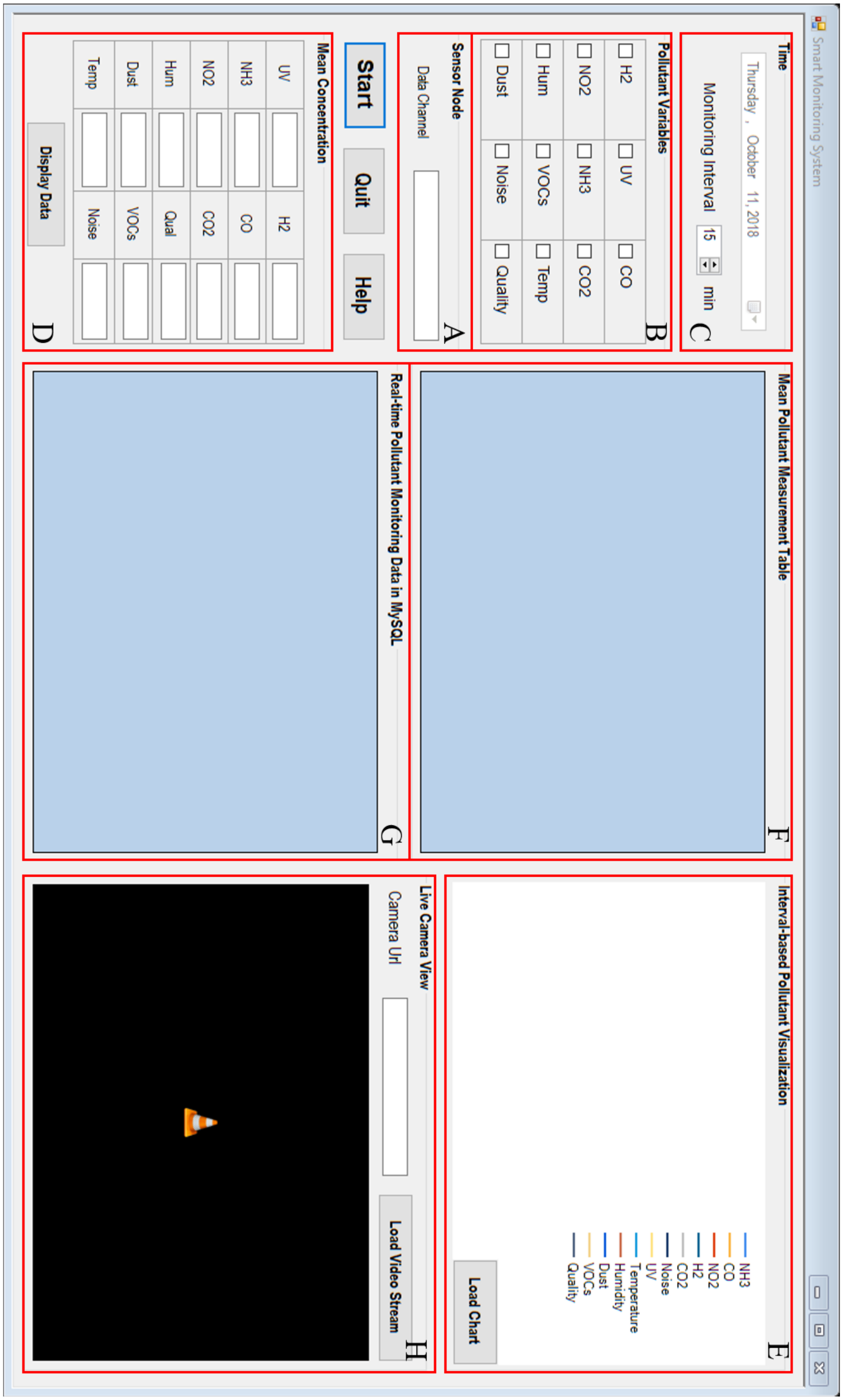


Figure 27 Graphical user interface

3.5 Proactive Alarm System

This sub-system aims to devise a tool to automate the analysis of the pollutant data and generate the warnings to decision makers when the pollutant emissions exceed the air quality standards. After the sensor data was archived in the database, the alarm system can be activated to review and analyze the real-time pollutant data in order to identify the major pollutants. When the pollutant emissions violate the air quality standards, warning emails would be generated and sent to the decision makers in an automatic and timely manner. Under the system, decision makers can obtain the timely feedback with respect to the most onsite pollutants and tack immediate actions. The overall architecture of the system is illustrated in Figure 28. Specifically, users are required to define the three parameters to activate the system. After the parameter setup, the system is to retrieve the archived pollutant data and compare the pollutant data with the air quality standards in order to examine whether the pollutant emissions exceed the standards. Provided that the pollutant emissions violate the standards, the system would generate the warning emails to decision makers in a timely manner.

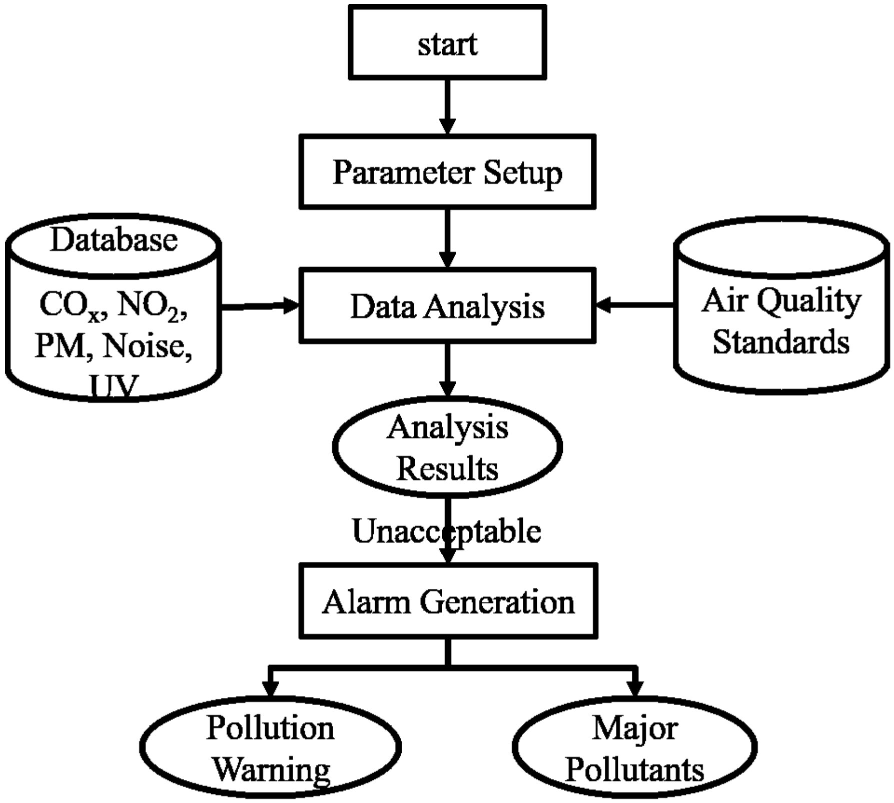


Figure 28 Flowchart of the alarm system

3.4.1 System Description

Initially, the parameters setup is to input the necessary parameters to activate the system. As shown in Figure 29, users are required to determine the sensor data collected from the sensor node of interest for the pollutant data analysis, while the analysis time interval in accordance with the air quality measurement rules needs to be specified. As mentioned before, the air quality is measured based on the average pollutant concentration measurement on the 1-hour basis, 8-hour basis, and 24-hour basis. Users can determine the analysis interval based on the measurement rules or even shorter than the measurement rules according to the decision makers' preference. Also, it is necessitated to identify the email address for the reception of the warnings when the pollutant emissions violate the standards.

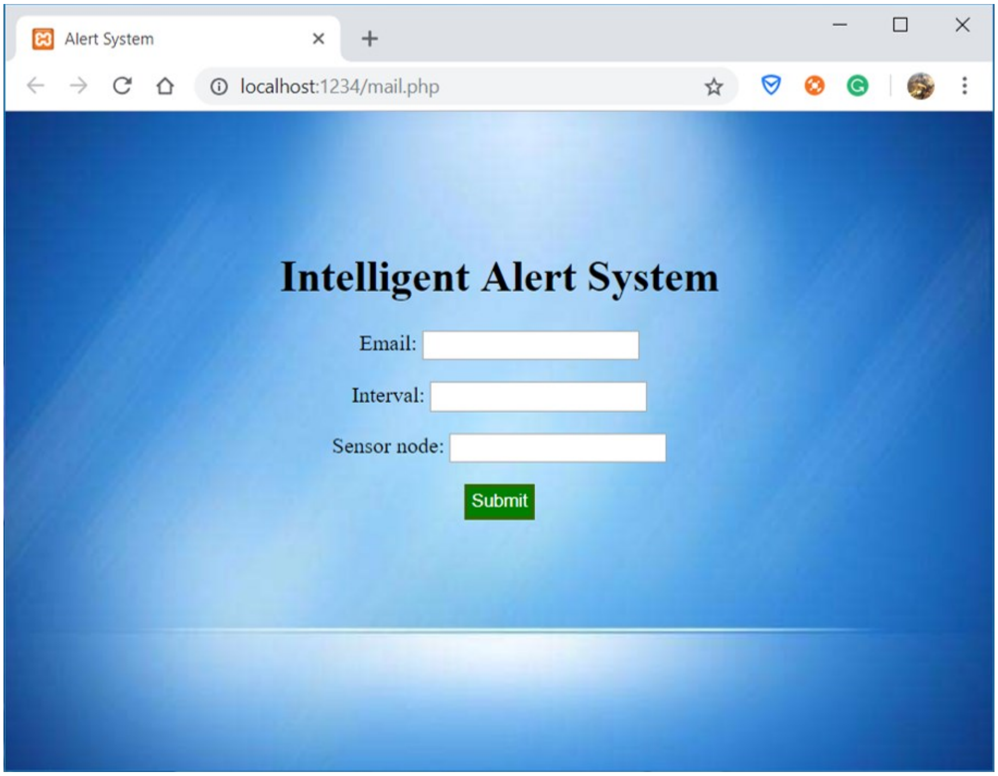


Figure 29 Parameter setup in alarm system

After all the parameters are determined, the system is automatically connected to the database in the server and retrieves the archived pollutant data in the database. Then, the major pollutants are identified through the comparison with the air quality standards. Thereafter, the analysis results are pushed and cached in a dedicated webpage as well as the specified alarm level and data entry time. The alarm level mainly consists of two types, fresh and polluted respectively. When the alarm level is polluted, the warning message will be emailed to the predefined email account immediately. Such way, the construction professionals can better understand the major pollutants emitted from the construction activities. Also, decision makers can obtain the feedback of the onsite air quality and take prompt actions to mitigate the pollutions.

3.6 Environmental Impacts Assessment System

The objective of this sub-system is to simulate the dispersion of the pollutants and evaluate the environmental impacts on the ambient air quality and the health of workforces. The Gaussian Plume-based atmospheric dispersion model is adopted in the system to simulate the air pollutant dispersion and estimate the downwind air pollutant concentrations under the specific meteorological conditions. This system can help practitioners better understand the potential impacts of the construction activities on the ambient air quality, especially in the downwind direction.

3.5.1 Gaussian Plume-based Dispersion Model

The dispersion model is adopted to mathematically simulate the dispersion of air pollutants in the ambient atmosphere. The dispersion model is to estimate the concentration emitted from any specified set of pollutant, at any location, at any period of time with any meteorological conditions (De Nevers 2000). The results of dispersion modeling can provide an estimation of location impacted areas and ambient concentrations. In this study, the dispersion model is based on the Gaussian plume idea. The model considers a point source such as a factory smokestack (which is not exactly a point but a small area that can be approximated as a point) and calculates the downwind concentration resulting from the point source (De Nevers 2000). Also, it takes into account the impacts of meteorological conditions on the pollutant dispersion. The graphical representation of the Gaussian plume-based dispersion model is described in Figure 30, where the origin of the coordinate system is placed at the base of the stack. The x-axis is aligned with the downwind direction. The contaminated gas stream (normally called a plume) is displayed emitting from the stack and then traveling in the x-direction and spreading in the y- and z-directions.

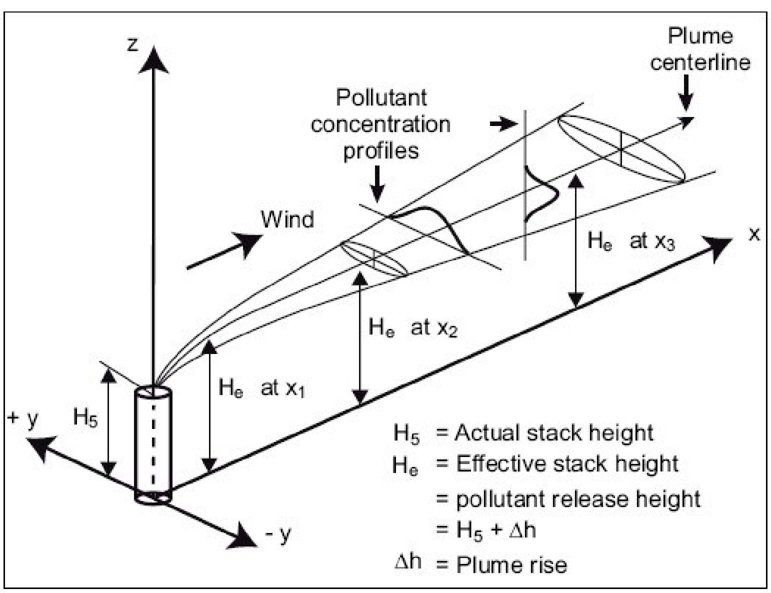


Figure 30 Mathematical illustration of Gaussian plume-based model

For the Gaussian plume computations, the plume is assumed to be emitted from the coordinate origin (0, 0, H) with the steady emission rate Q. The wind blows in the x-direction with speed u, and the speed is irrelevant to time, location or elevation. The model is used to compute the pollutant concentration due to the source at any point (x, y, z) for x > 0. The Gaussian plume model can be applied to mathematically simulate pollutant spreading in one, two, or three dimensions. In this study, the Gaussian plume idea with two-dimensional spreading is employed. The reason of the selection of two-dimensional spreading is mainly because the one-dimensional spreading is only concerned with the dispersion aligned in the direction of x-axis and the three-dimensional spreading is widely used in safety analysis where the puff of pollutants is the cloud that can be emitted by serious chemical plants or nuclear accidents. The equation mathematically describes the two-dimensional Gaussian Plume model as follow:

$$C = \frac{Q}{2\pi u \sigma_y \sigma_z} \exp\left(-\frac{y^2}{2\sigma_y^2}\right) \exp\left(-\frac{(Z - H)^2}{2\sigma_z^2}\right)$$

where C is the pollutant concentration at any point (x, y, z); Q represents the emission rate at the point source; u is the wind velocity; the values of σ_y and σ_z called horizontal and vertical dispersion coefficients in the unit of meters are based on experimental data and shown in Figure 31; H is the height of stack; y and z are the coordinates of the point of interest.

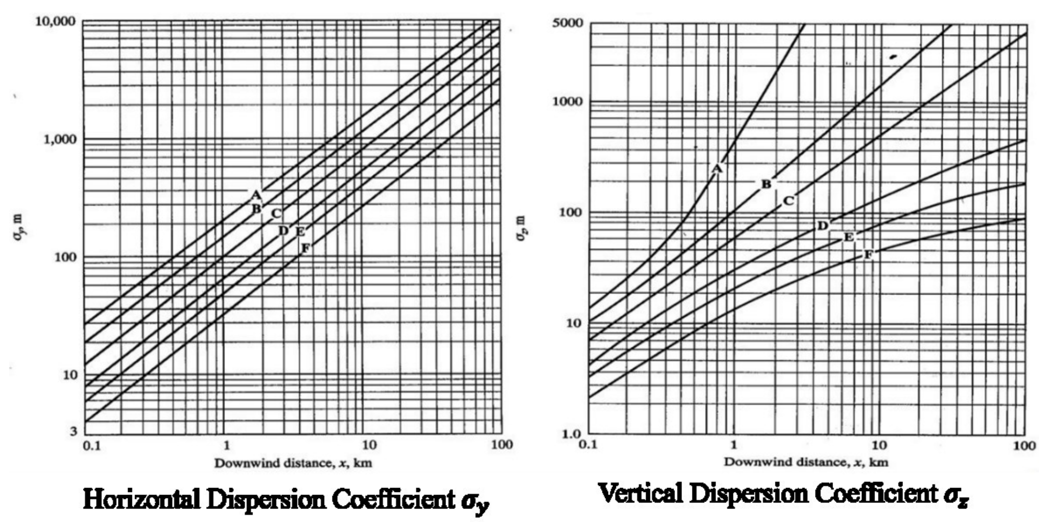


Figure 31 Horizontal and vertical dispersion coefficient

When determining the values of horizontal and vertical coefficients, the selection of labeled lines A through F is dependent on atmospheric stability. Atmospheric stability is one of the principal topics in meteorology (De Nevers 2000). On a clear, strong solar radiation heats the air in summer days with low wind velocity, which in turn mix pollutants well. The atmosphere is unstable, and the values of σ_y and σ_z will be large. On the other hand, in a cold night or a winter day, the air forms a layer which makes the atmosphere stable and absorbs pollutants. Then the values of σ_y and σ_z will be small. The classification of the atmospheric stability is described in Table 6.

Table 6 Atmospheric Stability Categories (Tunner 1970)

Key to Stability Categories					
Surface Wind Speed at (10m), m/s	Day			Night	
	Incoming Solar Radiation			Thinly Overcast or ≥ 4/8 Cloud	Clear or ≤ 3/8 Cloud
	Strong	Moderate	Slight		
0-2	A	A-B	B	-	-
2-3	A-B	B	C	E	F
3-5	B	B-C	C	D	E
5-6	C	C-D	D	D	D
≥6	C	D	D	D	D

3.5.2 Work zone-based Gaussian Plume Model

The work zones on the construction site are considered as the pollutant emission sources. The pollutant concentrations in each work zone can be continuously measured by the smart air quality monitoring system. The corresponding environmental risk on the ambient air quality and workforces' health can be assessed according to the air quality standards or users' preference. Specifically, the plume is assumed to be emitted from the work zone, as shown in Figure 32. The effective stack height is assumed to equate with the height of the major equipment involved in the construction operations. The average emission rate of each air pollutant can be obtained from the monitoring data analysis. Such way, for any given point in the downwind direction of the construction site, the potential environmental impacts caused by the ongoing construction activities in each work zone can be assessed.

Figure 32 Work zone-based Gaussian Plume idea (National Weather Service 2011)

A GUI is developed in Visual Studio C# environment to facilitate the air pollutant dispersion analysis, as shown in Figure 33. Specifically, the plume node of interest is determined in Box A, while the pollutant to be analyzed is selected in Box B. The measurement interval can be identified in Box C. The required input in the Gaussian Plume model, such as the wind speed, the horizontal and vertical dispersion coefficients and the coordinates of the downwind location, are listed in Box D. Accordingly, the potential pollutant concentration in the location of interest is computed and displayed in box E.

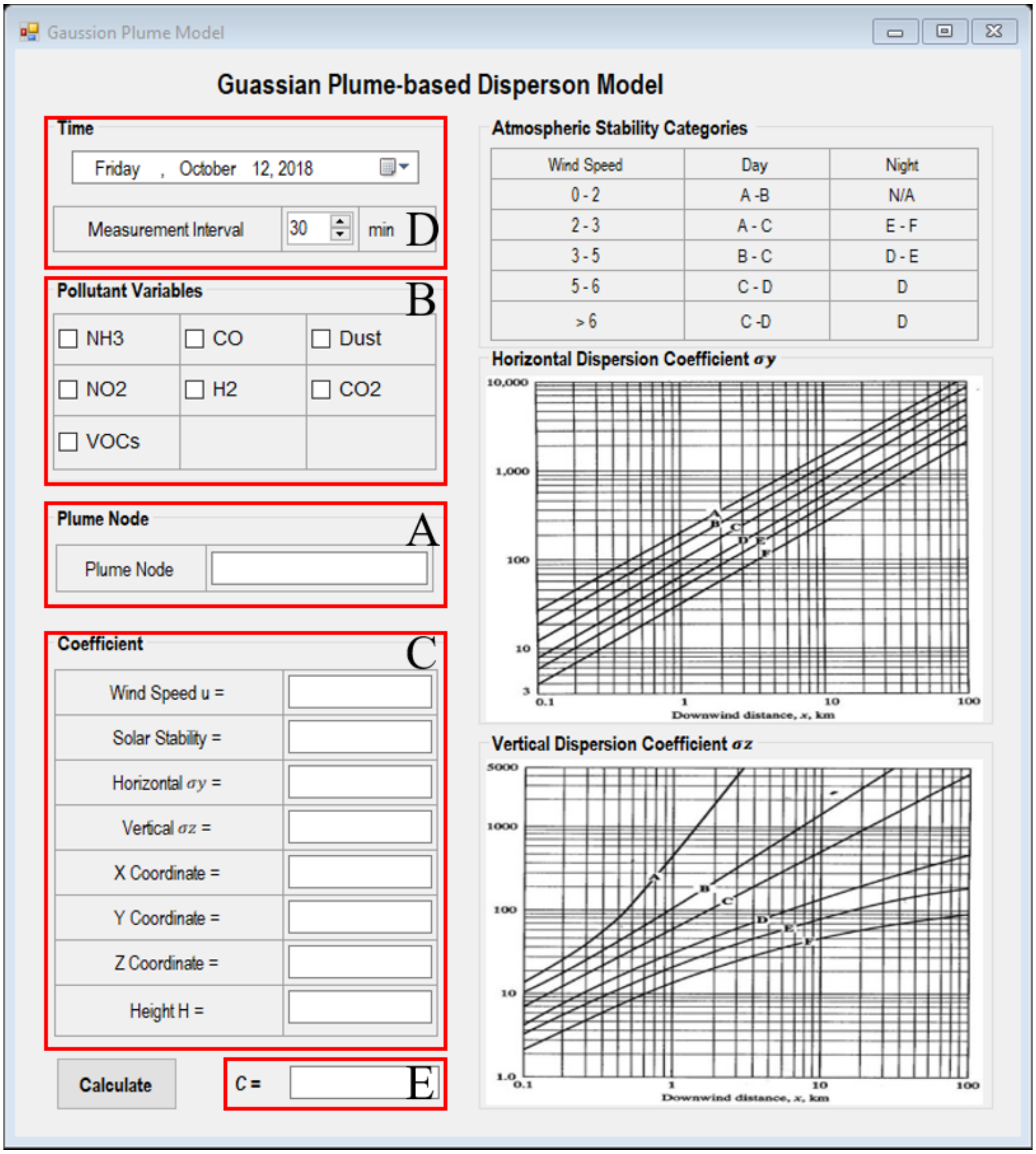


Figure 33 GUI of Environmental Impact Assessment system

3.7 Summary

This chapter presented an overview of the proposed IoT-based monitoring system. The system mainly includes three sub-systems, smart air quality monitoring system, proactive alarm system, and environmental impact assessment system. Specifically, the smart air quality monitoring system is to automate the monitoring and visualization of the air pollutant emissions on construction sites in a cost-effective and real-time manner. The proactive alarm system is to automatically analyze the monitoring data and generate alarms to decision makers when the air pollutant emissions exceed the air quality standards and regulations. The environmental impact assessment system is to simulate how the air pollutants disperse and estimate the pollutant concentration in the ambient environment under different meteorological conditions. The proposed system is cost-effective, portable and efficient, which can assist the decision makers in the evaluation of the environmental performance of the ongoing construction activities.

CHAPTER 4: IMPLEMENTATION AND RESULTS

This chapter describes the implementation of the developed system. The system consists of subsystems, namely smart air quality monitoring system, proactive alarm system, and the environmental impact assessment system. The system was tested on the real construction sites. The detailed description of implementations and results is presented as follow.

4.1 Implementation

The smart air quality monitoring has been mainly implemented in the Arduino Integrated Development Environment (IDE) and Microsoft Visual Studio .NET platform. It was tested to monitor and visualize the pollutant emissions from the real construction sites. The proactive alarm system has been implemented in PHP platform to analyze the real-time monitoring data and generate the warnings when the onsite air quality deteriorates, while the environmental impact assessment system has been tested in Microsoft Visual Studio .NET platform to simulate the air pollutant dispersions in the downwind direction. The systems were tested as a prototype in a Microsoft Windows 10 64-bit operating system with the hardware configuration of an Intel® Core (TM) i7-6700HQ CPU (Central Processing Unit) @ 2.6 GHz and an 8 GB memory.

4.2 Results

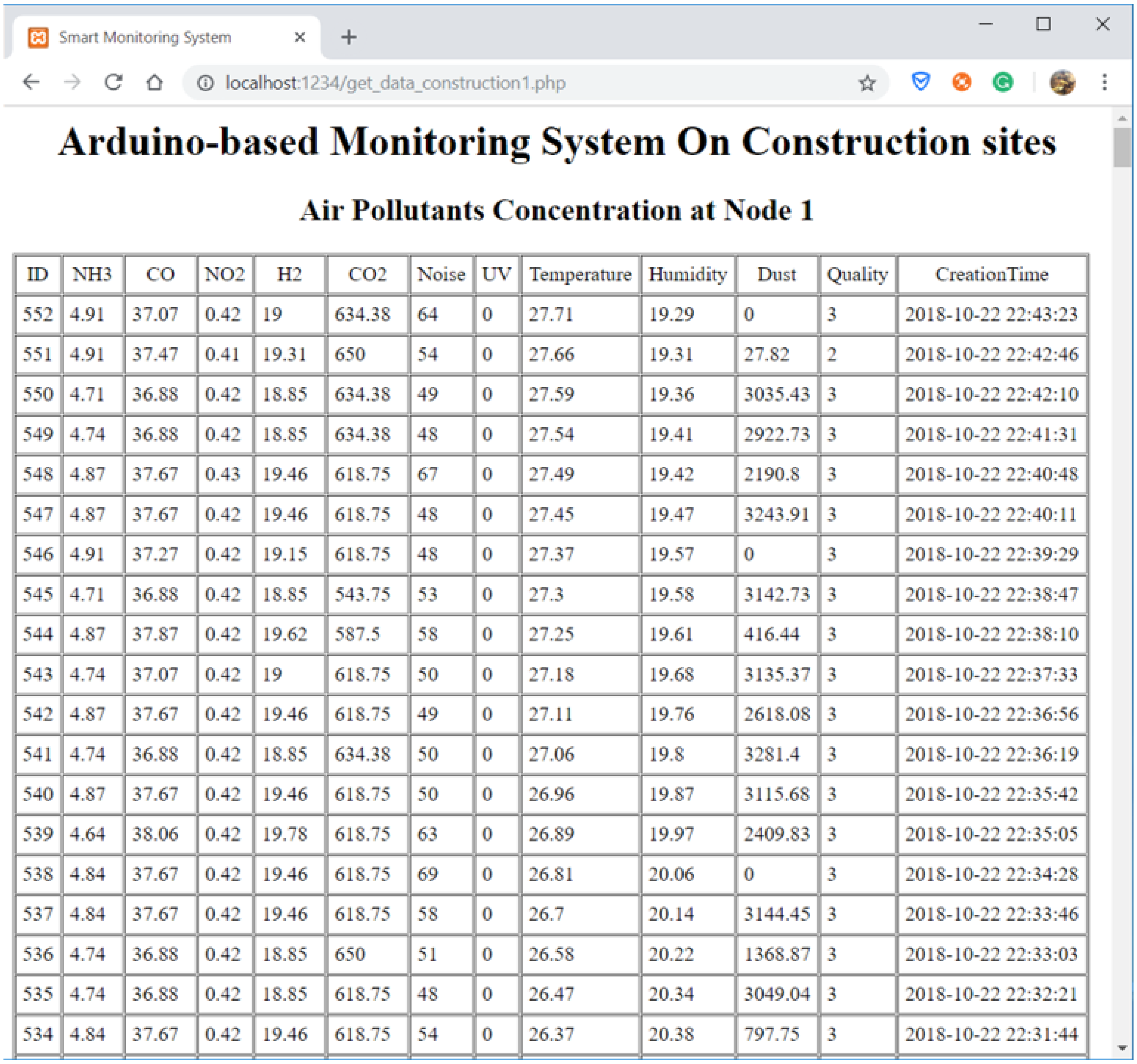
4.2.1 Case study I

The monitoring system was placed on the construction sites of the Amati condo project to monitor, visualize and assess the real-time onsite air quality. The Amati Condominiums is a new condo development project located in the prime area of District Griffintown of Montreal. The project is currently under construction of a 15-story building including a total of 239 units. Figure 34 illustrates the placement of the monitoring system on the construction site, while Figure 35 shows the image samples of the construction sites.

Figure 34 Placement of the proposed monitoring system

Figure 35 Image samples of Amati construction site

As shown in Figure 36, the real-time monitoring data from each sensor node is pushed to the server and displayed on a dedicated webpage. Specifically, the data entry ID, pollutant concentrations/levels and data entry time are depicted on the webpage. In the meantime, the monitoring data of each sensor node is archived in the database, as displayed in Figure 37. Figure 38 illustrates the camera webpage interface, while Figure 39 describes the archived video data in the server.

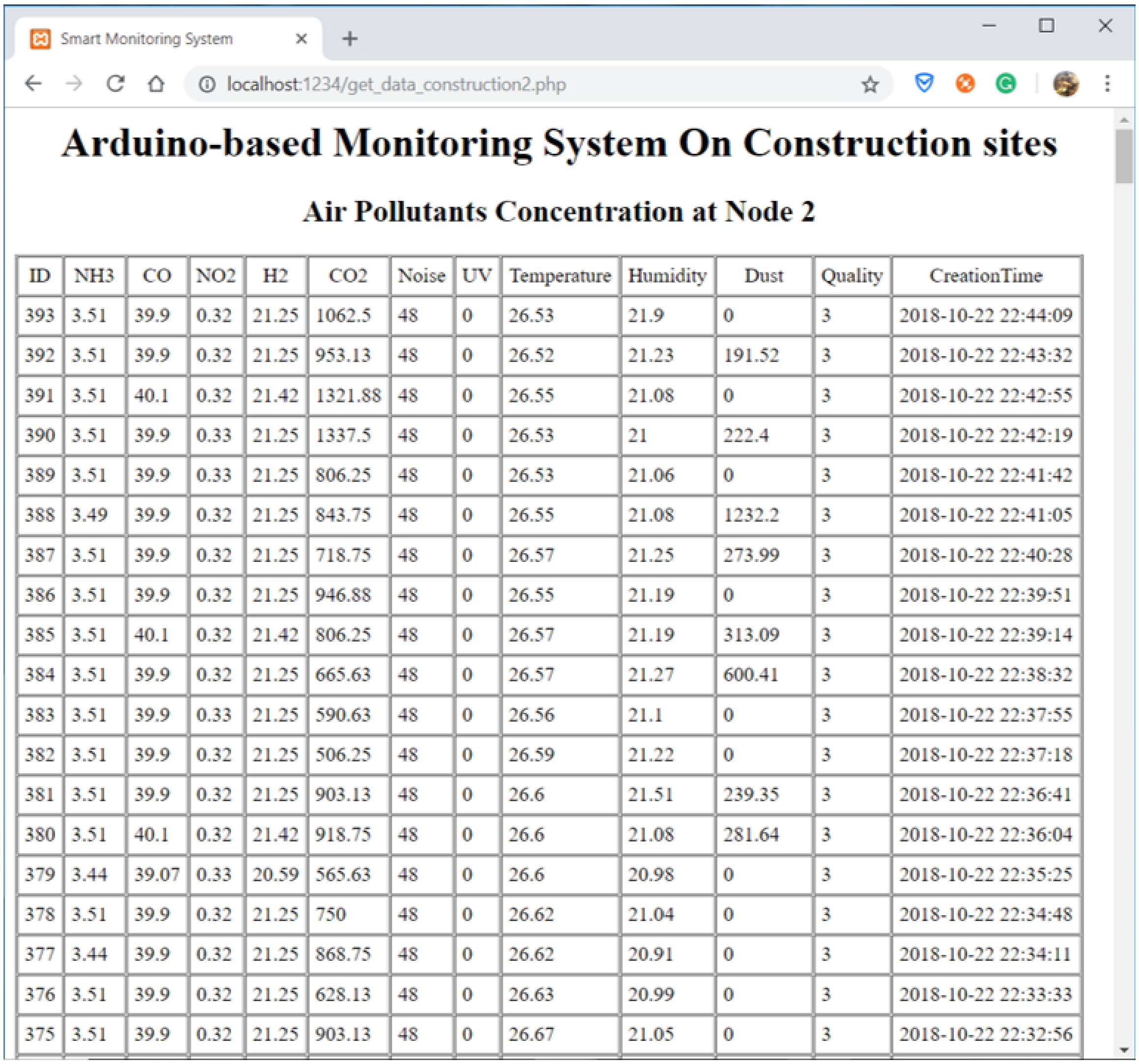


Arduino-based Monitoring System On Construction sites

Air Pollutants Concentration at Node 1

ID	NH3	CO	NO2	H2	CO2	Noise	UV	Temperature	Humidity	Dust	Quality	CreationTime
552	4.91	37.07	0.42	19	634.38	64	0	27.71	19.29	0	3	2018-10-22 22:43:23
551	4.91	37.47	0.41	19.31	650	54	0	27.66	19.31	27.82	2	2018-10-22 22:42:46
550	4.71	36.88	0.42	18.85	634.38	49	0	27.59	19.36	3035.43	3	2018-10-22 22:42:10
549	4.74	36.88	0.42	18.85	634.38	48	0	27.54	19.41	2922.73	3	2018-10-22 22:41:31
548	4.87	37.67	0.43	19.46	618.75	67	0	27.49	19.42	2190.8	3	2018-10-22 22:40:48
547	4.87	37.67	0.42	19.46	618.75	48	0	27.45	19.47	3243.91	3	2018-10-22 22:40:11
546	4.91	37.27	0.42	19.15	618.75	48	0	27.37	19.57	0	3	2018-10-22 22:39:29
545	4.71	36.88	0.42	18.85	543.75	53	0	27.3	19.58	3142.73	3	2018-10-22 22:38:47
544	4.87	37.87	0.42	19.62	587.5	58	0	27.25	19.61	416.44	3	2018-10-22 22:38:10
543	4.74	37.07	0.42	19	618.75	50	0	27.18	19.68	3135.37	3	2018-10-22 22:37:33
542	4.87	37.67	0.42	19.46	618.75	49	0	27.11	19.76	2618.08	3	2018-10-22 22:36:56
541	4.74	36.88	0.42	18.85	634.38	50	0	27.06	19.8	3281.4	3	2018-10-22 22:36:19
540	4.87	37.67	0.42	19.46	618.75	50	0	26.96	19.87	3115.68	3	2018-10-22 22:35:42
539	4.64	38.06	0.42	19.78	618.75	63	0	26.89	19.97	2409.83	3	2018-10-22 22:35:05
538	4.84	37.67	0.42	19.46	618.75	69	0	26.81	20.06	0	3	2018-10-22 22:34:28
537	4.84	37.67	0.42	19.46	618.75	58	0	26.7	20.14	3144.45	3	2018-10-22 22:33:46
536	4.74	36.88	0.42	18.85	650	51	0	26.58	20.22	1368.87	3	2018-10-22 22:33:03
535	4.74	36.88	0.42	18.85	618.75	48	0	26.47	20.34	3049.04	3	2018-10-22 22:32:21
534	4.84	37.67	0.42	19.46	618.75	54	0	26.37	20.38	797.75	3	2018-10-22 22:31:44

(a) Webpage display of sensor data at Node 1



Arduino-based Monitoring System On Construction sites

Air Pollutants Concentration at Node 2

ID	NH3	CO	NO2	H2	CO2	Noise	UV	Temperature	Humidity	Dust	Quality	CreationTime
393	3.51	39.9	0.32	21.25	1062.5	48	0	26.53	21.9	0	3	2018-10-22 22:44:09
392	3.51	39.9	0.32	21.25	953.13	48	0	26.52	21.23	191.52	3	2018-10-22 22:43:32
391	3.51	40.1	0.32	21.42	1321.88	48	0	26.55	21.08	0	3	2018-10-22 22:42:55
390	3.51	39.9	0.33	21.25	1337.5	48	0	26.53	21	222.4	3	2018-10-22 22:42:19
389	3.51	39.9	0.33	21.25	806.25	48	0	26.53	21.06	0	3	2018-10-22 22:41:42
388	3.49	39.9	0.32	21.25	843.75	48	0	26.55	21.08	1232.2	3	2018-10-22 22:41:05
387	3.51	39.9	0.32	21.25	718.75	48	0	26.57	21.25	273.99	3	2018-10-22 22:40:28
386	3.51	39.9	0.32	21.25	946.88	48	0	26.55	21.19	0	3	2018-10-22 22:39:51
385	3.51	40.1	0.32	21.42	806.25	48	0	26.57	21.19	313.09	3	2018-10-22 22:39:14
384	3.51	39.9	0.32	21.25	665.63	48	0	26.57	21.27	600.41	3	2018-10-22 22:38:32
383	3.51	39.9	0.33	21.25	590.63	48	0	26.56	21.1	0	3	2018-10-22 22:37:55
382	3.51	39.9	0.32	21.25	506.25	48	0	26.59	21.22	0	3	2018-10-22 22:37:18
381	3.51	39.9	0.32	21.25	903.13	48	0	26.6	21.51	239.35	3	2018-10-22 22:36:41
380	3.51	40.1	0.32	21.42	918.75	48	0	26.6	21.08	281.64	3	2018-10-22 22:36:04
379	3.44	39.07	0.33	20.59	565.63	48	0	26.6	20.98	0	3	2018-10-22 22:35:25
378	3.51	39.9	0.32	21.25	750	48	0	26.62	21.04	0	3	2018-10-22 22:34:48
377	3.44	39.9	0.32	21.25	868.75	48	0	26.62	20.91	0	3	2018-10-22 22:34:11
376	3.51	39.9	0.32	21.25	628.13	48	0	26.63	20.99	0	3	2018-10-22 22:33:33
375	3.51	39.9	0.32	21.25	903.13	48	0	26.67	21.05	0	3	2018-10-22 22:32:56

(b) Webpage display of sensor data at Node 2

Figure 36 Sensor data webpage display

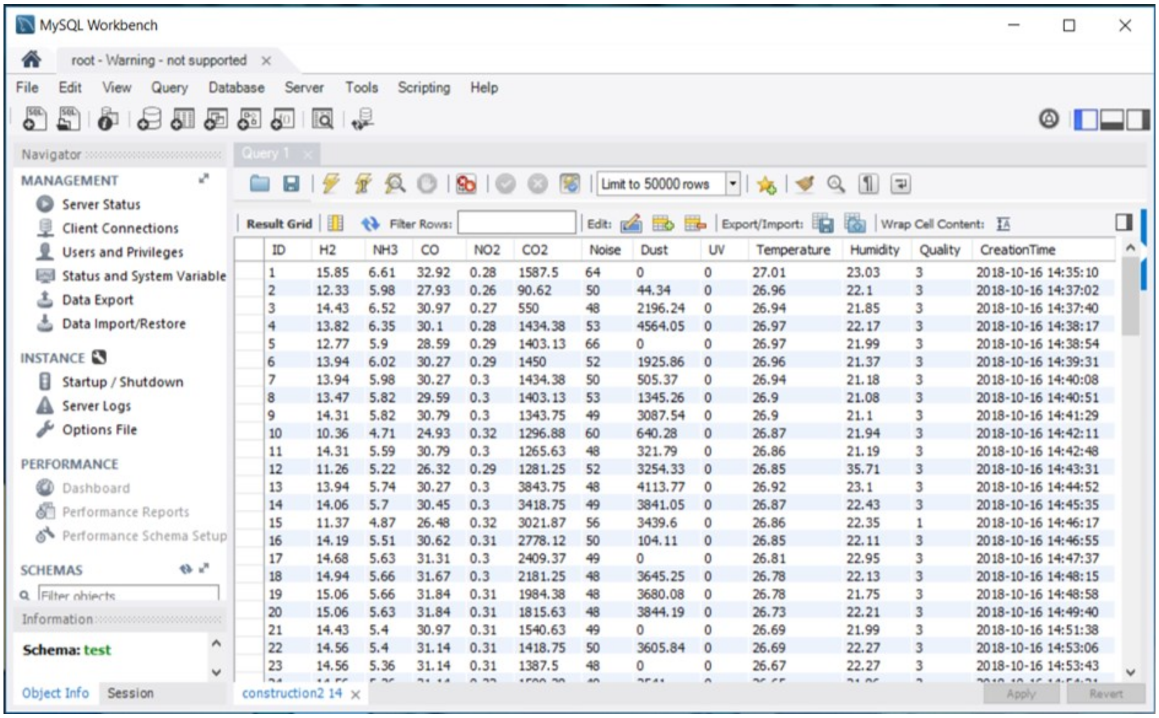


Figure 37 Data archive in database

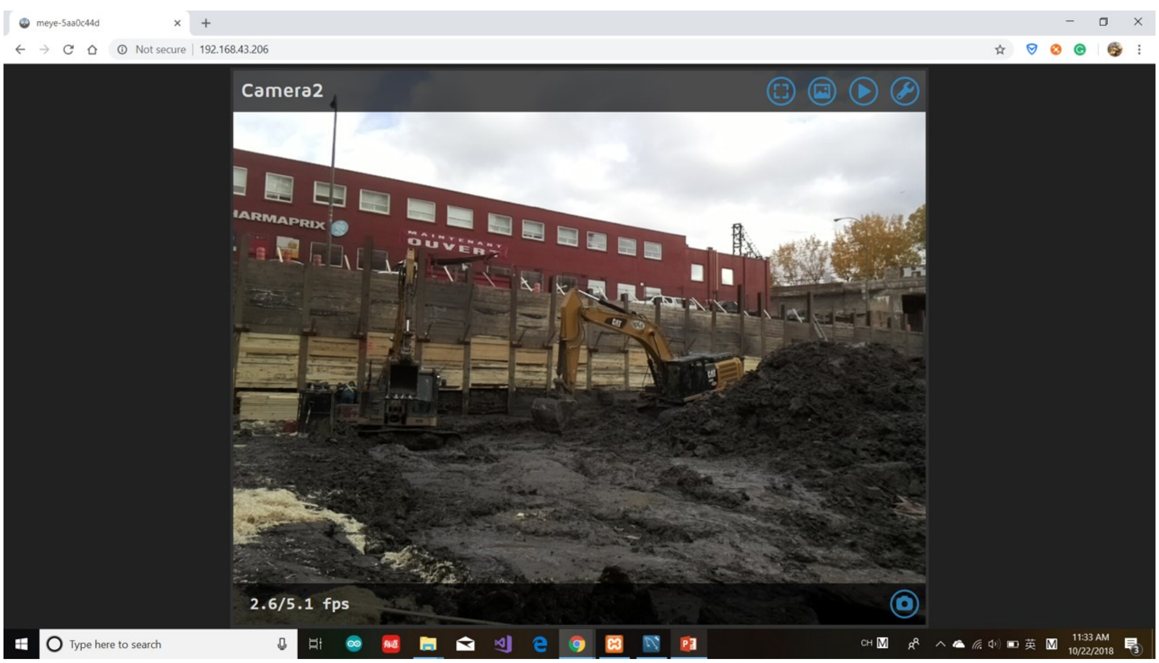


Figure 38 Camera module web interface

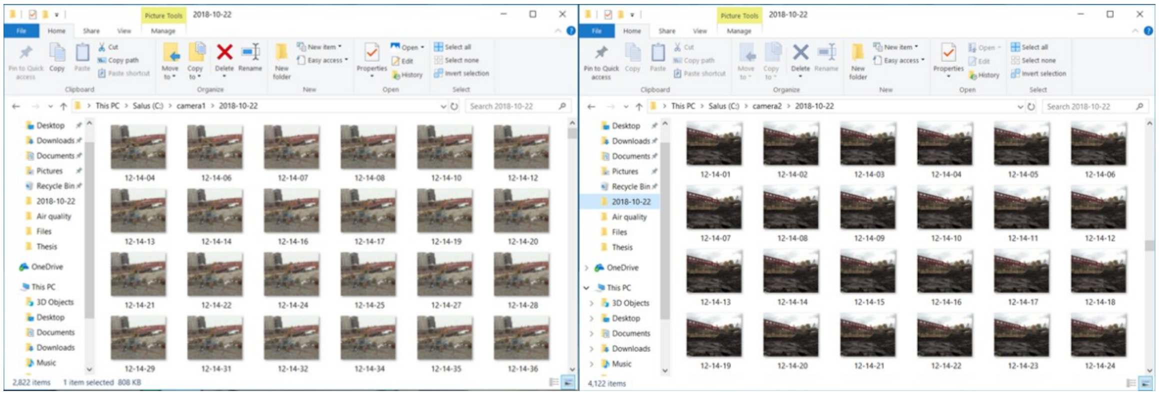


Figure 39 Digital data stored in server

When the monitoring data is archived in the database, users can launch the GUI to visualize the pollutant data and load the live video stream. Take the pollutant of CO_2 as an example, Figure 40 depicts the results of CO_2 monitoring data analysis and visualization, and the live video broadcast. Specifically, when the calculation interval (30 minutes) and the sensor node (construction1) are determined, the average CO_2 concentration is calculated and displayed in the red box, while the visualization results of the CO_2 emission trend is delineated in the blue box. In the graphical chart, the horizontal axis is for the period sequence, while the vertical axis is for the pollutant concentration. Thereafter, the pollutant concentration measurement and the visualization results will be updated every 30 minutes accordingly, as shown in Figure 41. Besides, the video stream of the sensor node is loaded in GUI by specifying the IP address of the camera in the green box. According to the visualization results and the live videos, decision-makers can better understand the environmental performance of the ongoing activities. Also, construction practitioners can approximately define the relationship between the pollutant emissions and the construction activities.

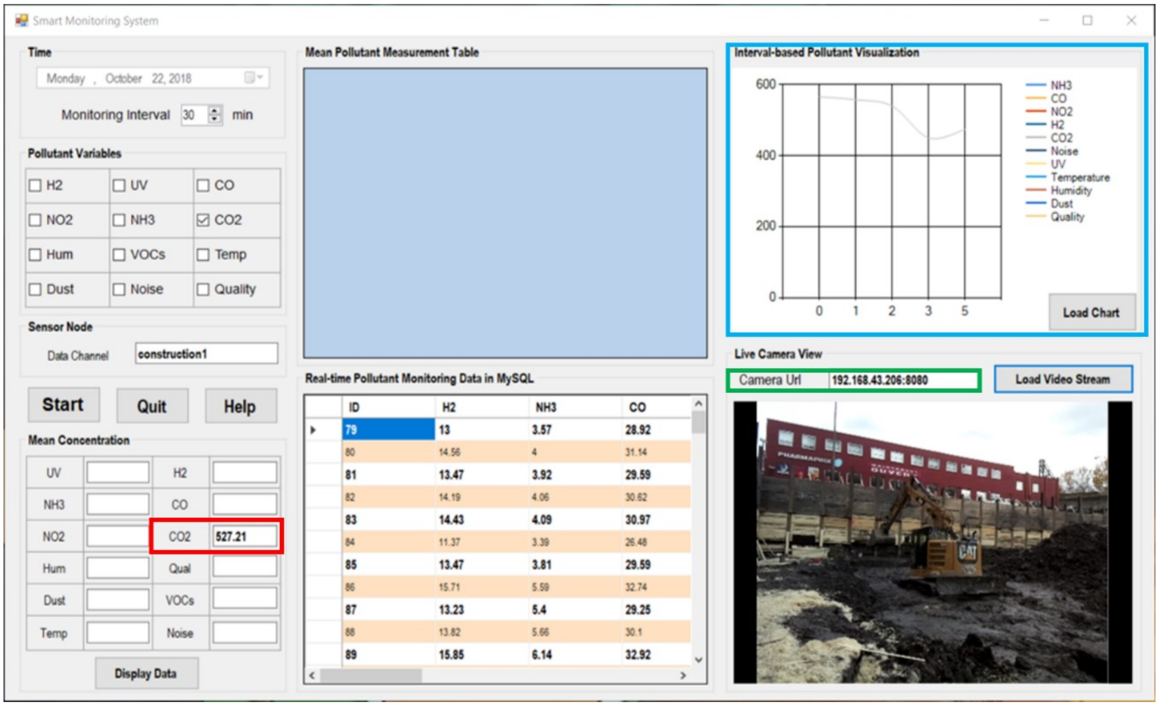


Figure 40 Monitoring and visualization results of CO2 in GUI

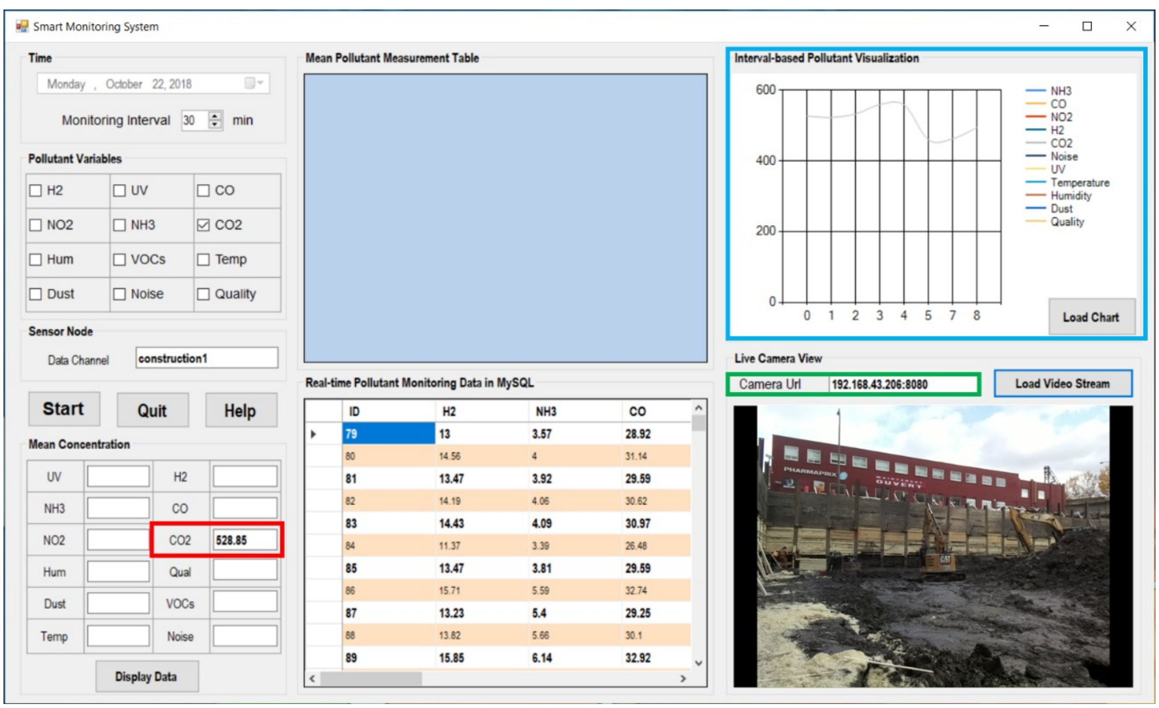


Figure 41 Updated results of CO2 in GUI

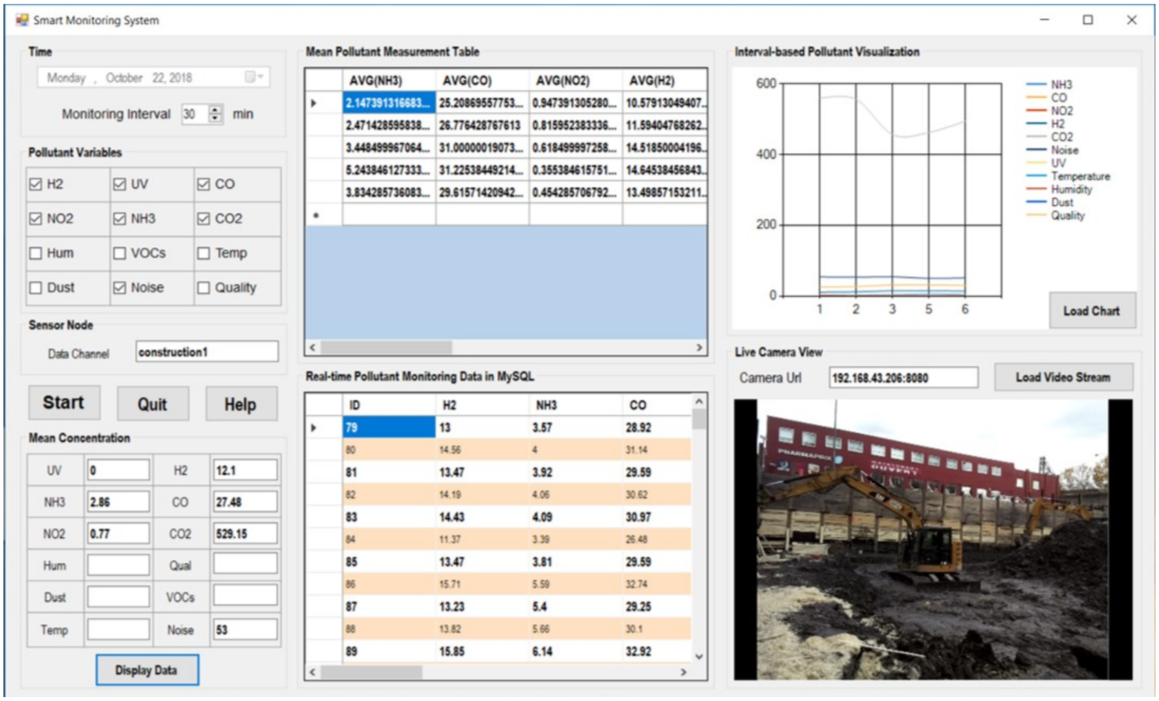
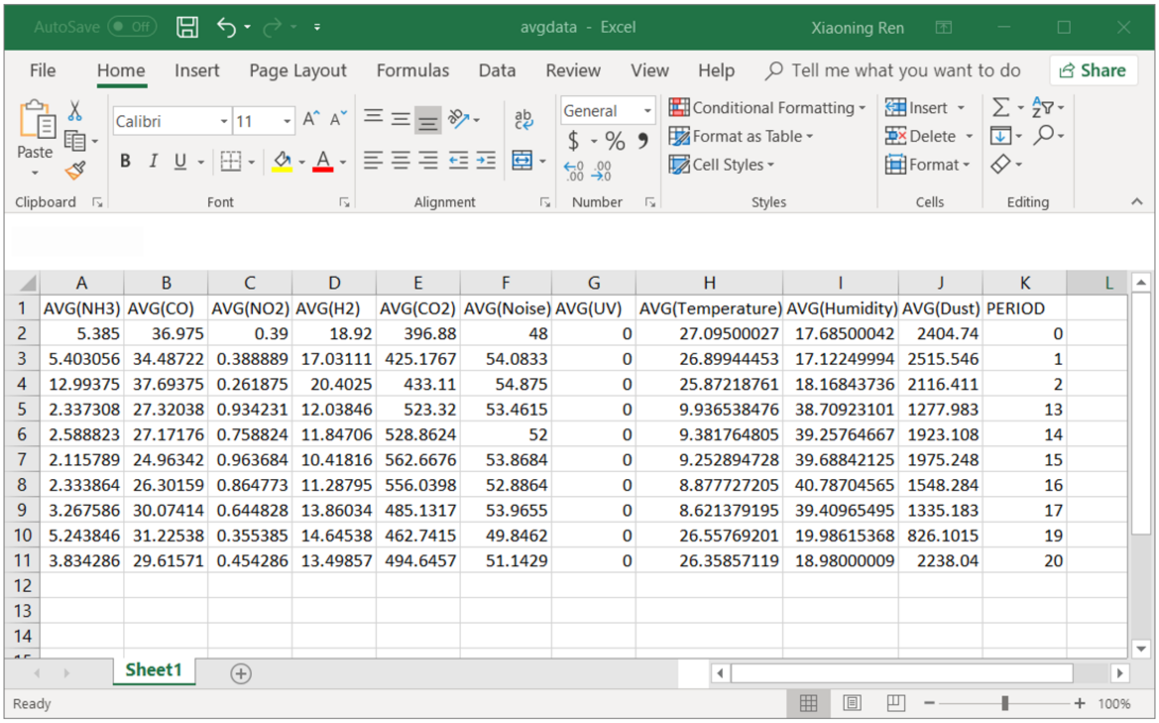


Figure 42 Monitoring and visualization results of pollutants in GUI

Figure 42 illustrates the average concentration values and visualizations results of the sensor data of CO, NO_2, NH_3, H_2, Noise and UV from the sensor node of construction1 on the 30 minutes basis. The average concentration of each pollutant is displayed in the mean pollutant concentration panel and updated every 30 minutes. The average concentration trend of each pollutant is continuously depicted and updated in the chart with distinct colors. Figure 43 describes the report of the average concentration/level measurement of each pollutant/parameter. As shown in the excel file, the calculation results of each pollutant/parameter in the selected time interval are ordered by the period sequence.



AVG(NH3)	AVG(CO)	AVG(NO2)	AVG(H2)	AVG(CO2)	AVG(Noise)	AVG(UV)	AVG(Temperature)	AVG(Humidity)	AVG(Dust)	PERIOD
5.385	36.975	0.39	18.92	396.88	48	0	27.09500027	17.68500042	2404.74	0
5.403056	34.48722	0.388889	17.03111	425.1767	54.0833	0	26.89944453	17.12249994	2515.546	1
12.99375	37.69375	0.261875	20.4025	433.11	54.875	0	25.87218761	18.16843736	2116.411	2
2.337308	27.32038	0.934231	12.03846	523.32	53.4615	0	9.936538476	38.70923101	1277.983	13
2.588823	27.17176	0.758824	11.84706	528.8624	52	0	9.381764805	39.25764667	1923.108	14
2.115789	24.96342	0.963684	10.41816	562.6676	53.8684	0	9.252894728	39.68842125	1975.248	15
2.333864	26.30159	0.864773	11.28795	556.0398	52.8864	0	8.877727205	40.78704565	1548.284	16
3.267586	30.07414	0.644828	13.86034	485.1317	53.9655	0	8.621379195	39.40965495	1335.183	17
5.243846	31.22538	0.355385	14.64538	462.7415	49.8462	0	26.55769201	19.98615368	826.1015	19
3.834286	29.61571	0.454286	13.49857	494.6457	51.1429	0	26.35857119	18.98000009	2238.04	20

Figure 43 Pollutant monitoring report

Then, users can input the required parameters to activate the proactive alarm system for the purpose of the onsite air quality measurement. As shown in Figure 44, the sensor node of interest (construction1), analysis time interval (30 minutes) and the email account (xiaoning_ren@outlook.com) to receive the warnings are specified in the web interface. Then, the system automatically analyzes the air quality in the predefined time interval. As displayed in Figure 45, the analysis results are listed by the order of the periodic sequence. Also, the major pollutants and the overall air quality are highlighted. It is manifest that the pollutant of NO_2 is the major pollutants during the earthmoving operation. In the meantime, the air quality warning is sent to the predefined email account, as illustrated in Figure 46.

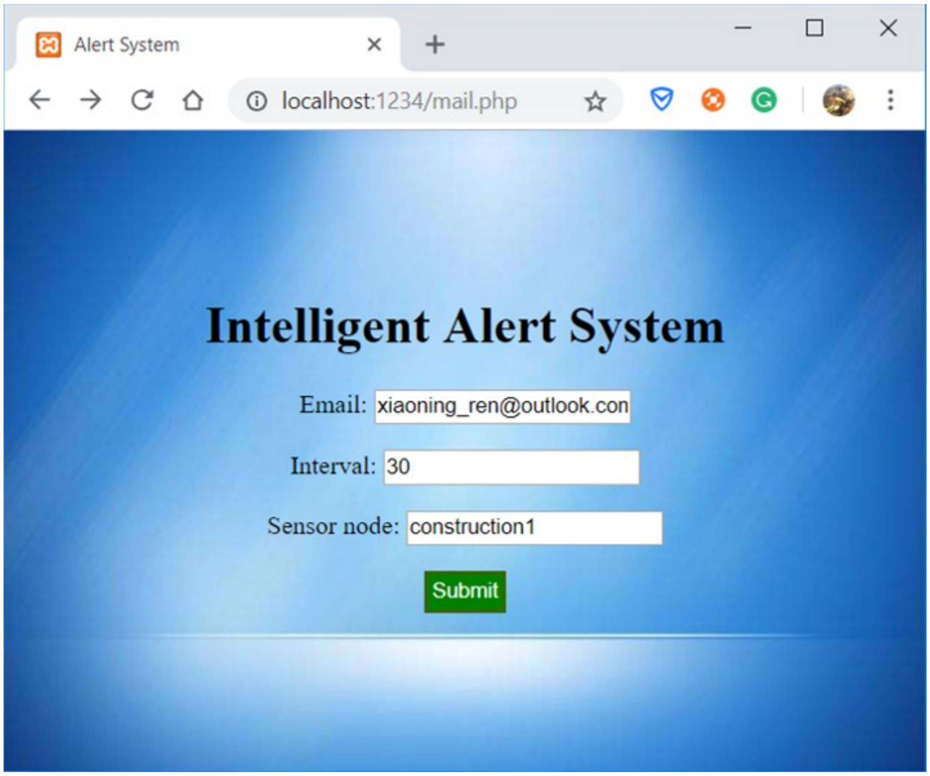
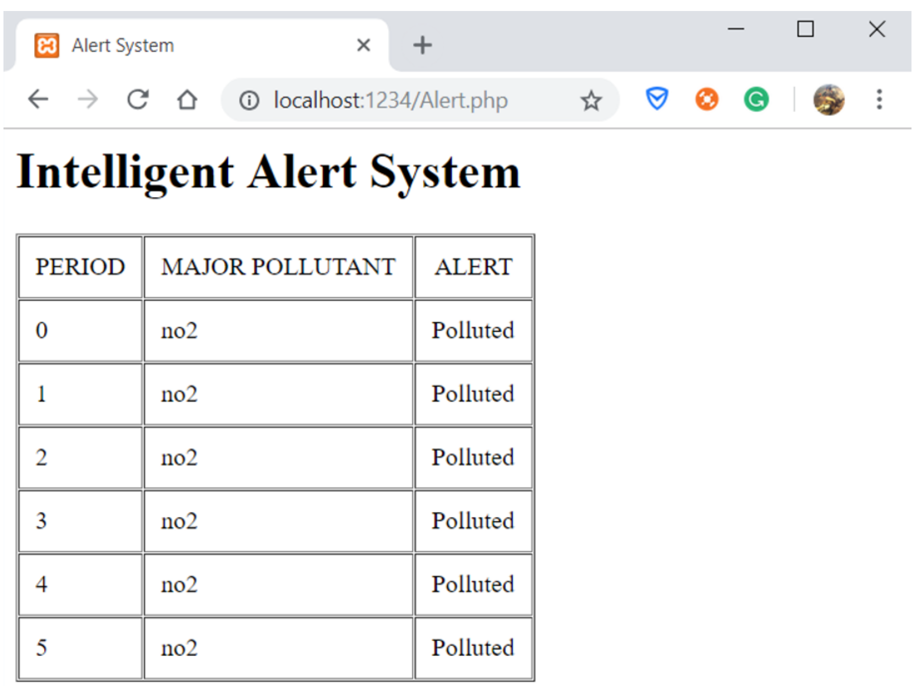


Figure 44 Parameters setup of alarm system



PERIOD	MAJOR POLLUTANT	ALERT
0	no2	Polluted
1	no2	Polluted
2	no2	Polluted
3	no2	Polluted
4	no2	Polluted
5	no2	Polluted

Figure 45 Sensor data analysis results

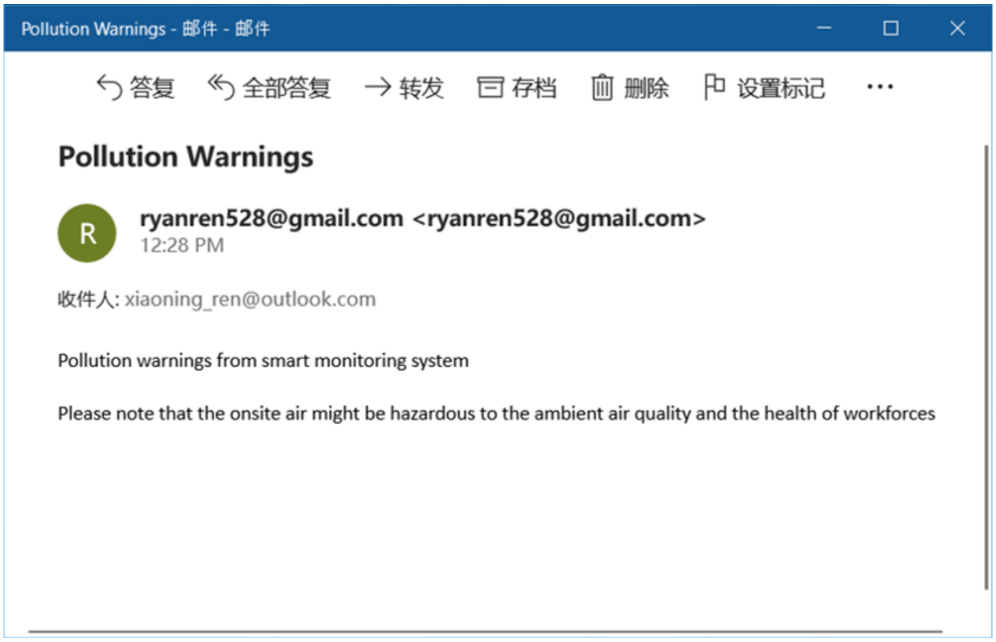


Figure 46 Pollution warning notice

On top of the onsite air quality, the potential impacts on the ambient air quality are predicted using the environmental impact assessment system. As shown in Figure 47, the concentration of pollutant CO at the location of 5 kilometers of the downwind direction is estimated. Specifically, the average CO emission rate at the work zone (plume node) of the construction jobsite is firstly calculated through the determination of measurement interval and the plume node. The meteorological conditions, such as the wind speed, the atmospheric stability, and the coordinates of the location of interest are listed in Table 7. Then, the corresponding horizontal and vertical dispersion coefficients can be identified in the graph. The plume height is defined as 5 meters, which is the approximate height of the operating excavator. Accordingly, the potential CO concentration of the location of interest is 0.002 μg/m^3.

Table 7 Parameters in Gaussian Plume-based model

Parameters	Height	Wind Speed	Time	Solar Radiation	Location	Stability	σ_y	σ_z
Value	5 m	3.6 m/s	Daytime	Moderate	(5000, 0, 0)	C	400	200

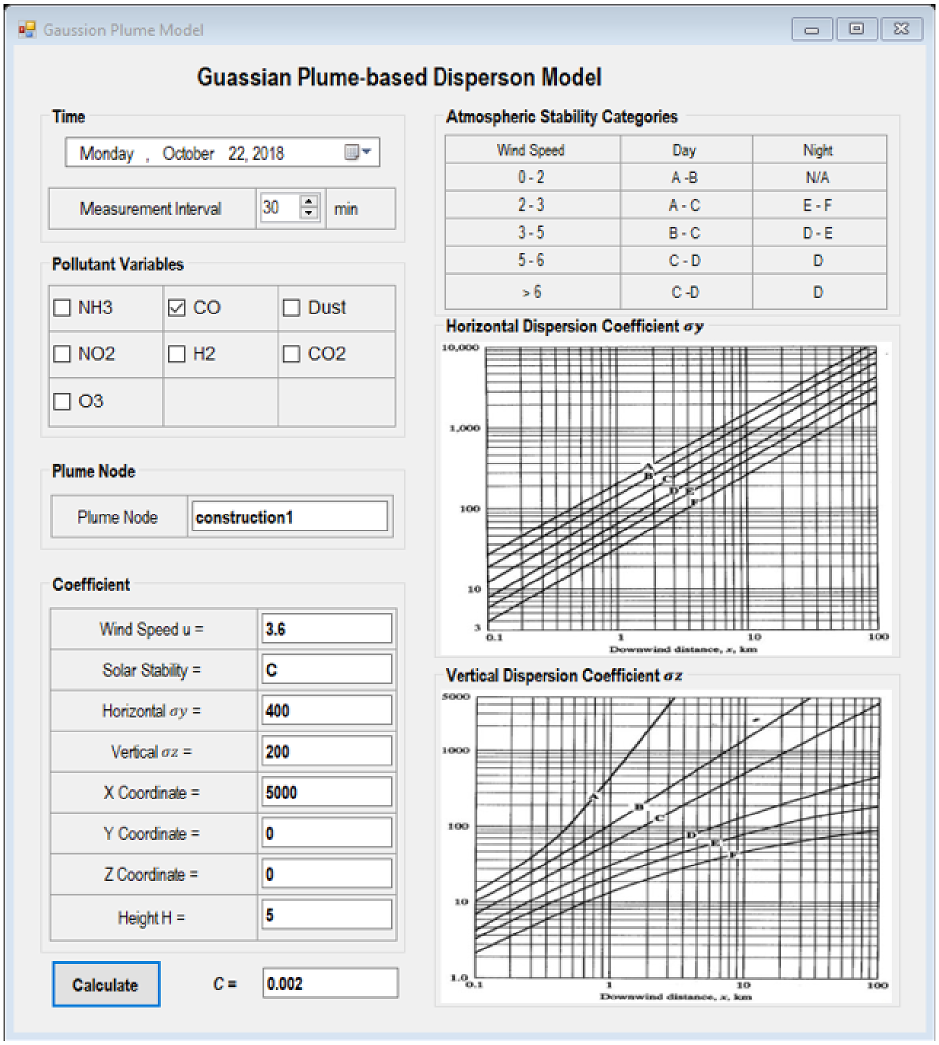


Figure 47 Estimation of air pollutant dispersion

4.2.2 Case study Ⅱ

The second case study was conducted on the construction site of Wastewater Infrastructure project in downtown Montreal. The Wastewater Infrastructure (WI) project funded by the governments of Canada and Quebec aims to ensure the capability of the water and wastewater systems in the province of Quebec is efficient and to meet the increasing public needs. Figure 48 illustrates the placement of the monitoring system on the construction site, and Figure 49 shows the image samples of the construction sites.

Figure 48 Placement of the monitoring system

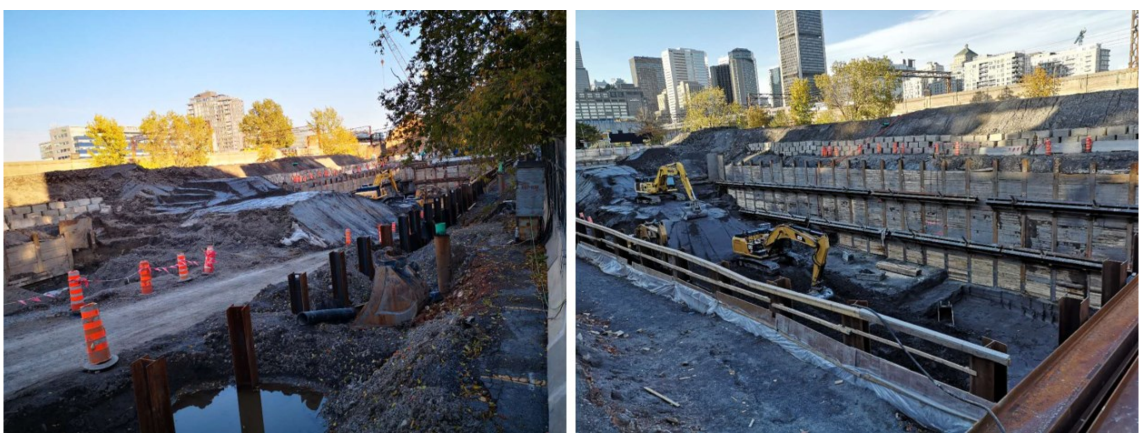


Figure 49 Image samples of WI construction site

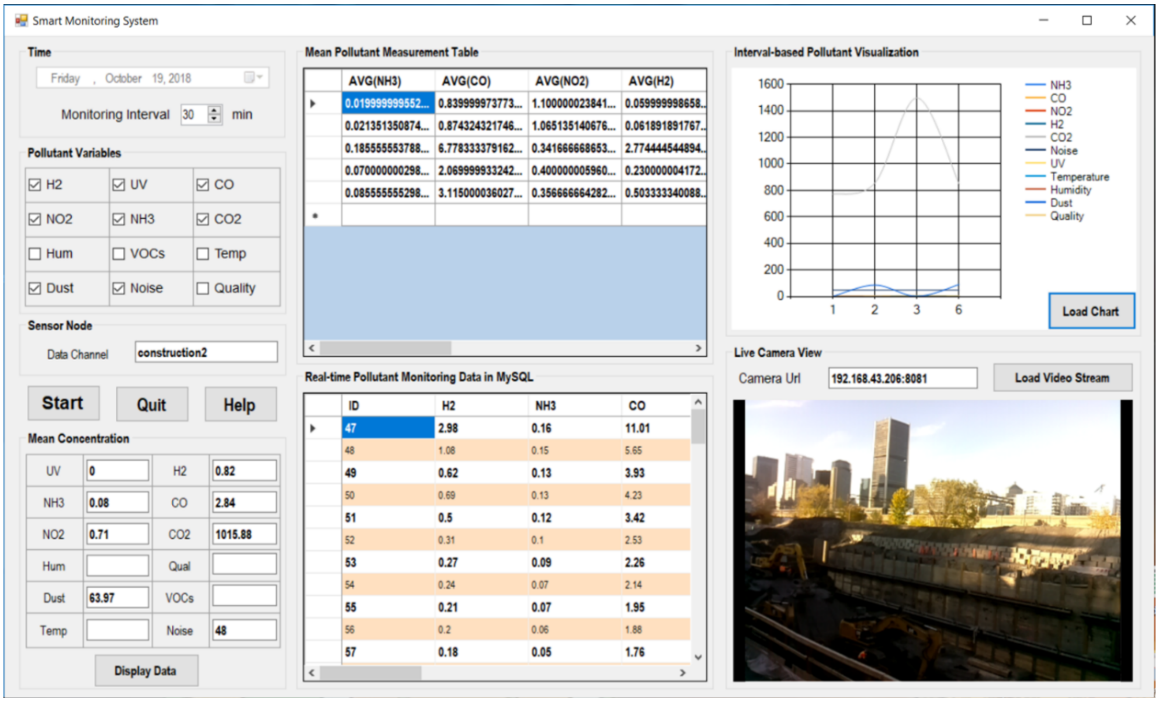


Figure 50 Monitoring and visualization results of pollutants in GUI

Figure 50 illustrates the sensor data analysis and visualization results on GUI. Specifically, the pollutants of CO_2, CO, NO_2, NH_3, H_2, Noise, UV as well as the parameters of temperature and humidity on the 30 minutes basis. The average concentration of each pollutant and the quality is displayed and updated in the mean pollutant concentration panel, while the corresponding concentration trend of each pollutant is graphically depicted updated in the chart. Also, the live video of onsite construction activities is continuously broadcasted in GUI. As shown in Figure 51, NO_2 and CO_2 are the major pollutants on the construction site. The meteorological conditions during the data collection are listed in Table 8. Accordingly, the horizontal coefficient and vertical coefficient are determined as 100 and 60 respectively. As shown in Figure 52, the potential pollutant emission concentration (NO_2) at the location (1000, 0, 0) of downwind direction can be estimated as 0.007 $\mu g/m^3$.

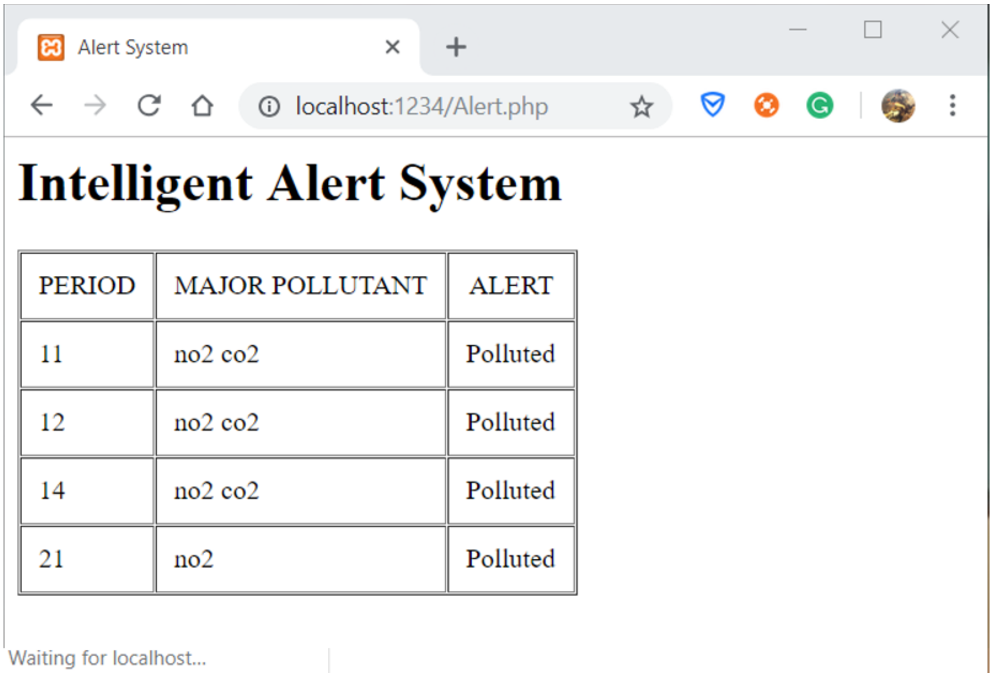


Figure 51 Pollutant data analysis results

Table 8 Parameters in Gaussian Plume-based model

Parameters	Height	Wind Speed	Time	Solar Radiation	Location	Stability	σ_y	σ_z
Value	5 m	6.4 m/s	Daytime	Moderate	(1000, 0, 0)	C	100	60

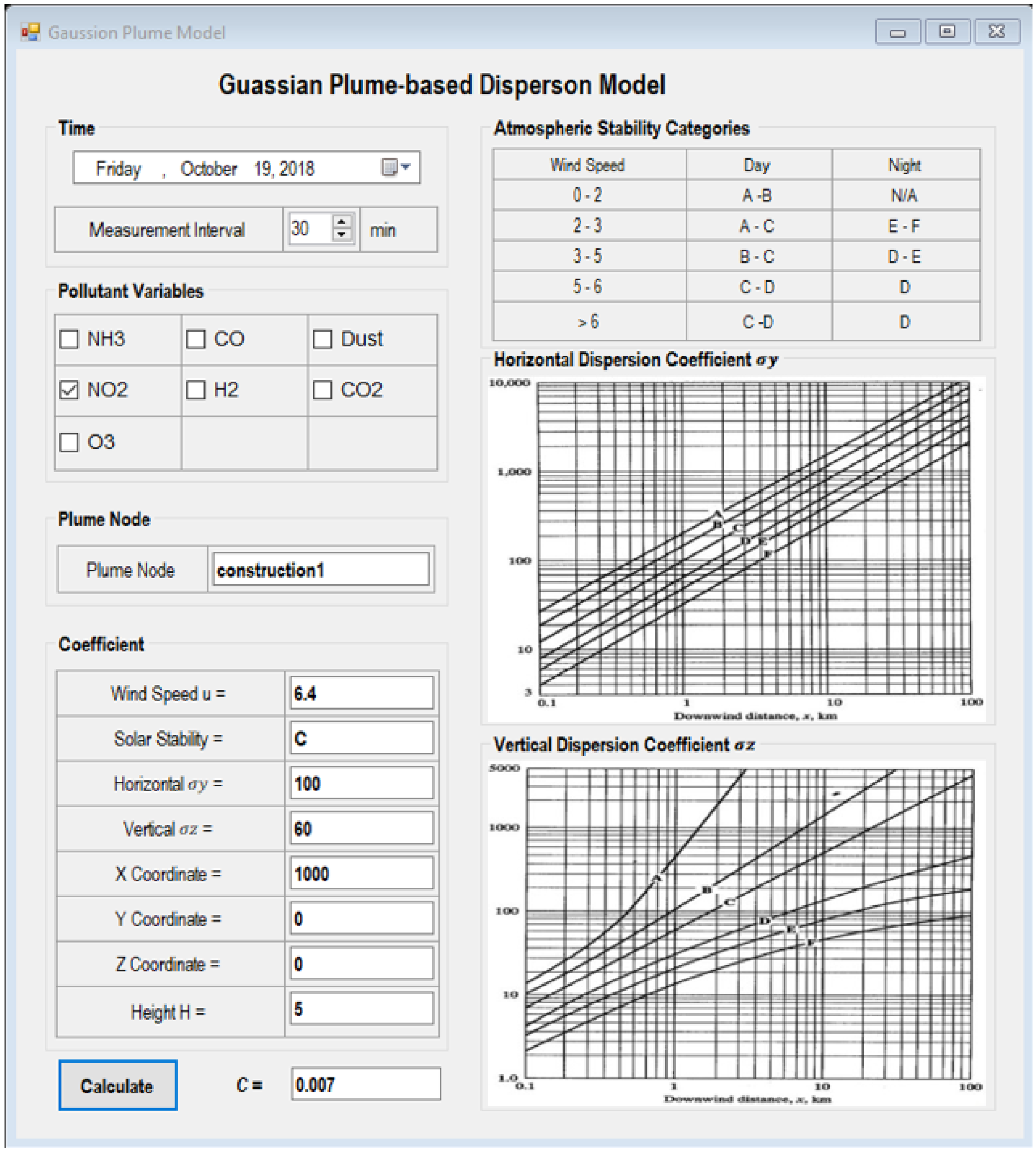


Figure 52 Estimation of air pollutant dispersion

4.3 Summary, Analysis and Discussion

This chapter presented the implementations of the IoT-based monitoring system on real construction sites. It describes the developed three sub-systems and highlights the developed GUI to facilitate the decision makers in the visualization of onsite pollutant emissions and analysis of the onsite air quality and the potential impacts on the ambient air quality. The proposed system was mainly coded in the Arduino Integrated Development Environment (IDE) and Microsoft Visual Studio .NET platform. The smart air quality monitoring system enables the construction practitioners to monitor and visualize the onsite pollutant emissions in a real-time, cost-effective and efficient manner. The proactive alarm system can assist the decision makers in the analysis of onsite air quality and provide proactive notices of the impacts on the onsite air quality and the health of workforces. The environmental impact assessment provides decision makers possibilities to evaluate the environmental impacts on the ambient air quality.

The test results showed the effectiveness and efficiency of the proposed monitoring system for the monitoring, visualization, and assessment of pollutant emissions from the earthmoving operations. According to the field tests, the major pollutant during the construction process is NO_2 in case study 1, while the construction activities in case study 2 produced a significant amount of NO_2 and CO_2. The reason for this phenomenon is mainly because the earthmoving operations are heavily dependent on the diesel-based non-road equipment (Figure 53). The pollutants of NO_2 and CO_2 are the major components of the diesel exhaust (Majewski and Khair 2006). Therefore, the results of the case studies can be validated by the previous findings.

Figure 53 Earthmoving operations

The IoT-based monitoring system outweighs the existing monitoring methods in the construction industry. The capabilities of each monitoring methods are shown in Table 9. All of the methods are able to collect the real-time pollutant data, but PEMS and fixed monitor are unable to visualize the emission data and evaluate the corresponding impacts. Also, they are incapable of providing the timely notice when the air quality is potentially hazardous. In addition, the proposed monitoring system gives construction practitioners more possibilities to achieve the real-time pollutant monitoring in a portable and affordable manner.

Table 9 Comparison of air pollutant monitoring methods in construction industry

Method	Data Collection	Data Analysis	Data Visualization	Proactive Alarm	Impact Assessment	Portability	Cost
PEMS	RT	NRT	No	No	No	No	>10K
Fixed Monitor	RT	NRT	No	No	No	No	>20K
Proposed System	RT	RT	Yes	Yes	Yes	Yes	<500

RT – Real Time
NRT – Not in Real-time

In addition, the proposed system outperforms the existing IoT-based monitoring system. As compiled in Table 10, the capabilities and limitations of the existing system are compared with the proposed system. All of these systems have the limitations in the data analysis and alarm generation when the air quality is hazardous. Although the work of Kim et al. (2014) and Kang and Hwang (2016) conducted the analysis of the air pollution monitoring data, their work was focused on the post-analysis other than the real-time air quality analysis. Therefore, these systems still cannot provide timely feedback when the air quality is hazardous. Also, most of these systems suffer from the long response time to collect the air pollutant data, which is deficient to reflect the real-time air pollution. In addition, these systems were mainly powered by the external battery. In contrast, the solar photovoltaic power supply module in the proposed system makes the system more sustainable and cost-effective.

Table 10 Comparison of existing IoT-based monitoring system

System	WSN Type	Gas	Power Source	Sensing Interval	Data Analysis	Alarm	Data Availability
Jiang et al. (2011)	Bluetooth	O_3, CO, NO_2	No	6 s	No	No	Web, App
Husain et al. (2016)	Bluetooth	CO_x, NO_x, Dust	Battery	20 min	No	No	Cellphone
Kim et al. (2014)	ZigBee	CO_x, NO_x, PM	Battery	N/A	Post-analysis	No	SD card Database
Pitarma et al. (2017)	ZigBee	CO_x	Battery	< 120 s	No	No	Database
Abraham and Li (2014)	ZigBee	CO_x, VOC	N/A	150 s	No	No	Database Web
Mansour et al. (2014)	ZigBee	O_3, CO, NO_2	N/A	200–300 s	No	No	Database Web
Phala et al. (2016)	GSM	CO_x, NO_2, SO_2	Battery	< 35 s	No	No	Text file GUI
Liu et al. (2011)	GSM	CO	Battery	600 s	No	No	Database
Postolache et al. (2009)	WiFi	CO, VOCs	N/A	5–60 s	No	No	Web
Kang and Hwang (2016)	WiFi	PM, CO	N/A	300 s	Post-analysis	No	Database
Proposed System	WiFi	CO_x, NO_2, NH_3, H_2, Dust, Noise, UV	Solar	30 s	Yes	Yes	Web Database GUI

CHAPTER 5: POTENTIAL APPLICATION AREA

This chapter describes the potential application areas using the proposed IoT-based monitoring system from this research. The research is focused on the monitoring and visualization and assessment of the air pollutant emissions during the construction process. The system is expected to automate and facilitate many applications, including the air quality monitoring and analysis of outdoor environment (e.g. urban area) and indoor (e.g. residential environment).

5.1 Indoor Air Quality Monitoring

Considering that most people spent more than 90% of their time in indoor environments, the indoor air quality significantly influences the health and comfort of the occupants (U.S. EPA 2017). The indoor air pollution has been consistently ranked as one of the top five environmental public health risks (U.S. EPA 2017), since the indoor air pollution can cause immediate or chronic health issues, such as fatigue and nausea, and chronic respiratory diseases, heart diseases and lung cancer (U.S. EPA 2003). Therefore, it is necessitated to monitor the real-time indoor air quality and provide the occupants with timely feedbacks in order to reduce potential health threats.

In current practices, a quantity of IoT-based indoor air quality monitoring systems have been developed to monitor the indoor air quality. However, the monitoring focus was mainly placed on the pollutants of CO, CO_2, and PM. Few efforts have been conducted to take into account other major indoor pollutants, which also influence the health of occupants. As shown in Table 11, the potential health effects of the indoor-related pollutants are described. Long-term exposures to these pollutants can contribute to severe health impairment. Also, the existing IoT-based monitoring systems were mainly focused on the pollutant data collection. No research efforts have been conducted to further evaluate the potential impacts of the pollutants on the occupants. In this case, occupants might stay in the polluted environment without any notice when the pollutant concentrations violate the indoor air quality standards, which in turn could incur the immediate or chronic health damages.

Table 11 Effects and sources of major indoor pollutants

Pollutant	Health Effects	Source
NO_2	Pulmonary disease; Respiratory edema and lung injury; Eyes, nose throat irritation; Acute or chronic bronchitis	Cooking; Fuel consumption
NH_3	Eye, nose and throat irritation; Bronchitis, fluid accumulation in the lungs; Potentially fatal	Construction materials (concrete anti-freezer); Decoration materials; Paints;
VOC	Headaches; Eye, nose and throat irritation; Loss of coordination and nausea; Damage to liver, kidney and nervous system; Cancer	Construction materials Decoration materials; Paints; Office supplies
Noise	Hearing loss; Cardiovascular issues, particularly hypertension; Cognitive impairment; Psychosocial effects	Traffic; Industrial machinery; Urban construction noise; Human activities; Appliance operations

The IoT-based monitoring system of my research can automatically collect the real-time indoor air pollutant data, simultaneously analyze the monitoring data and provide the timely feedback of the air pollution information. Therefore, it can be deployed in the indoor environment to provide occupants and facility an effective and efficient solution to monitor and evaluate the real-time indoor air quality. As illustrated in Figure 54, the proposed system was deployed in the school environment. Each sensor node is to collect and transmit the real-time air pollutant data to the server. Then, the average pollutant concentrations will be computed based on the measurement rule (e.g. 1-hour average measurement) and compared with the indoor air quality regulations. The analysis results will be pushed to a dedicated webpage. Also, the warning notice would be sent to the facility managers by emails when the pollutant emissions violate the regulations. This means, if the indoor air quality is hazardous to the occupants, the facility managers can obtain the timely feedback and take the immediate actions to mitigate the impact, such as emergency evacuation, increase ventilation rates, and so on.

Figure 54 Placement of monitoring system in indoor environment

5.2 Supplement the Sparsity of Outdoor Air Quality Monitoring Network

The outdoor air quality is routinely monitored by the network of sophisticated and well-established monitoring stations at fixed locations in most countries. The air quality monitoring network is usually funded, operated and maintained by local authorities and government. The network is designed for various purposes, ranging from the ambient air quality assessment to public health study. Generally, the monitoring stations in the network are built upon the spectroscopic instruments. The spectroscopic instruments use complicated measurement methods and require a lot of assisting tools, such as filters, temperature controllers, built-in calibrator and so on (Yi et al. 2015).

The monitoring stations are capable of identifying a variety of air pollutants with the reliable accuracy. The expenses of equipment purchase and installation are more than 100,000 U.S. dollars, which does not even take account into the long-term maintenance expenses. In addition, the specific locations with the continuous power supply for the placement of stations/equipment need to be well planned. As a result, the monitoring stations/equipment in the network are sparsely deployed. As shown in Table 12, the number of fixed monitoring stations in the major cities is described. Specifically, the Réseau de surveillance de la qualité de l'air (RSQA) (the Network) in the territory of Montreal relies on 15 monitoring stations (Ville De Montreal 2017), and most of them continuously measure concentrations of air pollutants such as O_3, CO, SO_2, NO_2, and PM. In the city of London, the London Air Quality Network (LAQN) consists of 22 monitoring stations in different London boroughs. It collects hourly concentrations of O_3, CO, SO_2, NO_2, PM and calculating the corresponding index. In New York, 18 stationary monitoring instruments were arranged to cover 1,200 km² area (NYSDoEC, 2016), while 35 stations were positioned in Beijing to monitor the area of 16,000 km² (BMEPB 2013). The sparse monitoring cannot reflect the high spatial variability of pollutants (Marshall et al. 2008) and easily lead to the inaccurate interpolation and deficient implications for the public health and environmental impacts.

Table 12 Number of stationary monitors in major cities

City	Number of Monitors	Coverage Area	Coverage Per Monitor
Montreal	15	500 km²	33
London	22	1,600 km²	73
New York	18	1,200 km²	67
Beijing	35	16,000 km²	457

Compared to the existing air pollution monitoring means, the proposed system has a great advantage in terms of expenses due to the employment of low-cost microcontrollers and cost-effective microsensors. With certain modifications, the IoT-based monitoring system can be used to supplement the sparsity of outdoor air quality monitoring network. For example, the WiFi module at each sensor node can be replaced by the GSM module to facilitate the real-time communication and data transmission. Then, the system can be deployed to the urban and suburban area of interest for the continuous air quality monitoring.

5.3 Project Progress Monitoring and Documentation

It is essential to monitor the construction progress to ensure the project can be completed as scheduled. Any delays in the construction process can contribute to the significant budget overruns. In current practices, the construction progress monitoring is usually dependent on the manual observations, which is labor-intensive and time-consuming. My research can be used to assist construction professionals in the automatic collection of the as-built information from digital videos. Instead of the travel to the site for the data collection, construction professionals can activate the GUI in the monitoring system to check whether the building components have been completed based on the live video stream. The digital videos, in hence, can significantly reduce the inspection time, especially for the remote site inspection. Also, real-time monitoring is instrumental for the early issue detection of the ongoing construction tasks, which provides the project managers with opportunities to take timely actions to minimize the impacts (Zhu 2011). Besides, the vision-based monitoring module of the proposed monitoring system is more cost-effective in comparison with the available construction cameras in the market. As shown in Table 13, the prices of major construction cameras are described. It is noted that the cost of the major construction cameras is expensive plus the expense of software and license. Therefore, the monitoring system can provide more possibilities to monitor the project progress in a cost-effective and efficient manner.

Table 13 Comparison of the surveillance system in construction industry

Product	Manufacturer	Specification	Price (USD)	Note
Work Zone Camera Time-laps Pro	Work Zone Cam	18 Megapixel	3,495.00	Extra license required
AXIS IP Camera M2025-LE	AXIS Communication	2 Megapixel	299.99	Extra software license Required
EarthCam HD Construction Camera	EarthCam	2 Megapixel	9870.00	Including software subscription
Monitoring module in the research	Raspberry Pi	8 Megapixel	66.33	No extra expenses

In current practices, the project documentation is still a tedious job for the site engineers. Usually, the engineers have to travel to the site to take notes or take pictures of the site conditions, weather, date and time, the construction task completed or not completed. The documentation process is labor-intensive and time-consuming. My research can facilitate the project documentation process by the unlimited and easy-to-access digital data instead of the manual data collection. Once the monitoring system is mounted on the construction sites, videos are captured from the standardized field of view to reduce the confusion resulted from multiple perspectives (Bohn and Teizer 2010). The standardized digital data can be instantly classified by date and time for further review. Some written reports become unnecessary, since the data has been included in the digital videos, such as date and time, weather conditions, site conditions etc.

CHAPTER 6: CONCLUSION AND FUTURE WORK

This chapter first reviews the motivations and objective of this research. Then, the descriptions of the systems created in this research are briefly outlined. Ultimately, the conclusions, recommendations, possibilities of future studies that grow out of this research are presented.

6.1 Review of Motivations and Objectives

Considering the substantial air pollutant emissions from the construction industry, "Green Construction" has been proposed as the future trend in order to minimize the impacts of construction activities on the environment. One critical challenge behind the proposal lies in the difficulty of current practices in the monitoring of air pollutant emissions, which is not in a cost-effective, efficient and real-time manner. For example, the PEMS has been employed to measure the real-world pollutant emissions from the operating construction equipment, while the fixed air pollution monitors were utilized to monitor the air quality of the construction jobsite and the nearby neighborhood. However, the significant amounts of the cost associated with the instrument purchase and maintenance impede their applications on a routine basis. Today, the primary methods used in the environmental performance evaluation of construction projects are still focused on the estimation models, such as the NONROAD model, DES-based models, and LCA models.

Several limitations have been identified with the emission estimation models, including the constant emission rates and ignorance of possible schedule delays and changes. In order to overcome these limitations, researchers have employed onboard measurement instrument, PEMS, to monitor the diesel exhaust from operating equipment during the real-world construction activities. The monitoring results can be used to assist researchers in the development of the inventories of the real-world fuel consumptions and pollutant emission rates. The effectiveness has been tested in two field studies with 39 typical construction equipment. Also, the government has placed the fixed air pollution monitors to continuously monitor the air quality at the jobsites of mega construction projects.

Although these two monitoring methods have been employed to monitor the real-time construction activity-related pollutant emissions, the application of these methods for the environmental impacts assessment of the construction activities is still limited. Specifically, the focus of these methods was only placed on the pollutant data collection. No further step was conducted to investigate the potential impacts of the pollutants on the onsite workforces. Consequently, they might continue to stay in the severely polluted environment, which would cause immediate or chronic health issues. Also, in current practices, no further efforts have been conducted to assess the impacts on the proximal areas. The construction sites are usually found in both urban and rural areas. As a major pollutant emission source, the construction activities-related pollution might impose significant impacts on the ambient air quality.

There are different types of construction activities involved in the construction project. It is impossible to monitor, visualize and assess the pollutant emission from all construction activities in one research study. Therefore, the focus of this research is placed on the air pollutant emissions produced from the earthmoving operations. The research effort consists of three parts: 1) create a smart air quality monitoring system to monitor and visualize the air pollutant emissions on construction sites, 2) develop a proactive alarm system to trigger warnings to construction practitioners when the air pollutant emissions exceed the air quality standards and regulations, 3) develop an environmental impact assessment system based on the Gaussian Plume-based atmospheric dispersion model to assess the potential impacts of the air pollutant emissions on ambient air quality. The research work in three parts is expected to provide a cost-effective and portable IoT-based monitoring system to facilitate the real-time monitoring, visualization, and assessment of air pollutant emissions on construction sites.

6.2 Review of Methods

Three subsystems have been developed in order to support the main objective of this research. The first subsystem is a smart air quality monitoring system, which consists of a wireless sensor network with the integration of microcontrollers, microsensors and HD camera. The system is to automate the monitoring and visualization of the air pollutant emissions on construction sites in a cost-effective and real-time manner. The sensor nodes of the network collect the pollutant data and construction activity videos and transmit the data to the remote server in real-time. The graphical user interface is used to visualize the pollutant data and broadcast the live videos.

The second subsystem created in this research is a proactive alarm system. The system is to automatically analyze the monitoring data captured from the first system in comparison with the air quality standards. Then, the analysis results are pushed and displayed on a dedicated webpage. When the pollutant emissions violate the standards, the warning notice will be generated and sent to the predefined email account to decision makers.

The third subsystem is an environmental impact assessment system based on the Gaussian Plume-based atmospheric dispersion model. The system is to simulate the air pollutant dispersion and predict the potential impacts on the ambient air quality under the specific meteorological conditions. With the system, the air pollutant emission quantities in each work zone are retrieved from the first system to calculate the average emission rates. Then, the Gaussian Plume-based dispersion model is adopted to estimate the downwind concentrations resulting from emissions in each work zone of the construction jobsite. Following that, the environmental impacts caused by the construction operation in each work zone are assessed in comparison with related regulations.

6.3 Discussion and Conclusion

A comprehensive literature review of the existing research highlights the limitations of the air pollutant emission monitoring in the construction industry in various aspects, such as pricey expenses with respect to the instrument purchase, operation and maintenance, incapability of pollutant visualization, timely analysis of onsite air quality, and so on. The costly expenses significantly impede their wide employment in the residential and industrial construction project, except the funding support from the government. Also, these monitoring methods fail to analyze real-time monitoring data and provide the timely feedback of the onsite air quality. Moreover, the existing monitoring methods are incapable of identifying the most pollutant contributory activities even with the air pollutant data.

Although some affordable IoT-based air quality monitoring system has been tested in the indoor environment, they were mainly limited to the air pollutant data collection instead of developing a comprehensive system to monitor, visualize and evaluate the real-time air quality.

In the monitoring of onsite pollutant emissions, the test results indicated the smart air quality monitoring system is capable of collecting and visualizing the pollutant emission in a cost-effective and real-time manner. The developed GUI is instrumental for decision-makers to identify the causal of the onsite air pollutions. Users can visualize the pollutant emission trends and load the live construction activity videos in GUI. Through the comparison, users can identify the relationship between the pollutant emissions and the construction activity. In the analysis of the pollutant monitoring, the test results help decision makers better understand the major pollutants emitted from the specific construction activities. As illustrated in the case studies, the pollutants of NO_2 and CO_2 are the major pollutants emitted during the earthmoving operations. The monitoring results are validated by the previous findings which identified construction process can produce a significant amount of pollutants. Also, the prompt feedback of the air quality provides decision makers with opportunities to mitigate the potential impacts on the health of workforces. In the pollutant concentration estimations, the Gaussian plume-based model can help construction practitioners better evaluate the environmental performance of the ongoing activities.

6.4 Contributions

This research is to develop a set of instrumental systems for the construction industry for the monitoring, visualization, and assessment of the air pollutant emissions on construction sites. This information can be used to evaluate the environmental performance of construction activities and promote the sustainability of the construction project. Specifically, the proposed system can:

1. Monitor the real-world pollutant emissions from construction activities in an automatic, cost-effective and real-time manner. This provides more possibilities for the existing air quality monitoring practices based on the pricey monitoring instruments.

2. Dynamically and continuously visualize the air pollutant emissions, which is instrumental for construction practitioners better understanding the pollutant emission trends.
3. Enhance the monitoring interactions by providing a user-friendly interface. The user interface can be used to review the pollutant data, visualize the pollutant emissions and broadcast the live videos. It is instrumental for construction professionals to analyze the relationship between the air pollutant emissions and the corresponding construction activities based on the pollutant monitoring results and the live construction activity videos.
4. Provide the timely notice to construction practitioners when the air quality is harmful to onsite workforces. The system automatically analyzes the monitoring data in comparison with the relevant regulations. Warning notices are generated and sent to decision makers when the pollutant emissions violate the air quality standards.
5. Simulate the air pollutant dispersion and assess the potential impacts on ambient air quality. The system simulates the air pollutant dispersion with the consideration of the specific meteorological conditions and estimates the pollutant concentrations at any location in the downwind direction. Then, the potential impacts due to the pollutant emissions from the construction activities at any downwind location can be estimated.

In addition to the construction-related pollutant monitoring, visualization and assessment, this research can be applied to:

1. Facilitate the monitoring of indoor air quality. Facility managers can employ the proposed system to monitor the real-time indoor air quality to promote occupational comfort. When the indoor air quality is deteriorating, facility managers can distribute the alarms and take actions to mitigate the impacts. Also, facility managers can use the monitoring data to evaluate the efficiency of the Heating, Ventilation and Air Conditioning (HVAC) system.

2. Supplement the sparsity of outdoor air quality monitoring network. The outdoor air quality monitoring network typically consists of numerous fixed air pollution monitors. Due to the pricey expenses and the specific placement locations with continuous power supply, the monitors are sparsely deployed. The cost-effective and portable monitoring system can be employed to supplement the sparsity of the deployment of the existing monitoring network. Also, it can provide more possibilities to explicate the air pollution levels of the area of hot spots for the public.
3. Facilitate the project progress monitoring and documentation. The vision-based monitoring module of the air quality monitoring system can provide construction managers with the easy-to-access and unlimited construction activity videos. Comparing with the widely adopted construction cameras, the module developed based on low-cost microcontroller and HD camera module is more cost-effective. With such system, construction managers can not only monitor the real-time onsite construction activities, but also store the progress-related data instead of the written documentation for further review.

6.5 Recommendations and Future Work

This research work aims to develop a cost-effective and efficient IoT-based monitoring system to facilitate the real-time monitoring, visualization, and assessment of the air pollutant emission on construction sites. It investigates the cost-effective and portable means of monitoring, visualizing and assessing the pollutant emissions from construction activities based on the microcontrollers, sensors and the IoT technology. The case studies in this research provide valuable experience that can be employed to guide the future work. Some recommendations for the future work are:

- Conduct more analysis on the pollutant data to investigate the relationship between pollutant emissions and the corresponding construction activity;
- More experiments are needed to test the consistency of the microsensors after serving a long period of time.

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