Developing an Environmental Monitoring Dashboard to Identify Construction Activities That Affect On-Site Air Quality and Noise

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On my honor as a University Student, I have neither given nor received unauthorized aid on this assignment as defined by the Honor Guidelines for Thesis-Related Assignments

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Abstract— **Construction sites are well known for being significant sources of air and noise pollution, impacting both individuals who work on those sites and surrounding communities. Construction projects on the Grounds of the University of Virginia are no exception. On-Grounds projects are located within one mile of UVA Health, meaning any pollutants, construction waste or noise from the project may impact a large number of people and individuals in educational, workplace, residential, and healthcare settings. While the presence of dust and other sources of pollution has been observed across jobsites, existing site management techniques do not provide opportunities to understand the causes or extent of various pollution events. The purpose of this project is to develop a prototype environmental monitoring dashboard which incorporates real-time data from air and noise quality sensors installed on-site, and link the data to specific construction activities on a detailed as-built schedule. The development of this type of monitoring system has become much more feasible in recent years due to the increased availability of affordable and reliable sensors and this project shows this type of technology can be utilized in a construction context. Sensors are installed in high traffic locations on-site including on the first two floors of the building under construction and in the jobsite trailer to specifically track noise, CO2, VOC, PM2.5, temperature and humidity levels at 5 minute frequency. Information related to on-site activities is collected through an analysis of construction documents, like a detailed schedule and plan sheets. Spatial trends found included the first floor of the site having higher PM2.5 levels, PM2.5 levels decreasing from the roadside to trailer side, and the second floor having higher noise levels. Time trends include lower noise and PM2.5 levels at noon and higher levels between 8AM-11AM and 1PM-3PM. Lastly, there the middle first floor sensor PM2.5 levels was found to be significantly correlated with a masonry subcontractor's daily hour with an R squared value of .6125.**

I. INTRODUCTION

This paper aims to explore the potential of deploying environmental sensors to monitor construction worker health, focusing on the benefits, challenges, and opportunities for[1] improving occupational safety and health in the construction industry. Construction work is a vital component of modern society, contributing to the creation of infrastructure and buildings that enable economic growth and development. However, construction workers are often exposed to hazardous environments, including noise and air pollution, which can have adverse effects on their health. One of the primary objectives of this study is to highlight the presence of particulate matter (PM 2.5) air particles and its harmful impact on the health of workers [1]. PM 2.5 refers to tiny particles in the air that are less than 2.5 micrometers in diameter, which may be produced from a variety of sources, including construction sites, traffic, and industrial activity. When construction workers are exposed to high levels of PM 2.5, it can have negative health effects. According to research, exposure to PM 2.5 can increase the risk of respiratory and cardiovascular diseases, as well as lung cancer [2]. Construction workers who are regularly exposed to high levels of PM 2.5 may be at increased risk for these health problems.

Our investigation delves into the relationship between occupational particle exposure and their negative health impacts. Previous research by Fang et al.[3], completed by conducting a thorough literature search and compiling a vast array of studies, presents a comprehensive selection process for identifying original articles through systematic review on the topic of occupational particle exposures and their link to cardiovascular disease. These studies spanned various industries and occupations, including gold mining, trucking, and synthetic rubber industry workers, among others [3]. The mortality outcomes assessed in these studies were overall cardiovascular disease (CVD), ischemic heart disease (IHD), and cerebrovascular disease, with large sample sizes, ranging from 3,431 to 176,309 workers, predominantly male, and excluding external and internal control groups [3]. Most of these studies used an external reference group for statistical comparison while some studies only used an internal reference or both [3]. Half of the studies estimated exposure with few presented estimates of exposure. Additionally, only one study presented exposure-response relationships using continuous exposure[3]. Most studies obtained the cause of death from death certificates and coded them with the International Classification of Disease (ICD) system, with the exception of a study on ceramics workers in China who were exposed to silica dust [3].

The effects of this environmental pollution impacts the surrounding community as well. To protect workers from exposure to PM 2.5, it is important to implement measures to ensure that work sites are properly ventilated and cleaned. Most importantly, construction companies should monitor air quality regularly to ensure that levels of PM2.5 remain within safe limits for work [4]. To address this issue, there has been a growing interest in deploying environmental sensors to monitor construction sites and protect workers from potential harm [5]. In particular, noise and air sensors can provide real-time data on exposure levels, allowing for the implementation of effective interventions and the creation of safer work environments. The data presented in this paper was collected and analyzed through deploying a set of environmental quality sensors throughout a construction site on the University of Virginia's (UVA) Grounds (campus). These sensors were strategically placed in a range at varying locations at the construction site to capture holistic changes within the environmental changes on and around the job site.

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II. BACKGROUND

Over the past few decades, even with the widespread use of computer technology, productivity in the construction industry has not improved at the same rate as in other industries. Specifically, the global annual average labor-productivity growth for construction has been 1 percent over the last twenty years.[6] Meanwhile, the productivity growth of the world economy has been 2.8 percent. This problem is more apparent in the United States as construction productivity is at the same level as 80 years ago [6]. Additionally, the construction industry continues to be one of the most unsafe industries in the United States. In 2020, there were 1008 fatal occupational injuries in the construction industry which was approximately 21 percent of total worker fatalities that year [7]. While there was a decrease in construction-related worker deaths compared to 2019, construction is still the industry with the most deaths by a significant margin. Even with vast advancements in technology, the slow evolution of the construction industry and slow adoption of different technologies have resulted in little to no improvement in both productivity and safety within the industry[8]. Also, construction sites tend to have a significant environmental impact on their surrounding areas' noise, water, and air quality[9]. These effects have both a short and long-term impact on the environment, the workers, and nearby pedestrians.

This paper assesses the application use of Internet of Things (IoT) sensors through a system architecture for a University of Virginia construction site to monitor the changes in the environmental conditions and their relationship to different locations, time of day, activities, and involved stakeholders. IoT sensors could provide real-time information about the changes in environmental conditions and be utilized . A McKinsey analysis[10] found that the construction industry was among the least digitized industries and has low adoption rates proving that there is slow innovation . The implementation of IoT technology is a catalyst for the Fourth Industrial Revolution – Industry 4.0. The current progress on this initiative specifically for construction sites is limited to known potential benefits. The literature lacks real use-cases of IoT and the impacts. Syamsul [11] mentions that IoT in the construction industry can help with smart communication, remote operation, supply replenishment, maintenance of equipment and machinery, energy savings, augmented reality, building information modeling, security control, environmental monitoring, worker health, and waste management. A construction site powered with the use of IoT technology provides enticing benefits but the feasibility and implications are unknown. There is a gap in understanding the societal impacts on the workers and the economic feasibility. Given that this hasn’t been fully implemented before, it is difficult to gauge time and financial constraints that may come up. This paper will discuss an ad-hoc implementation of a system through environmental sensors and a mock dashboard at a construction site.

III. METHODOLOGY

To assess the environmental safety of the selected construction site, environmental data from the site was determined to be needed. Six AWAIR Omni environmental Quality sensors were deployed on the selected construction site. These environmental sensors could be used outside as long as they are covered and provided a cost-effective option to observe air and noise quality on the site. After examination of the construction site, there were 8 possible sites that were covered and spaced out reasonably well. Installation proved difficult, as temporary power structures had to be created by the construction company electrician. In addition, weak wifi signals on site only allowed for 6 sensors, 4 outdoor and 2 indoor, to be operational. As seen on Figure 1, two sensors were in the site trailer, three sensors were located on the first floor of the construction site, with the last one being located on the second floor of the site. Figure 1 also shows how they were installed both in the trailer and on-site.

Once set up and fully operational, the data collected by the sensors was uploaded through wifi to a dashboard on the AWAIR website, where it could be downloaded for manipulation. Data was collected by the team for a total of two weeks. This amount of time was used to ensure that enough data could be collected for inference, while accounting for the fact that the site's temporary power was faulty and would disconnect occasionally. The air and noise quality data provided by the sensors was given in 5 minute increments, allowing the team enough information to observe trends while not overwhelming the team with unnecessary specificity. The combination of 2 weeks worth of data in 5 minute intervals provided the team over 4,000 observations from each sensor.

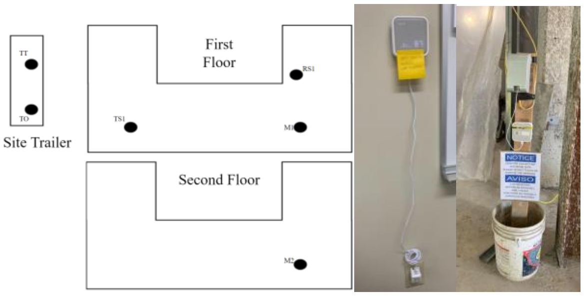


Figure 1. On-site sensor locations

The air and noise quality sensors provided many different metrics, including total volatile compounds, carbon dioxide concentration, PM2.5 levels, decibel levels, light levels, temperature, and humidity. The team decided to focus on analysis with PM2.5 and decibel data, as both metrics help to outline the air and noise quality of the site area. Through outside research[12], unhealthy PM2.5 levels were found to occur at a level of 35 µg/m³ or higher and harmful noise levels were found to occur at higher than 80 decibels [14]. These cutoffs were used in the team's analysis in characterizing differing levels of air and noise quality. In addition, data during site working hours of 7am to 5pm were used to give an accurate representation of environmental quality, while construction work is being conducted, the period of interest.

A. Overall Trends Analysis

The first part of analysis presented in this project is aimed to describe overall trends in air and noise quality on the construction site. These trends will first be captured by looking at how often environmental quality is dangerous through the percentage of time that a sensor shows unhealthy levels of PM2.5 or decibels. Secondly, the duration of bad quality exposure will be outlined through the average duration of unhealthy conditions before returning to healthy levels. Lastly, the environmental quality over time will be captured by looking at the composite average of site conditions at each working hour.

B. Connecting the Data to Specific Site Activities

The second part of the analysis provides an example of how data like that which was collected can be connected to specific site activities. Using site journals, daily schedules, and look-ahead schedules from the construction company, site operations were given a distinct time frame. This connection allowed for analysis between site activities and collected environmental data. To determine if certain activities were more harmful than others, environmental data was aggregated within each activity and activity type. Daily average PM2.5 levels were calculated for each sensor and compared with daily total labor hours for each of the four largest subcontractors on-site as listed in the general contractor's daily reports. This information was then analyzed to determine if there was a correlation between PM2.5 levels and the size of a particular subcontractor's presence on site. For the purposes of this analysis, if a PM2.5 value fell outside of two standard deviations of the mean PM2.5 levels for a given sensor, the data point was excluded. A similar analysis was conducted for one sensor using noise data. However, no meaningful correlations were found, and we chose to focus on PM2.5 data. Other sections of data were also processed to determine if they could be connected to other regularly scheduled events on site.

IV. RESULTS

A. PM2.5 Quality

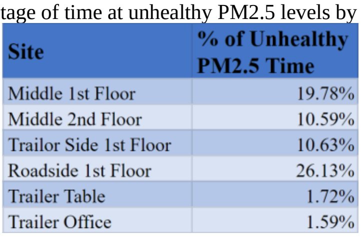
As previously mentioned, the first section of the analysis consists of identifying trends in PM2.5 and noise levels by looking at the percentage of work hours that each is at unhealthy levels, the average time of an event where they are at unhealthy conditions, and the average condition for each hour of the work day for each sensor location.

In Table I., it can be seen that the four outdoor sensors have a significantly greater percentage of time that PM2.5 levels are unhealthy than the indoor sensors. The percentage of unhealthy time outdoors is about six to sixteen times greater than indoors depending on the location. Within the outdoor sensors, the results show that the first-floor sensors are at unhealthy levels for a greater percentage of time than the second-floor sensor, specifically the middle 1st floor and roadside 1st floor sensors. Lastly, the roadside 1st floor sensor is at unhealthy levels for greater than 25 percent of the time which is a significant issue that should be addressed.

Table II. shows that the average durations of unhealthy PM2.5 events indoors are 39 to 113 percent longer than outdoors, depending on location. The two outdoor sensors with the greatest average duration are the roadside 1st floor and the middle 1st floor sensors, at 19.35 and 16.72 minutes respectively.

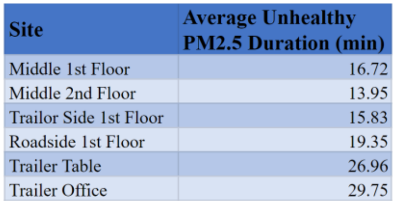
The last part of the PM2.5 analysis is the PM2.5 quality over time for each sensor can be seen in Table III. The outdoor sensors have significantly higher average PM2.5 levels for the work day. Throughout the workday, it can be seen for the outdoor sensors that the highest and lowest PM2.5 levels occur at the hours 1PM and 12PM, respectively. The table also shows that there are higher PM2.5 levels between 8AM-11AM and 1PM-3PM. As for the indoor sensors, the highest levels occur at 7AM and 8AM. Once again, the roadside 1st floor sensors and middle 1st floor sensors are the sensors with highest average PM2.5 levels for the workday.

Table I. Percentage of time at unhealthy PM2.5 levels by sensor location



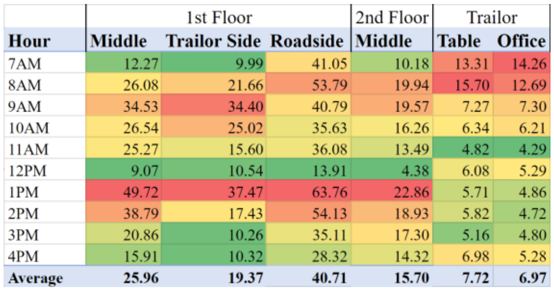
Site	% of Unhealthy PM2.5 Time
Middle 1st Floor	19.78%
Middle 2nd Floor	10.59%
Trailor Side 1st Floor	10.63%
Roadside 1st Floor	26.13%
Trailer Table	1.72%
Trailer Office	1.59%

Table II. Average duration of time at unhealthy PM2.5 levels by sensor location



Site	Average Unhealthy PM2.5 Duration (min)
Middle 1st Floor	16.72
Middle 2nd Floor	13.95
Trailor Side 1st Floor	15.83
Roadside 1st Floor	19.35
Trailer Table	26.96
Trailer Office	29.75

Table III. PM2.5 levels by sensor location and time of day



	1st Floor			2nd Floor	Trailor	
Hour	**Middle**	**Trailor Side**	**Roadside**	**Middle**	**Table**	**Office**
7AM	12.27	9.99	41.05	10.18	13.31	14.26
8AM	26.08	21.66	53.79	19.94	15.70	12.69
9AM	34.53	34.40	40.79	19.57	7.27	7.30
10AM	26.54	25.02	35.63	16.26	6.34	6.21
11AM	25.27	15.60	36.08	13.49	4.82	4.29
12PM	9.07	10.54	13.91	4.38	6.08	5.29
1PM	49.72	37.47	63.76	22.86	5.71	4.86
2PM	38.79	17.43	54.13	18.93	5.82	4.72
3PM	20.86	10.26	35.11	17.30	5.16	4.80
4PM	15.91	10.32	28.32	14.32	6.98	5.28
Average	**25.96**	**19.37**	**40.71**	**15.70**	**7.72**	**6.97**

B. Noise Quality

To find noise level trends the same three analyses were done as in the PM2.5 analysis, except this time it will be identified when levels are harmful, not unhealthy.

Table IV. shows the percentage of time that each sensor encountered harmful noise levels. The outdoor sensors, as expected, had harmful levels for a significantly greater percentage of time than the trailer sensors [13]. The outdoor noise levels are harmful a third to nearly half of the workday, depending on the sensor. The middle 2nd floor sensor has the highest percentage of time with harmful levels.

Table IV. Percentage of time at harmful noise levels by sensor location

Site	**% of Time with Harmful Noise**
Middle 1st Floor	36.70%
Middle 2nd Floor	48.33%
Trailor Side 1st Floor	40.75%
Roadside 1st Floor	33.50%
Trailer Table	0.07%
Trailer Office	0.02%

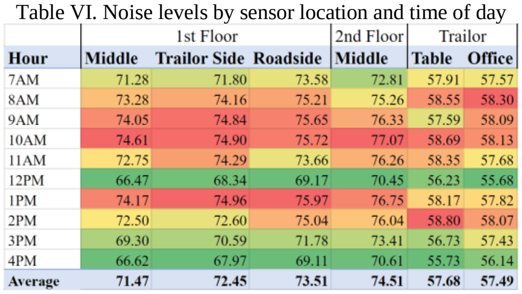
Once again, as seen in Table V., the outside sensors have significantly longer average harmful noise durations than the indoor sensors. The durations for the trailer sensors are very short, even zero for the office sensor. The middle 2nd floor sensor has the longest average duration, with it being nearly an hour.

In the analysis of the noise quality throughout the workday, the outdoor sensors have a higher average noise level than the indoor sensors shown by Table VI. From this analysis, the higher noise levels outside occur between 8AM and 11AM and during the hour of 1PM. Like in the PM2.5 analysis, the lowest noise levels occur at 12PM. The noise levels begin to decrease after 1PM as the workday concludes. For the trailer sensors, the higher levels occur in the morning between 8AM and 11AM. The middle 2nd floor sensor has the highest average noise level followed by the roadside 1st floor sensor.

Table V. Average duration of time at harmful noise levels by sensor location

Site	**Average Harmful Noise Duration (min)**
Middle 1st Floor	32.42
Middle 2nd Floor	51.74
Trailor Side 1st Floor	36.29
Roadside 1st Floor	26.44
Trailer Table	10.00
Trailer Office	0.00

Table VI. Noise levels by sensor location and time of day



	1st Floor			2nd Floor	Trailor	
Hour	**Middle**	**Trailor Side**	**Roadside**	**Middle**	**Table**	**Office**
7AM	71.28	71.80	73.58	72.81	57.91	57.57
8AM	73.28	74.16	75.21	75.26	58.55	58.30
9AM	74.05	74.84	75.65	76.33	57.59	58.09
10AM	74.61	74.90	75.72	77.07	58.69	58.13
11AM	72.75	74.29	73.66	76.26	58.35	57.68
12PM	66.47	68.34	69.17	70.45	56.23	55.68
1PM	74.17	74.96	75.97	76.75	58.17	57.82
2PM	72.50	72.60	75.04	76.04	58.80	58.07
3PM	69.30	70.59	71.78	73.41	56.73	57.43
4PM	66.62	67.97	69.11	70.61	55.73	56.14
Average	**71.47**	**72.45**	**73.51**	**74.51**	**57.68**	**57.49**

C. Correlation Masonry and PM2.5

Figure 2. shows the primary results of interest for the second portion of the analysis.

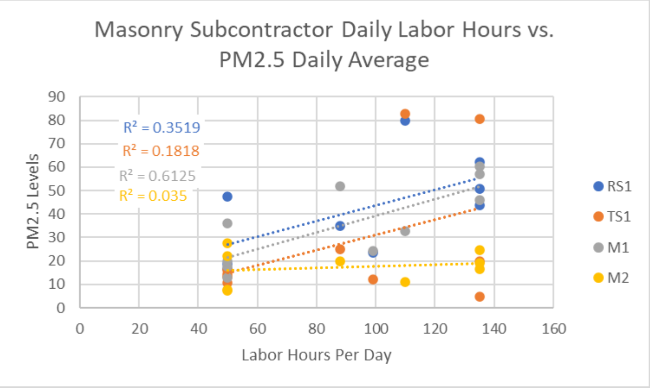


Figure 2. Subcontractor presence vs. PM2.5 daily average across site

Across all four on-site sensors, there was a slight to medium correlation between PM2.5 levels and daily labor hours performed by the masonry subcontractor. For the other three major subcontractors, results were mixed, including some instances of more manpower correlating very slightly with lower levels of PM2.5. The processing of the trailer sensor data in the meeting room showed there were several weekly spikes in CO2 levels on Wednesdays between approximately 1:30 and 2:30 throughout the data collection period.

V. DISCUSSION

As seen in the results, the first-floor sensors have greater average PM2.5 levels, average unhealthy durations, and percentages of time at unhealthy levels than the second-floor sensor. This may be due to these sensors being closer to ground and dust particles being more easily suspended at lower heights. The indoor sensors have lower average PM2.5 levels and percentages of time at unhealthy levels than the outdoor sensors because more dust is available to be suspended in the air by construction activities outside than inside. Unexpectedly, the average duration of unhealthy PM2.5 events are longer indoors than outdoors. The likely primary cause is that the indoor sensors are in enclosed areas so once unhealthy levels are reached it will take longer to dissipate when compared to the open-air outdoor sensors. The highest PM2.5 levels for the trailer sensors occur at the beginning of the workday which most likely is the time where there is most foot traffic at the site trailer as workers are arriving. From the three different parts of the PM2.5 analysis, it can be seen that the most significant PM2.5 levels occur on the roadside of the site and begin to lower as you go towards the site trailer. The higher levels could be a result of traffic on Emmet Street, the road adjacent to the site, or from deliveries being made from this side of the site as the entrance is near the portion of the building where the sensor is located.

The outside sensors had significantly greater average noise levels, average harmful durations, percentages of time at harmful levels than the trailer sensors. This is due to machinery and construction equipment being used for prolonged periods outside which is the most likely is the cause of the noise. Meanwhile, any high noise levels in the trailer are primarily due to conversations taking place. The indoor harmful events are short since they are most likely caused by multiple conversations taking place or even if the door to the trailer was left open for a short time. The mornings are average the loudest time within the trailer, thus there may be meetings there at those times. The location with most significance for noise level is the middle 2nd floor sensor. During the data collection, more work may have been performed on the upper levels of the building which may have resulted in the increased noise level on the second floor when compared to the first floor.

Both the noise and PM2.5 quality analyses show that 8AM-11AM and 1PM-3PM are most likely the times where the majority of work is done on site as levels are high. Specifically, 1PM looks to be the busiest with the highest noise and PM2.5 levels for the outdoor sensors. Lastly, they both show that 12PM is most likely lunch time as the levels drop significantly at noon.

The correlation between the size of the presence of the masonry subcontractor onsite with PM2.5 levels and their role as the masonry subcontractor suggests that they might have a direct impact on the PM2.5 levels. While correlation certainly does not equal causation, the analysis described in the methodology and results section of this paper represent the possibilities of the type of analyses that can be conducted using data like that which was collected by our sensors combined with site information, like schedules and daily reports. Drawing connections between specific causes of pollution using data could be used to more specifically target pollution mitigation strategies, saving time and money for both the general contractor and various subcontractors. The cause of the CO2 spikes in the trailer can be more confidently connected to the general contractor's weekly subcontractor meetings, given the week over week spike that appeared in the data almost exclusively during the meeting time and presence of fewer variables that might be affecting environmental factors in the trailer compared with on the site.

The difference in our level of confidence in tying these activities to relevant data trends highlights the difficulties inherent in using sensor data to better understand site activities. Construction sites are complex and constantly changing entities and this complexity contributed to challenges in setting up the sensors themselves and challenges in processing the data.

The volume of data our group was able to collect was limited due to sensor issues throughout the project. It took significant time to get temporary power set up on site to operate the sensors and even once the power sources were established, we had issues with the power shorting out and the sensors losing connection. Wifi was also not yet installed in the building during our project period and we had difficulties maintaining wifi connection to the sensors throughout the project, which limited data collection.

Processing the data was also challenging due to the limited data we were able to collect and a limited understanding of daily site activities because no member of our team was present on site everyday. Our on-site collection was ultimately conducted over a period of approximately two weeks at the beginning of March 2023. This data, while detailed, is only a tiny snapshot into the life of a multi-year project, meaning it is difficult to come to any strong conclusions related to responsibility for various pollutants and irritants. It is impossible to know based on the data we collected whether the trends we found and shared in our results are reflective of long-term trends or are temporary. Additionally, because we did not have a team member on site every day, it was difficult to know how accurate the scheduling information we were provided was, particularly because we were attempting to analyze data which provided site conditions every five minutes.

Despite these challenges however, this project shows that development of an environmental monitoring sensor system on a construction site is possible. Particularly if this type of system was used regularly by site personnel with detailed, real-time knowledge of site activities, this type of system could allow general contractors to pinpoint pollution causes and immediately and directly make improvements, creating a better environment for all.

VI. FUTURE WORK

Further implementation and application use in the construction industry is encouraged to fully understand the role of IoT technology. As mentioned before, the implications on social factors such as user privacy, user interaction, and changes to the work environment are unknown. Originally this paper analysis included conducting interviews with the construction workers to gather qualitative data regarding their opinion on the sensors and the data collected. However, due to project constraints, the interviews were not conducted. The data that would have been received from the interviews would have provided a unique perspective on the societal implications of IoT technology. Conducting interviews and surveys to receive feedback from the workers will be important to understand any issues that need to be addressed before fully implementing IoT technology in the construction industry. Additionally, future work should involve building a system dashboard that is connected to the devices and sensors. The effectiveness of the dashboard needs further assessment since the designed dashboard was not built with all the functionalities it requires. The dashboard design is an ad-hoc representation of what the system would look like once the system is in full effect. Some important functionalities to consider include building an interface that requires less analysis from the user and provides predictive analytics through alerts. The system should be able to dictate what improvements are needed and potential hazards. Ideally, to facilitate the user experience, an interactive Building Information Model (BIM) should be integrated into the system dashboard. Additionally, the system network should assess the benefit of using cameras on-site. The encapsulation of IoT technology in the construction industry will be successful with the addition of more components such as environmental monitoring through water sensors. Water monitoring represents another area of environmental monitoring on a construction site that this project was not able to explore. Future work should include investigating different systems for real-time monitoring of water quality impacts from construction sites depending on the hydrology of the surrounding area.

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On behalf of our capstone project team, we would like to thank Hourigan for their help in allowing us to use their Contemplative Commons construction site to conduct our project. Specific people, such as Jason Goydich, Ryan Roman, and Ryan Byrd, were very helpful and accommodating. They helped with providing coordination for temporary power structures and giving access to daily journals and schedules, both helping the team complete the project.

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