A Digital Twin-based System for the Indoor Environmental Quality Monitoring in Off-Site Construction Facilities

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Abstract

Off-site construction (OSC) is a well-established paradigm for achieving productivity, safety, and sustainability in construction. The key factor in its success is the efficiency of the workforce transforming blueprints into actual buildings and building elements. This has driven efforts to improve working conditions at the production facility, paving the way towards human-centric construction manufacturing. Achieving a safe and healthy indoor environmental quality (IEQ) is among the most critical aspects of this endeavor. Given the dynamic nature of IEQ in OSC facilities, there is a need for real-time performance monitoring as a means of identifying any deviations from IEQ standards and regulations. As such, the objective of this study is to develop a digital twin-based system for real-time monitoring of the IEQ of OSC facilities with continuous management and alerting features. The proposed *O-IEQ Alert System* encompasses four phases: (1) IEQ metrics identification, (2) data acquisition, (3) digital modelling, and (4) development of the IEQ alerting component. The system is successfully applied in a case study of a wall-production manufacturing facility. A web-based alert system is developed that presents real-time monitoring of the IEQ indices, including Air Quality Index, thermal comfort Predicted Mean Vote Index, and the Sound Level Index for each workstation along with the time-series trends. In case any of the indices does not fall within the defined threshold, an alert is issued to management to take the necessary corrective and preventive measures. The ultimate aim is to provide a safe, healthy, and productive working environment in OSC facilities.

Keywords

Indoor Environmental Quality; Digital Twin; Alert System; Off-site Construction; Human-centricity

1 Introduction and Literature Review

The off-site construction (OSC) method has emerged as an alternative to conventional construction approaches in an effort to industrialize the construction industry. In OSC, building elements are fabricated in off-site production facility and then shipped to the construction site for installation and assembly [1]. It is well-established as a successful approach to achieving a faster, more productive, safer, and more sustainable construction as compared to conventional methods [1].

Typically, an individual spends about a third of their life at the workplace [2] emphasizing the need to create safe and healthy working environments, especially that employees tend to carry their workplace experiences into their personal lives [3]. In OSC, the production facility acts as the workers' workplace as they undertake different activities of the building fabrication process. The setup in a controlled factory environment has paved the way into human-centric construction manufacturing which requires placing the well-being of workers at the center of production [4]. Well-being covers the physical, emotional, social, financial, vocational, and environmental aspects [5]. Human centric research in OSC has been evolving in several directions, such as ensuring safety [6], assessing and improving ergonomics[7], enhancing productivity [8], etc.

Achieving a safe and healthy indoor environmental quality (IEQ) is among the most critical human-centric factors. IEQ is impacted by several dimensions: air quality, thermal comfort, acoustic comfort, and lighting quality. Studies showed that there is a direct and strong correlation between IEQ and productivity. Individuals tend to perform their tasks more efficiently when they feel comfortable within the environment [9]. It is a core element in human-centric construction manufacturing as workers in these facilities can be prone to uncomfortable sound levels, indoor air pollution, and uncomfortable thermal state. These can be due to several factors such as the heavy use of machinery, construction material cutting and processing, the use of specific personal protective equipment (PPEs), the installed heating and ventilation systems, available natural lighting, visual comfort, etc. However, IEQ studies in OSC are limited to the acoustic comfort through identifying the noise sources in an OSC facility [10] as well as the workers' exposure level in an effort to identify safe and high-risk working areas [11].

Monitoring the IEQ is the first step into achieving a safe and comfortable indoor environment that meets the required IEQ standards and regulations set by different organizations such as ASHRAE [12], the World Health Organization (WHO) [13], the Environmental Protection Agency (EPA) [14], etc. However, monitoring on its own is not sufficient, and must be accompanied by an information interaction system that can be leveraged by management to make timely decisions. This can be achieved by developing a real-time monitoring and alert system to detect deviations from acceptable ranges. Once a deviation is detected, management is alerted to take the necessary measures. Digital twins (DT) can be used in this case as an integrated system to monitor and control the indoor environment [15]. DT systems are composed of three main components including physical space, virtual space and the information connection and processing between the two layers [16]. They have been successfully implemented for IEQ applications in the built environment. For example, Arsiwala et al. [17] created a DT-based solution to monitor the indoor air quality of existing building assets to enable data-driven decision making for retrofitting strategies. This ultimately helps achieve net zero carbon emission targets. In another study, Shahinmoghadam et al. [18] proposed a DT model in order to monitor thermal comfort in buildings in a virtual reality environment. The model also allows modifications to modify certain parameters that impact thermal comfort to study what-if scenarios based on the real-time thermal comfort data feed.

A review of the relevant literature showed that although the OSC industry is shifting more towards human-centric approaches, the IEQ applications remain limited. Moreover, IEQ directly correlates to the health, safety, and productivity of the individuals in the workplace, and therefore must be addressed in the context of OSC. Monitoring IEQ enables the detection of deviations from the established IEQ standards and regulations. In this regard, DTs have been successfully incorporated into IEQ real-time monitoring. However, IEQ applications in OSC have been relatively limited. As such, the objective of the present study is to develop a DT-based system for real-time monitoring of the IEQ of OSC facilities with continuous management and alerting features. The contribution of the system is bifold, 1) it provides a real-time assessment of the IEQ and 2) it can assist management to take the necessary corrective and preventive measures to ensure a safe, healthy, and productive environment.

2 Methodology

This study adopts the Design Science Research (DSR) method for developing the proposed IEQ monitoring system. DSR is a structured approach to developing artifacts that address an identified problem, and to demonstrate the artifact's effectiveness [19]. The method consists of the following four steps: (1) identifying the problem, (2) defining the objective, (3) developing the artifact, and (4) demonstrating the artifact [20].

In the present study, the first step is a thorough review of the literature to obtain a solid understanding of the current human-centric research in OSC, IEQ in OSC workplaces, and the potential of DTs in the built environment. The literature review reveals the importance of IEQ as a core element in the workplace. While the controlled indoor environment of OSC provides an opportunity to apply IEQ standards and improvements, applications of these standards in OSC are limited. The problem—in the present case, the gap in the literature regarding IEQ applications in OSC—having been identified, the system's objective is articulated in the second step of "Defining the objective." In the present case, the objective is defined as the development of a structured approach for real-time IEQ monitoring and alerting in OSC capitalizing on DT technology. With real-time monitoring of IEQ parameters, any deviations between the actual conditions at the factory and the identified thresholds can be detected. In the case of a deviation, management will be alerted, and the necessary measures can be taken. Ultimately, such a system helps to ensure the health, safety, and productivity of workers at the production facility. The third step is the development of the proposed system, and this comprises four phases: (1) IEQ metric identification, (2) data acquisition, (3) digital modelling, and (4) development of the IEQ alerting component of the system. The system employs DT-based tools that have been validated in the built environment, tailoring them to IEQ real-time monitoring in OSC. Several tools are leveraged, including sensor technologies, laser scanning, 3D modelling, Unity game engine, and web-based functions. Details on the development of the system are presented in section 3. The fourth step is to present an illustrative application, a case study of an OSC facility prefabricated components for residential projects—to demonstrate the system's applicability.

3 Proposed *O-IEQ Alert System*

The aim underlying the development of the *O-IEQ Alert System* (i.e., Step 3) is to provide a DT-based system for real-time IEQ monitoring and alerting in OSC facilities to promote the health, safety, and productivity of workers. As noted above, its development is composed of four phases: (1) IEQ metric identification, (2) data acquisition, (3) digital modelling, and (4) development of IEQ alerting component of the system. The following sub-sections outline the developed system (see Figure 1). It should be noted that the proposed system can be

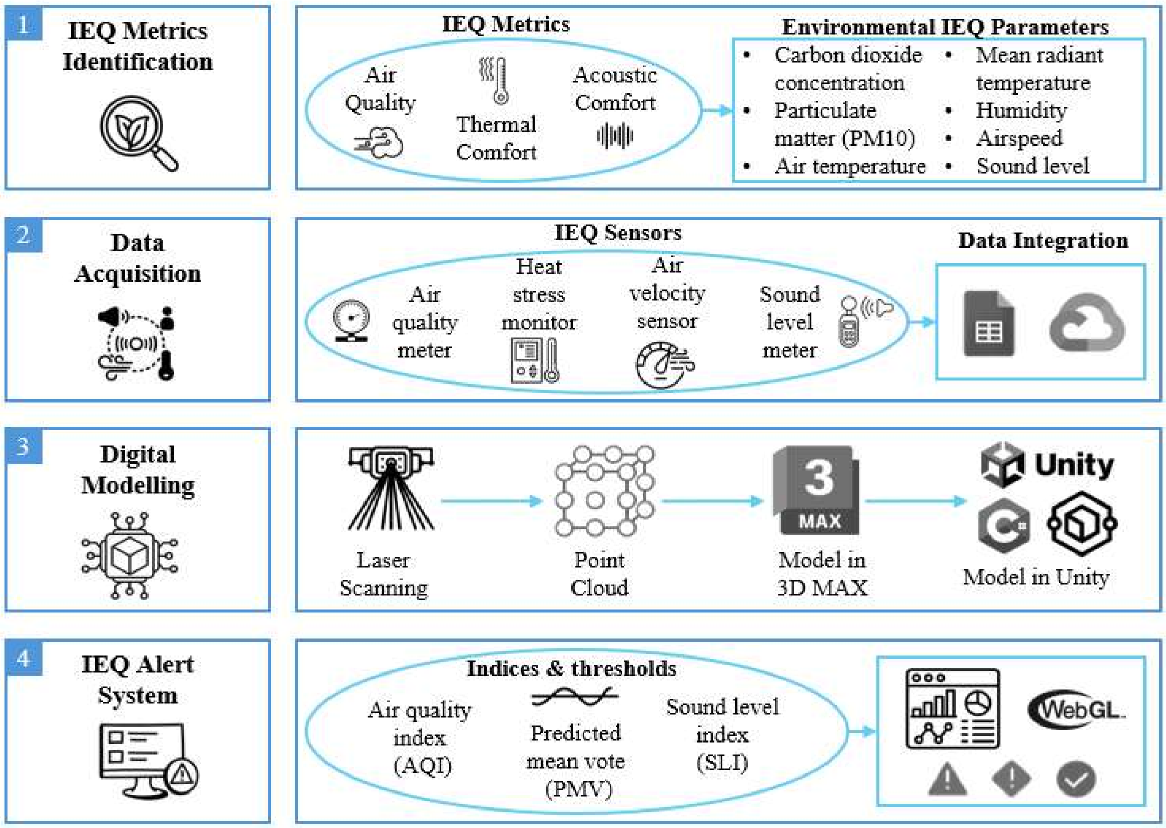

Figure 1. Proposed framework for the O-IEQ monitoring and alert system

customized as per the production operations as well as the IEQ needs and expectations of the production facility of interest.

3.1 IEQ Metric Identification

The proposed *O-IEQ ALERT System* encompasses three IEQ metrics: air quality, thermal comfort, and acoustic comfort. (Lighting quality may also be incorporated in future work.)

Indoor air quality is influenced by several parameters. In the present study, the system monitors levels of carbon dioxide (CO_2) and particulate matter (PM10). CO_2 is indicative of the freshness of indoor air, while PM10 measures the presence of coarse, harmful particles [21]

According to Fanger [22] a person's thermal comfort depends on six environmental and personal parameters: air temperature, mean radiant air temperature, relative humidity, air speed, metabolic rate, and clothing insulation. Air temperature refers to the temperature of the air surrounding the human body, while mean radiant air temperature refers to the heat radiated from a warm object. Air speed is the speed at which air circulates around humans. Relative humidity is the present state of humidity relative to the maximum humidity given at a certain temperature, and the metabolic rate refers to the physical effort required to perform tasks. Clothing insulation, finally, refers to the worker's ability to adapt their clothing to feel comfortable, while also considering the necessary personal protective equipment [22].

Acoustic comfort, meanwhile, has to do with the sound pressure levels perceived by the worker while performing tasks at the factory. Sound levels are influenced by the combined noise generated from different activities at the factory, whether manual or machine-based activities [11].

3.2 Data Acquisition

The parameters that affect the factory's IEQ having been identified, the next step is to develop a data acquisition system for collecting real-time data from each workstation. This is achieved by implementing various types of sensors at locations throughout the production facility. There are many types of sensors available for automated monitoring of IEQ parameters [23]. The selection of the sensors is typically case-specific and depends on sensor availability, range, accuracy, ease of use, ease of installation, cost, data transmission, and interoperability with other software.

Regarding the acquisition of IEQ data, an air quality meter can be used to measure the CO_2 and PM10 levels [24]. Personal parameters of thermal comfort are often assumed to be constant, whereas environmental factors—i.e., air temperature, mean radiant temperature, relative humidity, and air speed—are dynamic and must be monitored over time. Air temperature, mean radiant temperature, and relative humidity can be collected using a heat stress monitor, while air speed data can be collected using an air velocity meter [25]. To measure sound levels, a sound level meter can be employed [10]. Following the selection of commercially available sensors, sensing equipment is installed at the factory in accordance with the associated manufacturing guidelines.

The sensors, having been installed, data can be collected in real time at select intervals, such as one, five, or 10 minutes. The intervals are selected based on the criticality of the IEQ in the factory, as well as the variability of operations. Once the data on the different parameters is collected, it will undergo a process of data cleaning, processing, and structuring into the proper format so that it can be used as an input to the digital model. The specific steps depend on the selected sensors, the integration between the sensors, and the case study.

The cleaned and structured sensor data is then integrated with the digital model of the production facility (as discussed in the description of Phase 3 below) to ensure the link between the physical and virtual environments of the DT [26]. This integration is achieved by storing the sensor data in Google Sheets, with each row representing a single time stamp and each column representing a different IEQ parameter. These Google Sheets are hosted on a Google Cloud platform, which allows for separate sheets to be created for each workstation. An application programming interface (API) is then created in Google Cloud to integrate data from the sensors via the created Google Sheets. A URL link is then generated to present the data in JSON format. This allows for the data to be retrieved in the Unity modelling software. It should be noted that the APIs are restricted so that only employees of the case company and members of the research team can access the sensor data.

3.3 Digital Modelling

A 3D model that is reflective of actual production line operations in the facility and that represents the information flow of the IEQ indices and parameters in real time is critical, as it improves the user experience. In developing the 3D model, laser scanning is used to automatically measure and locate thousands of datapoints at the factory based on the selected positions of the laser scanners. This results in a spherical point cloud that maps to the factory. The point cloud, in turn, is imported to 3Ds Max for model development [26]. Finally, the model is imported to Unity software, which provides an interactive environment for the real-time monitoring and alert system.

3.4 IEQ Alert System

The purpose of the IEQ alert system is to provide a means of monitoring the quality of the indoor factory environment in real time. The system issues warnings if IEQ levels are not within the acceptable ranges set by the standards and regulations. Management can then take the necessary corrective or preventive measures to ensure a healthy, satisfactory, and productive environment for workers. For the alert system, three indices are selected corresponding with the three IEQ metrics of interest. The three indices are the Air Quality Index (AQI), Predicted Mean Vote index (PMV), and Sound Level Index (SLI). Each of these indices considers the influencing parameters identified in Phase 1 (see above). The indices having been identified, the next step is to determine the acceptable thresholds based on the relevant standards, guides, and regulations. A three-level warning system (good, fair, or poor) is introduced accordingly. Further details on the influencing parameters, index establishment, thresholds, and warning levels for each index are described as follows.

The AQI index is dependent on the CO_2 and PM10 concentration levels [21]. Since there is no universal index to measure the indoor air quality, the AQI was developed based on the thresholds of its dependent parameters. Table 1 shows the good, fair and poor ranges for the indoor CO_2 and PM10 concentration levels as per the ASHRAE 62.12 for CO2 [12]as well as the WHO [13] and the EPA [14] for PM10.

Table 1. CO_2 and PM10 levels

	Good	Fair	Poor
CO_2 concentration (ppm)	< 1,000	1,001–2,000	> 4,000
PM10 Level (ug/m³)	< 50	51–150	> 150

The next step identifies the 9 combinations of the CO_2 and PM10 levels to provide a qualitative indoor air quality index. If both CO_2 and PM10 are at acceptable levels, then the AQI is also acceptable with an index of 1. If either one is fair and the other is good, the AQI is moderate with an index of 2. If both are fair, the index will increase to 3. The index will be considered unhealthy at 4, if one is good and the other is poor. The index changes to 5 and becomes very unhealthy if either one becomes poor. Finally, the AQI index increases to 6 and becomes hazardous in case both parameters are in a poor state. Table 2 represents the developed AQI and its concern levels with a range from 1 to 6, with 1 being in good condition and 6 being in a hazardous state.

Table 2. AQI development

CO_2 Level	PM10 Level	AQI (index)	Level of Concern
good	good	1	Good
good	fair	2	Moderate
fair	good	2	Moderate
fair	fair	3	Moderate
good	poor	4	Unhealthy
poor	good	4	Unhealthy
fair	poor	5	Very unhealthy
poor	fair	5	Very unhealthy
poor	poor	6	Hazardous

Thermal comfort is dependent on 6 parameters, including personal and environmental parameters as per Fanger's model [22]. The metabolic rate and the clothing insulation are assumed to be constant values in the model. These can be selected based on the activity being performed by the worker and the clothing characterises respectively as per the ASHRAE Standard 55[27]. It should be noted that these values typically remain constant for a certain period and require an update upon major changes such as allocating a new worker to a certain task, entering a new season (winter and summer), or a change in the tasks of the production process, etc. As such, the manual selection of these values is feasible [28]. The environmental parameters include the air temperature, mean radiant air temperature, humidity, and air speed [22]. Based on these 6 parameters, thermal comfort can be quantified by calculating the Predicted Mean Vote (PMV) index as per the mathematical model developed by Fanger [22]. The PMV varies on a 7-class scale as follows: hot (−3), warm (−2), slightly warm (−1), neutral (0), slightly cool (−1), cool (−2), and cold (−4). Typically, a PMV between −0.5 and +0.5 reflects a comfortable indoor thermal environment.

The sound level index is developed based on the corresponding measured sound levels [11]. Table 3 presents the ranges of the noise levels, the level of concern, and the SLI. The SLI ranges from 1 to 6, with 1 being safe and 6 being extremely high risk.

Table 3. SLI development

Sound level dBA	Level of concern	Sound level index (SLI)
<66	Safe	1
66–71	Tolerable	2
71–76	Low risk	3
76–81	Moderate risk	4
81–85	High risk	5
85	Extremely high risk	6

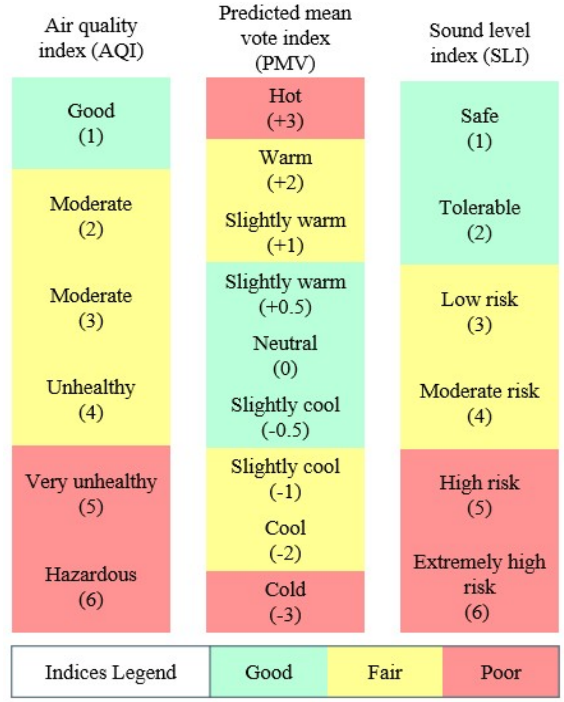

Figure 2. IEQ indices warning levels

Once the three IEQ indices are defined and established, the warning and alerting levels are introduced, as shown in Figure 2.

Once the indices, their thresholds, and warning levels are established, they are reflected in the Google Sheets on Google Cloud and thus are reflected in the APIs that feed data into the Unity model of the factory. A Canvas is created in Unity that shows two monitoring and alerting stages across two developed scenes. The first stage, Layout Scene, represents the layout of the production facility. This includes the sensors' location and status of the three IEQ indices for each workstation (good, fair, or poor). The second stage, Station Scene, shows the three indices' values, warning levels, and time series trends for each of the seven IEQ parameters for the station of interest. It should be noted that all indices, trends, and warning levels are updated in real time in Unity, given that the real time sensor data is fed via the API data integration.

The last step in the IEQ monitoring and alert system is to enable users (i.e., management at the production facility) to monitor the facility's IEQ remotely through a web-based decentralized network that can be accessed from any compatible browser [29]. Such solutions have been successfully applied in the planning of OSC projects [30] and are provided in Unity through the WebGL function as a JavaScript API [31].

4 Illustrative Application of the *O-IEQ Alert System*

The proposed *O-IEQ Alert System* is part of a larger study that aims to assess the quality of the indoor environment in OSC facilities to ensure a human-centric healthy, safe, and productive environment. A case study of a wall production line in an OSC facility is introduced to showcase an illustrative application of the proposed system. The application covers four stages of the process, including framing, sheathing, multi-function bridge, and the installation of windows and doors.

As discussed in the “Proposed O-IEQ Alert System” section, the three IEQ indices, including the AQI, PMV, and SLI, can be monitored by the *O-IEQ Alert System*, as well as the parameters of CO_2, PM10, air temperature, mean radiant air temperature, humidity, air speed, and sound level. Given that the data acquisition phase is under development, and the sensor installation and data collection steps are in progress, the authors used synthetic sample data to showcase the applicability of the system. This is a preliminary step that will help validate the system prior to real data acquisition and integration.

Although the authors relied on simulating data points to mimic the sensor data, the system is updating in real-time based on its acquired data. As such, the authors created a sample dataset with 200 data point stamps at 10-second intervals for each of the 7 parameters of interest. Then, the indices and the warning levels were accordingly calculated. The synthetic sensor data, along with the corresponding IEQ indices and warning levels, were uploaded to Google Sheets on Google Cloud, where the corresponding APIs were created. As such, the authors were able to replicate real-time data feed into the digital model for real time updating.

The digital model development of the production facility was achieved through laser scanning, whereby point cloud data was generated. The data was used to develop the model in 3Ds MAX, and the model was then transferred to Unity. The Unity model was uploaded to the web using the WebGL function to allow for online

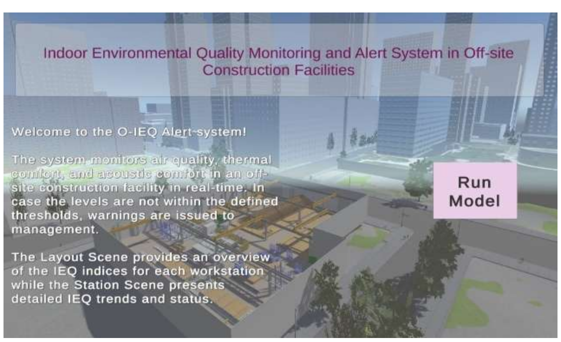

Figure 3. Web-based O-IEQ Alert System overview

and remote access to the system. As such, the model can be accessed through a URL, as shown in Figure 3. Figure 3 also introduces the aim of the system and its main outcomes.

Once the user runs the model, they will be taken to the Layout Scene, as shown in Figure 4. This scene presents the layout of the wall framing production line and the 4 stations understudy. Each of these stations is associated with a unique warning level, with coloured indices representing the IEQ index of interest. The user can select any of the 3 indices, and the warning levels will be updated accordingly.

Figure 4. Layout scene of O-IEQ Alert System

Once the user clicks on any of the stations, they will be taken to the Station Scene, as shown in Figure 5, providing more detailed insights regarding the IEQ. The user can view how the 3 indices are being updated and can select a certain index to view the time series of its corresponding parameters. Figure 5 shows the status of the framing station, where AQI is in a fair condition, and the PMV and SLI are in good condition. The user can select the other 2 indices to monitor the trends of the relevant parameters. It should be noted that the Layout Scene and the Station Scene are fed real time synthetic data using the aforementioned data integration workflow, and the indices, the warning levels, and the parameters trends are updated accordingly in real-time.

5 Conclusion and Future Work

In summary, this study proposed a digital twin-based system to monitor the IEQ of off-site construction facilities in real time with continuous management and alerting features. The developed *ALERT O-IEQ System* was developed in reference to the DSR method through identifying the need for the system, defining its objectives, developing and evaluating it. The system is composed of four phases including (1) IEQ metric identification, (2) data acquisition, (3) digital modelling, and (4) development of the IEQ alerting component of the system. An illustrative application was presented in a

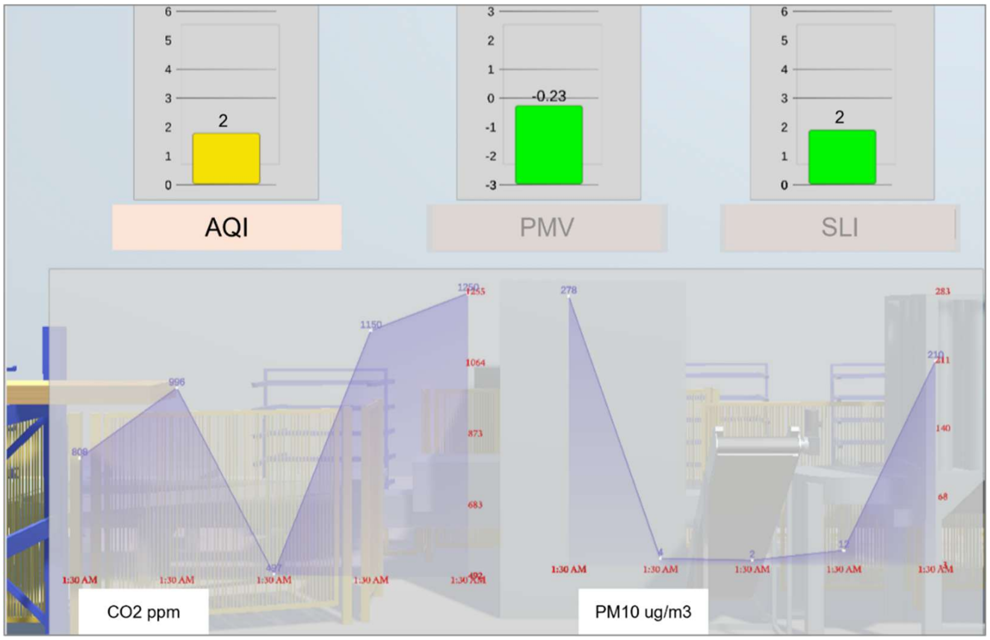

Figure 5. Framing station scene of the O-IEQ Alert System

wall-production manufacturing facility. A web-based Canvas in a 3D environment was developed to monitor the IEQ in real-time including the Air Quality Index, thermal comfort Predicted Mean Vote Index, and the Sound Level Index for each workstation. It also shows detailed insights into each workstation, including real-time time-series trends of the IEQ parameters (i.e. PM10 level, noise level, etc.). In case the IEQ is not within the acceptable thresholds, an alert is issued to the management in order to take the necessary measures. Certain limitations exist in the study that should be addressed. Firstly, the AQI index integrated in the developed system only considers two parameters, the CO2 and PM10 levels, while other parameters can impact the air quality. In the future, the AQI will be further developed to include the ground-level ozone, PM2.5, PM10, carbon monoxide, sulfur dioxide, and nitrogen dioxide as per EPA's U.S AQI to ensure more comprehensive and reliable air quality monitoring. Secondly, the system requires further validation to ensure its reliability in practice. As such, the system will be implemented on an actual case study of an OSC facility to test its effectiveness in the future.

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