A User Interface Informing Medical Staff on Continuous Indoor Environmental Quality to Support Patient Care and Airborne Disease Mitigation

A Technical Report submitted to the Department of Engineering Systems and Environment

Presented to the Faculty of the School of Engineering and Applied Science
University of Virginia • Charlottesville, Virginia

In Partial Fulfillment of the Requirements for the Degree
Bachelor of Science, School of Engineering

Jacob Rantas
Spring, 2020.
Technical Project Team Members
David Wang
Will Jarrard
James Sterchi

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

Arsalan Heydarian, Department of Engineering Systems and Environment

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Jacob Rantas
Department of Engineering Systems and Environment
University of Virginia
Charlottesville, VA, USA
jlr9wb@virginia.edu

David Wang
Department of Engineering Systems and Environment
University of Virginia
Charlottesville, VA, USA
dtw3fp@virginia.edu

Will Jarrard
Department of Engineering Systems and Environment
University of Virginia
Charlottesville, VA, USA
wej5ar@virginia.edu

James Sterchi
Department of Engineering Systems and Environment
University of Virginia
Charlottesville, VA, USA
jrs5qg@virginia.edu

Alan Wang
Department of Electrical and Computer Engineering
University of Virginia
Charlottesville, VA, USA
ahw9f@virginia.edu

Mahsa Pahlavikhah Varnosfaderani
Department of Engineering Systems and Environment
University of Virginia
Charlottesville, VA, USA
mp3wp@virginia.edu

Arsalan Heydarian
Department of Engineering Systems and Environment
University of Virginia
Charlottesville, VA, USA
ah6rx@virginia.edu

***Abstract*—This project seeks to investigate the under addressed issue of indoor environmental quality (IEQ) and the impacts these factors can have on human health. The recent COVID-19 pandemic has once again brought to the forefront the importance of maintaining a healthy indoor environment. Specifically, the improvement of indoor air flow has shown to reduce the risk of airborne virus exposure. This is extremely important in the context of hospitals, which contain high concentrations of at-risk individuals. Thus, the need to create a healthy indoor space is critical to improve public health and COVID-19 mitigation efforts. To create knowledge and provide insight on environmental qualities in the hospital setting, the authors have designed and built an interface to deploy in the University of Virginia Hospital Emergency Department (ED). The interface will display room-specific light, noise, temperature, CO_2, humidity, VOC, and $PM_{2.5}$ levels measured by the low-cost Awair Omni sensor. These insights will assist ED clinicians in mitigating disease-spread and improving patient health and satisfaction while reducing caregiver burden. The team addressed the problem through agile development involving localized sensor deployment and analysis, discovery interviews with hospital clinicians and data scientists throughout, and the implementation of a human-design centered Django interface application. Furthermore, a literature survey was conducted to ascertain appropriate thresholds for the different environmental factors. Together, this work demonstrates opportunities to assist and improve patient care with environmental data.**

***Index Terms*—Indoor Air Quality, COVID-19, Environmental Sensing, Human-Centered Design, Health Information Technology**

I. INTRODUCTION AND BACKGROUND

Recent research demonstrates that viral COVID-19 particles can remain suspended in the air for two hours or more [6], and the airborne nature of this virus has reminded the world of the importance of maintaining healthy indoor environmental quality (IEQ). This is especially true in hospital systems, which contain high numbers of at-risk patients and many potential grounds for disease spread if systems are not properly maintained.

A. COVID-19 Transmission in Hospital Setting

Hospitals across the country have taken steps to mitigate the risk of COVID-19 spread within their facilities. Operational protocols employed by many institutions, such as the University of Virginia (UVA) Hospital system, include mandatory social distancing throughout the complex, enforcing zero to one visitor policy [4], limiting services traditionally offered (valet, cafeteria, etc), and building out negative pressure isolation wings within the hospital for suspected and positive COVID-19 patients [1]. Similar to other indoor settings, hospitals have also made substantial improvements to their existing heating, ventilation, and air conditioning (HVAC) facilities and infrastructure. As a result of updated guidance through ASHRAE, HVAC standards have increased, diluting indoor air pollutants by introducing outdoor clean air [13]. Hospitals have also increased filtration standards, employing MERV-13 and higher across the entire facility [1]. Additionally, some hospitals have incorporated novel upper-room and in-duct UVGI systems to kill airborne pathogens present within the indoor environment [16]. However, few mitigation strategies deployed have utilized indoor air quality (IAQ) monitoring and awareness in their solution.

TABLE I
IEQ Factors Effect on Humans and COVID-19 Spread

IEQ Factor	Effect on Humans	Effect/Indication on COVID-19
Temperature	Higher temperatures (35°C) have an adverse impact on sleep [14] Higher temperatures (25°C) can result in lower self-rated performance, greater physical demand and frustration [10]	Higher levels → lower airborne particle spread, decreased half-life of virus Lower levels → higher airborne particle spread [22]
Humidity	Ideal relative humidity (RH) is typically 40-50%, 70-80% RH is more ideal for dust mites which can trigger respiratory symptoms [7]	Higher levels → lower airborne particle spread Lower levels → higher airborne particle spread [22]
CO_2	Concentrations above 1,000 ppm can result in hindrance of decision-making performance [18]	Higher concentrations indicate higher occupancy, increasing chance of airborne particle spread
TVOC	Exposure above recommended concentration of 500 ppb can lead to acute respiratory responses, headaches, as well as eye, nose, and throat irritation [12]	
$PM_{2.5}$	Exposure above recommended concentrations of 35μg/m3 can lead to acute respotory responses [21]	
Noise	Nighttime noise levels above 55 dBA can disturb sleep and boost heart disease risk [5] In ward settings, background noise should ideally be <35 dBA, <30 dBA at night, and peak no higher than 40 dBA [15]	
Light	Levels of >100 lux are necessary to suppress melatonin [15] Dementia patients exposed to >2500 lux experienced decreased agitation [22]	Not Applicable

B. IEQ Awareness and Implications

Lack of awareness regarding IAQ's impact on human health is of serious concern. The Institute for Health Metrics and Evaluation (IHME) estimates that there were 1.6 million premature deaths due to indoor air pollution in 2017, accounting for 3% of global deaths [17], emphasizing the importance of maintaining a healthy indoor environment. Expanding upon IAQ to overall IEQ, there are a variety of environmental factors that could impact patients' experience and recovery in hospitals. The factors in focus include temperature, humidity, carbon dioxide (CO_2), total volatile organic compounds (TVOC), particulate matter ($PM_{2.5}$), light, and noise. CO_2 particles are typically emitted through human respiration, TVOC particles are typically associated with smells and organic materials, and $PM_{2.5}$ is typically associated with dust particles. Table 1 displays the relevant IEQ factors and the impact each factor has on human health and airborne virus transmission.

C. Access to Information in the Emergency Department

As shown through some examples in Table 1, it is evident that through understanding IEQ factors' impacts on humans, healthcare providers can create a healthier and more comfortable environment for patients. Although information on IEQ impacts on patients is important, healthcare workers already struggle with information overload. A study conducted among healthcare workers in 2020 showed that the vast majority of respondents believe that information overload is a serious issue within the hospital, and especially the emergency department, [19] demonstrating there is a need to present information in an uncomplicated manner. By creating a simple, effective interface that presents data on the conditions of various IEQ factors within patient rooms and common spaces, healthcare workers will be able to optimize patient satisfaction with minimal mental burden. In working to design an interface implementable in a health care setting, several interfaces related to IAQ and COVID-19 risk were explored. In investigating Harvard's traffic light risk display, a similar approach was incorporated in strategically coloring items within this project's final product [9]. In investigating Duke's interface detailing indoor COVID-19 exposure risk, strategies were adopted to tie quantitative insights into an easily interpretable spatial display. The interface also assessed risk at variable inputs, inspiring the incorporation of a COVID-19 risk calculator within this ED application [20]. The Awair dashboard (IEQ sensor that was utilized for this study) inspired the incorporation of graphical display to identify factor behavior over an extended period of time.

II. Methods and Designs

A. Discovery Interviews and User Surveys

In order to better understand the healthcare workers workload, needs, and how the proposed user interface can assist them, a series of interviews were conducted with different stakeholders in the UVA hospital. Consistent with agile product development, these 8 interviews were conducted throughout interface design with physicians, nurses, nurse informaticists, data scientists, and other clinicians within and outside of the UVA Hospital and Emergency Department. Clinicians were interviewed as potential user groups, while data scientists and nurse informaticists were interviewed to understand the role of information technology in the ED and assess the existing capabilities of the department. Questions were formulated prior to interviews to understand and establish stakeholder needs, functional requirements, and responsibilities. These interviews were conducted with the ultimate goal of driving design insights to aid clinicians in their day-to-day and support the goal of the ED: maximizing patient health outcomes and satisfaction through efficient patient processing and treatment.

B. IEQ Score Threshold Determination

The Awair Omni sensors were utilized in this project based on the reliable data stream the sensors provide with minimal infrastructure and the team's familiarity with the devices, as several Awair Omnis are currently deployed in the UVA Living Link Lab [3]. To establish a personal understanding of IEQ factors, the team deployed sensors in various residential buildings and individual activity was logged to investigate how human behavior impacts sensor readings and IEQ metrics.

After establishing an understanding of typical IEQ factor levels in familiar contexts, the team determined a set of IEQ factor thresholds for a hospital environment. Through research, thresholds were established for what would be considered "Good , Okay, and Poor" for the different IEQ measures.

The humidity threshold was determined based on widely accepted typical indoor levels. CO_2, VOC, and $PM_{2.5}$ thresholds were determined from a study that investigated levels of these pollutants in 37 different hospitals [12]. Noise level thresholds were determined by a combination of recommendations from the World Health Organization (WHO) and the Hearing Health Foundation. The framework of "Good, Okay, and Poor" is applicable to all the measured factors except for temperature and light, which are separated into "Hot, Normal, and Cool" and "Bright, Medium, and Low" respectively as different patients have different ideal temperature and light levels.

Research suggests a patients' ideal temperature and light level may vary depending on their personal preference as well as their health background. A study had shown that elderly patients with dementia were less symptomatic when exposed to bright, 2500 lux light for 2 hours in the morning [11], indicating bright light would be ideal in this case. Conversely, patients with migraines are more sensitive to light and would require lower light levels.

C. COVID-19 Maximum Occupancy Calculator

A key component in the proposed interface involves calculating a metric of COVID-19 exposure risk based on room-specific IEQ composition. After investigating a range of calculators including those which displayed risk percentages for disease contraction [16], a calculator providing occupancy recommendations based on IEQ characteristics was selected for this project [2]. This COVID-19 Indoor Safety Guideline Calculator provides a guideline for risk assessment of COVID-19 spread indoors dependent upon occupancy and exposure time and calculates the maximum allowable occupancy for a given space using the equations below.

$$\lambda_c = \lambda_a + .6RH + \lambda_f + \frac{v_s(r)}{H} \tag{1}$$

$$\beta_a = (Q_b s_r p_m)^2 \frac{C_q}{V\lambda_c} \tag{2}$$

$$N_{max} = 1 + \frac{\epsilon(1 + \frac{1}{\lambda_c \tau})}{\beta_a \tau} \tag{3}$$

The calculator takes inputs including room characteristics (relative humidity, RH, room height, H, and volume, V), occupants' physiological (mean breathing flow rate, Q_b ,risk tolerance, ϵ, relative transmissibility, s_r) and behavioral (duration of occupancy, τ, mask efficiency, p_m) parameters, and HVAC considerations (the air filtration rate, λ_f, outdoor air exchange rate, λ_a) in combination with derived viral characteristics (infectiousness of exhaled air, C_q , effective settling speed, $v_s(r)$). These factors compute the concentration relaxation rate, λ_q,the airborne transmission rate, β_a, and the maximum occupancy limit, N_{Max} , for the specified space based upon the equations above [8].

D. Interface design and implementation

Many techniques were employed throughout the design of this interface, including the robust CRAP principles (contrast, repetition, alignment, and proximity). Contrast involves explicit differentiation between interface items in color, bolding, capitalization, etc. Repetition ensures consistent visual elements are replicated throughout separate pages of the interface. Not only does repetition afford a cohesive, unified design, but also is critical in reducing the cognitive burden of the operator amidst ever-present information overload. Alignment is employed through deliberate item placement on the screen, fostering connections between application elements and further increasing application usability. Lastly, proximity of design elements is key to organize information, increase holistic processing, and mitigate operator error.

Functional design considerations included minimizing the number of clicks required to access desired information, employing a minimalist design approach to consolidate information into key interface items, and emphasising navigational features (headers, tabs, buttons) to ensure an efficient and productive user experience. Designs were tested in rapid Figma iterations throughout interface development.

The final design portion was done within Django to create the prototype interface. Using the model-view-controller structure of Django, the site was created based on the information gathered from the interview stage. The diagram in Figure 1 explains the model aspect of the site, which symbolizes the sensor-hospital system.

Figure 1 shows the basis of the site and helps provide the format for its creation. The site logic defines that each department in the hospital will have a set of rooms, each

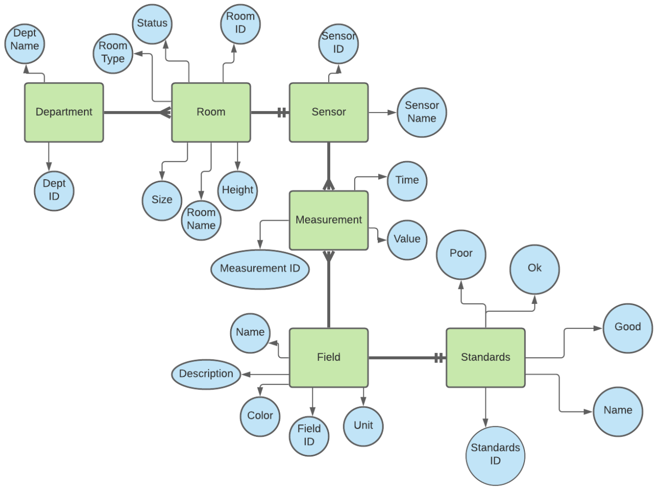


Fig. 1. Squares represent logic interaction of model, circles represent fields for each of the model instances. For example, every room object created in the database would have a department it is part of, a room type, a status, a room id, a size, a room name, and a height.

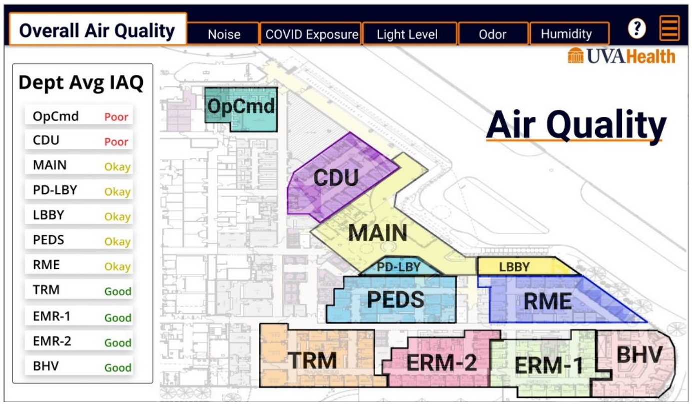
room includes a single Awair sensor, and each sensor will have a set of IEQ measurements (or sensor transmissions). Each transmission consists of an IEQ field, and by comparing the most recent transmission with the associated threshold, the current score will set accordingly (eg.,. “Good”, “Ok”). The visual design of the set will rely on the Figma wireframes and continued iteration and feedback from user groups (e.g., nurses).

III. RESULTS

A. *Interview Findings*

While interviews were entered with the initial idea of using this user interface to improve COVID-19 mitigation efforts in the ED, the authors quickly learned dozens of potential applications for the interface. Between applications in patient processing, event detection, historical analysis, patient satisfaction/outcomes, data integration, and more, this interface has substantial implications in the ED setting. Primary users were established as nurses operating daily within the ED, and secondary users were defined as administrators and physicians using reporting features to assess department success. Feedback drove core design considerations, ensuring an intuitive, highly functional, and plain english interface that does not contribute to information overload and alert fatigue experienced by ED staff. By including factor descriptions and thresholds from Table 2 into an interface page, nurses and other medical personnel can understand the significance of the information displayed. To culminate implementation efforts, thorough interface training will be administered as it is crucial to the interface’s adoption and proper use in the ED.

After showcasing Figma iterations, interviewees provided feedback related to usability and display, and assessed the efficacy of proposed design elements. The final Figma design in Figure 2 incorporates interview suggestions and feedback to model spatial interface design in the ED.



Dept Avg IAQ

OpCmd	Poor
CDU	Poor
MAIN	Okay
PD-LBY	Okay
LBBY	Okay
PEDS	Okay
RME	Okay
TRM	Good
EMR-1	Good
EMR-2	Good
BHV	Good

Fig. 2. Figma design

TABLE II
FACTOR THRESHOLDS

Factor	Good	Okay	Poor	Unit
Humidity	40-50	30-40,50-70	0-30,70-100	%
Noise (daytime)	<35	35-60	>60	dB
Noise (nighttime)	<30	30-40	>40	dB
CO_2	0-700	700-1500	>1500	ppm
VOC	0-500	500-1000	>1000	ppb
$PM_{2.5}$	0-25	25-35	>35	$\mu g/m^3$
Factor	Hot	Normal	Cool	Unit
Temperature	>80	68-78	<78	°F
Factor	Bright	Medium	Low	Unit
Light Level	>2500	2500-100	<100	lux

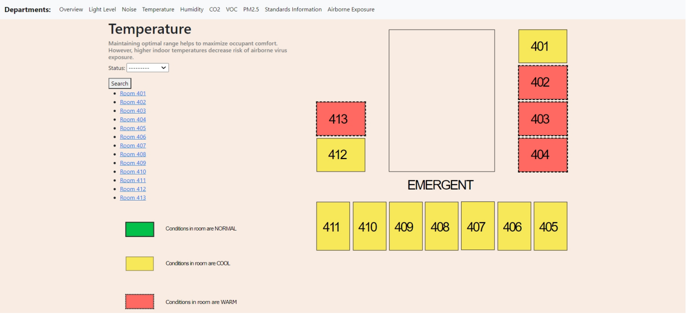
B. *Factor Thresholds*

Table II outlines the various factor thresholds that were determined through literature review.

These thresholds provide guidance as to desired IEQ factor levels in the ED, but should still be assessed in context with the appropriate situation. Thresholds were relaxed to aid in clinician decision making, as thresholds set exclusively at optimal levels would detract from the interface’s explanatory power with all rooms labeled as “Okay” or “Poor”. As different departments may have different standards and needs, flexible, adjustable thresholds will be employed to increase scalability of this interface.

The interface relied heavily on the interview process and Figma prototyping. By understanding the nurse’s workflow and typical responsibilities, it was important to create an interface that would help and not hinder their ability to complete their job. The feedback received made it clear the interface needed to be created in a way that would reduce the need for constant interaction and maintain simplicity for quick and efficient use.

Figures 3 and 4 illustrate an example of the two main pages of the Django web app. The type page allows for filtering by room occupancy, as well as providing an overview



Temperature

Maintaining optimal range helps to maximize occupant comfort. However, higher indoor temperatures decrease risk of airborne virus exposure.

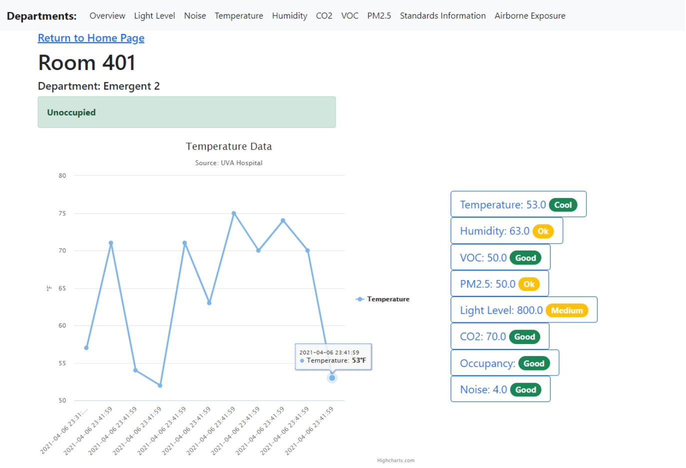
Status: ---------

🟩 Conditions in room are NORMAL

🟨 Conditions in room are COOL

🟥 Conditions in room are WARM

Fig. 3. Webpage



Room 401

Department: Emergent 2

Unoccupied

Temperature: 53.0 Cool

Humidity: 63.0 Ok

VOC: 50.0 Good

PM2.5: 50.0 Ok

Light Level: 800.0 Medium

CO2: 70.0 Good

Occupancy: Good

Noise: 4.0 Good

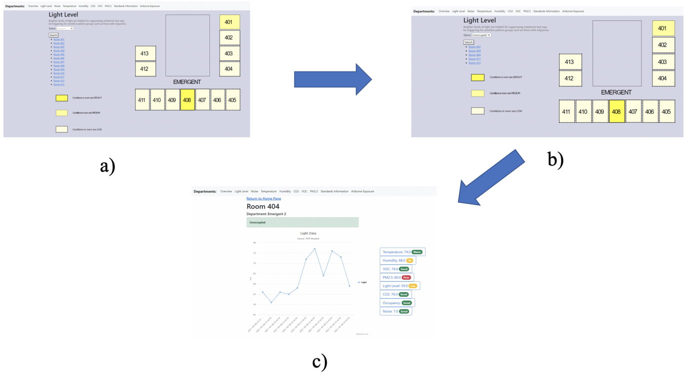
Fig. 4. Room View

of the specific department. On the department overview, the rooms are colored based on the field standards, allowing a user to quickly determine which rooms have the optimal conditions for their patient. The top bar of the page allows for quick movement between type pages and provides links to the overview (displaying room occupancy), the standards information (explaining the factor scores), and the airborne exposure tab (displaying airborne exposure conditions for the shared spaces).

The room page provides a room overview with relevant information about IAQ metrics and occupancy. By using the buttons on the right side, the user can change the graph to display the specific metric they are interested in. The data shown will then allow nurses to better address the room's environmental conditions and provide their patients with more personalized treatments.

C. COVID-19 Calculator

The COVID-19 calculator included in the interfaces calculates maximum occupancy thresholds for shared spaces in the ED based on applicable room IEQ and occupant behavioral factors. Through incorporating room size, holding established department HVAC characteristics fixed (ventilation rate, recirculation rate, filtration systems) and varying with time expected occupant behavioral considerations (respiratory and breathing rate, risk index), realistic occupancy guidelines are produced for shared spaces in the ED (adult and pediatric waiting rooms, nurse and physician workspaces, hallways). These guidelines could vary anywhere from 15 to 350 persons dependent upon expected behavior and real time sensor readings. These guidelines will assist ED staff in acting on appropriate COVID-19 mitigation measures when faced with overcrowded waiting rooms and shared spaces.



a)

b)

c)

Fig. 5. Use Case

IV. CASE STUDY

The implementation of this interface allows medical personnel to monitor more factors that could impact patient health, comfort, and safety. It also follows the three click rule - where any page and desired information on the interface is accessible in three clicks or less and embodies CRAP design principles. These can be seen through the following case study showcasing how a nurse would use the interface system to admit a patient with severe migraine headache.

The patient arrives at the hospital, checks in, and undergoes triage. After the healthcare provider recognizes the patient is having a migraine, the user navigates to the designed interface to survey room conditions. The user acknowledges the migraine patient is sensitive to light, so would navigate to and click the "light" tab on the top menu bar, redirecting the user to the department overview displaying room-specific light levels (FIGURE 5a). The user would then click the dropdown filter to show unoccupied rooms and search (FIGURE 5b). After locating a room considered to have "low" light conditions (pale yellow icon), the user selects the room to investigate if light and other conditions (noise) are optimal for this patient (FIGURE 5c). After confirming conditions are optimal, the provider assigns the migraine patient to the room that best fits their needs.

V. DISCUSSION AND CONCLUSION

A. Future Hospital Implementation

Full system implementation involves many of the steps taken above. Standardized sensor deployment at identical room heights and locations will be enacted to ensure data integrity, a critical observation from residential sensor deployment. Close attention will be paid to ensuring data privacy, a substantial takeaway gathered from user interviews, as the fully-built out product will integrate with Epic (hospital's management software) and require nurse log-in. Research is required to determine the lengths of necessary data and patient privacy protections.

B. Potential Functionality and Scalability

Several additional extensions and functionalities could further increase the usability and benefits this interface can provide. A historic reporting tool producing specified graphical trends and summary statistics could assist administration in improving department processes and performance. Incorporating customizable, specialized protocols for certain patient types (e.g., migraine, dementia, nausea, fever) can assist in rapid room recommendation for these patients, decreasing cognitive load required by nurses and decision makers. These customized protocols would allow nurses to incorporate their own knowledge in determining appropriate thresholds, and allow updates to the interface as more is discovered regarding these IEQ factors. Notifications could also be incorporated into the interface to assist in treatment of protocol patients (alerting when factors deviate from desired thresholds), fall detection (alerting when sensor detects a loud noise or patient calling for help) and general event detection. Finally, intelligent forecasting could be included in the individual room display to ensure IEQ factor levels stay within an acceptable range for protocol patients throughout their stay. By creating a predictive index of where factors will likely reside the next 5 hours, a provider can ensure IEQ levels will stay in a desired range.

C. Final Thoughts

The COVID-19 pandemic has brought increased awareness to IEQ in the hospital setting with regards to airborne virus risk exposure and occupant health. To increase IEQ awareness in the UVA Hospital, the team design a UI system to provide informatics about IEQ factors and allow healthcare workers to optimize environmental quality for themselves and the patients they support. Interface design considerations were iterated in agile development through continual interviews with relevant stakeholders (nurses and nurse informaticists, data scientists, etc) to provide critical insights with minimal mental burden. This project shows that by approaching the issue of IEQ from a systems perspective, healthcare workers and engineers can work together to develop innovative solutions that address unprecedented challenges to the hospital indoor environment.

VI. ACKNOWLEDGEMENT

This research was supported by the UVA Engineering in Medicine Seed grant. The research team would like to recognize a number of individuals for their feedback and contributions throughout the project. The team extends a special thanks to Dr. David Jarrard of The University of Wisconsin, Jane Muir of The University of Virginia School of Nursing, and Hessam Sadatsafavi, Jeff Carter, and Ashley Simpson of The University of Virginia Health System for their continuous valuable input throughout the design and development process.

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