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Q&A

How did you become involved in doing research?
I became interested in research through the McNair Scholars Program. As a McNair Scholar, I have had the opportunity to conduct and present research in communications systems and indoor air quality over the past two years. In fact, this research is a continuation of a literature review on living walls that I worked on this past summer with McNair.

How is the research process different from what you expected?
I have definitely learned to have patience throughout the research process. There were some times when I was working on my project where the experiments that I was running were producing odd results. While it was confusing trying to figure out why the experiment was producing odd results, that experience definitely helped me better understand how to conduct my research.

What is your favorite part of doing research?
I like being able to take a subject that you're interested in knowing more about and further exploring that topic. Most importantly, I like the feeling after completing a research project, regardless of the results, because that experience helps you become more knowledgeable in your subject of interest.

Quantifying CO_2 removal by living walls: a case study of the Center for Design Research

Eric Rivera

ABSTRACT
Indoor air quality (IAQ) is a good indicator of a healthy building environment, as it evaluates how indoor air affects the health and comfort of building occupants. This study investigated a living wall, designed for the Center for Design Research (CDR) as a means to improve IAQ, located at the University of Kansas. This study investigated the effectiveness of the living wall in reducing carbon dioxide (CO_2) concentration levels indoors, as well as the impact the mechanical system has in reducing CO_2 concentration levels. The research was designed in the computational fluid dynamics (CFD) program, FloVENT, which allowed for comparisons of the CDR under the following conditions: without the living wall, with the living wall with the air on and off and with the return air grilles placed behind the living wall. Data for the CO_2 concentration rates of the CDR was gathered from occupancy rates found in the CDR's construction documents, and the living wall's CO_2 absorption rates was gathered from previous studies, using the CO_2 absorption rates of the plant species Bird's Nest Fern. Data was then inputted to the four models of the CDR designed in FloVENT. Results showed that the living wall reduced CO_2 concentration rates by 56% and reduced the amount of CO_2 being returned to the recirculation system. Results of the study also hypothesize whether reduced airflow rates and the placement of supply and return grilles can further reduce CO_2 concentration levels. Further study will provide more information on whether these claims are true.

1. INTRODUCTION

An examination of indoor air quality (IAQ) looks at the cleanliness of the air inside a building and is a good indicator of the health and productivity of building occupants. Issues with IAQ started to develop in the United States during the energy crisis of the 1970s, when buildings began to be tightly sealed from the outdoors as a response to increasing heating and cooling costs (Heimlich, 2008). While doing so reduced both air leakage and heating and cooling costs, building occupants complained that they were feeling short-term discomfort from being inside the building. This discomfort, in which occupants experienced symptoms like dizziness, nausea, fatigue, and headaches, was known as Sick Building Syndrome (SBS). Other cases resulted in more chronic health effects that occurred after long-term exposure, such as respiratory and mental illnesses and cancer ("An Introduction to Indoor Air Quality," 2013). These were better known as Building Related Illnesses (BRI). IAQ is an especially concerning issue as North Americans spend more than 90% of their time indoors (US Environmental Protection Agency, 1989), and thus they are at risk if exposed to poor air.

Some sources of poor IAQ include improper ventilation of the building, infiltration and combustion from stoves and fireplaces. Additionally, building materials and certain household products can emit gases in the air that contain organic solvents known as Volatile Organic Compounds (VOCs) that can become trapped inside the building if the building is not being recirculated and being introduced with fresh air. One strategy to improve IAQ is to introduce vegetation indoors, which has been shown to improve indoor air quality by absorbing pollutants via photosynthesis and producing fresh air. Initial research on this topic was conducted by NASA in the 1980s (Wolverton et al., 1989), which showed that plants had the ability to remove the VOCs benzene, trichloroethylene, and formaldehyde. Results showed that up to 90% of benzene and up to 23% of trichloroethylene could be removed during a 24-hour exposure period. Further research has also shown that vegetation can also trans-locate other pollutants to the soil, where microorganisms break down the pollutants (Fujii et al., 2005). Additionally, plant leaves can trap particulate matter and heavy metals in the air (Ottele et al., 2010; Sternberg et al, 2010), as well as carbon dioxide (CO_2) (Fujii et al., 2005; J.-F. Li et al, 2010).

Vegetation can be introduced inside a building as an architectural feature known as a living wall. A living wall is any form of vegetation that can be fixed vertically to a wall or freestanding structure (Green Roofs for Healthy Cities, 2008). Living walls consist of a system that can be constructed from either pre-vegetated panes, vertical modules, or planted blankets that are fixed vertically to a structural wall or frame.

Living walls can be constructed with a variety of plant species that can provide optimal improvements to a building's IAQ. Since living walls encompass a large surface area (the area that is covered by the plants), they can also remove more pollutants from the air. Furthermore, living walls can improve health and increase productivity in the workplace (Dravigne et al, 2008). Living walls have the potential to improve IAQ in buildings. However, there has been little data that supports the ability of living walls in improving IAQ.

To determine the ability of vegetation to improve IAQ, several factors can be used. Factors such as light intensity and wind speed were investigated in J.-F. Li's study on green roofs (J.-F. Li et al., 2010). Results showed that during the day, a decrease of CO_2 concentration was reported when abundant sunlight was present. Meanwhile at night, an increase of CO_2 concentration in the air was reported due to lack of light. Additionally, a lower wind speed increased the absorption rate of CO_2 by the green roof. Since the pollutants were not being mixed as much in the air, the plants could trap pollutants more effectively.

One factor that has not been previously investigated is the role of supply airflow rates that are produced by mechanical ventilation systems. Girman et al. (2009) states in his review that previous IAQ studies did not include mechanical ventilation rates of the building sites investigated. These values are important because mechanized ventilation plays a major role in diluting the indoor air with outdoor air and thus, can affect the pollutant concentration in the air. Understanding how these mechanical systems work together with vegetation, such as living walls, can provide a better understanding of the effectiveness of living walls in removing pollutants from the air.

This research looked at the ability of living walls to remove CO_2 from the environment and the role of ventilation in the CO_2 removal by living walls. The Center for Design Research (CDR) at the University of Kansas, as shown in Figure 1, provided for a unique laboratory for this study.

2. RESEARCH DESIGN

2.1. The Building

The Center for Design Research (CDR), located on West Campus at the University of Kansas, was constructed in 2011 and is a multi-use facility designed to promote interdisciplinary research among faculty and graduate students, as well as to provide a place to hold conferences, meetings, and classes. The CDR contains various environmentally-friendly and energy-efficient features, including a living wall located in the north side of the conference room (as shown in Figure 2) that measures 12 ft. tall by 33 ft. wide. This organic vertical plant wall was designed using several types of fern. The purpose of the living wall is to help purify the air in the building. The wall is sustained using an irrigation system that operates on collected rainwater.

Figure 1: Center for Design Research (CDR), University of Kansas

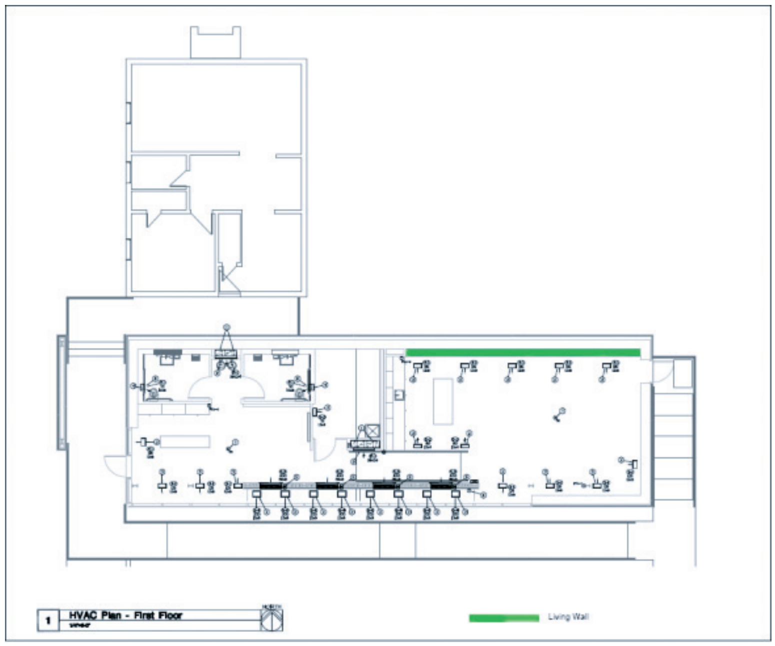

Figure 2: First floor plan of CDR illustrating location of living wall.

2.2. Data Collection

A computational fluid dynamics (CFD) program called FloVENT (FloVENT 9.3) was utilized to perform design simulations of the CDR. FloVENT models fluid and air flow and can also be used to measure the pollutant removal rate of an area over a period of time. FloVENT was used to measure the absorption rate of CO_2 by the living wall, as well as the CO_2 concentration levels throughout the CDR and near the return grilles.

2.3. Building Models

Another benefit of using FloVENT was that it allowed for the testing of the building under different building conditions without the need to make physical changes to the site. Therefore, the following models were designed in FloVENT:

Model 1 - The CDR without the living wall (which acted as a base case for the study)

Model 2 - The CDR with the living wall and mechanical system on

Model 3 - The CDR with the living wall and mechanical system off

Model 4 - The CDR with the return grilles placed behind the living wall (which acted as the experimental case in this study)

Three comparisons were done between these four models. First, Model 1 was compared to Model 2 to assess the role of living walls in removing CO_2 from the air. Model 2 was then compared with Model 3 to assess the role mechanical systems have on the living wall's ability in removing CO_2 from the air. Finally, Model 2 was compared to Model 4 to determine under which mechanical system configuration the living wall would provide the optimum reduction of CO_2 concentration levels in a building.

To model the CO_2 concentration rate in the building, people were added to the building models. Each of the people added were modeled as a cuboid to simulate the body with a heat source to simulate the head, and the heat source was given a source value representing CO_2 exhalation rates. The CO_2 exhalation rate of 1.833 X 10-5 kg/s was used, which was gathered from Dougan's study and converted from L/min (Dougan et al., 2004). As indicated below in Table 1, (ASHRAE 62.1-2007), the maximum occupancy of the conference room was 32 people, so 32 people were added in the conference room to each model.

The living wall was modeled as an enclosure with a heat source and volume region. The heat source was given a negative source value to represent the absorption rate of the living wall. This value was determined using the absorption rate from Birds Nest Fern based on results from Su and Lin's study (Su, Y.-M., & Lin, C.-H., 2013). The absorption rate of -1.1111 X 10-7 kg/m3*s was used for the study and was added to all models except for Model 1.

The supply and return system for Models 1-3 were designed as oriented in the construction documents (as shown in Figure 2). In the case of Model 4, the return grilles were placed behind the living walls. The size of the supply diffusers are shown below on Table 2. The supply diffusers S-3 and S-4 were not modeled because those diffusers were for the Trombe wall ventilation, which was not modeled in FloVENT. Airflow rates for S-1 and S-2 varied from 125 cfm to 135 cfm1. The return grilles were 36 in by 24 in; one was located in the back of the entry room between the restrooms and the other was located facing opposite the Trombe wall, near the entrance of the conference room. In Model 4, the return grilles were designed to be the size of the living wall and were placed behind the living wall.

2.4. Variables

Variables looked at in this study were: CO_2 concentration, local mean age of air (LMA), and speed of airflow.

2.4.1. CO_2 Concentration Rate

FloVENT allowed for the storage of contaminant types for the model simulations. CO_2 concentration rates were investigated in all three comparisons. The values of CO_2 concentration are given in kg of the pollutant per kg of air. To activate the storage of CO_2, the "Concentrations" options was activated from "PM Model > Modeling." CO_2 concentration was selected from the material library. One plane was designed for this research, at human head level (Y-axis plane at Y= 5.25 ft). CO_2 concentration rates were also investigated by the living wall (Z-axis, 1.0 ft) and the return grilles at the entry door and the conference room were gathered from the geometry tables in FloVENT. Values from this study ranged from 0 to 0.20 kg/kg.

2.4.2. LMA (Local Mean Age of Air)

One of the most common complaints in buildings is the lack of fresh air, which leads to the perception that the air inside is old and stuffy. LMA

VENTILATION CALCULATIONS - ASHRAE 62.1 - 2007 & I.M.C. 2009									
MECHANICAL VENTILATION									
SYSTEM	AREA	SQ. FT	CFM/ SQ. FT.	PEOPLE	CFM/ PERSON	REQD. VENT CFM	DESIGN VENT CFM	REQD. EXHST CFM	DESIGN EXHST. CFM
HP-1	CONFERENCE	510	0.06	32	5	191	194	0	-
	ENTRY/CORRIDORS	461	0.06	3	5	43	43	0	-
	RESTROOMS	112			0	0	0	140	140
	CATERING	162	0.18	2	7.5	44	45	0	160
	STORAGE	101	0.12	1	5	17	17	0	-
TOTALS		1346				295	299	140	300

Table 1: Ventilation calculations of the rooms in the CDR.

GRILLE, REGISTER, & DIFFUSER SCHEDULE							
MARK	MANUFACTURER	MODEL	SERVICE	FACE SIZE	NECK SIZE	DAMPER	NOTES
S-1	TITUS		SUPPLY	14X8	12X6	NO	
S-2	TITUS		SUPPLY	14X6	12X4	NO	
S-3	TITUS		SUPPLY	38X8	36X6	NO	
S-4	TITUS		SUPPLY	14X10	12X8	NO	
R-1	TITUS		RETURN	38X26	36X24	NO	
E-1	TITUS		EXHAUST	12X8	10X6	NO	
E-2	TITUS		EXHAUST	14X6	12X4	NO	

Table 2: Schedule of the supply diffusers, return grilles, and exhaust registers in the CDR.

calculates the average time taken for fresh air to reach a certain point in the room and is a good measure of the effectiveness of the ventilation system. Values of LMA are normally expressed in minutes, with low values indicating regions that receive a good fresh air supply and high values indicating regions that receive a poor fresh air supply. LMA values were investigated for the first and third comparisons. One plane was created for this research, at human head level (Y-axis, 5.25 ft). Values from this study ranged from 0-60 minutes.

2.4.3. Speed

Speed was investigated to look at the effect of the supply air on the CO_2 removal properties by the living wall. Speed also allowed for further investigation of the role of air flow speed in mixing CO_2 with the air. Thus, speed was investigated in all three comparisons. One plane was recorded for this research, at human head height (Y = 5.25 ft). Speed values from this study ranged from 0-10 ft/s.

3. RESULTS AND DISCUSSION

3.1. First Comparison (Model 1 vs. Model 2)

In the first comparison, the CO_2 concentration levels were lower in Model 2 by 56% (as shown in Figure 3 and Table 3). This confirms the living wall's ability to reduce CO_2 concentration levels in the CDR. Additionally, the results showed that CO_2 concentration levels were present by the living wall, having an average CO_2 concentration rate of 0.0105 kg/kg, confirming the living wall's ability to absorb CO_2. The amount of CO_2 taken in by the return grilles is also listed below in Table 3 and illustrates the return grilles' role in removing CO_2 from the air. Results showed that Model 2 was exhausting 45% and 47% less CO_2 back to the mechanical system in the entry room and conference room return grilles, respectively. This means that in Model 2, less CO_2 is being brought back into the recirculation system.

Further analysis showed that the average LMA was slightly higher in Model 2 (as shown in Table 4), not providing much information about the living wall's ability to produce fresh air. However, it should be noted that LMA values were more consistent in Model 2, whereas the LMA in Model 1 was slightly higher in certain areas in the conference room. This indicates that Model 2 was able to distribute fresh air throughout the building, and thus, the living wall may have played a role in this. A comparison of the air speed between both models shows that Model 2 produces similar air speeds to those of Model 1 (Table 5), with Model 2 having slightly higher air speeds by 1%. In Figure 5, Model 2 also shows more consistent air speeds in the conference room, which indicates that Model 2 provides more comfortable air for building occupants.

3.2. Second Comparison (Model 2 vs. Model 3)

Results from the second comparison showed that Model 3 had near-zero CO_2 concentration rates (as shown

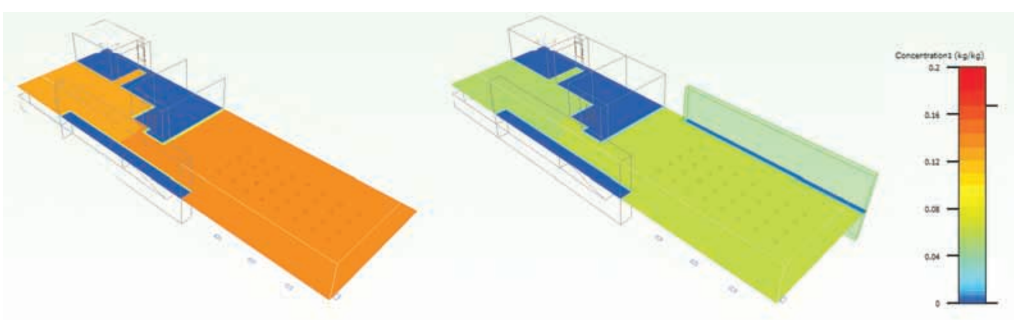

Figure 3: A comparison of CO_2 concentration between Model 1 (left) and Model 2 (right)

Average CO_2 Concentration Rates (kg/kg)			
	Model 1	Model 2	Difference
Y-Plane	0.114	0.0504	-55.8%
Living Wall	---	0.0105	---
Entry Room Return	0.10774	0.059045	-45.2%
Conference Room Return	0.10651	0.05688	-46.6%

Table 3: Quantitative comparison of CO_2 concentration between Model 1 (left) and Model 2 (right)

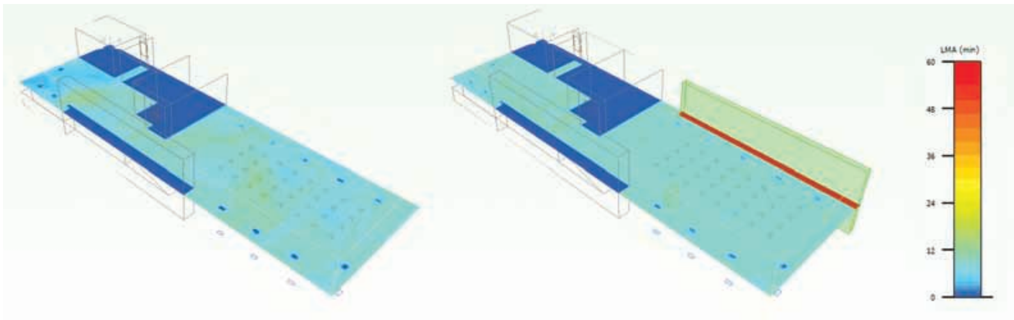

Figure 4: A comparison of LMA between Model 1 (left) and Model 2 (right)

Average LMA (min)		
Model 1	Model 2	Difference (%)
6.81	7.49	+2%

Table 4: Quantitative comparison of LMA between Model 1 (left) and Model 2 (right)

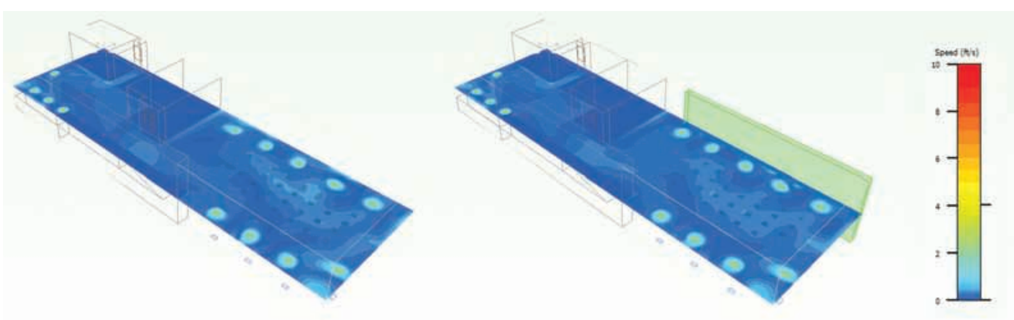

Figure 5: A comparison of wind speed between Model 1 (left) and Model 2 (right)

Average Wind Speed (ft/s)		
Model 1	Model 2	Difference (%)
0.162	0.163	+1%

Table 5: comparison of wind speed between Model 1 (left) and Model 2 (right)

in Figure 6 and Table 6). This may be because in Model 3, the mechanical system was not turned on, thus CO_2 was not being mixed with the air, which made it more effective for the living wall to absorb the CO_2 in the building. These results posed the question whether reduced airflow rates can increase the effectiveness of the living wall in reducing CO_2 concentration levels in the building. Since the speed in Model 3 was negligible (as shown in Table 8), these results could not prove whether this claim was true.

It should be noted that while the CO_2 concentration values around the return grilles were zero, this was because the supply air cfm was set to zero to simulate the mechanical system turned off; therefore, the return grilles were not returning air through the recirculation system.

In Model 2 the LMA is higher than the LMA in Model 3 (as shown in Figure 7). However, these results could not be compared side by side because LMA looks at the air being supplied into the building. Because Model 3 was not bringing in air, the LMA showed zero values (as shown in Table 7).

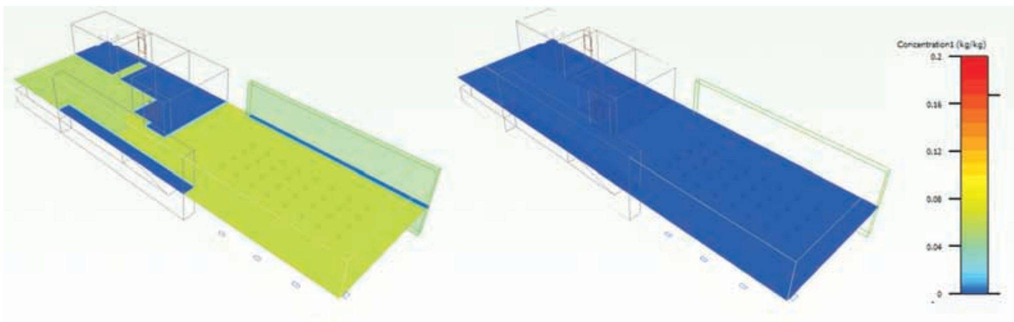

Figure 6: A comparison of CO_2 concentration between Model 2 (left) and Model 3 (right)

Average CO_2 Concentration Rates (kg/kg)			
	Model 2	Model 3	Difference
Y-Plane	0.0504	1 X 10-10	--~100%
Living Wall	0.0105	1 X 10-10	--~100%
Entry Room Return	0.05945	0	-100%
Conference Room Return	0.05688	0	-100%

Table 6: Quantitative comparison of CO_2 concentration between Model 2 (left) and Model 3 (right)

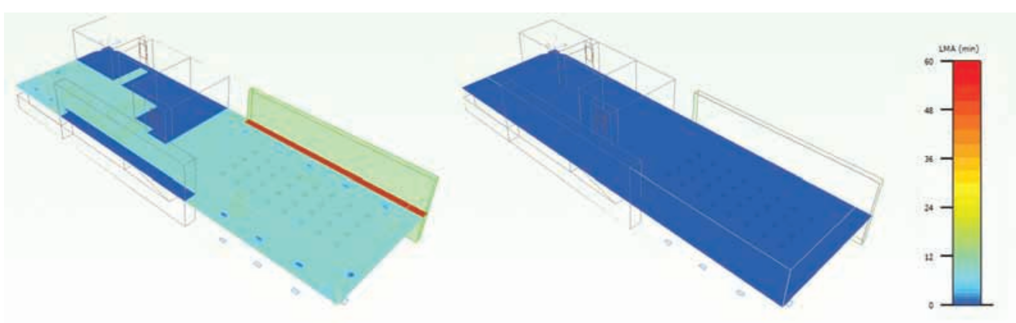

Figure 7: A comparison of LMA between Model 2(left) and Model 3 (right)

Average LMA (min)		
Model 2	Model 3	Difference
7.49	---	---

Table 7: Quantitative comparison of LMA between Model 2 (left) and Model 3 (right)

Average Wind Speed (ft/s)		
Model 2	Model 3	Difference (%)
0.163	---	---

Table 8: Quantitative comparison of wind speed between Model 2 (left) and Model 3 (right)

3.3. Third Comparison (Model 2 vs. Model 4)

In the final comparison, Model 4 produced results similar to Model 3 (as shown in Figure 8 and Table 9). The CO_2 values for Model 4 were lower than in Model 2 by 98%. This may be because of the proximity of the CO_2 source to the return grilles, which provide a deposit for CO_2 to leave the room. CO_2 concentration levels were also present in the living wall in Model 4, albeit having lower values than in Model 2. This may be because in Model 4, the air is quickly being returned to the return ducts from the supply diffuser. Also, the CO_2 concentration rates are listed below in Table 9. The reason for the low CO_2 concentration rates may be because of the size of the return grilles; since the return grilles were designed to be the size of the living wall; the CO_2 concentration rates would be lower. A test using different return grille sizes may further assess the role of the return grille size in removing CO_2 from the air.

LMA values were slightly lower in Model 4 than in Model 2, by 8%. It should also be noted that in Model 4, the LMA values near the living wall are zero, while areas further from the living wall are relatively higher. This may have been because the return grilles were very close to the supply

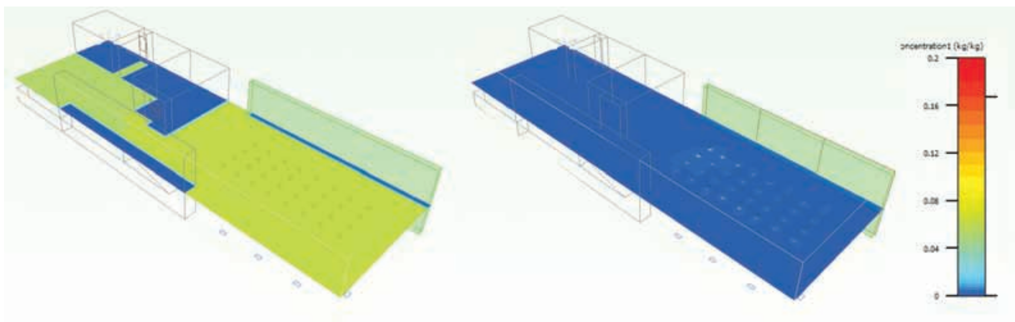

Figure 8: A comparison of CO_2 concentration between Model 2 (left) and Model 4 (right)

Average CO_2 Concentration Rates (kg/kg)			
	Model 2	Model 4	Difference
Y-Plane	0.0504	8.6 X 10-4	-98.3%
Living Wall	0.0105	4.65 X 10-4	-95.6%
Entry Room Return	0.059045	0	-100%
Conference Room Return	0.05688	0	-100%

Table 9: Quantitative comparison of CO_2 concentration between Model 2 (left) and Model 4 (right)

Average LMA (min)		
Model 2	Model 4	Difference
7.49	6.88	-8.1%

Table 10: Quantitative comparison of LMA between Model 2 (left) and Model 4 (right)

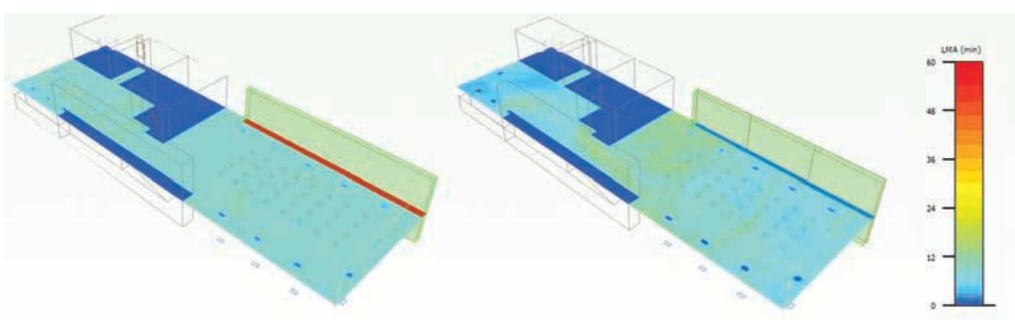

Figure 9: A comparison of LMA between Model 2 (left) and Model 4 (right)

diffusers, which meant fresh air was quickly being returned as soon as it was supplied to the room. This may also explain why certain areas in the conference room had a higher LMA.

An analysis of air speed between the two models shows that Model 2 provided a 4% higher air speed than Model 4 (as indicated in Table 11). Once again, the fact that the return grilles were placed behind the living wall may have been the reason for this.

This may indicate that a living wall system, in concert with a return grille system behind the living wall, may increase the productivity of the living wall, given the proper orientation of the supply diffusers and return grilles. Further analysis of the CDR under different return grille placements could provide a more accurate understanding of the role of return grille placement. Additionally, further study of the CDR under different supply grille placements can also provide a more accurate understanding of the role of supply diffuser placement.

4. CONCLUSION AND RECOMMENDATIONS

A case study of the CDR was done, using three building comparisons to assess the effectiveness of living walls in removing CO_2 from the indoor environment. The first comparison confirmed the living wall's ability to absorb CO_2. It also confirmed that the living wall helped reduce CO_2 concentration in the CDR by 56%, as well as providing more consistent fresh air throughout the building. Finally, it showed that less CO_2 was being returned into the recirculation system under the model of the CDR with the living wall. The second comparison poses the question that reduced airflow rates can increase the effectiveness of the living wall in reducing CO_2 concentration levels in the building. Further research using reduced airflow rates would have to be conducted to confirm the validity of this claim. The final comparison indicated that CO_2 concentration levels may be further reduced by living walls by installing return grilles behind the living wall. However, further research testing the placement of the supply diffusers and return grilles would have to be conducted to confirm this claim.

One of the limitations during the study was not having the proper equipment to conduct field measurements of the CO_2 concentration levels inside the building. Having this field data is valuable to the research as it would allow for the validation of the simulated models with actual measured data. Additionally, the case study would have been more valid with the determination of the exact absorption rate of the ferns in the living wall. This data can easily be gathered with a device such as a CO_2 sensor. Future study will be designed to resolve the aforementioned limitations.

5. ACKNOWLEDGEMENTS

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Average Wind Speed (ft/s)		
Model 2	Model 4	Difference
0.163	0.156	-4.3%

Table 11: Quantitative comparison of wind speed between Model 2 (left) and Model 4 (right)

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