The Modification of Buildings Based on the Mounds of Macrotermes for the Purposes of Thermoregulation and the Elimination of the Need for Modern Air Conditioning

Word Count: 4069

Abstract

The current way that the air conditioning of buildings is conducted is both overly expensive and harmful to the environment. Alternatives to modern air conditioning are not common, but one potential solution lies in the deserts of Zimbabwe. Macrotermes, a genus of termites found in this region, produce mounds that thermoregulate independently. The Eastgate Centre, a building in Zimbabwe, was designed to imitate this process and function without modern AC. The goal of this research is to find a way apply the same techniques to buildings that already exist. To test the potential of this, a scale model building with an added chimney and fans (similar to the Eastgate Centre) was compared to a similar model without modifications when exposed to a heat lamp that was representative of the sun. The temperatures at each level of each building were recorded over a number of trials with the light facing eight different sides of the building for five minutes. The differences in temperature between room temperature and the temperature after the light exposure were calculated and showed that, on average, the modified building resulted in a smaller difference than the control building. The mean for the modified building was 4.2583°C, while the mean for the modified building was 5.075℃. An ANOVA was run on the data that verified the design's promise and, therefore, suggested that it deserves further investigation, perhaps on a larger scale.

Introduction

There is a genus of the family Termitidae native to Africa and Southeast Asia called *Macrotermes*. Within this genus are numerous different species. For the purposes of this study, the focus will be on *Macrotermes natalensis*, *Macrotermes subhyalinus*, *Macrotermes vintrialatus*, *and Macrotermes michaelseni*. These four species are found throughout northern Namibia which is in southern Africa. The leading researcher in these termites is Dr. J. Scott Turner, a professor of biology at the University of New York College of Environmental Science and Forestry. In his study "Architecture and morphogenesis in the mound of Macrotermes michaelseni (Sjöstedt) (Isoptera: Termitidae,Macrotermitinae) in northern Namibia", Turner details his research in Namibia relating to the four termite species previously mentioned (Turner, 2000). He discovered that the mounds of these Macrotermitinae are found at a density of one to four per hectare throughout southern Africa.

Within the genus of *Macrotermes*, Turner found particular interest in the mounds of the *Macrotermes michaelseni*. These mounds have unique features, distinguishing them from those of the other species. The features worth noting include the spherical space below the mound, reserved for the queen, workers, and fungus garden, and the tunnel network in the mound, responsible for promoting the circular flow of air. As a whole, these mounds behave as if they were constructed for the regulation of the colony environment, conditions such as temperature, humidity, and concentration of gases, rather than for the habitation of the termite colonies themselves. Differing from *Macrotermes michaelseni*, the mounds of the species *Macrotermes natalensis*, *Macrotermes subhyalinus*, and *Macrotermes vintrialatus* contain large circular openings at the top connected to vertical chimneys. These chimneys are the basis of the induced flow model.

In a separate study, "On the Mound of *Macrotermes michaelseni* as an Organ of Respiratory Gas Exchange", Turner further develops the idea of this species' mounds being designed to regulate the internal environment. The research conducted for this article focused primarily on the interaction between the termite mounds and the internal and external gases rather than the physical characteristics and internal structural mappings. He claims that the mound is "simply the most visible component of a structure that extends well below the ground" (Turner, 2001). Prior to this study, there was an incorrect understanding of the means of gas exchange within the mounds of the *Macrotermes michaelseni*. It was believed that the mound could be classified by the thermosiphon model. Within this model, buoyant forces are deemed responsible for the circulation of air through the nest and surface tunnels. The colonies supposedly have a high metabolic rate, capable of producing hundreds of watts, and, therefore, heat. Resultingly, air would be heated and humidified, causing it to lose density and rise to the surface.

This thermosiphon style ventilation is actually found to be completely unsubstantial, based on the data Turner collected using tracer gases to analyze the rates and patterns of gas movement within the mounds. In reality, the gas exchange of the mounds is induced by the complex interaction between the kinetic energy in the wind, the metabolic convection in the nest, and the overall architecture of the mound, tunnels, and nest within. The ventilation movements of the mound are more tidal than they are circulatory, meaning they are driven by wind speeds and directions.

According to Jeremy Smith, an editor of *The Ecologist* with a Ph.D. in geography, these termites require "a constant temperature of 30.5°C" in order to survive (2007). But the temperatures of the region in which they inhabit can vary from 1.7°C to 40°C, so the mounds the termites construct are capable of both diffusing and restoring significant quantities of heat (2007). This need for precise temperature has been studied by Judith Korb, a professor of evolutionary biology & ecology at the University of Freiburg. She determined that the need is derived from many species of Macrotermes' "ectosymbiotic relationship with basidiomycete fungi of the genus Termitomyces" (Korb, 2003). This symbiosis is maintained through the termites' capabilities to thermoregulate their mounds and produce the optimal temperature for fungus growth. Korb's research also revealed that the mounds only fluctuate less 2°C on average, despite any outside temperature fluctuations (2003).

It is the regulatory complexities within the termite mounds that inspired architect Mick Pearce while designing the Eastgate Centre, a shopping center in Harare, Zimbabwe. Pearce found particular interest in the "termites' use of the thermal capacity of the ground and the mound, and their labyrinths of ventilation tunnels", according to Environmental Health Perspectives and Massachusetts Institute of Technology writer, Richard Dahl, in his article "Cooling Concepts: Alternatives to Air Conditioning for a Warm World" (Dahl, 2013). Using the model of the termite mound as a guide, Pearce was able to design the Eastgate Centre in such a way that it operates without the usage of traditional air conditioning.

This building relies on the concept of night flushing. At night, cool air is driven through tunnels in the concrete structure, so that it can cool the concrete ceiling that absorbs heat all throughout the day. The heat absorbed during the day travels through the same tunnels by means of fans and convection forces in the numerous chimneys found in the center of the building.

Dr. Turner, along which fellow researcher Rupert C. Soar, the Director of Freeform Construction Ltd and the Termes Trust in Namibia, and a lecturer at the University of Greenwich School of architecture and construction, argue that the Eastgate Centre is not as much like a termite mound as Pearce had perhaps thought. In their article "Beyond biomimicry: What termites can tell us about realizing the living building", the two claim that Pearce based his building on a dated conception of the inner workings of *Macrotermes* mounds (Soar and Turner, 2008). The only comparable feature between that the Eastgate Centre contains is the large stacks, resembling the large vents atop termite mounds of *Macrotermes natalensis*, *Macrotermes subhyalinus*, and *Macrotermes vintrialatus*. This portion of the building is based on the induced flow model. According to Turner and Soar, Pearce failed in his attempt to recreate the thermosiphon model, which is now rejected by most scientists in the field. In his attempt, Pearce had to turn to low capacity fans during the day and high capacity fans at night for ventilation.

But despite the difference from the original structure of termite mounds, Pearce's method proved to be ultimately successful. He was able to design the Eastgate Centre in a way that allows it to now function using merely "10% of the energy of comparably sized air-conditioned buildings in Harare" (Dahl, 2013). However, the process of dialing in on the exact thermoregulation requirements for the building took three years to reach their most optimized and efficient point. This had to do with the conditions and preferences of the occupants and the machinery within. And all that time spent and information gathered is only applicable to this specific building. Turner and Dahl speculate that some sort of living building will become the future for sustainable architecture, but, ultimately, this will also have to be something that is specific to singular buildings, and must be designed into them.

The purpose of this research is to find a simpler means to transform buildings that already exist into something that functions in a way similar to the Eastgate Centre and be capable of thermoregulation at a small fraction of the energy that it used prior. The complex elements of design worked into the Eastgate Centre make it nearly impossible to replicate the termite mound thermoregulation system in the same way for preexisting buildings. That is why an easily adaptable methodology is required in order to create an effective, yet inexpensive modification that can be applied to essentially any standing skyscraper. The new design will evaluated on the following categories: effectivity compared to Eastgate Centre and complexity of application.

Note. The extent of research conducted on termites of this genus and their mounds, while extremely thorough, is limited by a small number of researchers. This has resulted in a relatively minimal sampling of perspectives on the inner functioning of such mounds. This paper has attempted to maximize available information and include all seemingly substantiated viewpoints to construct a synthesized conception of these termites and their mounds.

Method

For the purposes of this research, it is necessary to construct a scaled down model of the proposed modified building to run sufficient tests to determine its effectivity. Although preferable, the utilization of a full sized building is completely impractical given the scope of this project. So instead, a small scale model will suffice as a basis to conclude upon whether or not the design is deserving of further testing or if it requires modifications.

The tests being conducted are comprised of temperature recording and analysis of the scaled modified building. This is one of the methods used by Turner in his study of termite mounds in the article "On the Mound of Macrotermes michaelseni as an Organ of Respiratory Gas Exchange". By utilizing similar methods to those conducted in mound research, the successful application of the techniques of termites can be better measured, as they have been proven to be the most successful. The temperature data from the experimental building model must be compared to that of a similarly constructed control building without any modifications. In order to accurately predict the effects of the modifications in a full sized building, the models must be exposed to directed heat, simulating the sun.

It was believed that by imitating the induced flow technique of termite mounds, a similar cooling effect could be established in preexisting buildings without any majorly intrusive renovations. The induced flow model makes use of a chimney that runs through the center of the mound, connecting to the inner tunnels, to channel hot air out. The Eastgate Centre relies on similar chimneys, serving the same purpose. This leads to the conclusion that the role of a chimney is crucial to the operation of a termite-styled thermoregulation system. Since the creation of a central chimney in buildings that have already been constructed would require a great amount of demolition and remove a major portion of the space in the building, having the chimney attached to the side of the building is a more productive alternative. Another seemingly essential component of the induced flow model in termite mounds is the ability to harness wind to force hot air to be vented out of the chimney. On a larger scale, wind becomes relatively insignificant compared to the massive size of a building. That is why the Eastgate Centre made use of fans to simulate wind and drive air through the chimney, to be expelled out the top. Fans must also be utilized for the modification of a preexisting building for the same reason. These two elements together, should be able to produce a lower internal temperature for a scaled building when compared to an equally scaled building without the modifications.

Acrylic glass, one-eighth of an inch in thickness, has been used to fabricate the models. This plastic, made out of polymethyl methacrylate acid, is beneficial as it has "exceptional weatherability, strength, clarity and versatility" (Plaskolite, 2017). This material was most fitting for this project because it allows for easy viewing of the thermometers and is relatively easy to cut. Both the experimental and control are 30cm in height and 15cm in width (with the exception of the chimney on the experimental model which adds an additional 5cm to one side) and comprised of three stories. Having three stories will provide a sufficient base of understanding of how the temperature differ from an upper to a middle to a lower level. The individual pieces of cut acrylic glass have been sealed together using a hot adhesive to ensure that the system is airtight in the manner outlined in a computer drafted model made prior to construction (Fig. 1). The dimensions and specifications for the cut pieces are as follows: Seven 30cm x 15cm rectangles, eight 15cm x 15cm rectangles, three 5cm x 5cm rectangles, one 15cm x 5cm rectangle, three 10cm x 1cm rectangles, one 35cm x 15cm rectangle with two 30cm x 5cm rectangles cut from inside (forming the largest wall of the chimney), one 30cm x 15cm rectangle with three 1cm x 5cm rectangles cut from inside (forming the wall flush to the chimney).

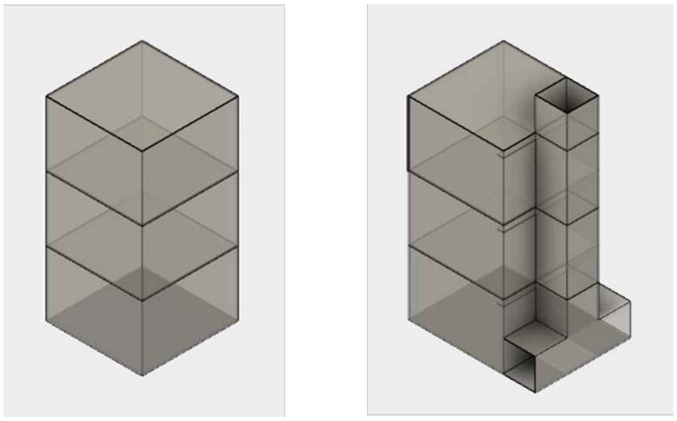

Figure 1. Computer-aided drawing developed using Autodesk Fusion 360 software

Glass thermometers were placed on the inside of each level. The building models were subject to a heat lamp 35cm away, angled down at 45° below horizontal, and with the bottom of the bulb at the same height as and facing the model. After five minutes of constant exposure, the temperature was recorded from each thermometer. This was then repeated twice for a total of three trials. Then the building was rotated 45° clockwise (Fig. 2) and the temperature was recorded three times. This was repeated for a total of eight distinct positions and an overall total of 24 trials for each building.

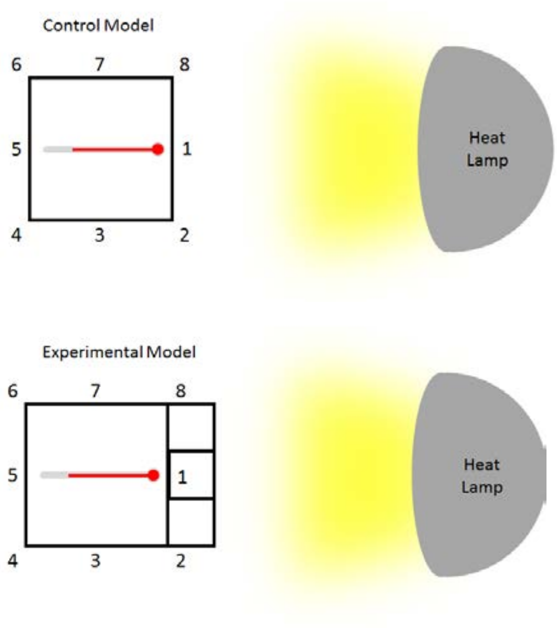

Figure 2. Diagram showing numbering used throughout tests to identify which side is facing the heat lamp for a specific trial.

Results

Table 1. Temperature per thermometer at varying positions for control building, after five minutes of light exposure

	Trial 1			Trial 2			Trial 3		
Position	Thermometer A (°C)	Thermometer B (°C)	Thermometer C (°C)	Thermometer A (°C)	Thermometer B (°C)	Thermometer C (°C)	Thermometer A (°C)	Thermometer B (°C)	Thermometer C (°C)
1	25.8	23.9	26.1	26.2	25.4	25.7	26.1	25.8	27.8
2	26	24.2	25.9	24.7	23.8	26	25.2	23.7	23.3
3	25	24.1	26.1	23.9	23.1	24.5	26	24.9	27.5
4	23.4	22.2	24.2	23.1	22	23.9	24.7	23.1	25.4
5	23.9	22.7	24	23.6	22.4	23.8	24.1	23.5	24.9
6	23.1	22.3	24.2	24	23.3	24.7	24.1	23.6	25.7
7	24	24	25.5	24.1	24.2	26.4	24.2	23.8	26.5
8	24.4	23.8	26.4	25.3	24.9	25	25	24.6	26.7

Table 2. Temperature per thermometer at varying positions for modified building, after five minutes of light exposure

Position	Trial 1			Trial 2			Trial 3		
	Thermometer A (°C)	Thermometer B (°C)	Thermometer C (°C)	Thermometer A (°C)	Thermometer B (°C)	Thermometer C (°C)	Thermometer A (°C)	Thermometer B (°C)	Thermometer C (°C)
1	26.1	24.5	25.8	26.5	26	26.1	24.9	25.2	26.2
2	26	24.5	24.3	26	25.5	25.5	25.5	25.6	25.7
3	25.5	25.2	25.6	26.2	26.3	26.5	25	25.7	26.6
4	24.8	23.9	24.1	23.9	23.1	24	24.4	23.7	25.1
5	23.9	23.7	23.5	24.2	24	25.3	23.5	22.8	22
6	23.8	23.8	24	24.3	24.2	25.1	23.6	23.5	25.1
7	24.1	24.1	24.2	25	25.5	26.1	23	23.1	24.9
8	25.5	24.3	24.1	24.3	25	24.7	24.1	23.9	24.5

Note. Thermometer lettering corresponds to the level of the building the thermometer is on with A being on the top floor, B being on the middle floor, and C being on the bottom floor.

The raw data collected from the thermometers showed no clear trends or correlations. The temperature seemed to vary relatively significantly but randomly based on the two variables shown here. During testing however, it was noticed some of the thermometers were displaying different temperatures than the 20°C when they were supposed to be at room temperature. To fix this calibration error, the actual temperatures displayed at room temperature for each thermometer were subtracted from the temperatures after the exposure, resulting in the adjusted data set.

Table 3. Adjusted change in temperature per thermometer at varying positions for control building, after five minutes of light exposure

Position	Trial 1			Trial 2			Trial 3		
	Thermometer A (°C)	Thermometer B (°C)	Thermometer C (°C)	Thermometer A (°C)	Thermometer B (°C)	Thermometer C (°C)	Thermometer A (°C)	Thermometer B (°C)	Thermometer C (°C)
1	5.966666667	6.466666667	5.466666667	6.366666667	7.966666667	5.766666667	4.766666667	7.166666667	5.866666667
2	5.866666667	6.466666667	3.966666667	5.866666667	7.466666667	5.166666667	5.366666667	7.566666667	5.366666667
3	5.366666667	7.166666667	5.266666667	6.066666667	8.266666667	6.166666667	4.866666667	7.666666667	6.266666667
4	4.666666667	5.866666667	3.766666667	3.766666667	5.066666667	3.666666667	4.266666667	5.666666667	4.766666667
5	3.766666667	5.666666667	3.166666667	4.066666667	5.966666667	4.966666667	3.366666667	4.766666667	1.666666667
6	3.666666667	5.766666667	3.666666667	4.166666667	6.166666667	4.766666667	3.466666667	5.466666667	4.766666667
7	3.966666667	6.066666667	3.866666667	4.866666667	7.466666667	5.766666667	2.866666667	5.066666667	4.566666667
8	5.366666667	6.266666667	3.766666667	4.166666667	6.966666667	4.366666667	3.966666667	5.866666667	4.166666667

Table 4. Adjusted change in temperature per thermometer at varying positions for modified building, after five minutes of light exposure

Position	Trial 1			Trial 2			Trial 3		
	Thermometer A (°C)	Thermometer B (°C)	Thermometer C (°C)	Thermometer A (°C)	Thermometer B (°C)	Thermometer C (°C)	Thermometer A (°C)	Thermometer B (°C)	Thermometer C (°C)
1	5.066666667	4.766666667	4.866666667	5.466666667	6.266666667	5.166666667	3.866666667	5.466666667	5.266666667
2	4.966666667	4.766666667	3.366666667	4.966666667	5.766666667	4.566666667	4.466666667	5.866666667	4.766666667
3	4.466666667	5.466666667	4.666666667	5.166666667	6.566666667	5.566666667	3.966666667	5.966666667	5.666666667
4	3.766666667	4.166666667	3.166666667	2.866666667	3.366666667	3.066666667	3.366666667	3.966666667	4.166666667
5	2.866666667	3.966666667	2.566666667	3.166666667	4.266666667	4.366666667	2.466666667	3.066666667	1.066666667
6	2.766666667	4.066666667	3.066666667	3.266666667	4.466666667	4.166666667	2.566666667	3.766666667	4.166666667
7	3.066666667	4.366666667	3.266666667	3.966666667	5.766666667	5.166666667	1.966666667	3.366666667	3.966666667
8	4.466666667	4.566666667	3.166666667	3.266666667	5.266666667	3.766666667	3.066666667	4.166666667	3.566666667

Note. When the measurement bias caused by the thermometers is factored out, the true effect of the modifications to the building can be determined. The data can then be categorized based on the variables of the experiment: position and thermometer location.

Table 5. Mean change in temperature for control and modified buildings, after five minutes of light exposure, based on building position

Position	Control Mean (°C)	Modified Mean (°C)
1	5.659259259	5.133333333
2	5.525925926	4.833333333
3	5.981481481	5.277777778
4	4.525925926	3.544444444
5	4.525925926	3.088888889
6	4.792592593	3.588888889
7	5.214814815	3.877777778
8	5.414814815	3.922222222

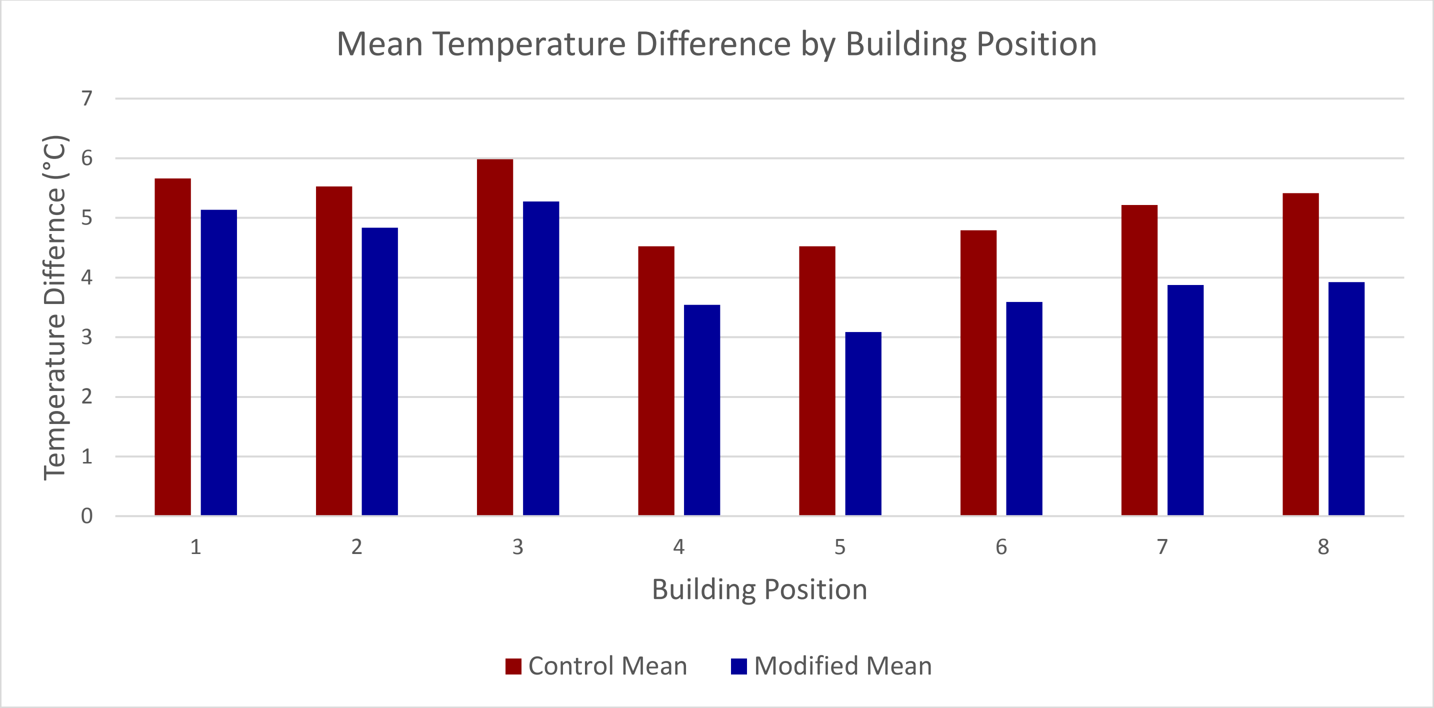

Figure 3. Mean change in temperature for control and modified buildings, after five minutes of light exposure, based on building position

With the exception of the statistics from position 3, the graph shows a decrease in the value of the mean temperature difference for both the control and experimental buildings from position 1 to position 5, and then an increase from position 5 to position 8. This observation is expected based on the nature of the thermometers being used to test. The relative distance between the light and the bulb of the thermometer has a noticeable effect on the temperature after light exposure. The mean temperatures at position 5 were the lowest, as the bulb was furthest away from the heat lamp at this position. The mean temperatures at position 1 were the highest (again excluding position 3), as the bulb was closest to the heat lamp at this position. The means at position 3, while not qualifying as statistical outliers, are most likely due to testing variability. It does seem out of the ordinary that both the control mean and modified mean would both be higher than expected on the same position, but there were no observable outside factors that could have led to this abnormality, so it must be due to uncontrollable variation within the testing.

Table 6. Mean change in temperature for control and modified buildings, after five minutes of light exposure, based on thermometer location

Thermometer	Control Mean (°C)	Modified Mean (°C)
A	4.62083333	3.72083333
B	6.42916667	4.7292
C	4.56527778	4.025

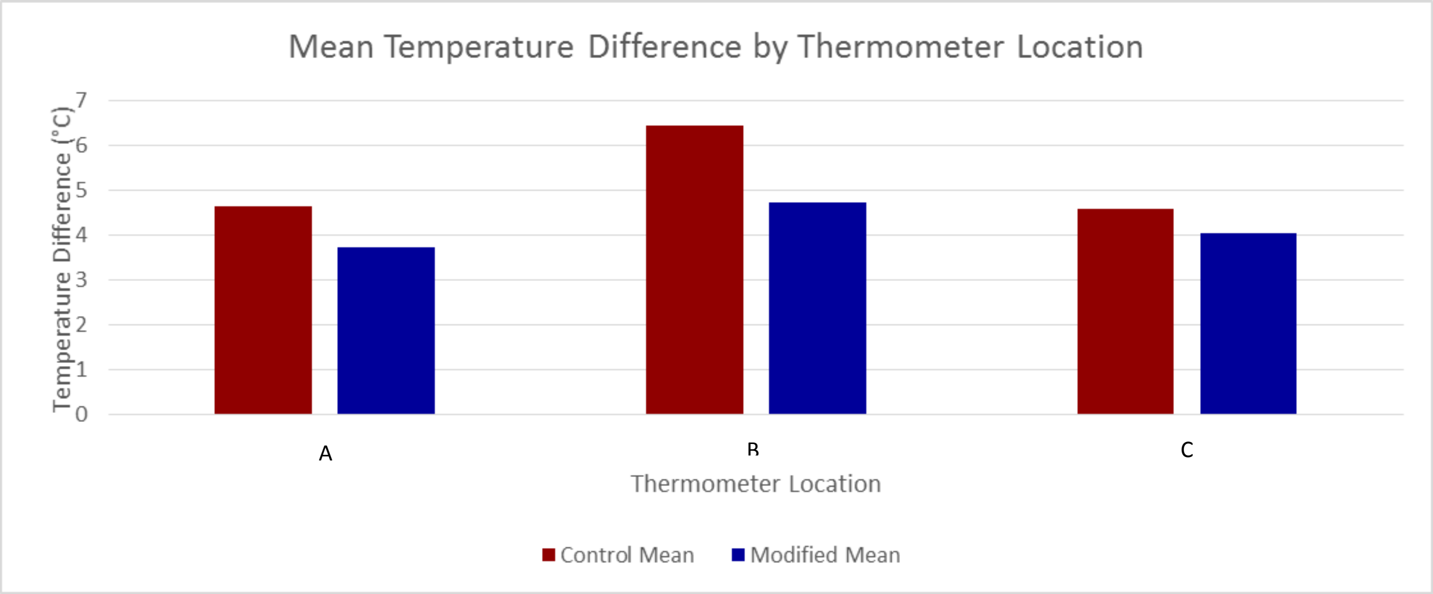

Figure 4. Mean change in temperature for control and modified buildings, after five minutes of light exposure, based on building position

It is clear, based on the graph of mean temperature difference and thermometer location (Fig. 4), that the thermometers in the middle of the model buildings experienced higher temperatures on average. The control building had a mean of roughly 6.429°C for temperatures recorded at thermometer B, while having significantly lower means of roughly 4.621°C and 4.565°C for thermometers A and C respectively. The modified building displayed a similar trend, just with a smaller discrepancy between the means. For thermometer B, the mean was roughly 4.729°C, while for thermometers A and C, the means were only roughly 3.721°C and 4.025°C respectively. This trend is most likely due to the height and angle of the heat lamp relative to the models. The lamp was angled such that the center of the bulb is pointing directly at the center of the middle floor of the building. This caused the thermometers in location B to receive be most affected by the lamp, explaining the previously stated trend. It would seem logical that the data from thermometer A would be consistently higher than that of thermometer C, as thermometer A, although not directly aligned with the center of the bulb like thermometer B, is the closest thermometer to the heat lamp. But this is only the case for the control mean. The modified mean for thermometer C proved to be unexpectedly higher than that of thermometer A. This result is speculatively due to the nearly undetectable heat produced by the fans. Although quantity of heat is miniscule, the close proximity between the fans and the wall of the lowest floor might have resulted in the discontinuity between the control and the modified model's trends.

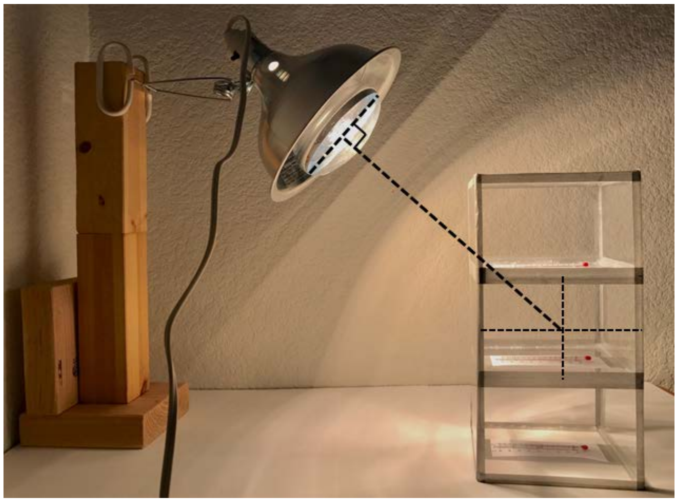

Figure 5. Photograph of control model testing apparatus with indication of light bulb direction

Table 7. Mean and standard deviation change in temperature for unadjusted and adjusted data of control and modified building models, after five minutes of light exposure

Data Set	Mean (°C)		Standard Deviation (°C)	
	Control	Modified	Control	Modified
Unadjusted Data	24.575	24.725	1.249873233	1.020321684
Adjusted Data	5.075	4.258333333	1.175518319	0.987805836

The unadjusted data set means for the entirety of the data collected showed a very slight difference between the control and modified building models, with the modified being higher. This means that the thermometers in the modified building recorded higher temperatures on average than those of the control building after being exposed to the heat lamp. The difference between these values was only 0.15°C. However, with the improper calibration of the thermometers factored out in the adjusted data set, there is a seemingly more significant difference between the means of the two models. The control model had a mean temperature difference of 5.075°C, while the modified had a mean temperature difference of 4.2583°C. The difference between these two means is much larger and more significant than that of the unadjusted data set, at 0.8167°C. The modified model also had a lower standard deviation of 1.0862°C than that of the control model, which was 1.1541°C.

Table 8. Results of 8x2x3 factorial ANOVA to determine statistical significance

Tests of Between-Subjects Effects					
Dependent Variable:	Result				
Source	**Type III Sum of Squares**	**df**	**Mean Square**	**F**	**Sig.**
Corrected Model	154.420a	47	3.286	5.822	0.000
Intercept	3069.164	1	3069.164	5438.165	0.000
Condition	30.250	1	30.250	53.599	0.000
Position	74.693	7	10.670	18.907	0.000
Thermometer	30.620	2	15.310	27.127	0.000
Condition * Position	8.228	7	1.175	2.083	0.053
Condition * Thermometer	0.732	2	0.366	0.648	0.525
Position * Thermometer	8.860	14	0.633	1.121	0.350
Condition * Position * Thermometer	1.037	14	0.074	0.131	1.000
Error	54.180	96	0.564		
Total	3277.764	144			
Corrected Total	208.600	143			
a. R Squared = .740 (Adjusted R Squared = .613)					

An 8x2x3 factorial analysis of variance was run on the adjusted data set to determine if the modified building showed statistically significant differentiation from the control building. The ANOVA results showed statistically significant main effects of condition, position, and thermometer as p≤.0005 for all of these variables. However, there were no significant interaction effects.

Conclusion

Based on the results of the ANOVA, it can be stated that the modified building's temperature was lower than the control building's temperature and this difference was statistically significant. This means that the attempt to design a model that reduced the need for modern air conditioning in a building was successful and the original design criteria were met. The design was also relatively simple, as only minimal construction would be required to remove small portions of the outer walls and to add a chimney and fans. So based on the scope of this research, the design was successful. The extent to which the design is successful in a real-world scenario is uncertain however, as a less than one degree Celsius difference was obtained, which is not enough from a practical perspective. Modern air conditionings allow for major temperature reduction from outside conditions, so the modifications being developed must be able to produce similar results if they are to be implemented. There is also the issue of the scale model’s translation to an actual building. There is a certain amount of unpredictability that comes with this translation, as there is no way to account for numerous factors, including wind, building insulation, humidity, heat convection, etc.

In order to broaden the relative reduction in temperature with the modification, in an attempt to provide a safeguard against these incalculable effects, future testing is required. By no means has the optimally simple yet effective solution been developed, but there are several ways to achieve results closer to such a goal. It would first be beneficial to make improvements to the testing method, to make the small-scale simulations more realistic.

Only a total of eight unique positions were tested in this experiment. A real building would have to be effective against the sun in every possible location. While it would be both inefficient and nearly impossible to test this fully, a broader range of positions should be used to create a more comprehensive idea of how the building will function at any given location relative to the sun.

If more floors were added to the scale model, it would become possible to assess the strength of the loss of cooling as height increased. This unavoidable phenomena cannot be fully measure based on just three floors, but is necessary, as the end goal is to devise a design effective on buildings ranging in size from one story buildings to skyscrapers. Most buildings also contain more than one room per floor. So the scale model should also be divided into rooms to see how wall partitions effect the distribution of temperature.

Given the difficulties encountered due to the improper calibration of the thermometers, a more precise measuring instrument should be used to obtain more exact results. Digital thermometers would be an ideal substitute, as they are not only more precise, but also make data collection easier for the researcher. In addition to that, digital thermometers can be made smaller than glass thermometers so more could be placed throughout each floor. This would allow for a more inclusive vision of how the temperature differs based on the location within the floor. This data would allow for the determination of weak spots within the floors, where temperature is significantly higher. Then a means could be developed by which the location could be cooled.

Logically, based on the design created, the greater the distance is from the chimney, the warmer the temperature should be. The Eastgate Centre utilizes a technique to eliminate this issue that was omitted from the design in this research so that it would more sufficiently meet the simplicity criteria set forth at the start. Underneath each floor of the shopping center is a channel system that draws the cool air from the chimney into the floor so that the hot air may leave through the openings in the top of the floors. The chimney is also divided into two sections, a cool sector that the air flows out of and a warm sector that the air flows in to. This division allows for more efficient management of heat through the separation of the air by temperature to prevent excess heat diffusion. The complexity of this design must be weighed in comparison to the reduction of the temperature that follows. The tradeoff between complexity and effectivity is crucial and a balance must be maintained when attempting to implement these more technical design elements.

While the design was effective from a cooling perspective, the heating capabilities of the design must also be eventually taken into account. Obviously, most buildings utilize air conditioning to both cool and heat the rooms, based on the season. This is not as much of an issue for the Eastgate Centre, as it is located in the tropical climate of Zimbabwe, where temperatures remain relatively hot year-round. But in order for the design to be considered effective in all parts of the world, heating techniques must be first explored and developed.

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