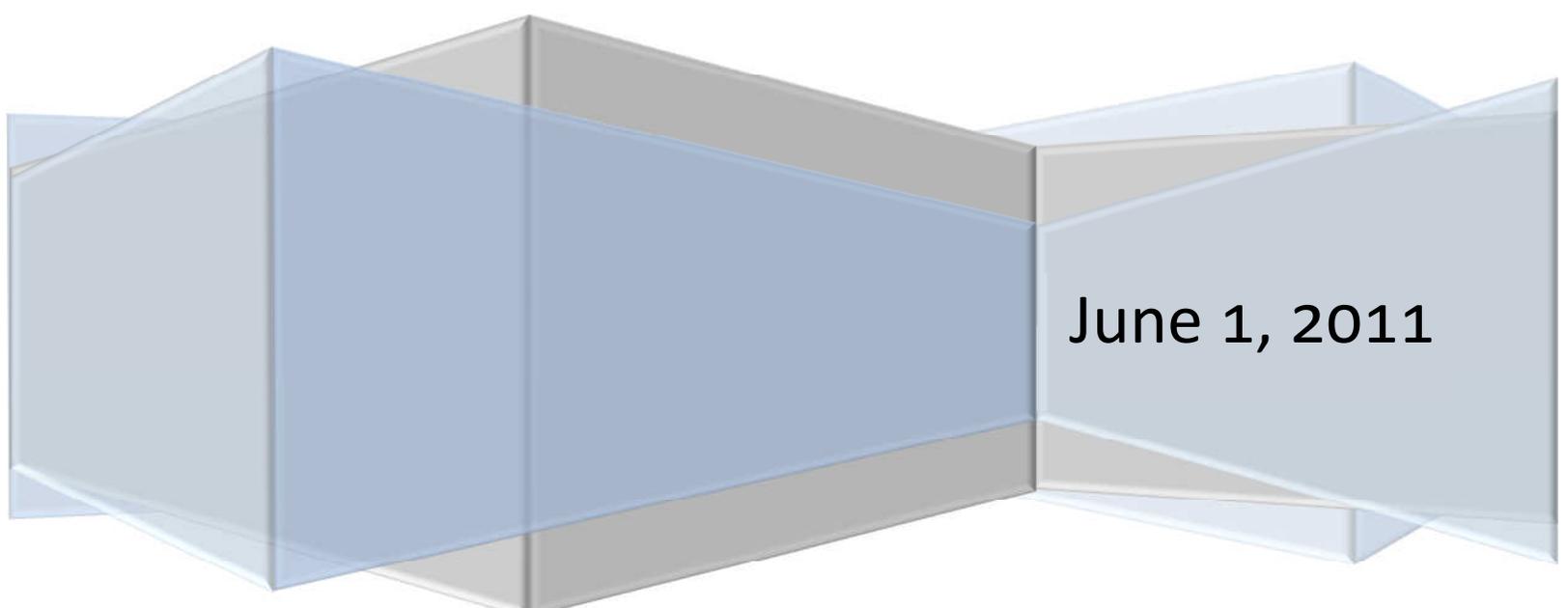# The Bronze Craft Corporation

Case Study – Bronze Craft Engineering Office

Energy Savings, Ambient Conditions, & Outside Influences of the Bronze Craft Engineering Office Across Multiple Micro Climates

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June 1, 2011

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Executive Summary

This study shows that by integrating the Smart Window Sensors' data into an automation system helped balance the temperature and humidity distribution throughout an enclosed environment and increase occupant comfort. Smart Window Sensor (SWS) units were installed on all operable windows in the Bronze Craft Engineering office. The SWS units reported the light, temperature, and humidity at each window. In addition to the units mounted on the windows, three units were mounted around the interior of the office space to gather readings and provide an accurate average for all of the microclimates within the office space. The Smart Window Sensors in conjunction with an automation program, automated HVAC thermostat, and an additional automated air circulator improved the ambient conditions of the office space.

The Smart Window Sensors allowed the impact of the largest source of temperature change in the office, the windows, to be quantified and therefore compensated for by an automation system. The effects of solar gain and thermal gain/loss were quantified and reduced. Specifically, the temperature variation across the room was reduced from 12.5 degrees to 5.4 degrees.

The influence of sunlight at the windows was measured and the lux level of the SWS units automatically controlled the overhead lighting to meet or exceed OSHA lighting level standards by turning unnecessary lighting off/on as required. As a result of the SWS data and the automation program controlling the lighting, an energy savings of 44% was achieved.

Introduction

Background

Founded in 1944, Bronze Craft is a leader in the commercial window hardware market and has focused its hardware designs around the commercial market's requirements. In the past decade, there has been an increasing interest in energy efficient building design within the architectural community. With this in mind, Bronze Craft has developed many window automation systems that utilize electric motors to remotely open and close windows. Having completed many commercial designs utilizing window automation, Bronze Craft switched focus to developing a sensor system dedicated to the real time measurement of ambient conditions directly at the windows.

The result of this product development is the Smart Window Sensor (SWS). The SWS unit is a wireless, solar powered, ZigBee enabled device that measures ambient light, temperature, humidity, the open or closed position of the window, and the locked or unlocked state of the window hardware. These specific measurements were selected due to our experience in the industry and understanding of aluminum windows used in commercial building construction.

Windows affect the lighting, temperature, and humidity of a room and can even influence these conditions so much that they make the room occupants uncomfortable in terms of excessive lighting, uneven temperature distribution, and pockets of humid air. The Bronze Craft Engineering office presented these same ambient condition issues. Therefore, the office space was chosen for this study.

Purpose

The goal of this specific case study was to quantify the performance of the Smart Window Sensors (SWS) in the Bronze Craft Engineering office. The office was outfitted with a basic automation system that would monitor, report, and react to the ambient light, temperature, and humidity readings of the SWS units in order to control and balance the ambient conditions across the 8 microclimates found in the office space.

Analysis of the human comfort levels of the occupants across the office space resulted in a few conclusions:

- Uneven temperature distribution – most notably during sunny days

- Workspaces located near the windows are exceedingly hot
- Workspaces away from the widows are exceedingly cold
- Uneven humidity distribution
  - Areas of the office feel more uncomfortable than others

Speculation of the possible causes of these temperature and humidity problems led to a few hypothesizes of the root cause of the issues:

- Solar gain
- Thermal gain (and loss)
- Poor HVAC setup/control
  - Single point temperature monitoring at thermostat controller
- Poor air circulation
  - No additional air circulation other than HVAC ducts
  - Circulation only when HVAC is actively cooling

In addition to these observances, it seems evident that the overhead lighting located near the windows is redundant when the sun is bright. All the overhead lighting is always kept on during working hours because the interior workspaces throughout the office do not get enough lighting even when the sun is bright at the windows.

Proposal

By creating a multi sensor network based upon the SWS technology, the data sampled from across all microclimates can be utilized to create a better picture of the office space. In conjunction with an integrated room automation system, the SWS units will improve the ambient conditions and therefore increase the occupants' comfort levels across all microclimates.

The primary SWS readings will measure the main influence of change, the windows. A handful of secondary sensors will quantify the distribution of ambient conditions across the interior (away from the windows) of the room. The SWS data will give a more complete picture of the microclimate variations in the office space. The data will then be utilized to identify indoor climate variation and develop plans to reduce variation across the office.

Scope

This case study reflects data gathered between April 11, 2011 and May 27, 2011 in Nashua, NH. The data recorded is specific only to this date, time, and weather. The exact measurements of any ambient conditions that are directly related to weather and time of year would be difficult to repeat consistently. However, generalizations can be made based upon reoccurring trends recorded across this sample period. The results of this study reflect only the conditions of this specific office space, but the implication of the findings can be directly related to other similar office space environments.

A few factors were not included in this analysis because their affect was considered to be minor compared to the other more major issues. A few items that were considered, but not included in the analysis:

- Thermal loss to interior walls
- Heat generated by occupants
- Heat generated by computers and electronics
- Temperature/humidity changes due to the opening and closing of doors
- Supplemental desk lighting for precision detailed work

Office Space Layout

The site of this case study was the Bronze Craft Engineering office. This area is a typical office space filled with desks, computers, tables, and other office environment objects. The basic layout of the office can be seen in Figure 1. The specifics of the area are detailed in the list below:

- Office Space Setup
  - Fully enclosed office space
  - Office area footprint of 712 ft^2
  - 7 cubicles and 1 meeting space
  - Office Air Volume of 6764 ft^3
  - 5 window banks with 13 operable windows (locations noted in Figure 1)
    - 10 windows facing south
    - 3 windows facing east
  - Window surface area of 163 ft^2
  - 1 HVAC system for the office space (details noted in Figure 1)
    - 3 Duct vents
    - 1 Air return
    - 1 programmable thermostat controller
  - 2 lighting zones/switches to control room lighting (locations noted in Figure 2)
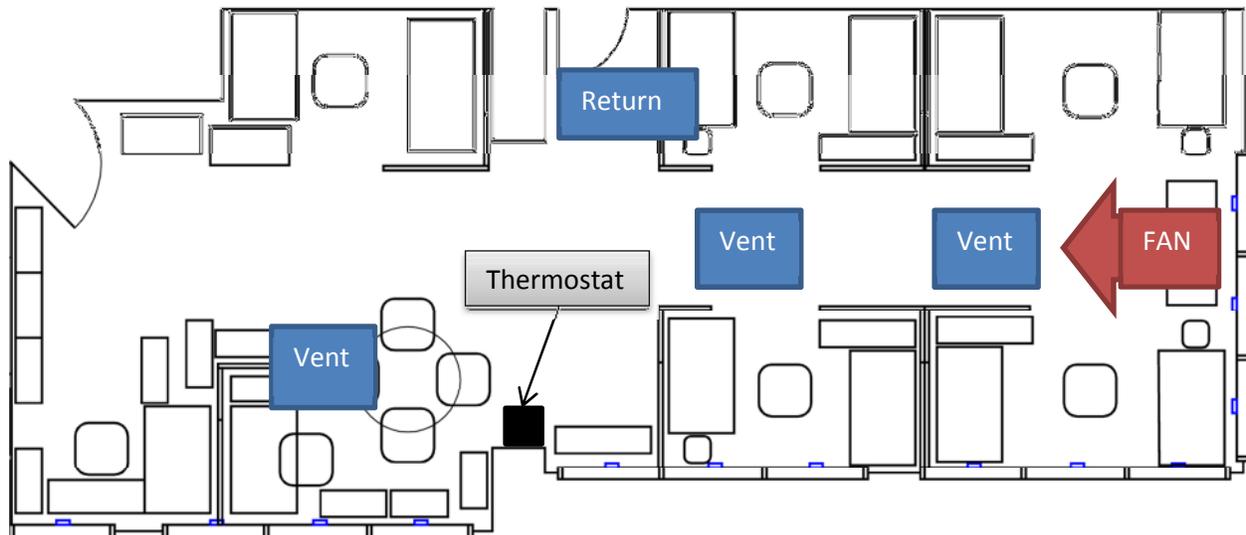   - 12 florescent light banks – each bank with 4 bulbs

Figure 1 – Engineering Office Space Furniture Layout & HVAC Details
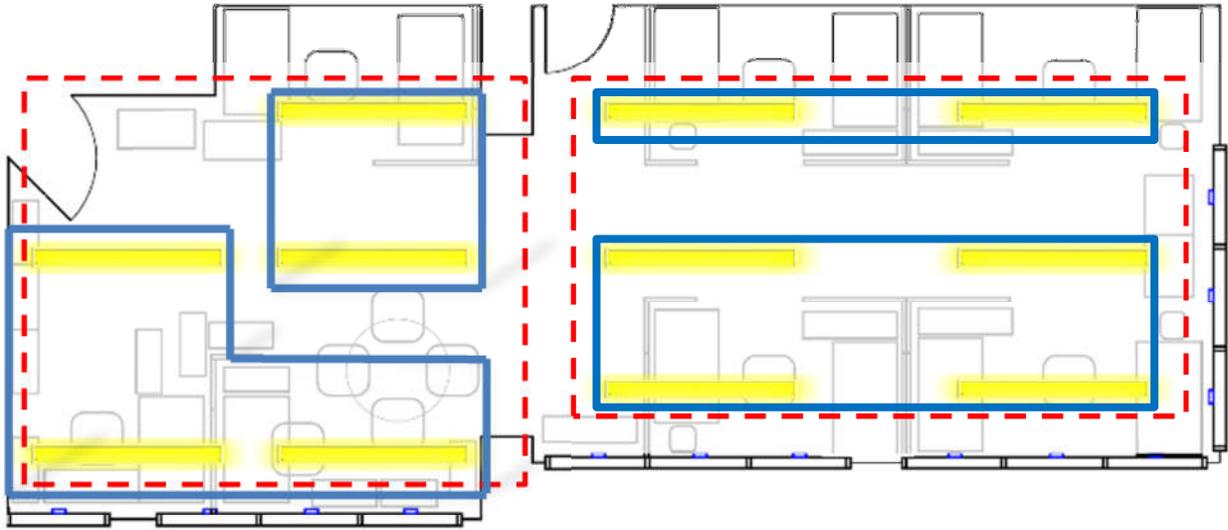**Note: Fan added after baseline data was gathered.**

Figure 2 – Engineering Office Lighting Fixture Locations – Shown in Yellow
Lighting Zones: Pre-existing shown in Dashed Red Lines & Modified shown in Solid Blue Lines

The office space was setup with 16 of the Smart Window Sensor units. Each of the 13 operable windows was retrofitted with a SWS unit and smart hardware for security integration. The units were mounted at the head of the hopper style windows at approximately 4 feet Above Finished Flooring (AFF). Two additional sensors were placed in the interior of the room at locations noted to be problematic by the room occupants. These interior SWS units were mounted at approximately 3 feet AFF to more accurately report conditions at the sitting height of the occupants. The existing programmable thermostat was replaced with a ZigBee enabled thermostat integrated with a SWS module. This thermostat SWS module was located at a height of approximately 5 feet AFF. The locations of all of these sensors are noted in Figure 3.

Figure 3 – Engineering Office Smart Window Sensors Locations

Baseline Measured Conditions

In addition to the 16 SWS units, 2 power meters were added in line to the wiring for the overhead lighting units. Digi Smart Plugs were also placed to divide and control the lighting into 4 independently controlled sections, as noted in Figure 2. The 4 lighting zones were divided based upon their proximity to the windows. Workspaces located without any direct access to the windows were separated from the workspaces located next to the windows.

After the SWS units were installed on all 13 operable windows and 3 interior locations, data was gathered over a period of a few weeks. The existing programmable thermostat was left in place to continue controlling the HVAC system and no changes were made to the overhead lighting controls. The sensors recorded data on light, temperature, humidity, and window access.

Temperature Issues

A sample of the measured temperature gradient is shown in Figure 4, with all temperatures given in degrees Fahrenheit. For this example, the weather was bright and sunny with a high temperature of 55 degrees. The data shown in Figure 4 is from a collection time of 11 AM.
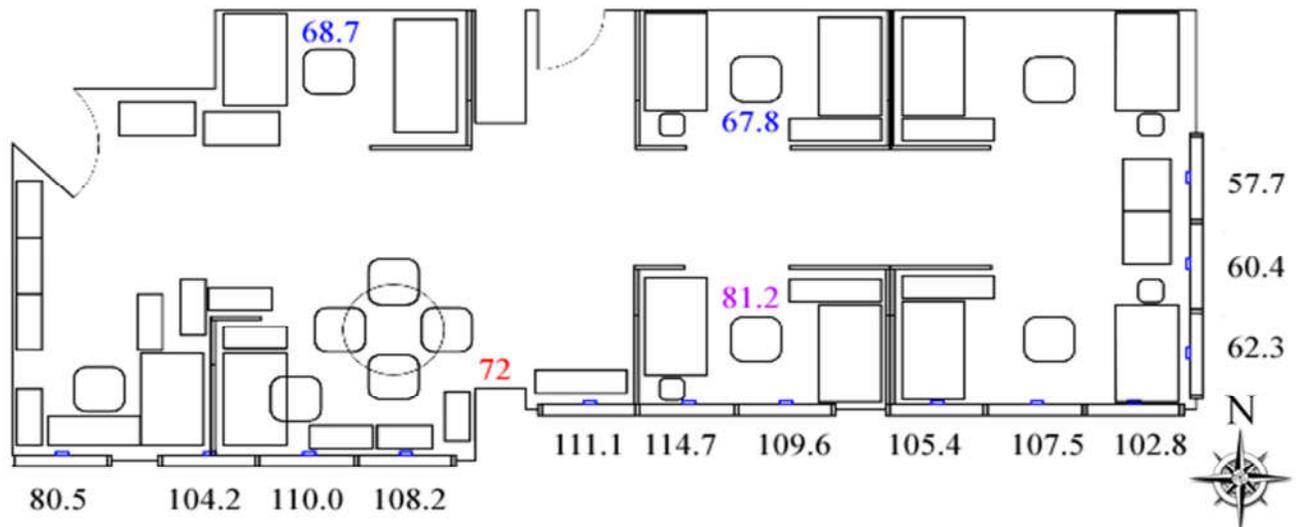

Figure 4 – Example of Baseline Temperature Measurements Showing Temperature Gradient

The data shown in black numbers is the data from the SWS units mounted to the window frames and represent the thermal/solar gain at the windows. Analyzing just this window temperature

data demonstrates the direct effect of the sun on these windows. It is evident that the sun is brightly shining on the southern exposure as the temperature of these windows is well above 100 degrees. These windows were experiencing a large solar gain. It is important to further note that the lower left window shows a temperature below the other southerly windows. This lower temperature reading is most likely due to the fact that there is a large shrub that partially blocks this window on the exterior of the building.

The easterly facing windows, on the right side of Figure 4, show a very different temperature reading of over 50 degrees cooler than the other windows. The readings of these windows are only slightly above the external ambient temperature. These easterly windows were no longer in any direct sunlight and were in fact below the average internal temperature of the room. These windows were actually generating a thermal loss for the room.

In addition to the 13 window mounted SWS units, 4 other temperature readings were recorded at various locations across the interior of the room. These additional readings further demonstrated the temperature gradient in the office space. For example, in Figure 4, 3 readings were taken at varying distances from the window. Directly at the window, the temperature was measured by the SWS unit at around 110 degrees. Only 4 feet away from the window, the temperature was measured at 81.2 degrees by a supplemental handheld temperature sensor. In addition, at a total of 12 feet away from the window, the temperature was measured at 67.8 degrees. The temperature gradient caused by the windows is obvious here.

This temperature gradient problem was further exacerbated by the location of the HVAC ducts located in this area. The vents in this area, see Figure 1, direct their airflow in all directions. However, the resulting airflow from these ducts at sitting height was noticeable by the interior workspace occupants whom felt that the vents were blowing directly at their workspaces. And conversely, the occupants of the window area workspaces reported that the airflow of the ducts was not noticeable. Through these observations, it appears that the airflow across this section of the office was not evenly distributed.

The programmable room thermostat was set to maintain a temperature between 70 and 74 degrees. In this example, Figure 4 shows, in red, that the thermostat was actually showing a temperature of 72 degrees, within the optimal temperature range of the program. However, the room occupants reported regularly having to manually override the thermostat settings due to the

uncomfortable temperature levels. Further analysis showed that programmed temperature levels were not changed during fair weather, but during hot and cold weather extremes (above 80 and below 60) the controls were manually overridden frequently. During hot weather, occupants with window proximal workspaces regularly felt hot and turned the HVAC system on to a cooler setting than the existing program. Meanwhile, the interior workspace occupants were felt too cold when the AC was on and had to override the system to turn off. This temperature gradient resulted in a constant battle for HVAC control between the occupants located near and away from the windows.

Humidity Issues

The sample data capture, shown in Figure 5, displays the SWS units' relative humidity levels captured at around 10 AM on a sunny day. The data shows that the levels across the windows range around 6% with a few areas that act as humidity pockets. The humidity levels across the interior of the office are much higher than the levels at the windows. Also, there are workspaces with much higher humidity pockets as compared to both the windows and the rest of the workspaces.
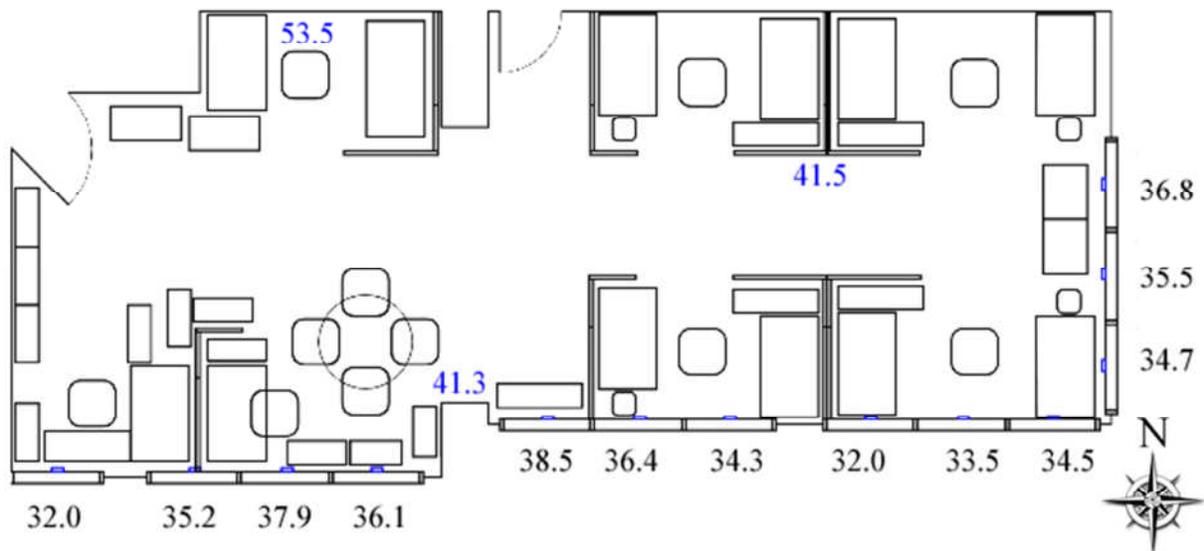

Figure 5 – Sample Humidity Distribution

It is important to note that the humidity levels are definitely affected by the outside air. On several occasions, office occupants opened a window. The data shown in Figure 6 shows a sample data capture of the humidity levels with an open window. On this day, the weather was overcast and rainy.

The humidity distribution can be seen as a bell curve with the peak of humidity levels at the open window itself, labeled with the 65.2 % relative humidity level.

Figure 6 –Humidity Distribution – With an Open Window

Lighting Issues

A simple time study was done on overhead lighting usage for the room. The lighting was turned on at the beginning of each workday, typically between 7:30 – 8 AM. Then the lights were turned off at the end of each workday, typically between 5–5:30 PM. The overhead lights were found to be on for around 10 hours each day. The overhead lighting was also only controlled by 2 manually operated light switches. Occasionally it was found that the lights were accidentally left on overnight.

The inline power meters found that the overhead lighting drew around 11.5 amps of current with all overhead lighting on. This current draw extrapolates out to around 13.9 kilowatt-hours (KWH) used for a typical work day with 10 hours of overhead light usage.

The governing standard for office workspace lighting levels is the Occupational Safety & Health Administration (OSHA) 1926.56(a) standard. In summary, the standard states that offices must have a minimum illumination intensity of 30 foot-candles which is equivalent to around 323 lux. The light level readings must also be taken at a height of 36" AFF. Utilizing this standard, measurements were taken, in lux, at each of the 8 workspaces in this office space, Figure 7. The lux measured at the windows, from the sun, averaged 5000 Lux during this data collection period.

Figure 7 – Lux Levels at all 8 workspaces
Blue: All overhead lighting on.   Red: All overhead lighting off

Applying the OSHA 1929.56(a) lighting standard, it is evident that with the overhead lighting on, the light levels at each workspace greatly exceed the minimum lighting level of 323 lux. With all of the overhead lighting off, the impact of the exterior lighting is most evident. The light levels across the interior workspaces fall far below the minimum level for the standard. However, the workspaces immediately adjacent to the windows meet and exceed the minimum of the lighting standard.

Baseline Data Conclusion

The baseline data gathered quantifies the perceived problems with temperature, humidity, and lighting. The perceived temperature gradient across the office space can be traced back to the solar gain, thermal gain, and thermal losses caused by the windows. Any improvements to the temperature distribution across the office space would need to consider the SWS unit's data when controlling the HVAC system. Additionally, it is evident that the impact of the windows on the room temperature must be quantified as well in order for proper HVAC distribution.

The humidity levels appeared to be impacted by several main factors. The first factor is that the positioning of the office furniture seems to prevent the existing HVAC from circulating the air around the room evenly. The second is that any open window will greatly impact the humidity levels of the room. Also, it is very important to note the relationship between humidity and temperature. As the temperature rises, the humidity level decreases when exposed to direct sunlight. The humidity pockets

in the office space can be eliminated by generating better air and HVAC circulation throughout the room. Window access must be controlled or compensated for in the HVAC.

When the sunlight is bright, it is evident that the workspaces near the windows do not require additional lighting. The overhead lighting could be turned off in these instances, but the interior workspaces are not illuminated to adequate levels by the sunlight and still require the overhead lighting to remain on. If new zones are created, the SWS light readings can be then utilized to adjust the overhead lighting nearest to the windows to reduce wasted energy.

Sensor Integration & Room Automation

Modifications to Existing Office Systems

The programmable thermostat was replaced with a custom thermostat controlled by an SWS unit for remote control and automation.

A simple fan was added to the room to act as an additional air circulator. This fan was connected to a smart power control powered by an SWS unit for remote control and automation. The fan was then able to circulate air even when the HVAC system was off. Also the position of the air circulator was able to be relocated for maximum air circulation and experimentation.

The wiring for the overhead lighting was modified to allow 4 Digi Smart Plugs to control the room in 4 distinct lighting zones, see Figure 2. The smart plugs allow remote and automated control of these 4 zones. The overhead lighting was divided to separate the lighting over the workspaces near the windows from the lighting of the workspaces at the interior of the office space.

Room Automation Software

Custom automation software was created to control the HVAC, air circulator, and 4 lighting zones. The function of the software was to gather the SWS units' light, temperature, and humidity data and process it to provide optimal occupant comfort levels. The software also processed the time and day to determine when to turn the room systems on or off based upon the office workday schedule.

For the thermostat controls, the software averaged the 3 interior mounted SWS unit's temperatures and used this 3 point average to generate a more accurate average temperature level for the office. This temperature data was then compared to the human comfort range chart that is based upon humidity level as well as temperature. The upper and lower bounds for the HVAC program was setup using this human comfort level chart. Slight modifications were made to these program temperature limits to compensate for the specifics of the office space. This tweaking was achieved through simple experimentation and occupant feedback.

The software also averaged the temperature of the SWS units mounted on the windows. Then this average window temperature was used to compute the amount of radiant heat being given off by the windows. For this calculation, a radiant heat formula was derived using the thermal capacity of air, the emissivity factor of glass, the Stefan-Boltzmann Constant, the room volume, the total window surface area, and radiating energy formula. This formula relates the temperature of the windows, as measured by the SWS units, to the average room temperature, as measured by the interior located SWS units.

The software computed the results of this radiant heat calculation in degrees per minute. For example, with an average SWS window temperature reading of 110 degrees and an average interior office temperature of 72 degrees, the software determined that the temperature of the office interior was being increased by the windows at a rate of 0.84 degrees per minute. However, if the SWS window temperature average was only 80 degrees, then the software would calculate the radiant temperature increase to be only 0.16 degrees per minute. The software would then override the fan control to circulate the air to help minimize the office temperature gradient (as seen in Figure 4) caused by the windows when a specific radiant threshold was hit.

The software controlled the air circulator fan based upon the temperature level. The on/off threshold was set to the midpoint of the HVAC comfort range. This allowed the air of the room to be better circulated once the temperature levels increased past the midpoint of the comfort range and continue circulating until the HVAC turned on and lowered the temperature below midpoint of the comfort range.

For the lighting, the software took the average light values of the windows nearest the 2 window light zones. Once a threshold was met, these window light zones were set to turn off while the interior lighting remained on during normal working hours.

Results of SWS Integration & Automation

Lighting Levels

  The software utilized the SWS lighting level data to control the lighting based upon a threshold of 5000 lux. The lux levels of each workspace were measured once above this threshold level. For this example, the lighting as measured at the windows was around 7500 lux. The window proximal lighting zones (see Figure 2) were turned off while the interior lighting zones were on. The lux levels at each of the workspaces were all measured well above the OSHA 323 lux lighting standards, see Figure 8.
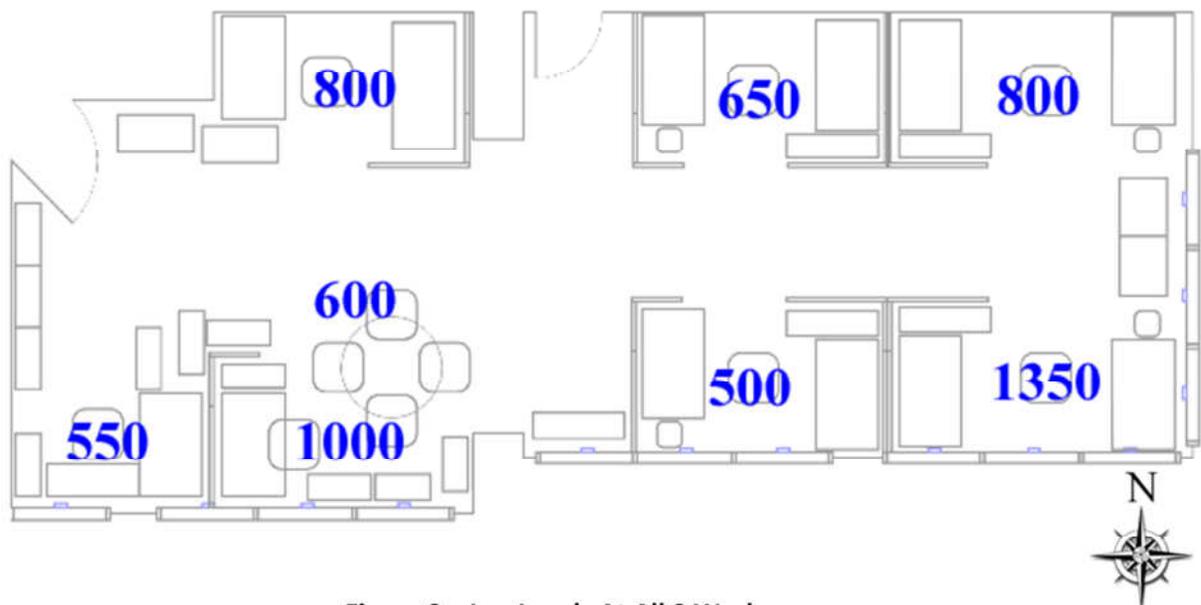
Figure 8 – **Lux Levels At All 8 Workspaces**
Interior Overhead Lighting On, Window Adjacent Lighting Off

Lighting Power Savings

  During this sample period, the window lighting was automatically turned off at around 10 AM during sunny weather. The window zone lighting was able to remain off for a large portion of the day. On average, the lighting turned back on around 2 PM. The inline power meters were used to find the average power used during these sunny days. Using the same parameters of lighting on from 7:30 AM to 5:30 PM, the SWS lighting automation used around 7.8 kilowatt-hours (KWH). Comparing this to the baseline power usage of 13.9 KWH, an energy savings of 44% was shown to be possible.

Temperature & Humidity Balance

Utilizing the window mounted SWS unit's temperature readings did reduce the occupant perceived effect of the window thermal gain. The temperature distribution of the office space was better balanced across the office space and the occupants did report an improvement in their comfort levels. However, the gradient across the office was not eliminated. The temperature distribution across the office dropped from 12.5 degrees (Figure 4) to 5.4 degrees (Figure 9). The change in the perceived temperature gradient seems to be directly related to the air circulator's role in moving the air around the room. Though not quantified directly, the HVAC system appeared, through observation, to run for shorter periods and stay off for longer periods. Further evaluation of the HVAC runtime is recommended (see the Recommendations section for further analysis) as no true conclusion can be made on possible energy savings at this time.
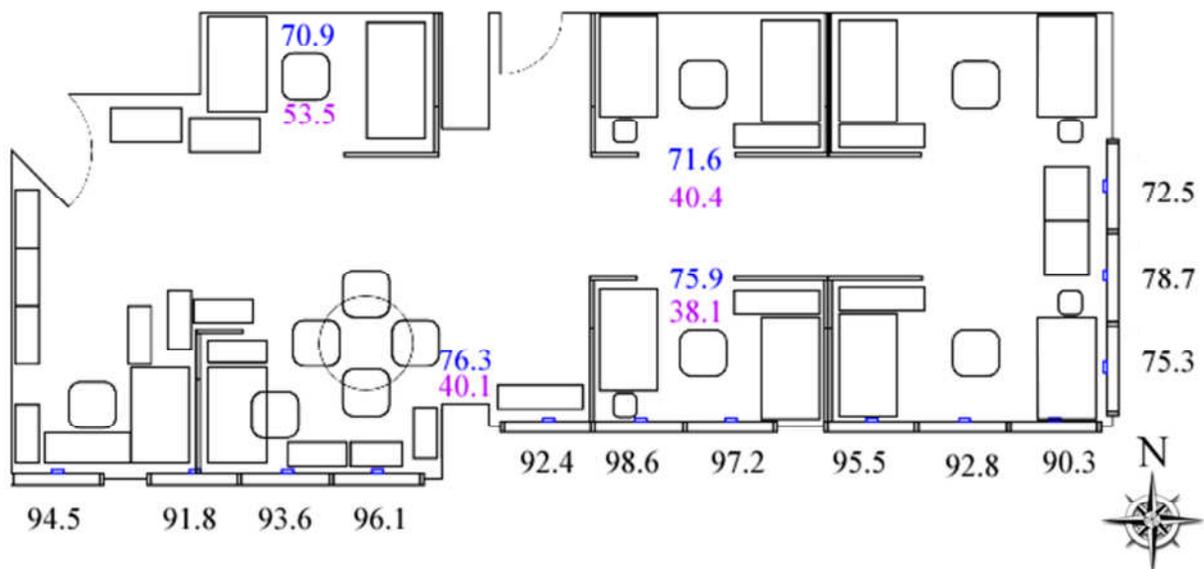

Figure 9 – Temperature and Humidity Distribution Across the Office Space
Black: Window Temperature.   Blue: Interior Temperature.   Purple: Interior Humidity

Recommendations

The SWS units showed that when real time data is used properly, vast improvements can be made to the ambient conditions of a room. However, there are several other changes that were not made, but identified for further evaluation during the course of this case study.

1. The HVAC runtime seemed to have changed, but the exact on/off time was never monitored. Measuring the exact runtime and the power usage of the HVAC could show massive savings. The addition of a low power fan to act as an air circulator vastly improved room conditions and delayed the start of the HVAC saving energy and money. Adding simply inline power meters to the HVAC and fan would allow the benefits of the air circulator to be quantified in KWH.

2. During work hours, the automated lighting would turn on and off. The occupants directly under the affected lighting reported that they were surprised and startled by the sudden changes in lighting. Integrating dimmable lighting ballasts would reduce the visible effects of the lighting changes.

3. The inverse relationship between temperature and humidity was observed throughout this case study. Also, the effect of sunlight on temperature, and therefore humidity, played a major role in influencing the ambient conditions. However, the lux level was never directly related to the humidity levels. Integrating the lux levels into the HVAC automation programming could help reduce the need for extra air circulation used to prevent the formation of humidity pockets. Further experimentation and analysis of this relationship is recommended.

4. The single fan has proven to be effective at circulating the air and helping distribute the HVAC. However, adding additional air circulators dedicated to respond to high radiant energy levels would help window proximal workspaces cool down and at the same time have less impact on the interior workspaces if aimed properly.

5. The thermostat settings of the automation program were set to meet the human comfort range and the adjusted to help compensate for any broad temperature gradients in the office space. However, more research and experimentation is required. During days where the temperature was cooler outside than inside, the occupant perceived temperature felt too cold. Conversely, on extremely hot days the occupant perceived temperature felt too hot. Logically, hot days will require more HVAC to maintain the optimal interior temperature levels. If the outside temperature was integrated, the automation program could compensate for these extremely hot days by adding additional air

circulation or redirecting HVAC airflow through dampers. This exterior temperature change could then help the occupant comfort levels be more consistent across a larger range of weather.

6. A few pockets of humid air still exit around the office. However adding extra air circulators as previously mentioned should alleviate this issue.

Conclusion

The integration of the Smart Window Sensor units into the Bronze Craft Engineering office greatly improved the ambient conditions, occupant comfort, and energy usage. The Smart Window Sensors proved that thermal gains or losses at the office windows have the largest influence on ambient room conditions. The SWS units allowed the largest influence on ambient conditions, the windows, to be closely monitored by the automation program. Using this window data and combining with the data from the interior mounted sensors, the temperature gradient, humidity balance, and lighting levels of the room were improved. The temperature gradient across the room was reduced from 12.5 degrees to 5.4 degrees and the pockets of high humidity were dissipated.

The influence of sunlight at the windows was measured, quantified, and applied to both increase comfort and save energy. As a result of the SWS data and the automation program, an energy savings of 44% was achieved for lighting. Applying this energy savings across an entire building can lead to a large energy and therefore monetary savings.

The Smart Window Sensors in conjunction with an automation program, automated HVAC thermostat, and an additional automated air circulator improved the ambient conditions of the office space. Overall, this study shows that by integrating the Smart Window Sensor data into an automation system can help balance temperature and humidity distribution throughout an enclosed environment and increase occupant comfort. Increasing the occupants comfort levels led to less discomfort due to temperature and humidity and, though not quantified, could have also led to increased work productivity.

Further utilizing the Smart Window Sensor data could even make it possible to predict and preemptively respond to outside influences like thermal gain or the opening of the windows before the effects are felt by the occupants. The benefits of the Smart Window Sensors are evident. The only limit to the potential of the SWS units is how effectively the data is utilized by the automation programming.