Energy-saving strategies for luminaire level lighting controls

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Executive summary

The Lighting Research Center at Rensselaer Polytechnic Institute (LRC) conducted a study to determine how various parameters affect the energy savings from luminaire-level lighting controls (LLLCs), also called luminaire-integrated controls, in an open office setting. The investigated parameters were:

1. The field of view of the built-in motion sensor.
2. The delay time between when the last occupancy is detected and when the luminaire is turned off or dimmed.
3. The number of luminaires that turn on and off together in groups.
4. If the luminaires dim to a low level or turn off completely when no motion is detected.

Laboratory measurements were made of five LLLC motion sensors that were commercially available in 2015 and 2016 to determine the field of view of each when detecting medium motion. Field measurements were made in a 47.5m x 19.5m (156ft x 64ft) open office with a 2.6m (8ft 7in) high drop ceiling that included 60 occupied cubicles. A photometric simulation was conducted to determine a simulated layout of 2ft x 4ft LED troffers that would provide an average illuminance of 323lx (30fc) on the work plane. At each location in the open office where a troffer would be in the simulated lighting layout, two data loggers with motion sensors, one with a wide field of view and one with a restricted field of view, recorded the occupancy over two days. The recorded data was used in a custom Matlab program to determine when each luminaire in a simulated installation of would be on, dimmed, or off over the two days, and total energy use was calculated. Twenty-one simulations were conducted to determine how energy use varied with changes in the four investigated parameters.

The results illustrated that LLLCs have significant energy savings potential in open offices; the average energy use of the 21 simulations represented a 43% energy reduction compared with the calculated manual-control base case.

The results also showed that choices made during LLLC selection (e.g. sensor field of view) and commissioning (e.g. delay time, grouping, dimming vs. turning off during vacancy) have an impact on potential energy savings. For example, in the monitored open office:

- Setting the delay time to 5 minutes reduces energy use by 21% compared with using the typical default of 20 minutes.
- Leaving troffers ungrouped reduces energy use up to 29% compared with connecting troffers into groups of 8.
- Selecting a narrow field of view sensor LLLC reduces energy use by 18% compared with using a wide field of view sensor.
- Turning off troffers completely during vacancy reduces energy use up to 14% compared with dimming troffers to 20% light output when vacancy is detected under the troffer but there is occupancy elsewhere in the room.

Additional savings are likely to result from setting the high-end trim (task tuning) and from the photosensors built into LLLCs. This study addressed energy savings only from motion sensors.

Selecting LLLC products and settings for maximum energy savings has the potential to adversely impact occupant satisfaction. Lighting specifiers and installers need to balance energy savings with the needs of occupants, though these human factors considerations were beyond the scope of this study.

Introduction

Automatic lighting controls for interior commercial spaces can be grouped into three categories:

1. Zone controls. One motion sensor and/or photosensor control multiple luminaires.
2. Luminaire-level lighting controls (LLLCs), also called luminaire-integrated controls. One motion sensor and photosensor are integrated into each luminaire. In many products, the LLLCs in multiple luminaires can be programmed to communicate with one another directly through a mesh network for the purpose of grouping luminaires.
3. Connected lighting. The luminaires are connected to a central control system, which may also be controlled and monitored remotely via the internet. The luminaires often have integrated controls, but may rely on connected zone controls instead.

This study focused on the second category, LLLCs that are not connected to a central control system, though the energy savings results would be applicable to connected lighting as well. The primary reason for the interest in this category is that studies have shown that in open offices, LLLCs have the potential to reduce energy use compared with traditional zone controls (the first category), but do not incur the additional installation capital and labor of connected lighting (the third category). Zone motion sensors reduce energy use in open offices by only 10% compared with manual switches because if even one occupant is present in an area, then all of the lights are turned on.[1] In contrast, a number of studies have found that luminaire-integrated controls reduce energy use by 47% on average compared with manual switches because the sensors have finer spatial granularity.[2]

Despite the previous studies on these controls, there has been a lack of understanding of how changing some parameters when selecting and installing LLLCs will impact energy savings in open offices. The parameters investigated for this study were:

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[1] Jennings, J., Colak, N., & Rubinstein, F. (2002). Occupancy and time-based lighting controls in open offices. Journal of the Illuminating Engineering Society, 31(2), 86.

[2] This is based on an unpublished literature review conducted by the LRC in November 2015. Seven studies covering 11 installations were included in the review. The literature review is available upon request.

1. The field of view of the built-in motion sensor. The wider the angle covered by the motion sensor, the lower the expected energy savings because more motion events will trigger the luminaire to turn on.[3]
2. The delay time before the luminaire is dimmed or shut off when no occupancy is detected. Delay times guard against false negatives in motion sensors; the longer the delay time, the greater the chance the occupant will make a sufficiently large motion before the light is turned off, thereby reducing the chance of annoying the occupant. However, when the monitored area is actually unoccupied, the delay time results in wasted light.
3. The average group size of the luminaires. In LLLC products that can form mesh networks, luminaires can be programmed into groups so that if motion is detected by one luminaire, then all luminaires in the group will turn or remain on. Typically, they are programmed using a hand-held remote-control device provided by the manufacturer. Occupants may wish to group luminaires for aesthetic reasons or to identify a cohesive work department. However, the greater the number of luminaires in a group, the greater the energy use. For example, if the number of luminaires grouped together is equal to the number of luminaires controlled by a traditional zone control, then the energy savings should be the same as that from traditional controls (approximately 10% compared with manual controls, as discussed above).
4. Switching off versus dimming. At least one manufacturer offers the feature that luminaires can dim to a low level rather than turn off completely when no motion is detected under that troffer, but there is still occupancy detected elsewhere in the room.[4]

Methodology

This study measured the occupancy pattern of an open office and then used that data in a computer simulation to determine when each troffer would be on, dimmed, or off over a two-day period. There were two benefits of this approach compared with actually installing LLLCs. First, it was more cost effective. After data was collected from the field once, 21 different simulations were run. This avoided needing 21 separate field study periods and the installation of any new lighting equipment. Second, it eliminated changes in occupancy patterns as a variable between different conditions. On the other hand, a drawback to this approach is that

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[3] From a human factors standpoint, if the field of view is too small, then the light might not turn on even when there is motion in an area the troffer is intended to illuminate, but investigating this was beyond the scope of this study.

[4] This is the default functionality of the Philips SpaceWise DT LLLC, for example. http://images.philips.com/is/content/PhilipsConsumer/PDFDownloads/United%20States/ODLI20170627_001-PDF-en_US-PLt-17062UM_SpaceWise_DT_user_manual.pdf. Page 13. Accessed Oct. 23, 2017.

human factors, such as occupants' preferences for different group sizes and delay times, could not be assessed.

Energy savings from daylighting and high-level trim were not included in this study.

The following steps were taken to carry out the study.

Study site identification.

After visiting multiple potential study sites, an open office area on the second floor of the New York State Energy Research and Development Authority (NYSERDA) headquarter building at 17 Columbia Circle, Albany, NY was selected. This area had outer dimensions of approximately 47.5m x 19.5m (156ft x 64ft) and included 63 cubicles, of which three were unoccupied during the measurements. Most cubicles were about 3m x 3m (10ft x10ft), though a few were smaller, and the cubicle walls were 1.5m (5ft) high. The drop ceiling was 2.6 m (8ft 7in) high. Along the perimeter of the room, there were 13 closed off areas (private offices, stairwells, file rooms, and a closet) that were not included in this study. Please see Appendix: Plan view of open office" to see the layout of the office.

Figure 1: A portion of the NYSERDA study site.

Sensor field of view measurements

The fields of view of five commercially available LLLC passive infrared (PIR) motion sensors were measured. The sensors were purchased for the Easily Commissioned Lighting Controls Phase 2 and Phase 3 studies conducted by the LRC for Bonneville Power Administration and the Lighting

Energy Alliance[5] between January 2015 and February 2016. The following LLLCs were included in the measurements:

1. Cree SmartCast CIF-10V-CWCSNSR (wireless 0- 10V dimming/switching interface with SmartCast technology).
2. Eaton (Metalux) Encounter LED Luminaires with integrated controls (luminaire model 24EN-LD1-40-UNV-L835- CD1-SVPD1-U).
3. Finelite High Performance Recessed (HPR) LED Luminaires with WattStopper FS-305 (fixture integrated PIR occupancy and light level sensor).
4. LG Simple Choice LED Luminaires with integrated Sensor Connect control system (luminaire LGE-2X4SC-40-35-4000-TB).
5. Philips SpaceWise Luminaire integrated control system with built-in sensor (luminaire model 2DLG49L840-4-DUNV-DIM).

Also, the field of view of the motion sensor built into an Onset HOBO UX90-005 Room Occupancy and Light Logger was measured.

The field of view was measured by mounting each luminaire or sensor on a suspended frame in a laboratory space at the LRC. Any sensitivity setting was left at the default value. The height of the sensor was measured for each installation, but all were approximately 2.9m (9ft 8in) above the floor. The blinds and doors of the laboratory were closed. The nadir (the point directly below sensor) was marked on the floor and lines at 30°, 60°, and 90° from the long axis of the luminaire were also marked on the floor. An LRC staff person, wearing a long-sleeve shirt, positioned himself far from the luminaire along one of the marked lines. He approached the luminaire along the line while reaching one arm out in front of him and waving the arm across the line just above the floor. His hand traveled 0.3m (1 ft) on either side of the line at a speed of 0.3 m/s. At the location that his hand was first detected by the sensor (as shown by either the troffer or an indicator LED illuminating), the distance to the nadir mark was measured. This process was repeated for a total of five measurements along each of the three lines. The fifteen distances were averaged and the sensor field of view was calculated. The sensor field of view here is defined as the angle of the cross section of the detection cone, as shown in Figure 2.[6]

[5] Available at https://www.bpa.gov/EE/Technology/EE-emerging-technologies/Projects-Reports-Archives/Documents/BPA%20Lighting%20Controls%20Phase%202%20final%20report_11302015.pdf and https://www.bpa.gov/EE/Technology/EE-emerging-technologies/Projects-Reports-Archives/Documents/Easily%20Commissioned%20Lighting%20Control%20Phase%203%20Report_FinalReport_November152016.pdf

[6] The field of view should technically be the solid angle (in steradians) of the cone that the sensor can detect motion within, but a different definition is used here for simplicity.

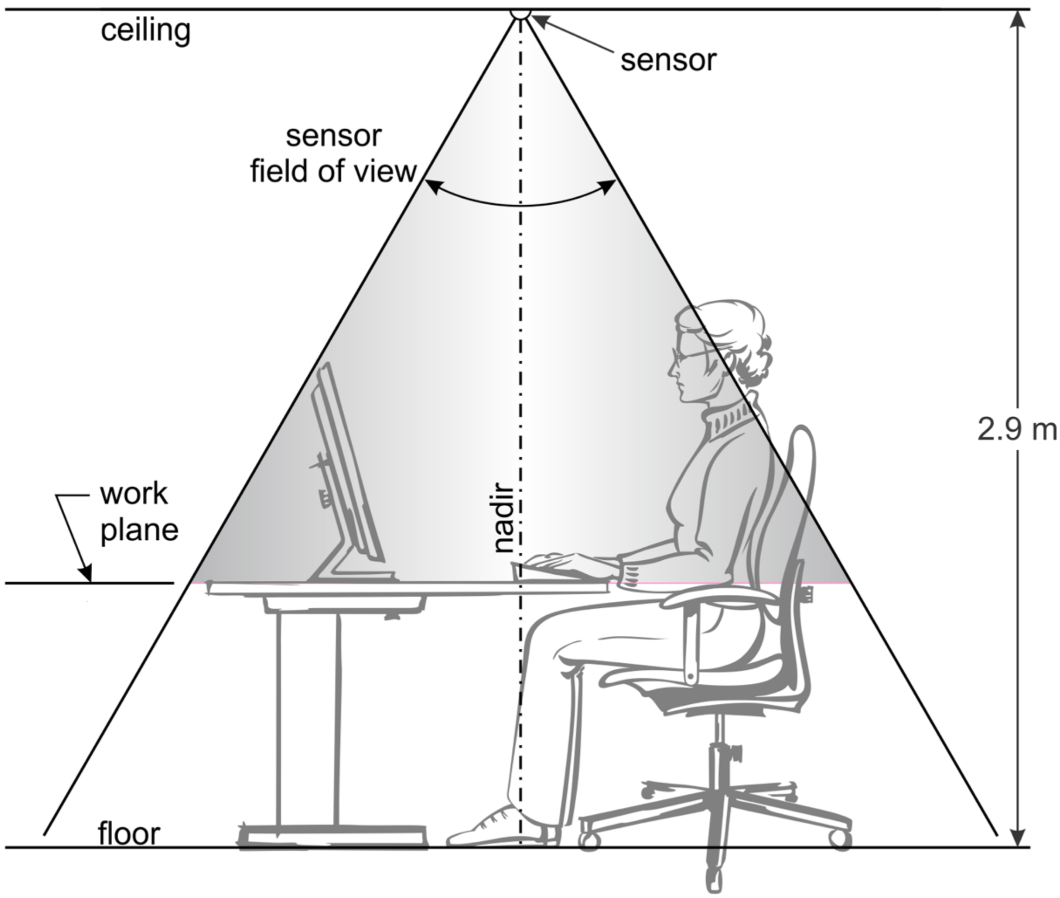

Figure 2: In this report, the sensor field of view is defined as the angle of the cross section of the cone that the sensor can detect motion within.

Due to the way that PIR sensors detect motion, they can detect major motion, such as walking, at a greater distance than they can detect minor motion, such as typing. The hand-waving movement used here represents a medium motion.[7]

The distance between the sensor and the hand during these measurements was different than the distance to the work plane during the field installation. In the LRC lab, there was approximately 2.9m (9.5ft) between the sensor and the hand, but at the NYSERDA site there was about 1.7m (5.5ft) from the sensor to the work plane. It is possible that this would change the angle of detection in a field deployment.

The findings of these measurements are shown in Figure 3, along with the rated values for each sensor. Two manufacturers, LG and Onset, specify different angles for two different directions from the sensor; the average of the two angles is used here.

[7] Dorene Maniccia, Robert Wolsey, "Specifier Reports: Occupancy Sensors." Lighting Research Center, 1998, p. 6. http://www.lrc.rpi.edu/programs/NLPIP/PDF/VIEW/SROS2.pdf

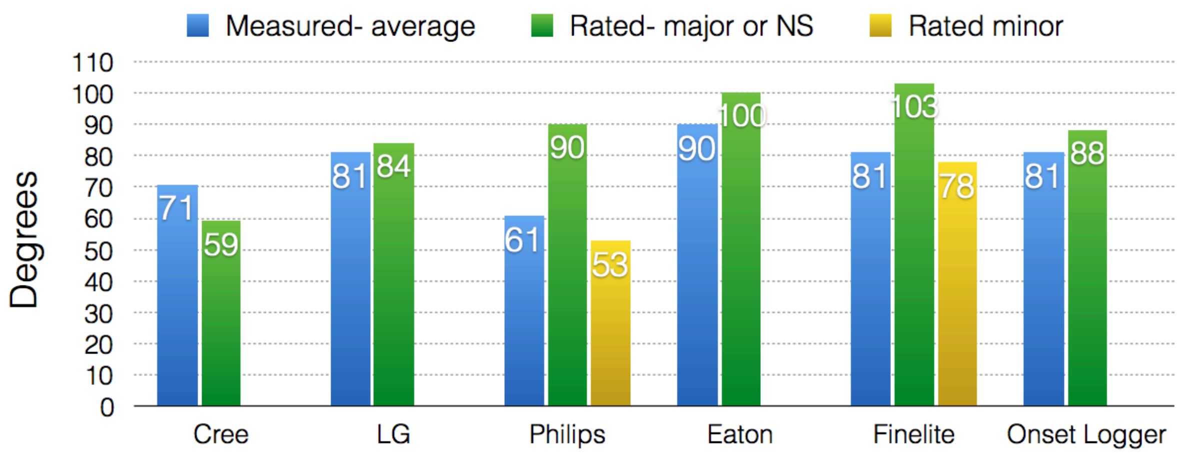

Figure 3: Sensor medium-motion field of view measurements (blue) along with rated values for major or not-specified (NS) motion (green) and minor motion (yellow).

Two manufacturers, Philips and Finelite, specified separate fields of view for minor and major motion. As discussed above, the movement used in this study is a medium motion, but, as shown in Figure 3, it was detected closer to the rated minor motion field of view than rated major motion field of view for those two sensors.

Overall, the measurements agreed with the rated values. On average, the measurements were 10% off from the rated values, using the minor motion rated values for Philips and Finelite.

Simulated lighting layout

The occupancy pattern of the open office was measured by data loggers mounted at the locations that LLLC sensors would be if they were actually installed in the room. To know these locations, a lighting layout was created, but not installed.

The simulated lighting layout was created using AGi32 software to simulate work plane illuminance levels in an open office. The simulated room was 47m x 18.3m x 2.6 m (154ft x 60ft x 8ft 7in) with reflectances of 80% from the ceiling, 50% from the walls, and 20% from the floor. The simulated room was populated with 52 cubicles that were 3m x 3m (10ft x 10ft) with a partition height of 1.5m (5ft), though the layout of the cubicles did not match the layout of the actual open office.

The LRC simulated lighting this room using four different 2ft x 4ft LED troffers from common brands, with an average flux of 4146 lumens. Published IES photometric files were used for each. As shown in Table 1, the troffers would need to be spaced at about 3.8m x 3.0m (12.5ft x 10ft) to achieve the desired average illuminance.

Table 1: Simulated LED troffer spacing to achieve an average workplane illuminance of 30fc (323lx).

Brand	Model	Power demand (W)	Lumens	Spacing to achieve 30fc average illuminance on workplane	
				Rows	Columns
Cree	CR24 40L-35K-10V	38.6	3886	3.7m (12ft)	3.2m (10ft 6in)
Eaton Cooper Metalux	24EN-LD1-40-UNV-L835- CD1-SVPD1-U	33.9	4082	3.8m (12.5ft)	3.0m (10ft)
Finelite	HPRLED-A-2x4-DCO-SO- 3500K-120V-SC-C1-OBB	26.9	3680	3.8m (12.5ft)	3.0m (10ft)
Philips	2DLG49L840-4-D- UNV -DIM	48.1	4936	3.8m (12.5ft)	3.0m (10ft)

The LRC used a simulated spacing of 3.7m x 2.4m (12ft x 8ft) because the spacing of an actual installation would be constrained by the drop ceiling grid, which would result in a higher average illuminance. The locations of the simulated troffers are shown in Appendix: "Plan view of open office."

Occupancy measurements

Occupancy patterns were measured by mounting Onset Hobo UX90-005 Room Occupancy and Light Loggers with passive infrared (PIR) motion sensors at the same locations that LLLCs would be in the open office if they were installed based on the photometric simulation discussed above. At each simulated LLLC location, two data loggers were mounted. One was restricted by a paper cone over the sensor to a narrow field of view of 61° (the narrowest measured field of view, for the Philips sensor, as shown in Figure 3). Tests confirmed that motion outside of this field of view was not detected. The other Onset Hobo logger had an unrestricted sensor to measure the wide field of view. Its unrestricted detection cone has an angle of 81°, equal to the average measured field of view of the remaining four LLLC sensors. In this report, a "narrow field of view" refers to a detection cone with a 61° cross section and a "wide field of view" refers to a detection cone with an 81° cross section.

Figure 4: A paper cone was used to restrict half of the Onset Hobo data loggers' sensors to a narrow field of view of 61°.

The data loggers were placed along a short side of each simulated troffer location. The maximum sensed floor area for narrow and wide field of view sensors is shown in "Appendix: Plan view of open office." The two data loggers on each simulated troffer side were separated by about 0.3m (1ft) to avoid the paper cone on the narrow field of view logger from obstructing the coverage area of the wide field of view logger. The loggers were placed in consistent locations, always on the west side of the simulated troffer with the logger without a cone to the north of the center line and the logger with a cone to the south of the center line.

At each simulated location, occupancy was logged for two days. Because only 40 data loggers were available, but there were 170 measurement sites (85 simulated troffer locations, 2 data loggers at each location for wide and narrow fields of view), the LRC measured only a portion of the open office at a time. The loggers were programmed to start recording at 12:01 AM following installation. The LRC used the occupancy data for the 48 hours of the next two business days and discarded data collected after that. In one case, data recording started at 12:01 AM on a Friday, so the data from the following Monday were used for the second 24-hour period. All the data the LRC used were recorded on business days, and no holidays were included. The following two-day periods in 2017 were used for collection:

- May 24-25.
- May 31-June 1.
- June 6-7.
- June 9,12.
- June 14-15.

Although the data were collected over five different two-day periods, the computer simulation assumed that the data were all from the same two-day period. The LRC did not observe any differences in occupancy that would indicate that this assumption would skew the results.

Figure 5: Data loggers with and without cones on the ceiling of the NYSERDA study site. This row of the simulated LED troffer layout happened to coincide with the existing 1ft x 4ft fluorescent troffer locations, but many of the troffer locations did not.

Base case energy use

The base case is assumed to be manual light switches operated by the room occupants. All of the lights are assumed to be turned on by the first person entering the open office in the morning and turned off by the last occupant at night. Between the two modeled business days (discussed above) the average first occupancy was at 6:49 AM and the average last occupancy was 10:22 PM, meaning that the lights would be on for 15 hours and 33 minutes per day if they were manually controlled.

The occupancy data seemed to indicate that the last occupant(s) was cleaning staff. On the first modeled day, there was a period of 48 minutes between the last steady occupancy and when the cleaning staff arrived. On the second modeled day, there was a period of 2 hours 35 minutes between the last steady occupancy and the arrival of the cleaning staff, but this was interrupted by two short periods of occupancy. For the base case, the lights are assumed to stay on between the period of last steady occupancy and when the cleaning staff arrived.

Sometimes the last person to leave an open office with manual controls neglects to turn the lights off, so they remain on overnight. Compared with this situation, the assumed base under-estimates energy use, so the calculated energy savings would be conservative. (Actual lighting use was not monitored at the test site for this study.)

Computer simulations

Matlab software by Mathworks, Inc. (Natick, MA, USA) was used to process the data collected by the data loggers. A custom program was written to determine when each luminaire would be on, dimmed, or off during the 48-hour simulation period. An object-oriented program was created with a class of objects to represent each of the physical components. The object classes were sensor, luminaire, zone, and simulation. The sensor class of objects contained the 48 hours of occupancy data collected by the HOBO sensors. If there were multiple files for a sensor they were spliced together to make a contiguous set of data. The luminaire object class represented the position of the luminaire and contained two sensor objects: one wide angle and one narrow angle. The zone object class contained one or more luminaires and defined the set of rules that would determine the state of its member luminaires based on their sensor occupancy state. The simulation object was a container for all the sub-objects and controlled the master clock for the simulation. When a simulation was run the zone objects would query the associated sensors and determine the state of the luminaires from 0 to 48 hours in 1 minute increments. The state value of a luminaire was 0 to 1 with 0 representing off, 1 representing full on, and fractions representing the percent dim (e.g. 0.2 = 20% output). The metric luminaire minutes is computed as the sum of all luminaire states during the entire simulation. Graphics were generated for each minute of the simulation by querying the state of the luminaires and sensors and plotting a representation.

The simulations had the following parameters:

- Narrow or wide field of view.
- LLLC groups. These were defined by the investigators and included no groupings and nominal groups of 2, 4, and 8. Due to the odd number and the layout of the troffers, it was not possible for all groups to have the nominal number of troffers per group. The nominal groups of 2 had an average actual group size of 1.98, the nominal groups of 4 had an average actual group size of 3.70, and the nominal groups of 8 had an average actual group size of 7.73. Please see “Appendix: Troffer groups” to see the groupings that were selected. Groups of 8 troffers may still be smaller than the number of troffers controlled by a single zone control sensor.
- Vacancy mode. Most simulations were run so that a troffer turned completely off when no occupancy was detected by its group (after the delay time). At least one manufacturer offers a feature so that the troffers will dim to a default level of 20% when vacancy is detected under that troffer but there is occupancy somewhere else in the room, and all troffers will turn off completely if no occupancy is detected anywhere in the room.
- Delay time of 1, 5, 10, or 20 minutes from the last time motion was detected to when the troffer is turned off or dimmed.

Energy Savings

The energy use for each simulation is calculated in terms of “troffer-minutes.” One troffer-minute is defined as one troffer being on at full power for one minute. One troffer on at 20% light level is equivalent to 0.2 troffer-minutes. (It is assumed that the power is reduced to 20% of the full power level.) The computer simulation was used to calculate the total number of troffer minutes in the open office over the modeled two-day period. Because each simulated troffer is assumed to have the same power demand at full light output, energy use is proportional to the number of troffer-minutes. Each simulation result is presented as a percentage of the base case discussed above, which is equivalent to 79,305 troffer-minutes per day.[8]

Two additional energy uses are not accounted for here. First, the standby power demand of the LLLCs is not included in the calculations. This would increase the energy use shown in the results by a small amount because the base case manual switches do not have a standby power demand. Second, for most LLLC products, when a manual switch is used to turn on the lights (e.g. the first occupant entering the space in the morning), all troffers turn on initially, and then turn off or dim after the delay time if the space underneath is vacant. This initial energy use is ignored.

Electricity Cost Savings

The average power demand of the troffers shown in Table 1 is 37W. As discussed above, the base case time of use is 15 hours and 33 minutes per business day. Assuming 261 business days per year and that the lights are off during non-business days, the base case energy use is 150kWh/year per troffer.

The average price of electricity for US commercial end users is US$0.1104/kWh.[9] The average price of electricity for Canadian medium-power-demand customers is CA$0.1230/kWh,[10] which is equivalent to US$0.09688.[11] The average of these two prices is US$0.1036/kWh.

Based on the above energy use and price of electricity, the average cost of electricity is US$15.60 per troffer per year.

Results

The results for the simulations that investigate the effect of both the field of view and the delay time are shown in Figure 6. With a delay time of 20 minutes and not grouping the troffers, LLLCs with wide fields of view reduce energy use by 40% compared with the base case, resulting in electricity cost savings of US$6.20 per year per troffer. LLLCs with narrow fields of view reduce energy use by 48% compared with the base case, resulting in electricity cost savings of US$7.50 per year per troffer.

On average, the narrow field of view reduces energy use by 18% compared with the wide field of view because each wide field of view sensor detects more motion events than the narrow field of view sensor at the same location.

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[8] 85 troffers on for 15 hours 33 minutes per day.

[9] https://www.eia.gov/electricity/monthly/epm_table_grapher.php?t=epmt_5_6_a. Accessed Nov. 9, 2017.

[10] http://www.hydroquebec.com/publications/en/docs/comparaison-electricity-prices/comparison-electricity-prices-2017.pdf. Page 22. For power demand of 1,000kW.

[11] Exchange rate of 1 CAD = 0.787638 USD on Nov. 9, 2017.

Reducing the delay period time from 20 minutes (a typical default value) to 5 minutes reduces energy use by an additional 14% for the wide field of view and by an additional 21% for the narrow field of view relative to the 20-minute-delay energy use, providing an additional electricity cost savings of US$1.40 to US$2.70 per year per troffer. Reducing the delay time to 1 minute further reduces energy use, but is more likely to result in false-offs.

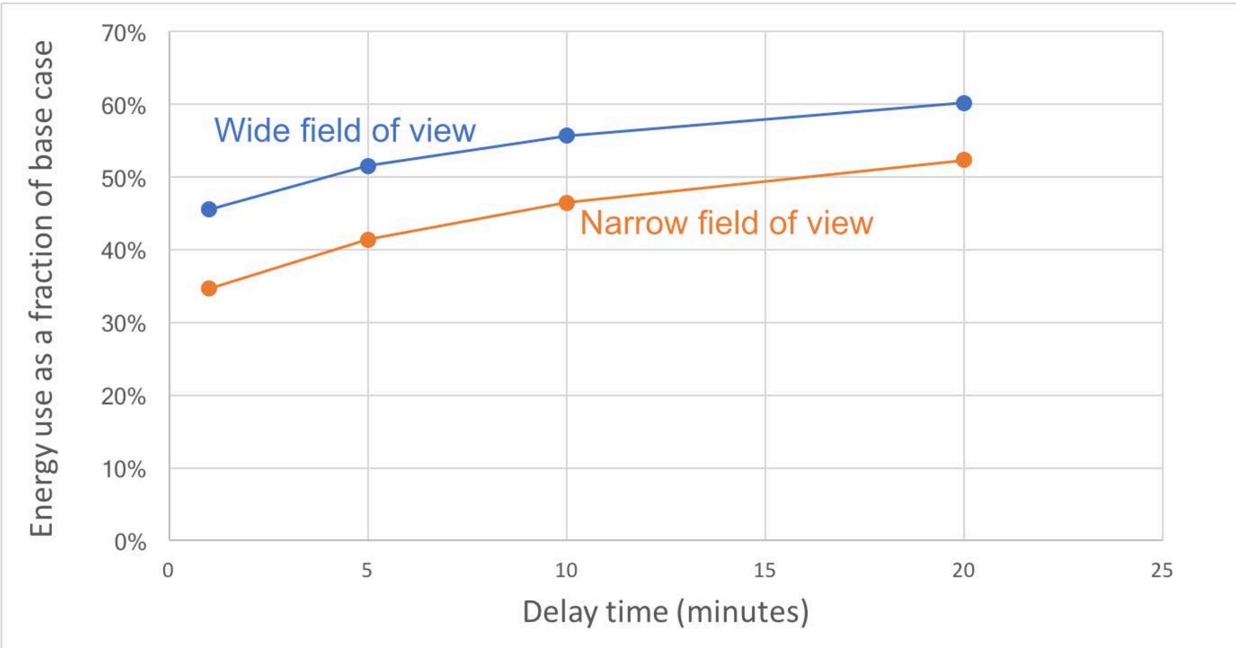

Figure 6: Lighting energy use vs. delay time and field of view. In these simulations troffers are not grouped together and troffers are turned off (rather than dimmed) during vacancy. Energy use is reported as a fraction of the calculated manual-switch base case.

Figure 7 shows the results from using different group sizes. A group size of one indicates that the LLLCs are ungrouped, which is the default condition. The results show that when LLLCs are grouped into pairs, energy use is increased by 10% for the wide field of view and by 18% for the narrow field of view compared with ungrouped LLLCs. When LLCs are in groups of eight, energy use increases by 25% for the wide field of view and by 42% for the narrow field of view compared with ungrouped LLLCs. Linking troffers into groups of eight increases electricity costs by US$2.20 per troffer per year for wide-field-of-view LLLCs and by US$3.40 per troffer per year for narrow-field-of-view LLLCs.

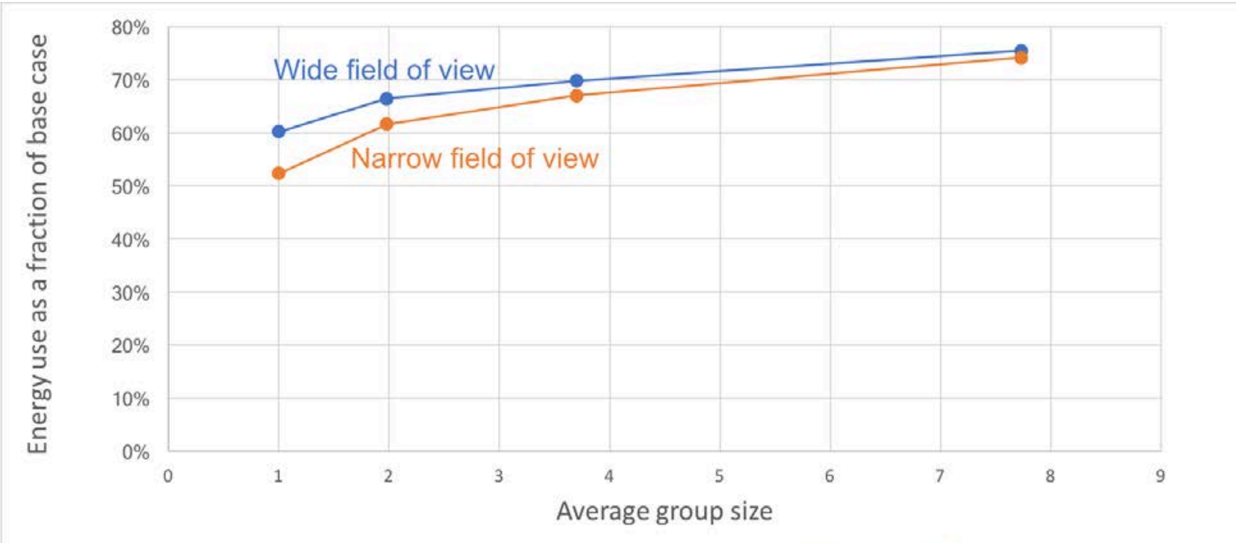

Figure 7: Lighting energy use vs. average group size and field of view. In these simulations, delay time is 20 minutes and troffers are turned off (rather than dimmed) during vacancy. Energy use is reported as a fraction of the calculated manual-switch base case.

Figure 8 shows the results if a troffer were to dim to 20% rather than turning off completely when no motion is detected under that troffer, but there is still occupancy elsewhere in the room. The results show that with dimming, the lighting uses 17% more energy than if the troffers turned off completely, with a 20-minute delay time. This would increase electricity costs by US$1.40 per troffer per year.

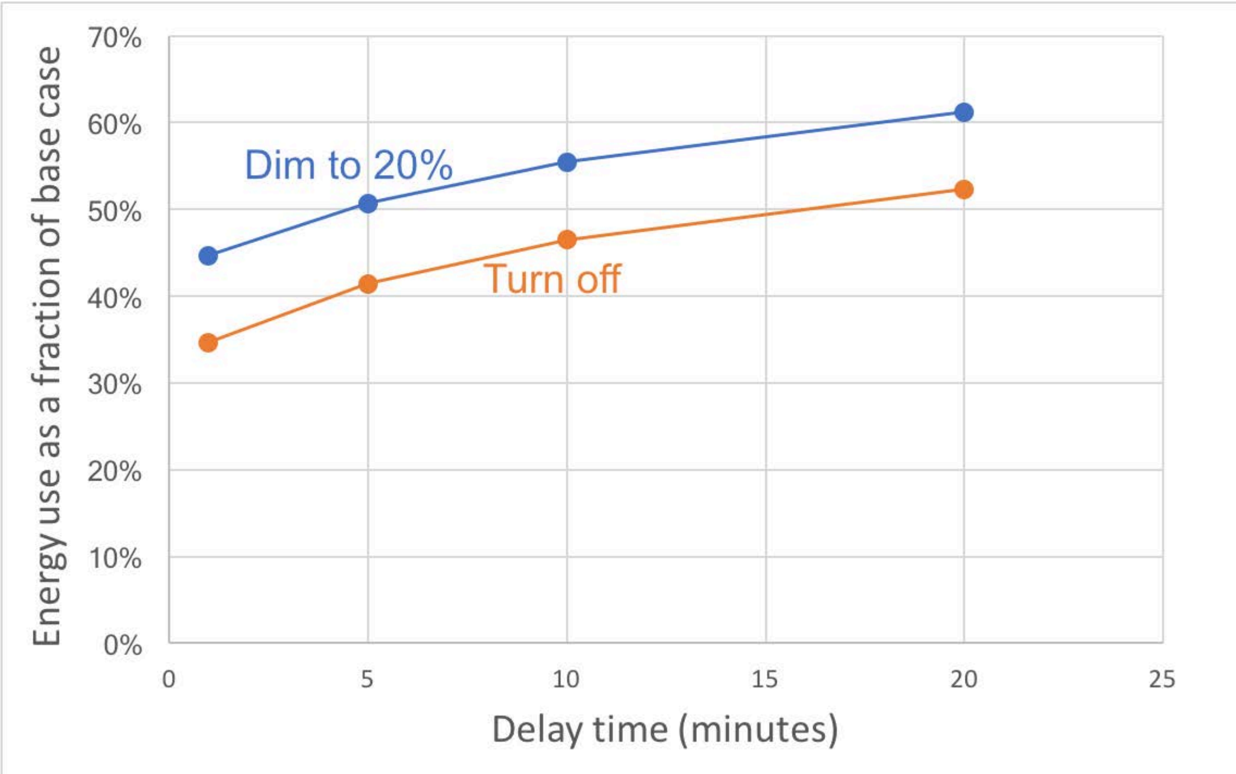

Figure 8: Lighting energy use vs. delay time and whether a troffer dims to 20% or turns off completely if no motion is detected under that troffer but there is occupancy elsewhere in the room. In these simulations troffers are not grouped together and the field of view is narrow. Energy use is reported as a fraction of the calculated manual-switch base case.

As shown in Figure 9, sensors that include minor aisles (the narrower east-west aisles between cubicle blocks) within their field of view detected a greater average occupancy rate than sensors that don't include any aisles, and sensors that include major aisles (wider aisles at the perimeter of the office) detected an even greater average occupancy rate.[12] Based on this observation, an attempt was made to examine whether avoiding including in LLLC groups any sensor that detects motion in an aisle would reduce energy use. However, less than half the troffers could then be included in groups. Such limitations would be overly restrictive in a real-world setting, so simulations were not carried out for these configurations. Also, unless separate aisle lighting is provided, an occupant could be walking in the aisles in darkness when the surrounding cubicles are unoccupied.

[12] The division of sensors into these three categories was based on the narrow field of view, but the analysis was also run for the wide field of view sensors using the same categorization.

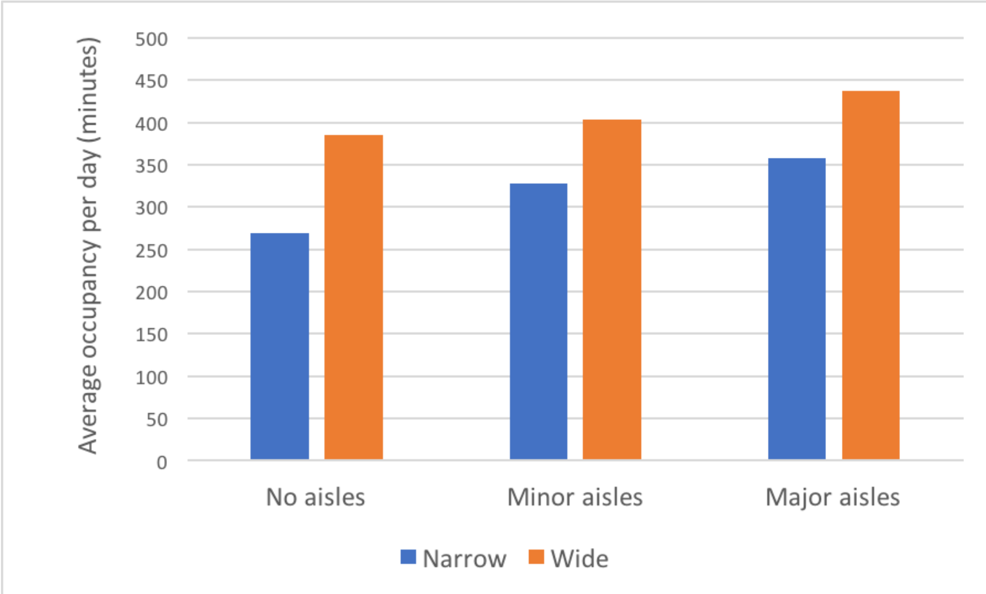

Figure 9: Average occupancy per day detected by sensors that include no aisles, minor aisles, or major aisles in the detection area based on the narrow field of view.

Discussion

The results show that in open offices, LLLC selection (e.g. sensor field of view) and commissioning (e.g. delay time, grouping, dimming vs. turning off during vacancy) leads to large differences in energy savings. The scenario leading to the least energy use (narrow field of view, 1-minute delay period, ungrouped, turn off when unoccupied) uses 35% of the base case (manual switches) energy use, while the scenario leading to the most energy use (wide field of view, 20-minute delay period, nominal groups of 8, turning off during vacancy) uses 75% of the base case energy, more than double the lowest energy use case.[13]

Additional savings are likely to result from setting the high-end trim (task tuning) and from the photosensors sensors built into LLLCs. This study addressed energy savings only from motion sensors.

Jennings et al (2001) found that zone controls in open offices with 15 to 20-minute delay periods resulted in a 10% reduction in energy.[14] Maniccia et al (2001) studied energy savings from zone controls with delay times ranging from five to 20 minutes in five other commercial spaces— break rooms, classrooms, conference rooms, private offices, and restrooms— and

[13] The case of dimming to 20% with groups of 8 was not examined because this functionality is not offered by the product that the dimming scenario is based on.

[14] Jennings, J., Colak, N., & Rubinstein, F. (2002). Occupancy and time-based lighting controls in open offices. Journal of the Illuminating Engineering Society, 31(2), 86.

found that energy savings ranged from 17% to 52% with a 20-minute delay period.[15] The results from these studies, along with the delay-time results from this study, are shown in Figure 10. The lower potential energy savings from using zone controls in open offices compared to other commercial spaces is likely due to higher occupancy rates of open offices. These results illustrate that using LLLCs rather than zone controls in open offices can result in energy savings comparable to using zone controls in spaces with lower occupancy rates.

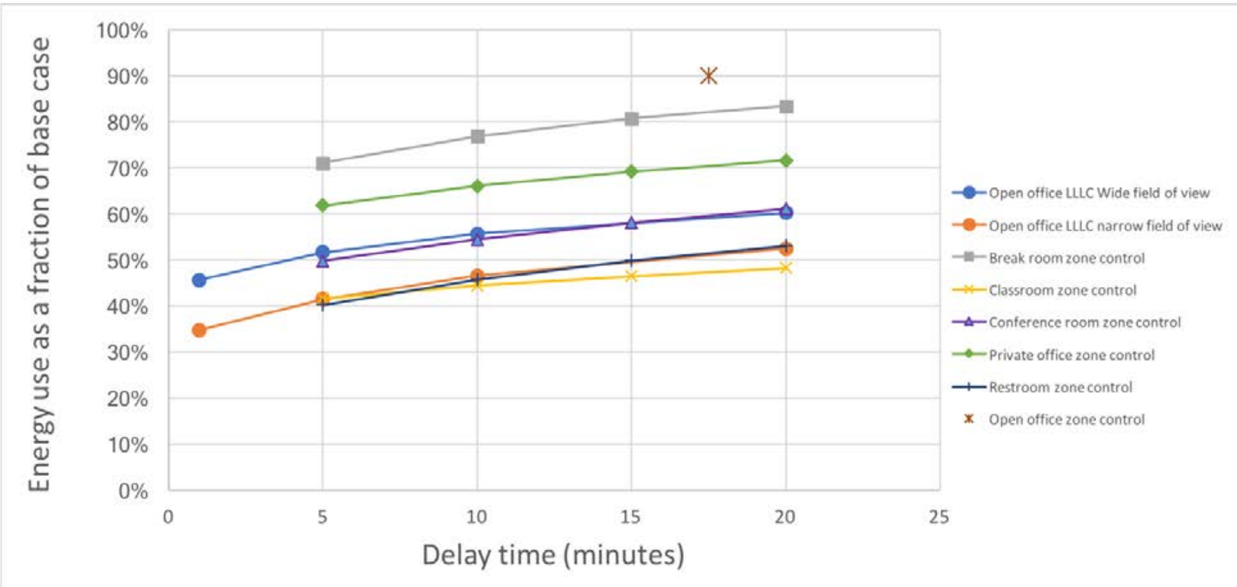

Figure 10: Lighting energy use vs. delay time. LLLC narrow and wide field of view results are from this study, zone control results for break room, classroom, conference room, private office, and restroom are from Maniccia et al 2001, and the zone control result is from open offices are from Jennings et al 2001. In the LLLC simulations, troffers are not grouped together and troffers are turned off (rather than dimmed) during vacancy. Energy use is reported as a fraction of the manual-switch base case.

Energy savings need to be balanced against occupant satisfaction. For example:

- A 1-minute delay period may lead to an unacceptable number of false-offs if the motion sensor is not sensitive enough to detect fine motion.
- A narrow field of view may not sense motion in the full area that the troffer illuminates.
- Compared with dimming during vacancy, troffers that turn off completely may leave a lone occupant feeling uncomfortable when no daylight is available (i.e. The entire open office is dark except for the area where the occupant is.), there may be a perception that the overall space is darker, and the lights switching on and off would be more noticeable to occupants in adjacent zones.

In addition to human factors, energy savings also need to be balanced against life cycle costs. The life of LED products was traditionally thought to not be affected by on-off cycling, as

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[15] Maniccia, D., Tweed, A., Bierman, A., & Von Neida, B. (2001). The Effects of Changing Occupancy Sensor Timeout Setting on Energy Savings, Lamp Cycling and Maintenance Costs. Journal of the Illuminating Engineering Society, 30(2), 2001, pp. 97-110. http://www.tandfonline.com/doi/abs/10.1080/00994480.2001.10748356

fluorescent lamps are. However, a recent study by the LRC's Alliance for Solid-State Illumination Systems and Technologies (ASSIST) found that cycling LEDs does shorten their life.[16]

It is beyond the scope of this study to address these human factors issues and life-cycle analysis, but lighting specifiers must take these questions into account.

At least one LLLC manufacturer offers the feature of dimming a troffer rather than turning it off completely when no motion is detected under that troffer but there is still occupancy detected elsewhere in the room. This could have the benefits of improved aesthetics (by avoiding a "checker board" pattern of the troffers) and providing a sense of comfort and security to one or a few occupants when no daylighting is present. The downside to this strategy is that it used an additional 17% energy compared with turning troffers off completely (assuming a 20-minute delay). A modification of this feature to provide occupants with a sense of comfort would be to use the photosensors to provide a minimum light level when the space is occupied. This would result in troffers turning off completely during the day (assuming the presence of some daylighting or light from other troffers) but dimming at night during occupancy.

As discussed above, it would be impractical to avoid including LLLCs that detect motion in aisles as a means of reducing energy use. Instead, at least one LLLC sensor includes a shield that can be positioned to avoid detecting motion in high traffic areas. It was beyond the scope of this study to investigate the effectiveness of such shields.

The energy cost savings ranged from $6.20 for an ungrouped wide-field-of-view LLLC with a 20-minute delay to $9.10 for an ungrouped narrow-field-of-view LLLC with a 5-minute delay. One study found that the average incremental cost for installing an LLLC in an LED troffer at the time of manufacture is approximately $17.[17] Therefore, the simple payback would be 1.9 to 2.7 years.

Conclusion

This study illustrates the significant energy savings potential of LLLCs in open offices. The average energy use of the 21 simulations reported on here was a 43% energy reduction compared with the manual-control base case.

This study also found that choices made during LLLC selection (e.g. sensor field of view) and commissioning (e.g. delay time, grouping, dimming vs. turning off during vacancy) have an impact on potential energy savings. For example, in an open office:

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[16] http://www.lrc.rpi.edu/programs/solidstate/LEDSystemLife.asp

[17] Energy & Resources Solutions. 2016. "Emerging Technologies Incremental Cost Study Final Report." North Andover, MA. http://www.neep.org/sites/default/files/resources/NEEP%20Incremental%20Cost%20Study%20FINAL_061016.pdf. See Table 3-9 on page 28. The incremental cost is based on the only two rows of the table that give a dollar amount per fixture for adding LLLCs at the factory.

- Setting the delay time to 5 minutes reduces energy use by 21% compared with using the typical default of 20 minutes.
- Leaving troffers ungrouped reduces energy use up to 29% compared with connecting troffers into groups of 8.
- Selecting a narrow field of view sensor LLLC reduces energy use by 18% compared with using a wide field of view sensor.
- Turning off troffers completely during vacancy reduces energy use up to 14% compared with dimming troffers to 20% light output when vacancy is detected under the troffer but there is occupancy elsewhere in the room.

These variations in potential energy savings indicate that utility and other efficiency incentive programs should consider basing energy savings calculations on the settings of the as-installed LLLC system rather than average values.

Selecting LLLC products and settings for maximum energy savings has the potential to impact occupant satisfaction and life cycle costs. Lighting specifiers and installers need to balance energy savings with the needs of occupants.

LLLCs represent an important opportunity for lighting energy savings and warrant further study. Topics for further investigation could include occupant acceptance of different LLLC parameters, the impact on life cycle cost savings potential, energy savings in spaces other than open offices, energy savings from shielding sensors from high-traffic areas, and the creation of a calculator to estimate energy savings based on selected parameters.

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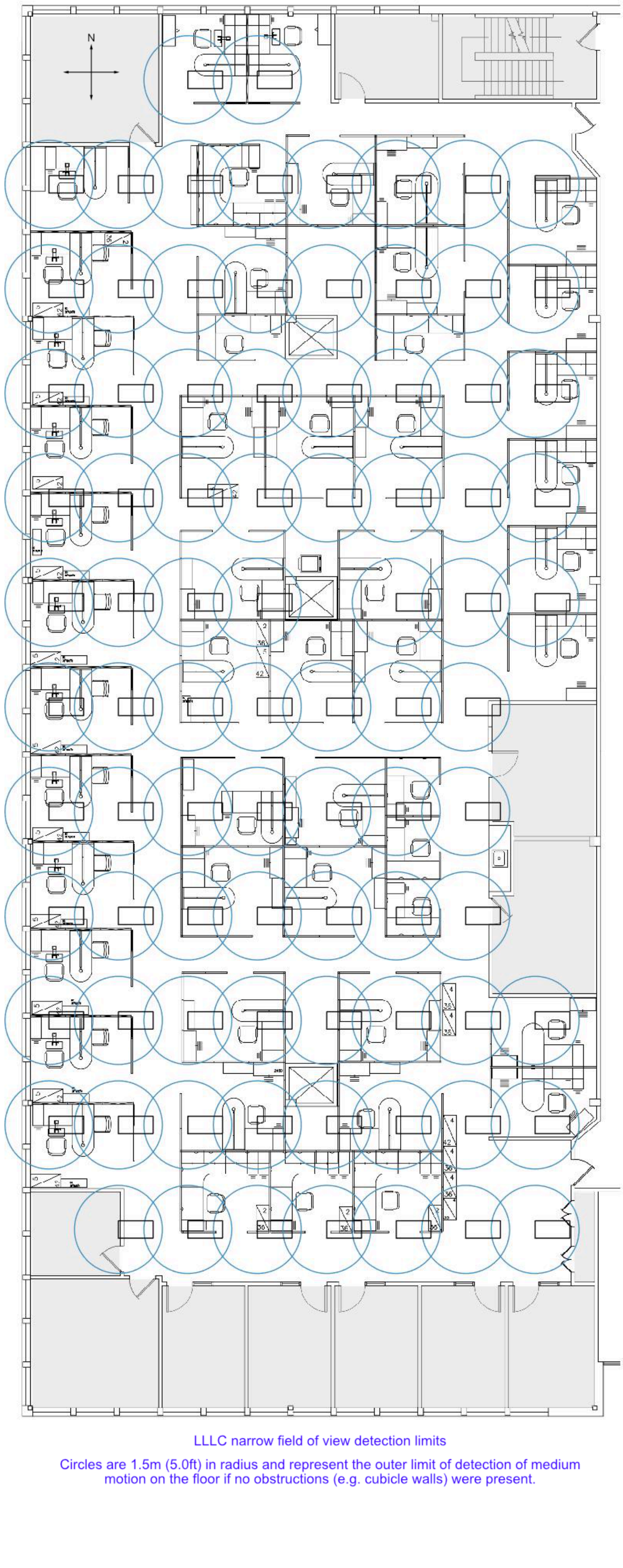
Appendix: Plan view of open office

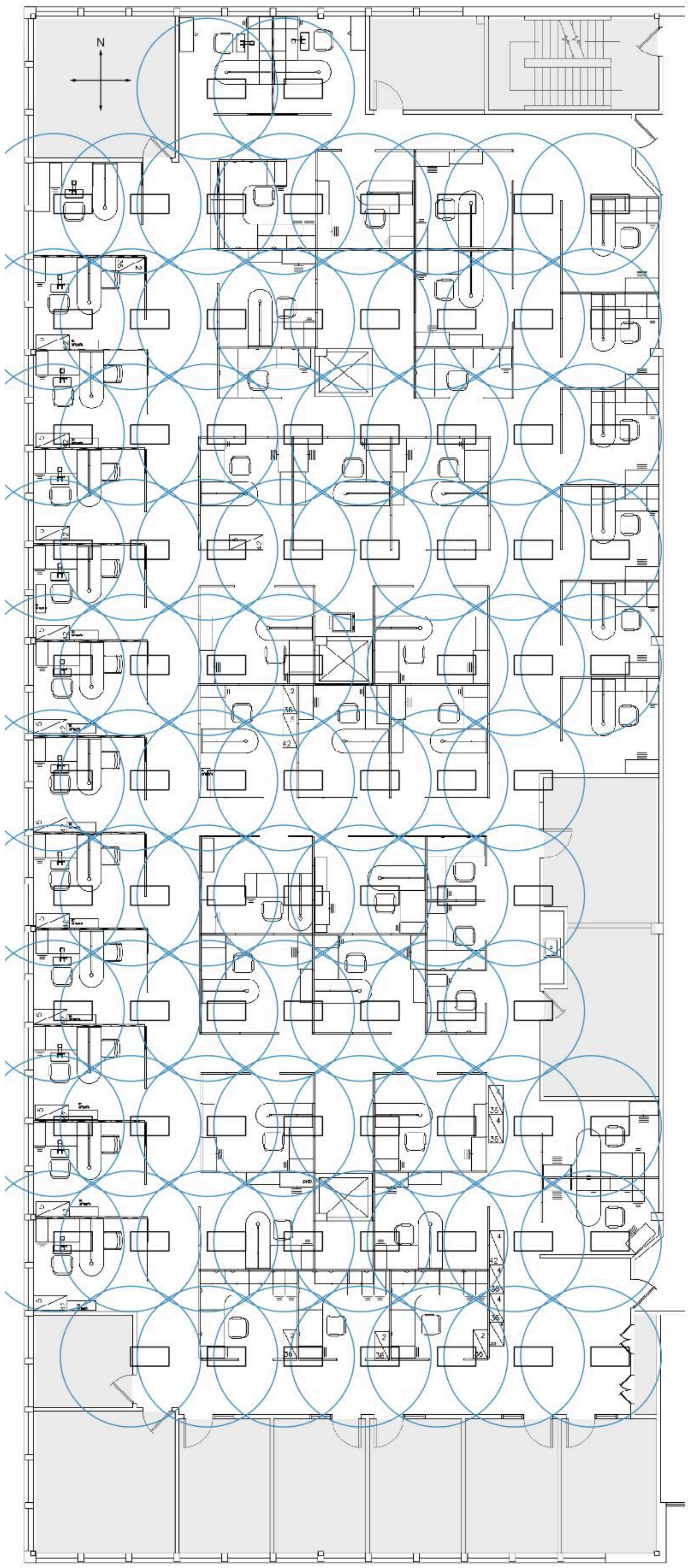
The simulated layout of the 2ft x 4ft troffers is shown by the rectangles. The circles indicate the LLLC limits of detection with a narrow field of view.



LLLC narrow field of view detection limits

Circles are 1.5m (5.0ft) in radius and represent the outer limit of detection of medium motion on the floor if no obstructions (e.g. cubicle walls) were present.

The circles in the image below indicate the LLLC limits of detection with a wide field of view.

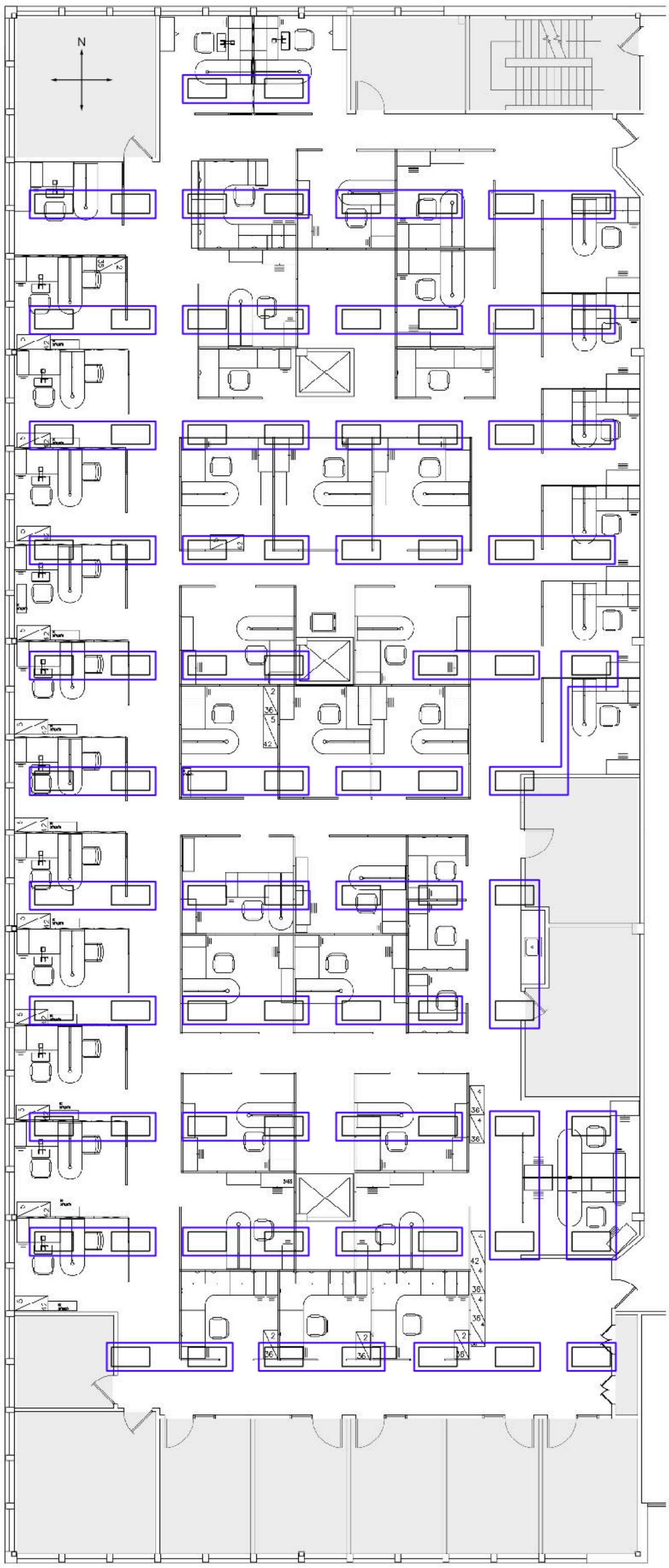


LLLC wide field of view detection limits

Circles are 2.2m (7.3ft) in radius and represent the outer limit of detection of medium motion on the floor if no obstructions (e.g. cubicle walls) were present.

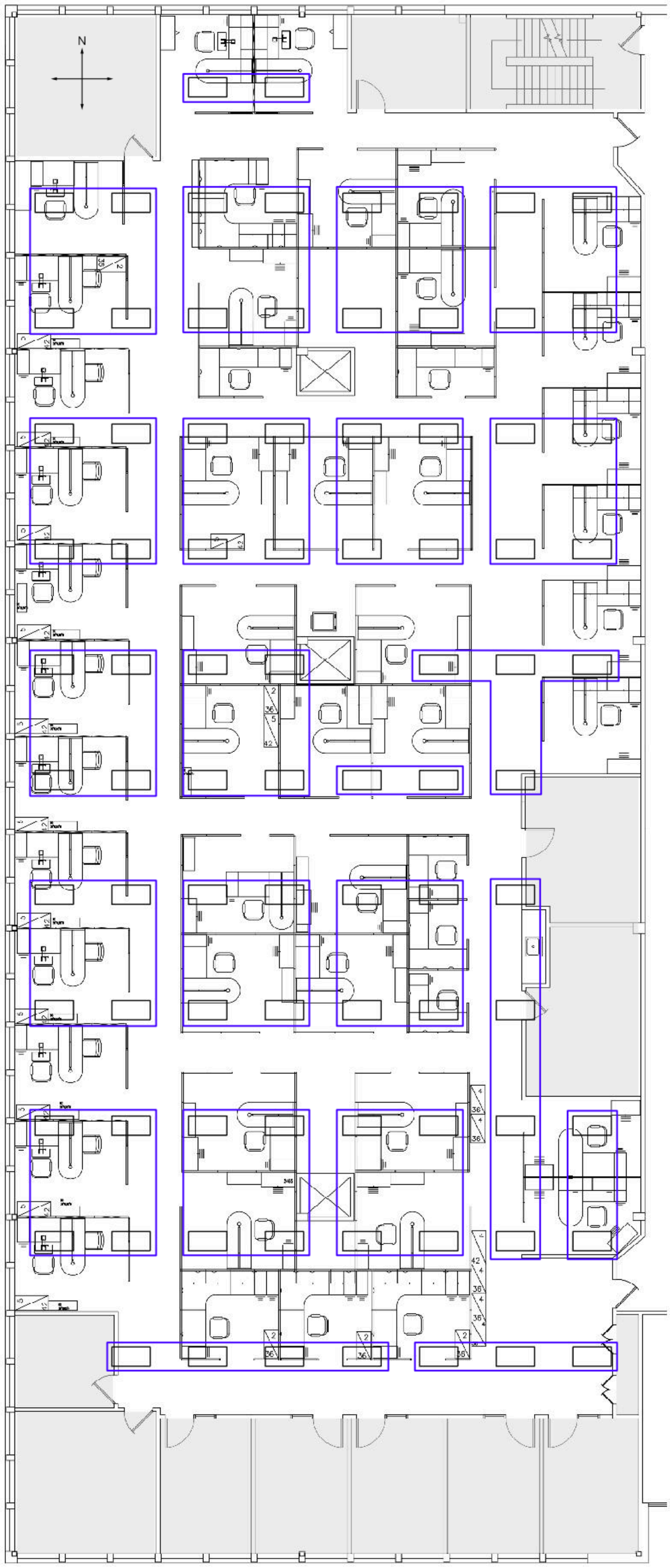
Appendix: Troffer groups

Nominal groups of 2 are outlined in blue.



Nominal groups of 2
Actual average group size 1.98

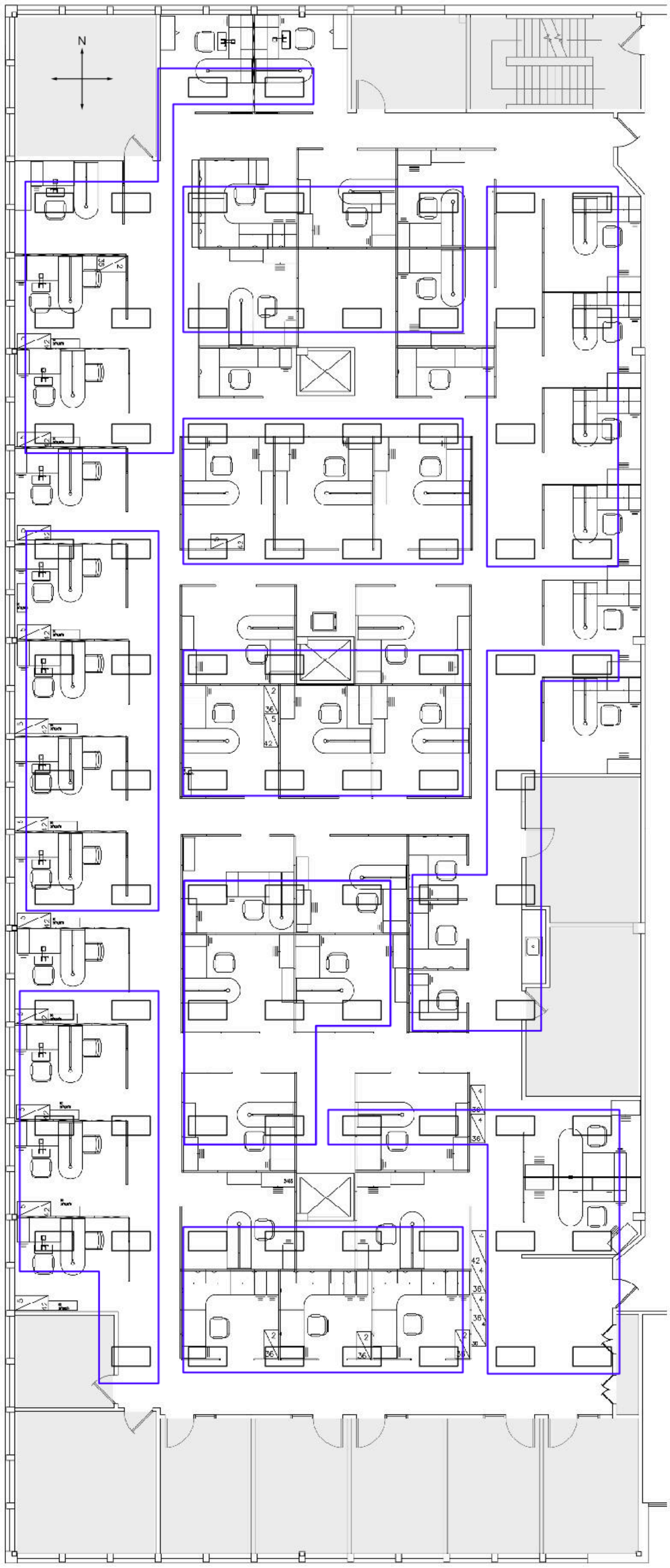
Nominal groups of 4 are outlined in blue.



Nominal groups of 4

Actual average group size 3.70

Nominal groups of 8 are outlined in blue.



Nominal groups of 8

Actual average group size 7.73