A Case Study of Luminaire-Level Lighting Control

Lighting the Northwest Energy Efficiency Alliance (NEEA) Office in Portland, OR

Pacific Northwest
NATIONAL LABORATORY

October 2023

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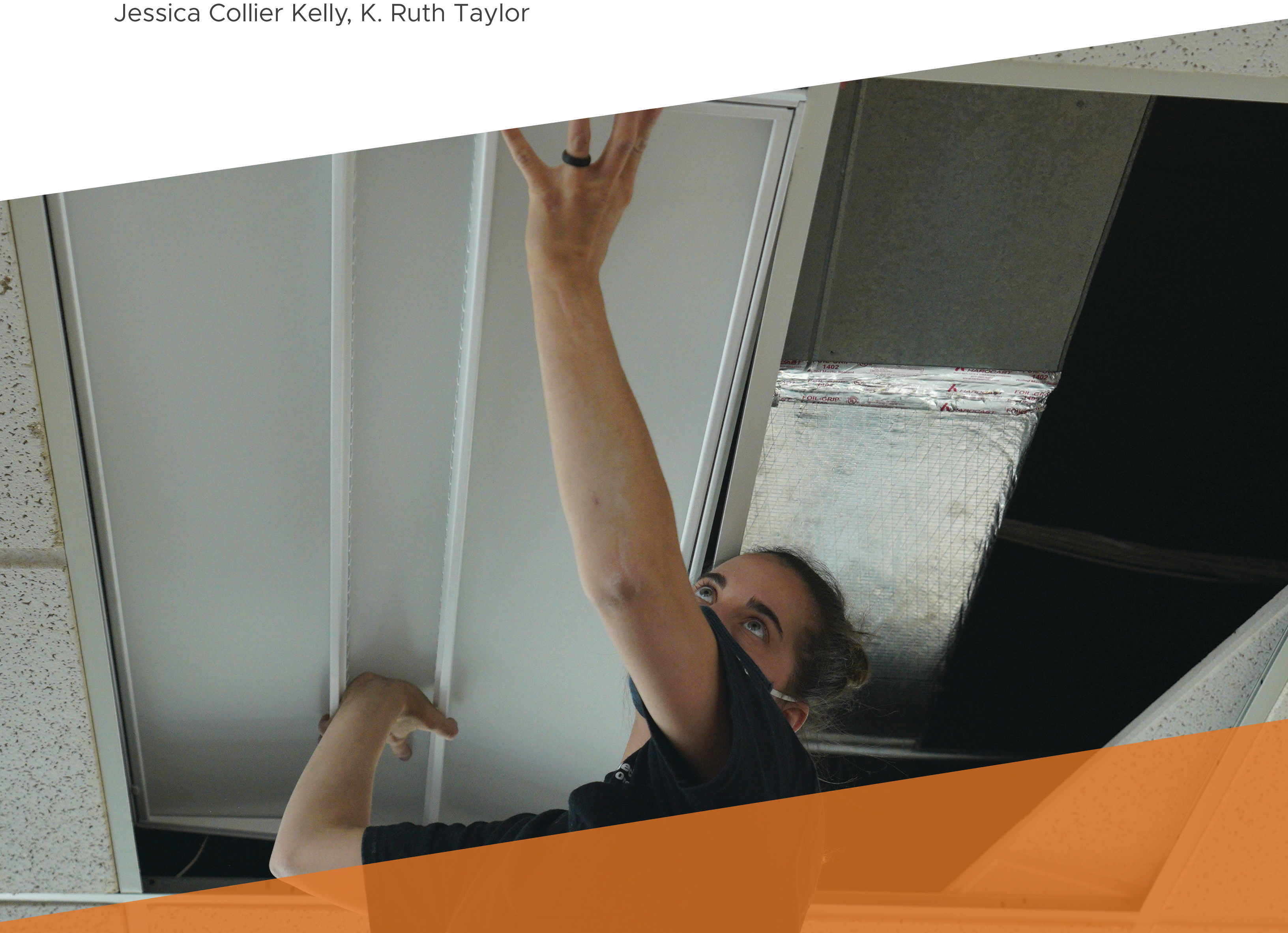

CONTENTS

- Introduction | 2
- Observational Findings from Installation and Initial Programming | 5
- Performance Evaluations | 10
- Conclusion | 16

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INTRODUCTION

In addition to the energy savings accomplished by light-emitting diode (LED) technology upgrade or replacement, adoption of advanced lighting control systems can further reduce energy use and provide greater operational benefits. Lighting fixtures are being replaced with more efficient LED technology, but advanced lighting controls have yet to gain similar traction. For maximum energy savings and building resiliency potential, installations should consider both efficient lighting technology and connected or networked lighting controls that are designed to allow for greater system flexibility and monitoring, data reporting capabilities, or enhanced dynamic lighting capabilities, such as tunable-white lighting.

What happens when these systems are installed in the real world? Are the advantages and energy savings realized? By observing the design, installation, programming, and ongoing use of connected lighting systems in real-world settings, it is possible to identify the strengths, challenges, and points of human-technology interaction that may be new or unfamiliar to those responsible for implementing or maintaining the lighting system. Ultimately, understanding and experiencing each stakeholder's interaction with the technology can enable the research team to synthesize feedback for manufacturers, improve industry understanding of the technology, and increase adoption.

The Northwest Energy Efficiency Alliance (NEEA) office in Portland, OR is a single-floor installation that puts tunable-white lighting, interoperability, and luminaire-level advanced control capabilities to the test. Compared to simpler, "out-of-the-box" systems that minimize field-adjustable settings, the system used in this space allowed for granular field adjustments, which required the system specifier, client, and programming agent to make additional decisions regarding system operation while the system was being programmed. This report communicates the observational findings from the installation, programming, and ongoing operation of an advanced office luminaire-level lighting control (LLLC) system.

FIELD EVALUATIONS

Pacific Northwest National Laboratory conducts field evaluations of advanced solid-state lighting systems to collect empirical data and document building owner and end-user experience with lighting systems. The evaluations produce independent, third-party data and recommendations for use in decision-making by lighting manufacturers, designers, facility managers and other professionals. Real-world installations often reveal product limitations and application issues that are not apparent from laboratory testing. The evaluations include the gathering of feedback from the everyday people who live, work and play under the lighting systems in a variety of space types. For more information and additional resources, please visit ***energy.gov/eere/ssl/solid-state-lighting***.

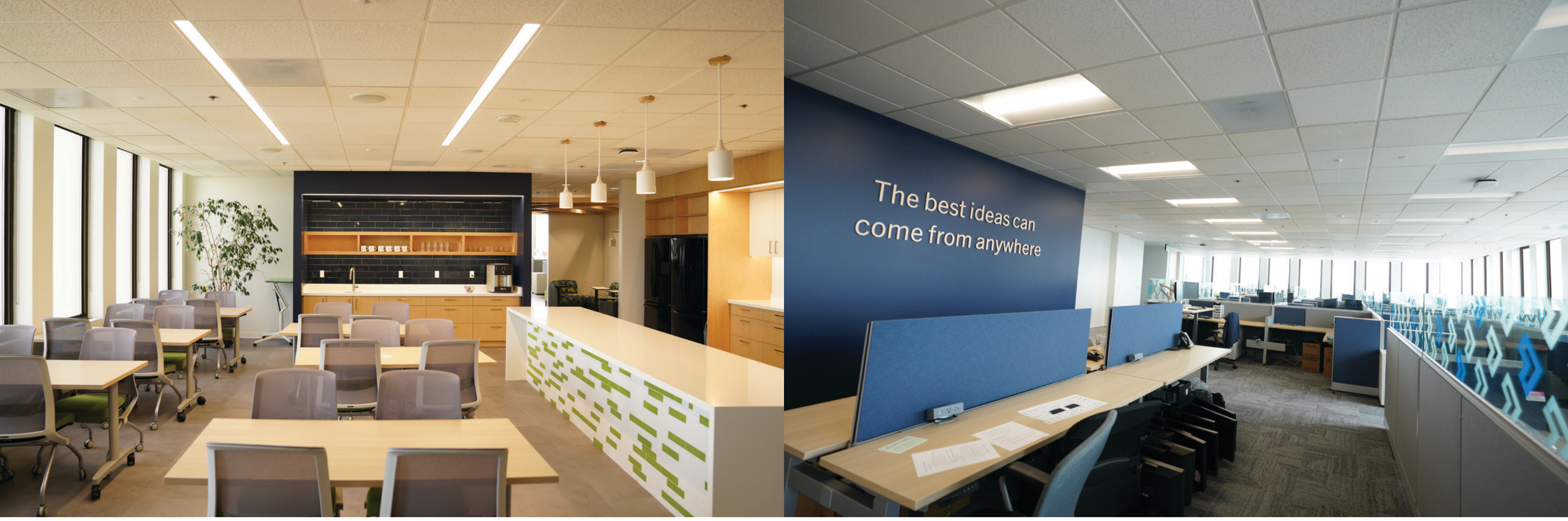

Figure 1: Photographs of the NEEA breakroom and an open office area. *Photo credit: Pacific Northwest National Laboratory.*

NEEA Office – Downtown Portland, OR

The NEEA office is located on the 13th floor of a multi-tenant building in northeast Portland; *Figure 1* shows photos of the office. The 16,000-ft^2 office suite is primarily open office space with cubicle workstations and includes conference and meeting rooms, private offices, and a large breakroom and kitchen. In 2020, NEEA acquired the office space and initiated a general office redesign, as well as a one-for-one replacement of the luminaires and the introduction of a new lighting control system. The design and project management were executed by NEEA with input from the Next Generation Lighting Systems Industry Committee; the new lighting and control system were installed by a local electrical contractor in May 2021. The control system was programmed by the manufacturer, Enlighted, in June 2021.

Office Lighting and Control System

The lighting system in the prior NEEA office space allowed occupants to independently control the luminaires in their proximity via a desktop app, which often led to user complaints. After this experience, it was decided to eliminate localized, individual control for each user and leverage the flexibility of the system to schedule, automate, or program suitable controls for each space. The specification was written to support NEEA's energy efficiency mission and create a test bed for the lighting industry's latest technological capabilities and known challenges, such as interoperability and white tuning. The required features and capabilities included general lighting quality and control requirements, specific control functions, reporting capabilities, and upgradability compliance, among others, as summarized in *Figure 2*. Other capabilities that were not required but were of interest included workstation hoteling management, asset tracking or real-time location services, temperature and humidity monitoring, BACnet integration, and automated fault detection.

Lighting Design

The lighting system consists of eight luminaire types, including a Finelite recessed lensed 2x4 troffer, 2" and 4" wide recessed linear luminaires, and direct/indirect pendants, Signify recessed downlights, Kelvix under-cabinet tape light, and various decorative pendants. The recessed troffer, linear fixtures, pendants, and downlights produce a white-tuning range between 2700 and 6500 K by mixing various outputs of a cool and warm LED array. The under-cabinet tape light is also tunable, and can produce correlated color temperatures (CCTs) as low as 1800 K. As the system was designed to be an LLLC, the majority of the fixtures, including the recessed troffers and recessed linear fixtures, have an integral Enlighted micro sensor embedded in the fixture housing. The remaining luminaires, including the downlights, decorative pendants, and under-cabinet tape light, communicate with remote sensors that in some cases control more than one luminaire. *Figure 3* shows the luminaire layout.

LUMINAIRE REQUIREMENTS

TROFFERS AND LINEAR

- Lumens per watt (lm/W) ≥ DLC Premium
- Unified glare rating ≤ 19

DOWNLIGHTS

- 4" Aperture
- 110 LPW
- < 40° cut-off

ALL

- Tunable white
- CRI 90+, R_9 50+
- Compatible with DALI D4i driver

CONTROL SYSTEM REQUIREMENTS

GENERAL SYSTEM REQUIREMENTS

- Wireless communication between sensors and wall controls
- Configurable settings for end user
- Open API for integration with other systems (HVAC)
- Demand response capabilities via Open ADR 2.0a
- Luminaire-level sensor and control in all troffer luminaires and linear luminaires
- Remote sensor control for recessed downlights

LIGHTING CONTROL CAPABILITIES

- Manual continuous dimming
- Scene control
- High-end trim
- Spectral tuning/tunable white
- Occupancy sensing/vacancy control
- Daylight responsive control

REPORTING CAPABILITIES

- Space utilization tracking
- Energy consumption and reporting using measured data
- Open API for energy, occupancy sensor, and maintenance data
- Luminaire diagnostics including temperature, hours of operation

UPGRADABILITY

- Sensors and system shall be upgradable and compatible with D4i drivers installed in luminaires
- Sensors shall fit into standard circular or rectangular knockouts defined within Zhaga Book 20
- System shall be upgradeable with firmware updates for a period of 9 years

Figure 2: Luminaire and control requirements for the office lighting system. The Industry Committee developed the specifications to test emerging control system features and capabilities.

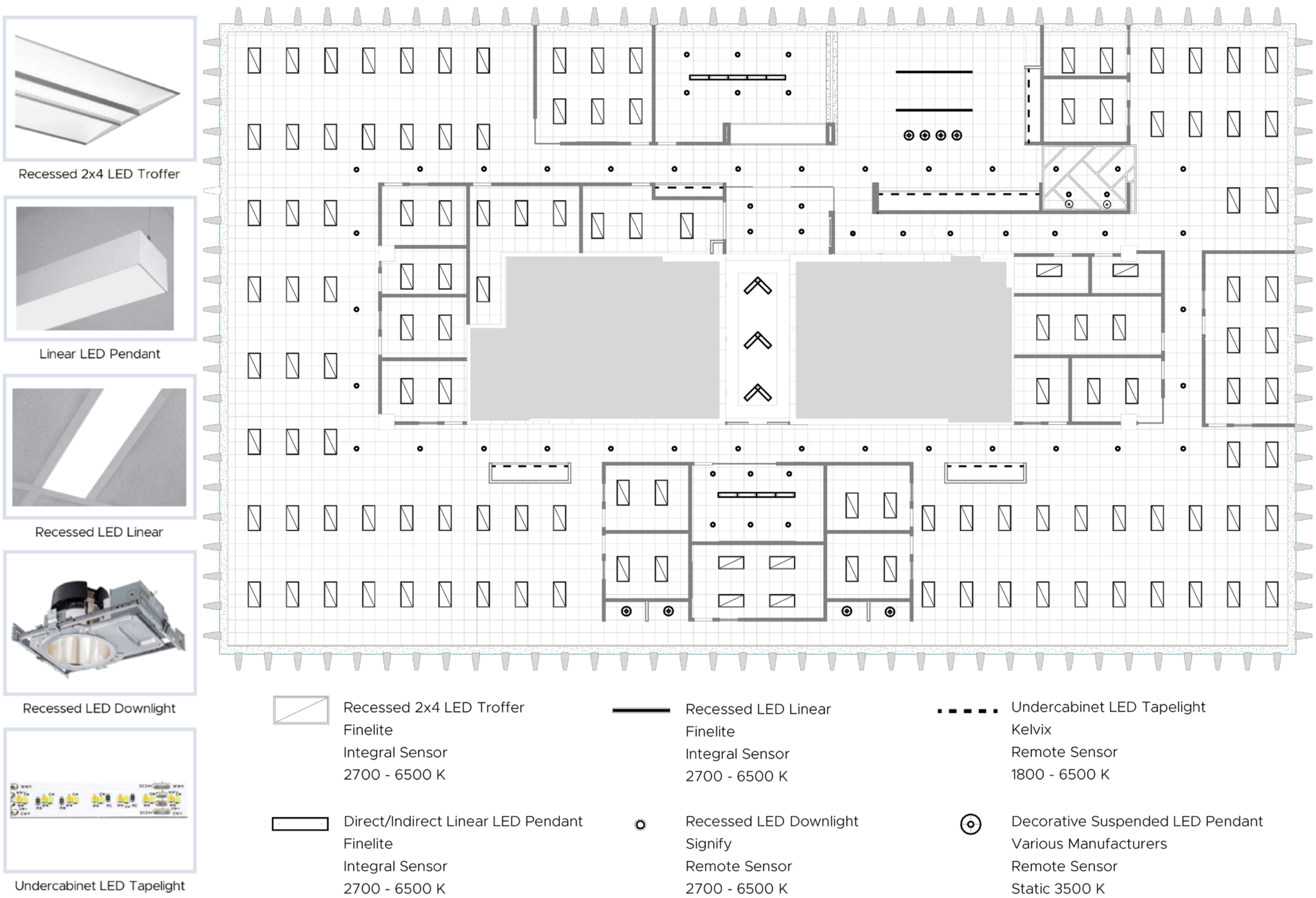

Figure 3: Lighting layout and office plan. The recessed troffers, recessed linear fixtures, and linear pendants have integral Enlighted micro sensors embedded in the fixture housing. The recessed downlights, decorative pendants, and under-cabinet tape light communicate with remote sensors.

Lighting Controls

The Enlighted controls platform is a wireless internet of things (IoT) system that uses distributed intelligence with the goal of increasing system resiliency and flexibility. The distributed intelligence in the sensors and user interfaces store schedules and certain settings locally to maintain local lighting operation regardless of the overall network status. The sensors and user interfaces communicate wirelessly via a proprietary digital protocol.

The luminaires use dedicated Signify drivers that are both DALI D4i and DALI Device Type 8 compliant. Integral and remote sensors transmit control signals from the sensor or user interface to the drivers via an interoperable adapter cable designed to connect most 2-wire drivers. The digital drivers are designed to control both the color temperature and the intensity with a single channel which is designed to be more precise than non-uniform scaling methods used with analog controls.

All spaces were equipped with the same manual wall controller, shown in *Figure 4*. The user interface, called Enlighted Room Controls, was designed to allow the user to turn the assigned fixtures on or off, raise or lower the light level, increase or decrease the CCT, rotate between preset scenes, and return to the scheduled lighting conditions after an override event.

The system uses three gateways that communicate wirelessly with the sensors and a dedicated server that can be on site or cloud based. The gateway transmits data captured by the sensors to the onsite server via a hard-wired ethernet connection for storage, analysis, and reporting. The gateway also returns data to the sensor when firmware updates are available or when profile settings are changed, for example. In this office, each gateway is connected to devices within a 5,000- to 7,000-ft^2 area.

While it is possible for the Enlighted IoT platform to tie into other building systems or building management systems, this feature was not exercised in the NEEA offices because there are multiple tenants in the building responsible for controlling and maintaining the lighting system in their space. The administrator portal used to change the lighting controls can only be accessed on site.

Figure 4: Functionality of the Enlighted Room Controls panel.

OBSERVATIONAL FINDINGS FROM INSTALLATION AND INITIAL PROGRAMMING

Installation

System installation and programming took place over a 5-week period in May and June 2021. The majority of the installation was completed between May 3-7, 2021, and continued part-time through programming in June. An overview of the observed activities is illustrated in *Figure 5*. Upon arrival, the installing contractor (IC) noted that they did not receive any design documentation to review ahead of time. The IC, the Pacific Northwest National Laboratory (PNNL) research team, and members of NEEA reviewed onsite parameters such as the location of existing luminaires and decided on orientation for the luminaires with integral sensors to optimize sensor location within the replacement scheme. Previously, the occupancy sensors were ceiling mounted, and were easily located for appropriate coverage. With integral sensors, the location is limited by the location of the luminaires themselves and luminaire orientation should be reviewed prior to installation in each typical space configuration.

The 2x4 troffers with integral sensors represent nearly 60% of the luminaires in the space. The lead IC and two electricians found the replacement

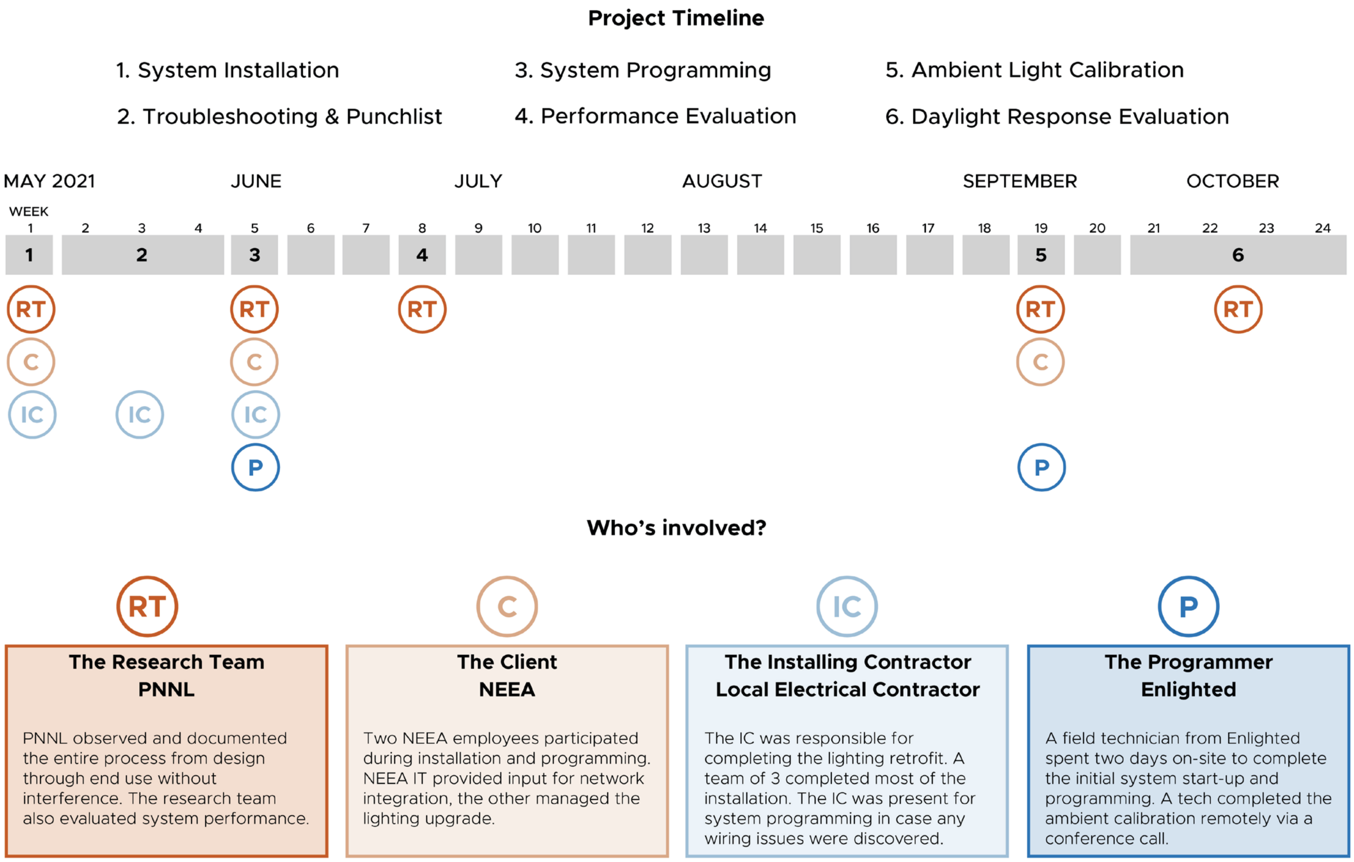

Figure 5: A summary of the project timeline from system installation through evaluation, including who was involved in each activity.

Issue	Resolution
Warm LED array not energized (cool LED array only), red sensor status	1. IC fixed a loose connection between the adapter cable and the sensor. 2. IC reversed polarity of two wires between the adapter cable and the sensor; however, this was originally thought to be a driver issue and the driver was ultimately replaced. 3. IC reversed polarity of two wires between the adapter cable and the sensor. 4. IC reversed polarity of two wires between the adapter cable and the sensor.
Blinking blue sensor status	5. A blinking blue indicator can mean that no energy measurement device is detected, which may be related to faulty components in the luminaire driver. The IC fixed a loose connection between the adaptor cable and the sensor; however, the driver was ultimately replaced.
Luminaire powered with half warm, half cool CCT, red sensor status or no status	6. IC fixed a loose connection between the adaptor cable and the sensor. 7. IC reversed polarity of two wires between the adapter cable and the sensor.

Table 1: A summary of the unexpected behaviors of 7 luminaires and solutions provided by the IC or the manufacturers.

process to be straightforward and felt the integral sensors simplified the process; it took approximately 30 minutes to remove and replace each fixture. After the 2x4 troffer luminaires were installed, 5% (seven luminaires) required troubleshooting. The IC easily resolved the problems; *Table 1* provides a summary. When the issues were initially discovered, the manufacturer expected them to be related to faulty drivers and sent several replacements to the site. During installation, the IC was told that polarity did not matter when connecting the integral micro sensor to an adapter cable in the luminaire. However, while waiting for the drivers to be delivered, the IC discovered that reversing the polarity ultimately corrected operation for four of the seven troublesome luminaires.

With a variety of building-wide and individual tenant renovations in a large office building, it can be challenging for property managers or facility staff to maintain up-to-date records and construction documents. In this case, updated as-built drawings for the office space were not available, and the lack of accurate drawings in addition to common onsite revisions resulted in important issues to consider in future projects:

- In several cases, inaccurate drawings and last-minute renovation alterations resulted in an incorrect quantity of equipment. The IC identified that there were not enough troffer luminaires, downlights, or wall control devices on site.
- Outdated drawings misled the design team on the current state of the emergency lighting approach. The drawings suggested that emergency-designated troffers were connected to a backup generator. During installation, the IC discovered that the existing emergency circuiting was substantially different than the design documents. This led to a complete redesign of the emergency lighting system during installation and several thousand dollars of unnecessary equipment and labor costs. Enlighted provided the IC with a revised line diagram that used existing equipment and maintained the control flexibility provided by an LLLC.
- Despite an accurate design specification, incompatible drivers were sent for the under-cabinet tape light; new drivers were delivered to the site.
- The new linear fixtures were too wide for the original opening in the metal ceiling grid. A subcontractor was hired to modify the metal grid to accommodate the new fixtures.

Throughout the installation, a member of the NEEA Information Technology (IT) department was on site to oversee the installation of the server in the NEEA IT room, located within the office suite. NEEA IT worked to configure the server within their ecosystem and communicated with Enlighted support to log in to the server prior to system programming.

System Programming

Laying the Groundwork

The system was programmed by an Enlighted field technician over 2 days in early June 2021. The programmer began mapping the sensors by pointing a laser at the sensors and located each on a digital reflected ceiling plan within the control system management application. Several disconnected sensors were discovered during this process; however, the IC was on site during programming to support troubleshooting, and the loose connections were easily resolved. Next, individual sensors were assigned to one of the three gateways based on location. To map the user interfaces, the programmer engaged “discovery mode” by pressing buttons on each keypad and located the interface on the same drawing. Sensors were then assigned to each user interface to enable local control.

Once the system had registered all the sensors and user interfaces, the programmer began defining basic operation for each space type based on the sequence of operations (SOO) document developed for the project. The settings for each space type are defined by time of day: morning, day, evening, and night. Maximum intensity, minimum intensity, ramp-up time, occupancy timeout, and sensor sensitivity

Period	Minimum Light Level when On (0-100%)	Maximum Light Level when On (0-100%)	Ramp-up Time (0-10 secs)	Occupancy Timeout (0.1-200 mins)	Occupancy Sensor Sensitivity (0-10)	Daylight Response Sensitivity (0-10)
Morning (6 a.m.)	0	80	2	3	1	5
Day (7 a.m.)	30	80	2	10	1	5
Evening (6 p.m.)	0	80	2	3	1	5
Night (9 p.m.)	0	80	2	3	1	0

Table 2: Configuration is defined according to the time of day. For each time period, NEEA specified the minimum and maximum intensity, ramp-up time (i.e., how quickly the luminaires reach maximum intensity), occupancy timeout duration, and sensor sensitivity settings. For occupancy sensitivity, 0 means the function is disabled and a setting of 1 provides the greatest sensitivity. For daylight sensitivity, 0 means the function is disabled. In this case, a setting of 10 provides the greatest dimming response.

were set for each space type. *Table 2* provides an example of the settings assigned to the open offices. NEEA defined the maximum and minimum intensities as well as the occupancy timeout duration. Default settings were adopted for the ramp-up time and sensor sensitivities.

Digging into Details

In addition to configuring the timeclock and other automated settings, the specification included detailed instructions as well as setpoints for occupancy and vacancy settings, grouping, daylight response, spectral tuning, manual dimming, scene control, and high-end trim. NEEA requested that the lighting in the open office areas and common spaces turn on to a dimmed level in the morning via timeclock control. When occupancy is detected, the intensity increases to the programmed maximum intensity until occupancy is no longer detected, at which point the intensity decreases to the minimum intensity. In the conference rooms and private offices, NEEA requested vacancy operation, where the lighting remains off until a user turns the lighting on at the wall switch. Adjusting the sensitivity of the occupancy sensor essentially alters the sensor's field of view. With a range of 0-10, this can be a useful setting to reassess if occupancy sensing is not operating as intended or if the occupants are not satisfied. For example, lighting in some private offices may turn on when occupants walk by in the hallway. Reducing the sensor's field of view can help confine the control and reduce false signals.

The system allows for luminaire grouping definitions for user interfaces, occupancy sensing, and daylight response. In the private offices and conference rooms, these groups are largely identical; the luminaires in private offices operate as a single group in response to occupancy or daylight dimming control signals. NEEA requested that each luminaire in the open office and common areas respond to occupancy control signals independently, a benefit provided by the LLLC approach. NEEA decided during programming that the luminaires in the open offices should be grouped for daylight response to maintain visual uniformity. As daylight grouping was not specifically provided in the design documentation, the programmer applied a default grouping strategy that was code compliant and modeled after Title 24 code requirements. The programmer defined a primary and a secondary daylight zone in each open office area. The size of the zones varies between 2 and 10 luminaires.

Like occupancy sensitivity, daylight response sentivity is a programmable input. Increased sensitivity will enable a more aggressive response to available daylight. The flexibility of the LLLC system allows for additional settings related to daylight response, including the role of each sensor (e.g., report only, report and act) and whether the group should dim in response to the maximum sensor reading in the group, minimum reading, or an average of all sensors in the group. Further, the programmer can input duration thresholds and rate-of-change thresholds to fine-tune operation.

The settings for spectral tuning are currently limited in comparison. A location-based schedule is automatically created to smoothly transition between setpoints for sunrise, solar noon, sunset, and night (as specified in profile programming). The setpoints are based on a programmable ratio between warm and cool LED outputs. Lastly, scene control was used in the conference rooms to provide various intensity levels as well as a presentation scene to support screen viewing.

System Programming Follow-up

The system was fully functional at the end of the second day of programming. During the process, the programmer identified one issue with the manufacturer-approved design and submitted a support ticket for assistance.

The office architecture features coffee bars and printing alcoves with recessed linear lighting in the corridors leading to the open office spaces. The luminaires are programmed to increase intensity to full output when occupancy is detected. One integral sensor was wired at each end of the same linear fixture so that an occupant approaching from either direction would trigger the lighting to change. At the time, the programmer identified this as an issue that cannot be programmed as intended, as a luminaire cannot be assigned to more than one sensor. Ultimately, one sensor was disabled in each fixture. After the initial programming, the manufacturer provided a solution to achieve the original design intent. Instead of being physically disabled, the sensor should have been digitally disassociated with the luminaire to appear “fixtureless.” This allows both sensors to be programmed as a group so that the fixture responds when someone approaches the coffee bar from either direction.

IMPORTANCE OF THE SEQUENCE OF OPERATIONS

Onsite adjustability is a major benefit of advanced digital lighting controls; however, it is critical that the client and lighting specifier discuss and document the system-specific configuration settings within the architectural drawings as well as the control intent narrative (CIN) and SOO design documents prepared by the specifier. Detailed, organized documentation can increase programming success and client satisfaction post-occupancy.

The CIN is typically organized by space type and allows the lighting specifier to select a system that will provide the appropriate functionality. Later in the design process, the SOO is developed considering the manufacturer-specific setpoints required for programming. While the CIN is used to generally describe control system capabilities and requirements, the SOO should contain contractually enforceable language and provide prescriptive instructions for system programming.

Specifiers should include documentation of grouping for all control strategies, including occupancy response, daylight response, preset scenes, and intensity/color control, as applicable to each project. In addition, facility managers and onsite staff should know which settings are adjustable and understand why the setpoints were chosen to have an appropriate expectation of system operation. The following are examples of setpoints and details to include in an SOO document:

- Building hours of operation and other scheduled programs
- Occupancy/vacancy method and timeout duration
- Daylight response event details (e.g., How often should a change occur? Should the changes be instantaneous or over some length of time? Should the lighting dim to a specified minimum or dim to off?)
- Demand response event details (e.g., Will lighting respond similarly to demand response on weekdays, weekends, and holidays?)
- Night lighting and emergency lighting methods and zoning
- Maximum and minimum lighting levels
- Control-strategy-specific grouping (e.g., occupancy, demand response, daylight response)
- Scene settings, including intensity and color
- Manual override event details (e.g., What happens at the end of a manual override? How long should each manual override last?)

As it is not uncommon for setpoints to be omitted from design documents or changed during the construction process, it is equally important for the lighting specifier and facility team to document the eventual programmed settings. Creating an “as-built” document for the lighting control system can support future troubleshooting and inform system settings for future projects.

Date	Operation	Enclosed Spaces	Open Office
06/2021	On	4600 K	4600 K
	Auto	3500 K	3500 K
10/2021	On	4600 K	4600 K
	Auto	6500 K, tunable schedule enabled	3500 K
11/2021	On	4600 K	4600 K
	Auto	All lighting turns off or 3500 K	3500 K

Table 3: Operation of the wall controls over time. Immediately after installation in June 2021, turning the lighting on at the wall switch resulted in a color temperature of 4600 K, while the lighting that turned on automatically turned on at 3500 K. Behavior of the "On" and "Auto" buttons on the wall controls changed over time.

The final step in the programming process was to train the sensors to recognize the ambient contribution from surrounding luminaires to tailor the performance of daylight responsive dimming. The ambient training session took place after dark; an Enlighted employee conducted the training via a video call with members of the research team on site. The automated process took about 20 minutes to complete. The training essentially establishes a baseline ambient electric lighting contribution that allows the sensor to factor ambient electric light into the daylight dimming response.

PERFORMANCE EVALUATIONS

Lighting Quality and General Functionality

Several weeks after the initial installation, the research team returned to evaluate system performance. At this time, the team identified unusual behavior with the user interface operation and reported the problem to the manufacturer. As previously mentioned, the lighting in the enclosed spaces was programmed to remain off until a user manually turned it on; however, the lighting in the open offices was turning on automatically in the morning. The lighting following the automated program turned on at 3500 K, as specified. However, when a user manually turned the lights on via the user interface in an enclosed space, the lighting turned on at 4600 K instead of the specified 3500 K. The origin of the 4600 K setpoint remains unclear. When the system was initially programmed in June 2021, pressing the "Auto" button in all space types returned the lighting to the specified 3500 K; however, behavior of the wall controls continued to change over time, as summarized in *Table 3*. When the team returned in October, it was discovered that the tunable schedule setting was enabled in certain spaces. A month later, pressing "Auto" in enclosed rooms turned all the lighting off, resetting the room to the originally scheduled "vacancy mode." As of the writing of this report, the manufacturer is still working to resolve the issue.

The evaluations of the lighting quality and dimming performance also offered an opportunity to test system interoperability. All measurements were captured at night with a calibrated Konica Minolta CL-500A.[1] The evaluations provided the following outcomes:

- CCT was consistent as the downlights, troffers, and recessed linear and pendant fixtures were dimmed. Measurements were taken at several luminaire types at full, 80%, 50%, 30%, and 15%

[1] Serial Number: 10002008

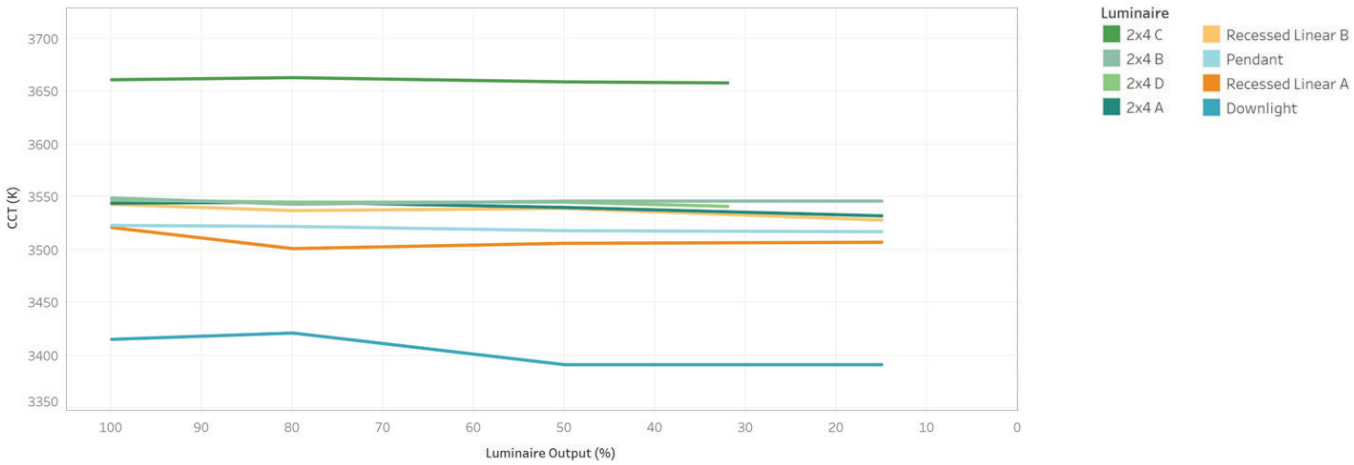

Figure 6: CCT measurements at eight luminaires. The measurements were taken approximately 2" from the surface of each luminaire. Apart from one troffer (2x4 C) and the downlight, the CCT measurements were consistent with one another over the dimming range. Measurements were captured at 100%, 80%, 50%, 30%, and 15% output.

luminaire output, as defined by the control system interface. All luminaires were programmed via the control system interface to 3500 K. *Figure 6* shows that most of the measured values were between 3500 and 3550 K, with the exception of one downlight and one troffer.

- The control system communicates CCT settings to each luminaire driver via a precise digital signal in degrees Kelvin. Upon receipt, each luminaire driver interprets that signal according to internal driver programming. As digital controls allow for two-way data transfer, the luminaire driver sends the interpreted value back to the control system as the "measured" or reported CCT output of each luminaire. CCT values reported from 24 luminaire drivers were highly consistent (varied between 3502 and 3508 K), which was expected as all luminaire drivers received the same 3500 K signal from the control system. Measurements captured at the same 24 luminaires (approximately 2" from the surface or luminous aperture) varied between from 3391 and 3663 K, most likely due to differing LED components within each luminaire and imperfect handheld measurement techniques.

Occupancy and Vacancy Settings

The research team developed an evaluation protocol to test general occupancy and vacancy sensor performance as well as occupancy sensitivity to minor motions such as reading a book or typing on a laptop. The steps of each protocol are summarized below.

Occupancy or Vacancy Function:

1) Complete measurements when the room/area is unoccupied.
2) Turn all lights on with wall switches, as appropriate.
3) Exit the room and close the door or move well outside of the sensor coverage area.
4) Wait for timeout period.
5) Record result: Pass = lights turn off at timeout, Fail = lights do NOT turn off at timeout.

1) For private rooms, enter the room to test vacancy.
2) Record result: Pass = lights do NOT turn on automatically, Fail = lights turn on automatically.
3) Repeat steps 3 – 5 above.

The research team found that turning the lights on at the user interface in vacancy-controlled rooms initiated a control override that doubled the timeout period. For example, the lighting in the manual-on private offices was programmed to turn off after 3 minutes of vacancy; however, it was observed that the lighting turned off after 6 minutes of vacancy. In the open offices, the automatic-on lighting turned off as programmed, after 3 minutes of vacancy.

Occupancy Sensitivity, Minor Motion:

1) With all lights on, sit at a typical occupant location in the space.
2) Hold the magazine or book and turn pages.
3) Conduct the test for timeout period + 1 minute.
4) Record result: Pass = lights do NOT turn off automatically, Fail = lights turn off automatically.

Occupancy Sensitivity, Micro Motion:

1) Repeat steps 1 – 4, right. Micro motion is tested by typing continuously on a laptop placed on a desktop or table for the duration of the timeout period + 1 minute.

All of the locations passed the minor motion sensitivity test and all but one private office space passed the micro motion sensitivity test. In the open office areas, each luminaire responds to occupancy signals independently. The evaluators observed that the lighting in their immediate vicinity stayed on, while fixtures that were triggered as the evaluators were walking to the testing location dimmed as specified to 30% output after the timeout period. Due to the individually controlled nature of the LLLC system, maintaining a minimum fixture output of 30% instead of dimming to off can reduce the contrast and “checkerboard” pattern that occupants may dislike or find distracting in an office space.

Despite the positive evaluation outcomes, NEEA adjusted the occupancy timeout period in the large conference rooms and private offices from 10 minutes to 45 and 120 minutes, respectively, after several occupants reported being left in the dark. Further, as interaction with the user interface essentially doubles this timeout period, the lighting in private offices will stay on for up to 4 hours after occupants leave the space.

Daylight Responsive Controls

The research team developed testing protocols to further understanding of the ambient light sensitivity sensor adjustment and the effect on dimming response.

Ambient Light Sensitivity Testing

Within the control system, a programmer can adjust the sensor sensitivity to ambient light to between 0 and 10. A value of 0 means that the feature is essentially turned off, and a value of 10 will enable the maximum dimming range. The value is typically set to a manufacturer default of 5, as this setpoint is not frequently included in design documentation. While the default setpoint of 5 will enable operation of the feature, this setting can impact potential energy savings if set too low and occupant satisfaction if the dimming response is too aggressive. The following protocol was developed to document the change in luminaire response over the sensitivity range.

Protocol:

1) Close all blinds. Configure appropriate sensitivity level (between 0 and 10) within the control system interface. Wait 10 minutes for the configuration update.
2) Open all blinds; turn on all lights in the room. Wait 5 minutes for daylight dimming response to settle.
3) Record luminaire output levels (0-100%) from the control system interface.
4) Turn off all lights.
5) Adjust sensitivity level and repeat steps 1-4.

Ambient light sensitivity was tested in a south-facing open office space and a north-facing conference room. The lighting in the north-facing

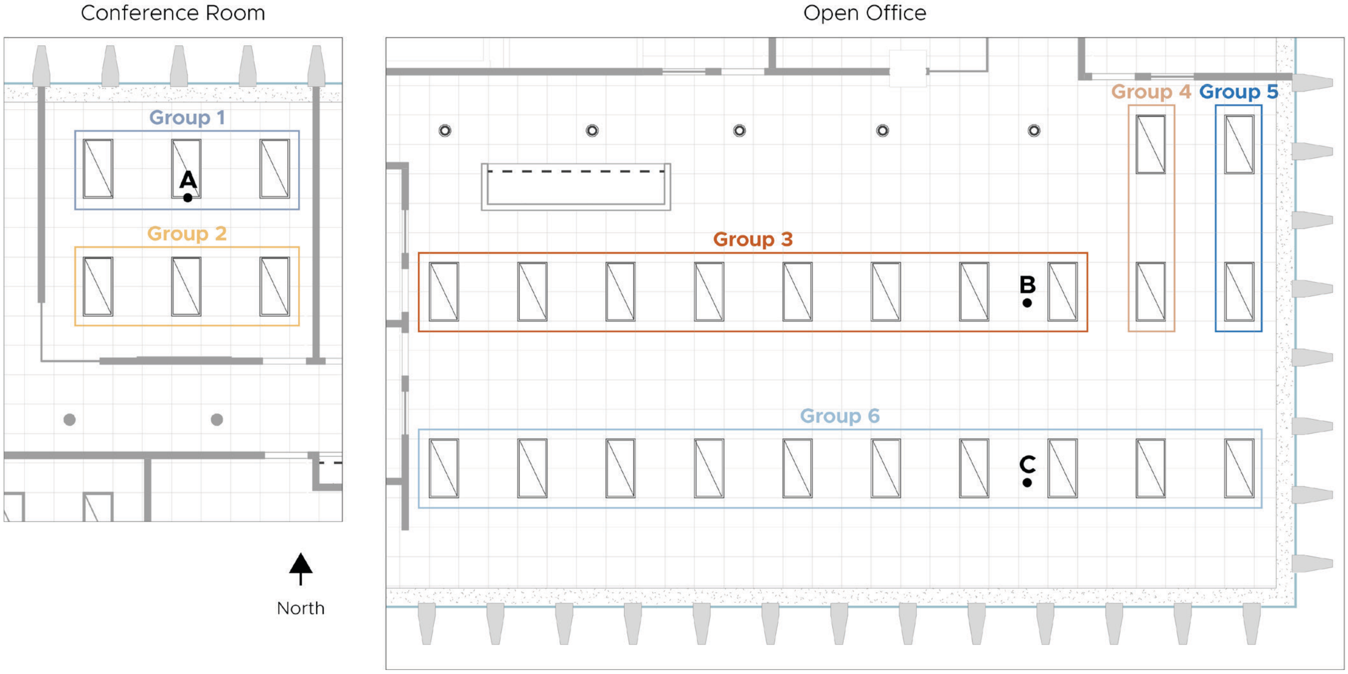

Figure 7: Daylight groups for a north-facing conference room (left) and a south-facing open office (right). In each space, the programmer defined daylight groups following a primary and secondary daylight group facing north, south, east, and west. Horizontal illuminance measurements for locations A, B, and C are discussed below.

conference room included two daylight groups, as shown in *Figure 7*. There were four larger daylight groups in the open office.

In the conference room, the luminaires in Group 1 closest to the windows dimmed to as low as 16% output at the maximum sensitivity setting illustrated in *Figure 8*. The luminaires located farther from the windows in Group 2 remained at 72% output over multiple sensitivity settings. When the sensitivity was set to 0, all the luminaires returned to the maximum daytime output of 80% as expected. As daylight conditions did not change during the test, the results suggest that a substantial range of dimming performance can be achieved simply by changing the sensor sensitivity. At the default setting of 5, Group 1 would have dimmed to approximately 50%, even though there was enough available daylight for the system to dim to 16% output.

In the open office, Groups 3 and 4 dimmed to off at the maximum sensitivity setting while Group 1 did not dim in response to available daylight at any sensitivity setting. Similarly, at the default setting of 5, Groups 2, 3, and 4 would have dimmed to approximately 40% output instead of achieving greater dimming or turning off in response to the available daylight.

Although detailed field-adjustable settings are not always readily available to specifiers, it is important to understand how decisions made during programming influence system operation. Ask for more information regarding programming inputs after the final system has been selected.

Dimming Response to Available Daylight

The research team measured the dimming response to available daylight in several spaces to verify that the system was performing as specified. For these office spaces, NEEA wanted to maintain a nominal 300 lx on the horizontal task plane, meaning that when ambient light

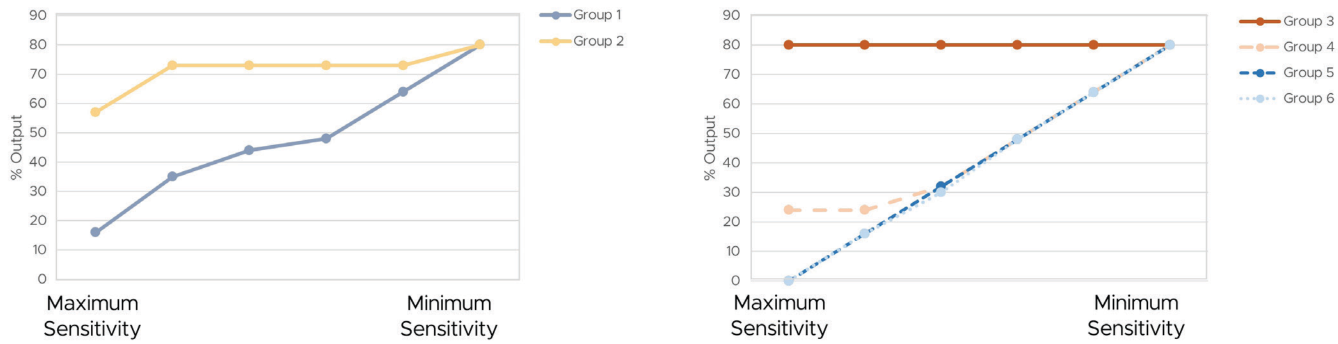

Figure 8: Dimming performance over the ambient sensitivity range for a conference room and an open office space. In the conference room, Group 1 varied between 80% and 16% dimming under the steady daylight conditions. In the open office, Groups 5 and 6 dimmed to off at the maximum sensitivity setting while Group 3 did not dim at any sensitivity level.

above this threshold is detected, the system should respond by dimming. As the sensors capturing this measurement are rarely located at the task plane, field adjustable settings such as sensor sensitivity can help fine-tune performance as necessary. The team evaluated the dimming response at the maximum sensitivity setting, which allowed for the greatest daylight response dimming range.

Protocol:

1) Adjust the daylight response sensitivity from the default setpoint of 5 to the maximum response, 10. Wait 10 minutes for the configuration update.
2) Close the blinds and turn on all lighting to maximum output (80% in this office).
3) Measure illuminance at task plane at specified locations.
4) Open the blinds, wait 5 minutes for the lighting to respond.
5) Repeat step 3.
6) Turn off the lights.
7) Repeat step 3.

This protocol allows the research team to capture maximum illuminance due to the electric lighting, the illuminance level during daylight response dimming, as well as the illuminance due to daylight only. If illuminance levels in the daylight dimming state fall significantly below the specified threshold of 300 lx, the system may be responding too aggressively. Likewise, if the available daylight measurements are significantly above the threshold, the electric lighting system should dim or turn off in response.

Measurements were collected on clear days in September and October between 11 a.m. and 2 p.m. A summary is presented in *Table 4*. Illuminance was measured on the conference table under a luminaire in the primary daylight zone in the north-facing conference room (Location A). When the blinds were closed and the lighting was on to 80% output, the horizontal illuminance was 435 lx, which already exceeded the target illuminance of 300 lx. After the blinds were open and the system dimmed in response to available daylight, illuminance increased to 502 lx. The luminaires in the primary daylight zone dimmed to 4% output in response to available daylight entering the space. Although the secondary daylight group dimmed very little in response (80% to 72%). Daylight provided approximately half of the measured horizontal illuminance.

In the south-facing open office, horizontal illuminance was measured on two workstations; one was located near the building interior (Location B) and the other was located along the southern window wall (Location C). Daylight contribution alone exceeded the 300-lx target in both the primary and secondary daylight zones. In the primary daylight zone, the luminaires dimmed

Measurement Location	Room	Daylight Group	Electric Light *(Blinds closed, lighting on)*		Daylight and Electric Light *(Blinds open, lighting on)*		Daylight *(Blinds open, lighting off)*	
			Horizontal Illuminance (lx) | % Output					
A	North Conference	Group 1 - Primary	435	80	502	4	277	0
B	Southeast Open Office	Group 3 - Secondary	484	80	753	80	328	0
C	Southeast Open Office	Group 6 - Primary	545	80	1808	40	1678	0

Table 4: Horizontal illuminance measurements were collected in a conference room and an open office space. Measurements were collected for three lighting conditions to document the lighting control system dimming response to available daylight.

form 80% output to 40% output when the blinds were open while the luminaires in the secondary group did not dim at all.

As previously mentioned, the daylight groups in the open office space contain 8 to 10 luminaires that were programmed to use the average ambient light sensor reading to determine an appropriate dimming response. Although there was abundant daylight in the space, the fluctuation of conditions over the large daylight groups most likely resulted in a lower average sensor reading and therefore a greater electric lighting contribution was maintained. The distinction between primary and secondary daylight groups is aligned with the daylight penetration in the space; however, smaller groups may allow for greater daylight response dimming in the open office space. Although the system can respond to ambient light individually as a feature of the LLLC approach, NEEA decided to group the luminaires to reduce a more noticeable or potentially distracting response that may be associated with individual luminaire control. NEEA has considered reducing the size of several daylight groups from 8 or 10 luminaires to 3 to 5 luminaires with a goal of achieving greater dimming response without creating a “popcorn effect” or “checkerboard” appearance.

DAYLIGHT PENETRATION IN OFFICE SPACES

Even with generous glazing and no surrounding building obstructions, available daylight at desk locations further from the windows was found to be significantly less than at desks along the window wall. For example, in the north-facing open office, available daylight measured on the desktop of a workstation against the window wall was 436 lx, while the horizontal illuminance measured at an interior workstation was only 157 lx. In the south-facing open office with direct sunlight, the horizontal illuminance measured at a workstation along the exterior wall was 1,678 lx compared to 328 lx measured at an interior workstation.

Tunable-White Lighting

During the initial performance testing, the team visually observed consistent white-tuning regardless of the luminaire type. All luminaire types responded similarly to the color temperature control settings applied via the control system. In addition, the team observed that all lighting paired to a particular wall control user interface responded similarly when the color temperature was increased or decreased. At this time, the schedule-based tunable lighting feature has not been tested as NEEA has decided to maintain a static CCT of 3500 K. End users may still manually adjust the CCT at the user interfaces in each space.

CONCLUSION

Observing lighting installations in real-world settings can help close the gap between the promised energy savings, operational benefits, and inevitable people-related barriers to successful and continued adoption of advanced lighting control systems. Overall, the system managed to pass Enlighted control signals through Signify drivers on to luminaires from several manufacturers, including Finelite and Kelvix. All luminaires responded similarly to intensity and color tuning control signals; however, unexpected behavior related to rooms operating in vacancy mode remains an issue, with lighting turning on to odd color outputs.

The LLLC installation in the NEEA office space reiterated the importance of accurate and thorough documentation as well as the benefit of separating system "wants" from system "needs." Inaccurate as-built documents led to numerous costly onsite revisions. If possible, onsite conditions should be reviewed prior to procurement. Additionally, the terminology and information required to program the system did not always align with design documentation as system-specific information is often not available. Manufacturers and their sales representatives may choose to provide specifiers with a programming template prior to the installation so that the specifier can provide information tailored to the specific settings for the appropriate system.

Compared to incumbent technologies, advanced lighting controls are highly capable and often are delivered with greater capability than is required for the project. Even 2 years post-installation, neither NEEA nor the research team has fully exercised all of the features and capabilities of the IoT platform. Instead, NEEA has focused on operation of the system "needs" – manual operation, dimming, high-end trim, automated scheduling, occupancy sensing, and daylight response – before enabling the extra capabilities or services such as white-tuning or asset tracking.

Focusing on system needs has still introduced complexity. The field-adjustable occupancy settings have allowed NEEA to deviate from initial programming and improve functionality for their space and employees; however, the adjustment resulted in excessive timeout durations that do not support their energy goals. Further, the numerous, granular settings contributing to the daylight response may overcomplicate operation, which can lead users to disable functions altogether in favor of occupant comfort or satisfaction.

As the office renovation was completed during the pandemic, when most employees were working remotely, use of the lighting controls remains minimal. Looking forward, the research team will continue to monitor user interactions with the system as employees return to the office.

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