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A High-Fidelity Medium Office Baseline Model for Evaluating the Impact of Design Decisions and Occupant Behavior on Lighting Control Performance

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Abstract

Reference building models can serve as a common baseline for research investigations and evaluations of design choices. Despite lighting being one of the largest single users of electricity in commercial buildings, lighting systems in reference buildings are commonly modeled as maximum building-type or space-type power densities defined in building energy codes. Further, energy use is typically estimated by modulating the lighting power over the course of a day via simple occupancy schedules that may not accurately portray human behavior or the performance of occupancy-based lighting controls. While this approach is suitable for some use cases, it is not adequate for exploring the impact of luminaire selection, space-specific control strategies, and occupant behavior. This paper presents the development of a high-fidelity reference model of a medium office building that includes interior architecture, an occupant distribution model, and a detailed lighting design intended to support more realistic evaluations of lighting control strategies and approaches to modeling occupant behavior. The model includes 13 market-representative LED luminaires, meets occupant lighting needs by complying with applicable recommended practices defined by the Illuminating Engineering Society (IES), and meets energy code power density and control strategy requirements in ANSI/ASHRAE/IES 90.1-2019. The luminaire-level connected load (26,037 W) of the lighting layout is lower than what would be estimated by simple building-type (34,304 W) and space-type (31,200 W) power density methods. The model includes 12 space types and 107 rooms with workstations for 268 occupants. The interior architecture varies on each of the three floors to introduce room and space-type diversity that further exposes the impact of design choices and occupant behavior. The model has already been used as a baseline for research on circadian lighting design strategies, lighting–HVAC data integration, and whole-building life-cycle assessments—demonstrating its utility as a common reference for a range of lighting research.

Keywords: reference building models; building information modeling; lighting energy modeling; medium office building; lighting controls; digital twin-ready models; building performance and energy efficiency

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1. Introduction

Reference building models can serve as a common baseline for exploring the impact of a wide variety of building system design decisions. For example, reference building

models are commonly used to quantify the energy savings achieved by successive editions of ANSI/ASHRAE/IES 90.1 Energy Standard for Buildings Except Low-Rise Residential Buildings [1] (henceforth referred to simply as 90.1) and to study the effect of combined energy conservation measures and location on building performance [2]. Additional example uses that highlight their diverse utility include investigations of region-specific internal loads and occupancy patterns [3], strategies for urban heat island mitigation on the scale of a city block [4] and the effects of roof material, heating system, and snow load on energy use [5]. Across these examples, the reference model is used as a high-level, largely fixed baseline and the object of study is a single varied parameter.

Despite lighting being one of the largest single users of electricity in commercial buildings [6], existing reference models generally represent lighting systems very crudely, typically as lighting power density (LPD) at the building level that is then modulated over the course of a day via simple occupancy schedules. While this approach may be adequate for some use cases, including aforementioned energy code developments or estimations of regional or national energy use, it is not adequate for exploring the impact of luminaire selection, space-specific control strategies, and occupant behaviors that determine how a lighting system actually performs once it is installed in a real building.

1.1. Reference Models for Lighting Systems

Reference building models have been previously used by lighting practitioners for use cases including investigation of the effects of light-filtering cellular shades on energy and daylighting [7] and evaluation of the impact of window-to-wall ratio on energy consumption when daylighting controls are implemented [8]. In another example, twelve reference commercial building models were utilized to simulate lighting power density and daylighting controls impact on building energy consumption and life-cycle costs and assess the economic and environmental impacts of building energy codes [9]. Notably, these and other existing examples are largely focused on daylighting or energy code impacts on large populations of buildings and use reference models with lighting systems represented by LPD at the whole-building or space level.

Lighting practitioners have recognized the limitations of existing reference models and their common use of LPD-based modeling and have created higher-fidelity reference models with additional detail required for their specific research questions. For example, Reinhart et al. [10] created a widely used 3D model of an office room with desks and computer stations for daylighting simulation work and Geisler-Moroder et al. [11] created a partial model of a real building, containing only a single small office and a factory hall, to compare daylight and electric lighting simulation tools. The focus on specific research questions limits the reusability of these and other models with similar origins, which are commonly small and overly simple, do not represent a realistic whole building, or do not incorporate a luminaire-level design with control strategies across varied space types. In some prior work, lighting practitioners have only realized the limitations of existing reference models after analyzing the results of their work. In one instance, researchers that attempted to use reference models with whole-building-level lighting systems to train and evaluate model-predictive controllers for lighting and shading systems concluded that the demonstrated performance was hampered by the lack of realistic variability and space use [12]. These examples highlight the need for reference models with greater detail and broad applicability.

Reference models are finding utility for emerging building system integrations and digital twin use cases. Modern lighting systems can measure and report a wide range of operational (e.g., input voltage, energy use) and environmental conditions (e.g., occupancy, temperature) at a granular level (i.e., building space, luminaire). The data produced by

such systems can be readily used to support energy management and system maintenance, as well as a wide range of other use cases. However, the context for this data is missing from reference building models that do not contain rooms and space-type details, or, for example, the relationship between lighting and HVAC zones that is necessary for designing HVAC systems that utilize occupancy data provided by lighting systems.

1.2. Research Objectives and Contribution

The usefulness of reference building models is well-proven for many lighting use cases. However, growing interest in using reference building models to explore complex design decisions (e.g., how to implement control strategies) and the impact of occupant behavior, or demonstrate novel tools and workflows (e.g., digital twins, automated commissioning, fault detection and diagnostics) is stymied by models with low-fidelity representations of lighting systems. This paper addresses this gap by presenting a high-fidelity reference model for a complete and realistic medium-sized office building (HFMOB), with full and varied architectural detail, and a luminaire-level lighting system. The HFMOB is intended to serve a role similar to other reference building models, by providing a common reusable baseline that others can use for comparative analysis or application demonstrations.

The claim that the HFMOB is realistic is supported with significant documentation of its development, including how the lighting design incorporates realistic lighting equipment, follows recommended industry practices for controlling the lighting and serving occupant needs, and meets applicable energy codes. The HFMOB builds on an existing reference model by adding realistic interior architecture that drives the lighting design choices and introduces space-type variation that drives variation in occupant behavior and expected occupant distribution. The motivation for publishing the HFMOB model was interest in using it to support a growing set of use cases. The paper concludes with references to some existing known uses, as well as others on the horizon.

2. Methods

Prior to initiating the development of the new reference building model, two options were considered: develop an entirely new model, or start with an existing reference model, and incorporate new realistic details that are consistent with the defined properties of the model. Starting with an existing model increased usability, offered the potential benefit of user familiarity, and reduced the required task. The following sections include an overview of existing models that were considered for use as a starting point, followed by a detailed explanation of how the new realistic details were developed and added to the chosen model—including interior architecture, space types and corresponding occupant distributions, lighting layout, and lighting control strategies.

2.1. Existing Reference Models

In 2011, Lawrence Berkeley National Laboratory, PNNL, and the National Laboratory of the Rockies developed a suite of Commercial Reference Building Models. The portfolio included 16 building types representing approximately two-thirds of the commercial building stock in the U.S. Each model contained the following information [13]:

- Building program: location, total floor area, plug and process loads, ventilation requirements, occupancy, space environmental conditions, service hot water demand, and operating schedules;
- Building form: number of floors, aspect ratio, window fraction, window locations, shading, floor height, and orientation;
- Building fabric: exterior walls, roof, floors, windows, interior partitions, internal mass, and infiltration;

- Building equipment: lighting loads, HVAC system types, water heating equipment, refrigeration, component efficiency, and equipment control settings.

To support energy code development programs, PNNL subsequently published enhancements to the original suite of Commercial Reference Building Models [14,15], resulting in the Commercial Prototype Building Models, which are regularly updated with input from industry experts as the codes are modified.

The current publicly available set of Commercial Prototype Building Models maintained by the Building Energy Codes Program (BECP) contains 16 building types and 19 climate locations, resulting in 3344 total building models representing approximately 75% of commercial building stock [16]. These BECP models were created to be used in EnergyPlus (Golden, CO, USA) and are publicly available for download as EnergyPlus model input files (.idf) and the corresponding output files (.html) for representative climate locations. Each model also has a scorecard in the form of an Excel (Redmond, WA, USA) spreadsheet that summarizes the details and assumptions included in the EnergyPlus input files. The Excel scorecards typically include a schematic floor plan showing the space types or thermal zones included in each model; however, three-dimensional building models are typically not provided.

The spatial resolution in the BECP models varies among building types. Spatial resolution is often directly related to the thermal zones, which vary in size and specificity based on the program of the building. Some models include interior architecture and space type definitions within these thermal zones, but the thermal zone definitions are typically the lowest level of spatial definition. Importantly, for models without such interior detail, the thermal zone definitions are also used to define occupant load, LPD, and building water use, among other building system attributes. For example, the current BECP medium office model does not contain any interior architecture, and defines just one space type, office, as shown in Figure 1. The medium office model contains 15 thermal zones, consisting of one core zone and four perimeter zones on three floors. The occupant load and LPD are uniform across all 15 thermal zones.

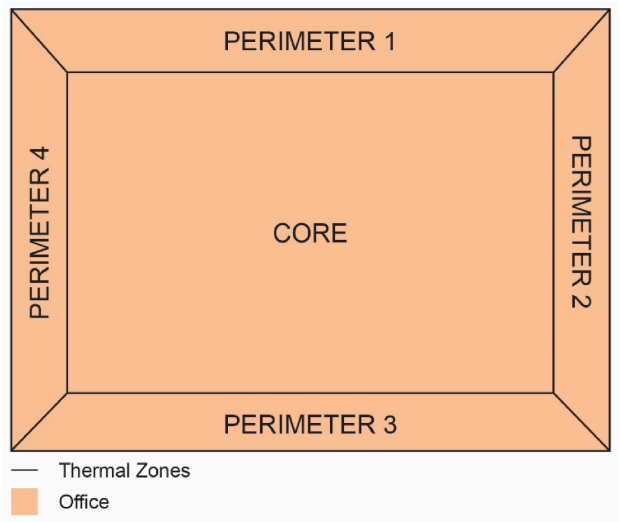


Figure 1. Building Energy Codes Program medium office building model floor layout.

In contrast, the BECP hospital model has greater spatial detail, including some interior partitions, and multiple space types—as shown in Figure 2, adapted from BECP Hospital Prototype Scorecard (updated 18 October 2018). The five-story model contains 10 unique space types (e.g., exam, corridor, operation) and four thermal HVAC zones (e.g., VAV 1, VAV ICU) with LPD and occupant load values assigned to each space type. This increased

level of spatial detail allows designers and energy modelers to consider space-specific code requirements, energy consumption profiles, and occupant behaviors in their analysis, which can result in a more realistic portrayal of building operation. The BECP models are very familiar to a wide range of building and lighting practitioners and are commonly used for analyses of impacts on large populations of buildings. However, they are less commonly used to evaluate the impact of design decisions for representative buildings. This is particularly true for lighting control design decisions, as none of the BECP models contain full interior architecture or a luminaire-level lighting layout.

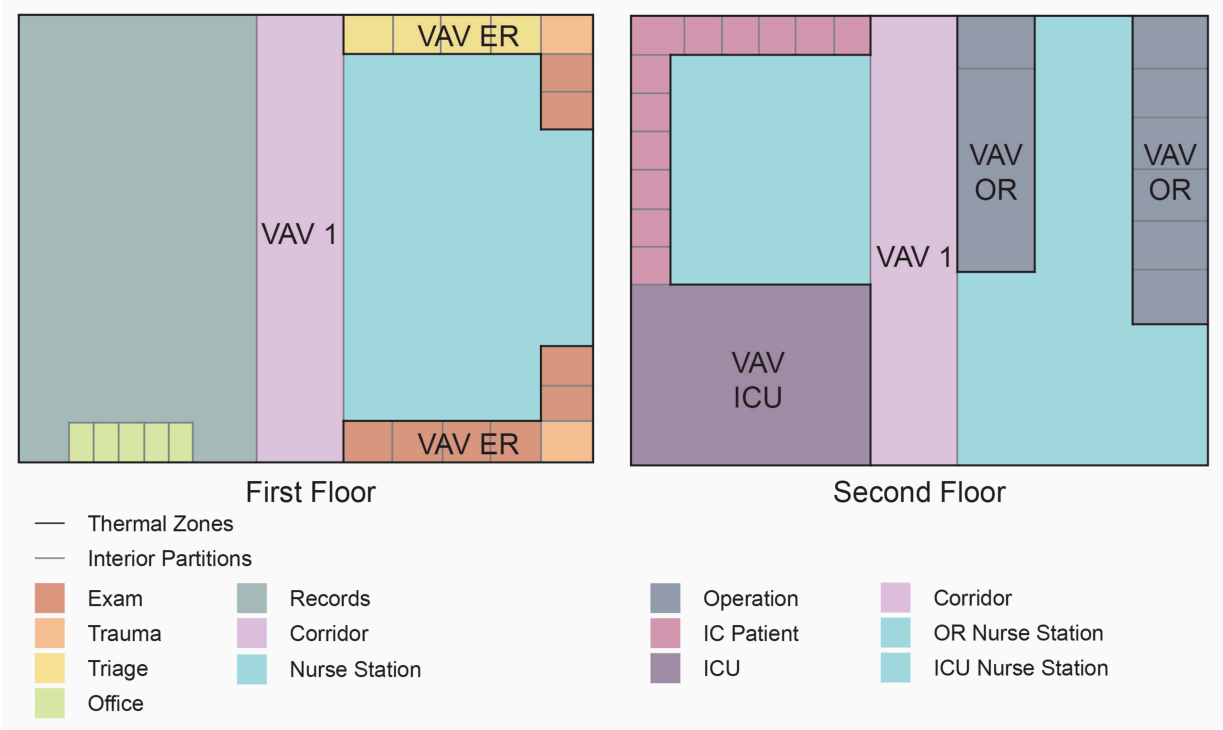


Figure 2. Building Energy Codes Program prototype hospital building model layout.

To expand the current Commercial Building Prototype Model suite, Oak Ridge National Laboratory (ORNL) developed models for building types that were not included in the original BECP development, such as courthouses [17], and created derivative models for some building types, including but not limited to supermarkets, to incorporate details covered by changes in energy codes [18].

The BECP medium office model is perhaps the most used and familiar model in the set of prototypes, and most cited in the literature. In 2019, ORNL developed a derivative medium office building model with spatial resolution similar to the hospital and other prototype buildings as well as varying LPD, occupant density, and plug and process loads based on space type [19]. The ORNL medium office building defines 12 space types; allocation of each space type was based on prior research completed by PNNL that resulted in the development of a National Commercial Construction Characteristics (NC3) database [20] for the purpose of understanding common commercial design practices for a given building type. Two simplifications were implemented in the ORNL model: the core thermal zone is the same for all three floors, and the space types were allocated in the same manner for the second and third floors. The resulting programmatic floor plans are shown in Figure 3. The core area (the border is defined by the corridor/transition space type) contains open office, active storage, stairway, lobby, restroom, electrical/mechanical, and dining areas. The remaining open office space, enclosed office space, conference rooms, classroom, and lounge are located around the exterior of the floor.

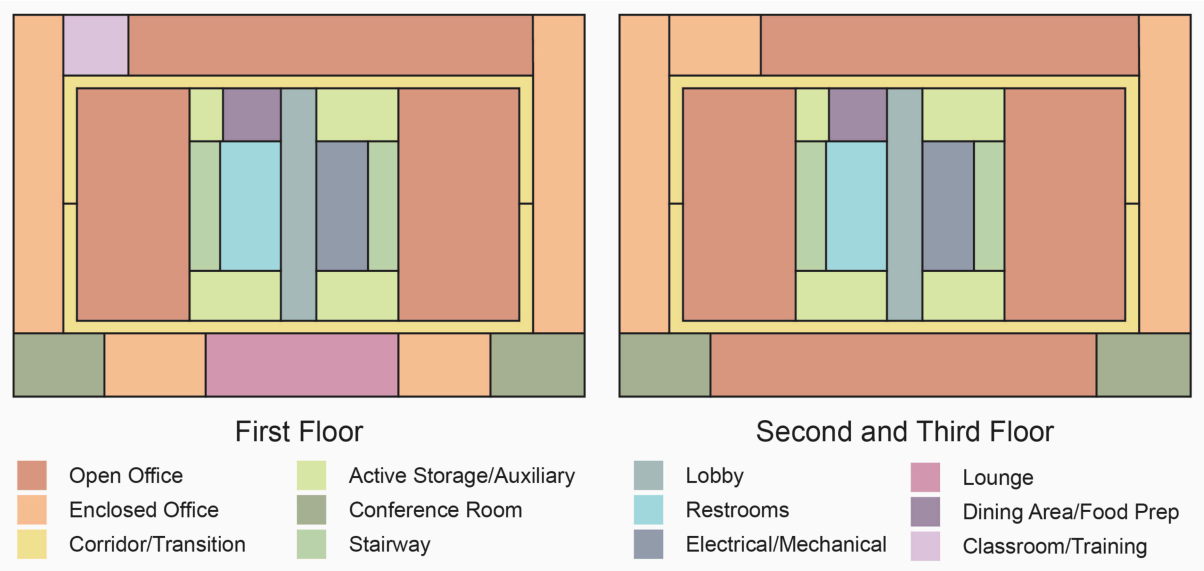


Figure 3. Oak Ridge National Laboratory medium office model floor layout.

The ORNL model has varying LPD, occupant density, plug load density, as well as ventilation load by space type—as defined in 90.1 and ANSI/ASHRAE 62.1, as appropriate. The lighting system was represented as the maximum power allowance for 10 interior space types; no lighting power was assigned to the storage, lounge spaces and food preparation spaces. Occupant density (people/ft^2) was varied by space type; however, the maximum number of occupants differs from the BECP model [19]. Table 1 summarizes the differences between the original BECP medium office building model and the ORNL model.

Table 1. Comparison of space-specific lighting power and occupant density in the BECP and ORNL medium office models [19].

Prototype	Space Type	Percent of Total Area	Lighting Power Density (W/ft^2)	Maximum Occupant Density (People/ft^2)
BECP	Office	100	0.82	0.005
ORNL	Active Storage/Auxiliary	7.1	-	-
	Stairway	3.7	0.69	-
	Restroom	3.6	0.98	-
	Open Office	42.4	0.98	0.006
	Lobby	3.7	0.90	0.010
	Electrical/Mechanical	3.0	0.42	-
	Corridor/Transition	9.1	0.66	-
	Conference Room	5.2	1.23	0.050
	Enclosed Office	18.7	1.11	0.005
	Dining/Food Prep	0.9	0.65	0.010
	Classroom/Training	0.6	1.24	0.035
	Lounge	1.8	-	-
	Food Preparation	0.4	-	-

Compared to the BECP model with just one space type, lighting power in the ORNL model was 13% higher (0.93 vs. 0.82 W/ft^2) and plug loads were 5% lower (0.71 vs. 0.75 W/ft^2). Although the introduction of space types and varying occupant densities in the ORNL medium office model provides significant additional utility for HVAC system

designers, it provides less utility to lighting system designers, as it still does not contain full interior architecture or a luminaire-level lighting layout.

2.2. New Reference Model Development Approach

The BECP medium office model was chosen as the starting point for the development of a new high-fidelity medium office building model (HFMOB). As noted previously, the BECP reference models are perhaps the most familiar set of reference models to lighting and other building practitioners, and the medium office building is perhaps the most commonly used reference in the set. Use of the BECP model as a starting point offers advantages beyond familiarity, as its definition of structural, envelope, and thermal details is well-vetted and accepted as realistic and representative of its building class. The following sections summarize characteristics defined in the BECP model, and the development and addition of new details to create the HFMOB—including a complete interior architecture, a furniture layout that defines nominal occupancy and associated workstation plug loads, a room-specific lighting layout with realistic products and lighting control strategies. The HFMOB was developed in Autodesk Revit (San Francisco, CA, USA), an architectural design and three-dimensional building information modeling tool.

2.3. Structural, Envelope, and Thermal Characteristics

The BECP medium office model is a three-story, 53,600 ft^2 (163.8 ft $\times$ 109.2 ft) structure with a steel frame and built-up roof (i.e., roof membrane + roof insulation + metal decking). The foundation is an unheated 8 in. concrete slab-on-grade poured directly onto the earth. The building has a 33% window-to-wall ratio, and roughly 4 ft tall ribbon windows uniformly wrap the building on all three levels. The building contains 15 thermal zones: four 15 ft deep perimeter zones and one core zone per floor where the core zone occupies 60% of the total floor space. The floor-to-ceiling height of each floor is 9 ft with a 4 ft plenum space between each level. The structural, envelope, and thermal characteristics defined in the BECP model were incorporated into the HFMOB without modification.

2.4. Interior Architecture

The BECP medium office model has two elevators, and interior partitions are created with 2 $\times$ 4 uninsulated stud walls. Beyond these specifications, the model includes very little detail regarding the interior architecture. The 12 space types included in the ORNL model (i.e., open office, private office, conference rooms, storage or auxiliary rooms, corridors, stairs, restrooms, mechanical, lounge, lobby, food prep and dining space, and a classroom or training room) were leveraged in the development of the HFMOB; however, the distribution of the space types was altered to introduce variation between the second and third floors. Table 2 summarizes the development and distribution of 107 rooms in the HFMOB. The percent of total area for each listed space type was adapted from the NC3 database.

While some spaces and services were uniformly distributed across all three floors, others were purposefully varied to explore the consequences of unique spatial adjacencies, lighting control zone sizing, and occupant densities. For example, the dining and food preparation spaces and many of the building services appear in the same location on each level, but the ratio of open office space to private office space varies from floor to floor, as shown in Figure 4. On the third floor, all open office spaces are located next to one another in the southeast corner of the building, while on the first floor, the open office spaces are dispersed throughout the floor. These variations are simply intended to represent multiple design strategies within the same simulation model and understand the impact on lighting design and control strategies at varying levels of building occupancy.

Table 2. HFMOB space type distribution.

Space Types	Percent of Total Area	Area (ft^2)	Number of Spaces per Floor		
			Floor 1	Floor 2	Floor 3
Open Office	42.0	22,456	3	5	3
Enclosed office	18.5	9878	16	6	17
Corridor/Transition	9.2	4939	2	1	1
Active Storage/Auxiliary	7.5	4024	4	5	8
Conference Room	5.0	2668	2	3	2
Stairway	4.2	2244	2	2	2
Lobby	3.8	2034	2	1	1
Restroom	3.7	1958	2	2	2
Electrical/Mechanical	2.9	1539	2	2	2
Lounge	1.5	829	1	1	1
Dining/Food Prep	1.1	581	1	1	1
Classroom/Training	0.7	355	0	0	1
Total	100.0	53,505		107	

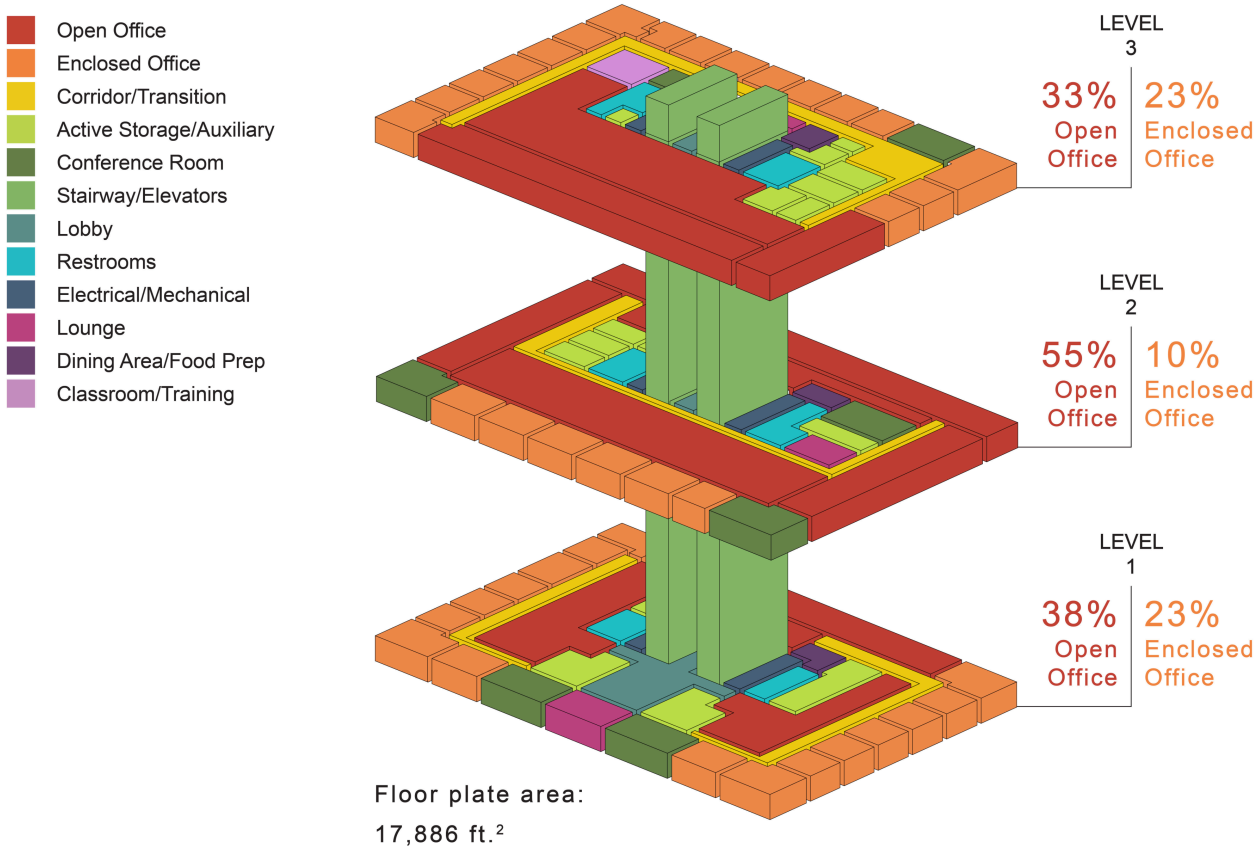


Figure 4. HFMOB interior architecture layout.

To maintain a relationship consistent with the BECP model, the 15 ft perimeter depth was held constant and further divided into specific rooms. Figure 5 displays the relationship between the original perimeter and core thermal zones for the second floor, and a table summarizing all thermal zones is in Appendix A.

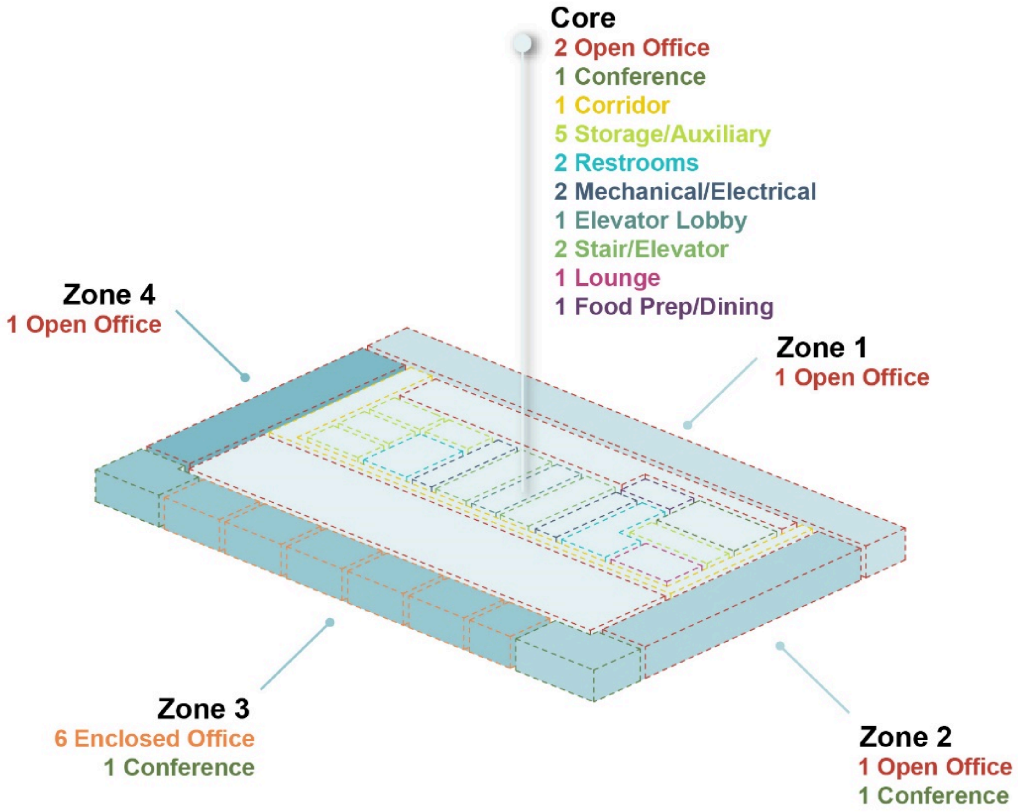


Figure 5. Relationship of space types to thermal zones on the second floor of the HFMOB.

2.5. Occupant Distribution

The BECP model assumes that occupants are evenly distributed throughout the core and perimeter thermal zones. In reality, apart from the actual workspaces, occupancy is more complex and requires more intricate methods to be fully understood [21]. Typically. building service spaces such as the electrical and mechanical rooms, restrooms, and storage rooms are located near the core of the building, while offices are located toward the exterior of the building closer to windows to provide natural light and access to views. These general design principles were applied to the interior architecture of the HFMOB and resulted in a significantly non-uniform occupant distribution that differed from the original BECP model.

In the open and private offices, a representative furniture layout was created to determine the number of primary workstations, and therefore the nominal occupancy, in each space. Apart from two shared offices on the third floor, all the private offices have one primary occupant. In the open offices, cubicle-style workstations are arranged in modules of two, four, six, or eight occupants. Example furniture layouts used throughout the HFMOB are shown in Figure 6.

In the HFMOB, the open and private office spaces were considered regularly occupied, while the other space types (i.e., conference rooms, classroom) were considered partially occupied. The regularly occupied spaces contain a primary workstation for all 268 occupants, as summarized in Table 3. In total, 85% of the 268 primary workstations were located in open offices. For simulation and analysis purposes, it is expected that occupants would spend most of their time in office space and some of their time in partially occupied spaces, and would visit the remaining space types, such as the restroom and lobby, for short periods.



Figure 6. HFMOB example furniture layouts, for private and open offices.

Table 3. HFMOB occupant workstation distribution.

Floor	Workstations	Private Office	Open Office
1	68	16	52
2	112	6	106
3	88	20	68
Total	268	42	226

In open offices, the occupant load varies between 59 and 169 ft^2 per person. In the private offices, the occupant load varies between 143 and 355 ft^2 per person. In addition to the regularly occupied office spaces, furniture models in the conference rooms and classroom result in maximum occupancy levels of 12 and 19 people per room, respectively. For all other space types, the nominal occupancy is 0. While the furniture layout is included to estimate occupant load, the information can also be used to estimate workstation-related miscellaneous electrical loads, and to conduct light- and health-focused simulations or analyses related to occupant behaviors and energy consumption. Complete floorplans are provided in Appendix B.

2.6. Lighting System

Lighting for office environments has two primary functions: (1) to provide an appropriate amount of light for the tasks occupants perform in the space and (2) to provide an appropriate quality of light to create a comfortable and visually appealing work environment for the occupants. This is primarily accomplished through design of the distribution of light throughout a space and fixture specification, which includes selecting the form factor, optics and glare control, color characteristics, lumen output, and dimming capabilities. Equally important are the lighting controls, which either allow the occupants to interact with the lighting system or automatically adjust lighting characteristics in response to a signal, such as a schedule, a change in occupancy, or a change in available daylight. The indoor lighting system described below includes a space-specific layout, LED luminaire specifications, and energy code-compliant control strategies for the medium office model. Control intent and lighting layouts are in Appendix C. Exterior lighting is not included.

2.7. Lighting Layout

The lighting layout was designed using typical architectural lighting practices, including the use of recommended design guidance established by the IES and incorporation of lighting control strategies outlined in 90.1. Lighting design is often considered in terms of layers, where the first layer provides general, ambient illumination in the space and any subsequent layers provide additional accent, task, or decorative lighting, as appropriate for each application. General design practice for office spaces includes lighting the ceiling and vertical surfaces to balance spatial brightness in spaces with windows and reduce distracting shadows. The lighting layout in the HFMOB is representative of a contemporary office designed by a building engineering firm. The open office workspaces were designed with general indirect/direct illumination that lights both the work surface and the ceiling, as well as a variety of task and accent lighting that highlights vertical surfaces, including artwork and other displays. In contrast, the private offices have direct illumination, with a secondary layer of light intended to increase vertical brightness. The conference rooms and classroom also have direct illumination and a secondary layer of light to illuminate a teaching or display wall in each space. In the corridors and lobbies, the lighting is primarily designed to highlight points of interest such as elevators and stairways to help occupants navigate the space. In lounges and dining spaces, indirect light is used to create a visually comfortable and more casual environment for occupants.

2.8. Lighting Equipment and Application

A total of 13 LED luminaire types were selected from an ASHRAE database of 50+ sample products that represent currently available technology. Luminaires with rated lumen outputs, efficacies, and distributions necessary to meet the visual task needs for office workers as defined by IES recommended practices were selected for the model. The luminaires were also selected to compliment the architectural characteristics and create the visual environment described in Section 2.7. The luminaire types include four varieties of recessed downlights, a direct/indirect linear pendant, a direct/indirect round pendant, a surface-mounted low-bay luminaire, three varieties of recessed troffers, a linear wall grazer, a linear wall wash luminaire, and an undercabinet task light. The ASHRAE database provided several specification options regarding the lumen output, distribution, color quality, and accessories for each form factor and mounting type listed. The resulting luminaire specifications are described in Table 4.

Table 4. HFMOB luminaire specifications.

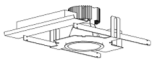
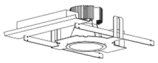
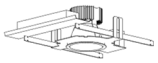
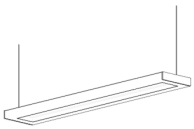
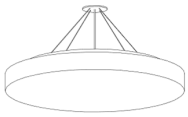
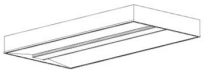
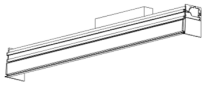
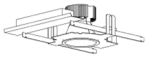
Fixture ID	Location	Description	Mounting	Dimensions	Output (Lumens)	Color	Electrical
A-1 Qty. 88 	Open office, corridor, lobby, lounge	Round open downlight, fixed aiming, wide distribution	Recessed in ceiling	4″ Aperture	1869	3500 K, 80 CRI	21 W, 277 V
A-2 Qty. 14 	Restroom	Round lensed downlight, fixed aiming, wide distribution	Recessed in ceiling	4″ Aperture	1892	3500 K, 80 CRI	22 W, 277 V
A-3 Qty. 10 	Open office, lounge	Round open downlight, adjustable aiming, medium distribution	Recessed in ceiling	4″ Aperture	1892	3500 K, 80 CRI	22 W, 277 V
B-1 Qty. 352 	Open office	30% Direct/ 70% indirect linear pendant with downward diffuse lens, batwing indirect distribution	Suspended from ceiling, bottom of luminaire at 8′-0″	48″L × 8″W × 2″H	3410	3500 K, 80 CRI	31 W, 277 V
C-1 Qty. 20 	Open office, corridor, lobby, lounge, dining	20% Direct/ 80% indirect round pendant with diffuse lens	Suspended from ceiling, bottom of luminaire at 8′0-0″	36″ dia. × 4″H	4200	3500 K, 80 CRI	35 W, 277 V
D-1 Qty. 28 	Stairway, electri-cal/mechanical	Linear lowbay fixture with diffuse lens	Recessed in ceiling	48″L × 10″W × 4″H	4200	3500 K, 80 CRI	35 W, 277 V
E-1 Qty. 9 	Dining	Linear task light	Under cabinet	24″L × 4″W × 1″H	780	3500 K, 80 CRI	13 W, 277 V
F-1 Qty. 128 	Enclosed office, storage, conference, classroom	2 × 4 Recessed troffer with high-performance lens	Recessed in ceiling	48″L × 24″W	4600	3500 K, 80 CRI	40 W, 277 V
F-2 Qty. 12 	Storage	2 × 2 Recessed troffer with high-performance lens	Recessed in ceiling	24″L × 24″W	3774	3500 K, 80 CRI	34 W, 277 V
F-3 Qty. 16 	Storage	1 × 4 Recessed troffer with high-performance lens	Recessed in ceiling	48″L × 12″W	3774	3500 K, 80 CRI	34 W, 277 V

Table 4. *Cont.*

Fixture ID	Location	Description	Mounting	Dimensions	Output (Lumens)	Color	Electrical
G-1 Qty. 120 	Open office, enclose office, restroom, classroom	Perimeter slot wall grazer with direct distribution	Recessed in ceiling	48″L × 12″W	3774	3500 K, 80 CRI	28 W, 277 V
H-1 Qty. 4 	Lobby	Round open downlight with wall wash distribution	Recessed in ceiling	4″ Aperture	1980	3500 K, 80 CRI	20 W, 277 V
H-2 Qty. 52 	Open office, corridor, conference, lobby	Linear open wall wash	Recessed in ceiling, set back from wall	48″L × 4″W × 4″H	2275	3500 K, 80 CRI	25 W, 277 V

In most applications in the HFMOB, the indirect/direct pendants (B-1, C-1), low-bay surface mounted (D-1), and three troffer luminaires (F-1, F-2, and F-3) provide general or ambient lighting in a space; the undercabinet luminaire (E-1), wall grazer (G-1), and select downlights (A-1, A-2) provide task lighting; the remaining downlights (A-3, H-1) and wall wash luminaire (H-2) provide accent lighting.

The HFMOB lighting design targeted two well-established and accepted benchmarks: horizontal and vertical illuminance levels, as defined in the 10th edition of the IES Handbook [22] and interior power allowances and required control strategies defined in 90.1-2019 [1]. Notably, the HFMOB lighting design is considered realistic because it follows dominant industry practices and achieves recommended visual performance while remaining energy-code-compliant. However, it should be noted that this lighting design was not empirically validated against real-building lighting performance, as the HFMOB is a reference, not a real building.

Horizontal illuminance simulations were completed in lighting simulation software, AGi32 Version 22.0 (Littleton, CO, USA), a commonly used industry tool for performing such lighting simulations, for select spaces in the model to verify that the system would satisfy visual task levels. The simulation was completed with a light loss factor of 0.9 and typical surface reflectance values (80% ceiling, 50% walls, 20% floor). The simulation results summarized in Table 5 show that the lighting meets or exceeds space-specific horizontal illuminance levels recommended by the IES [22] for office applications. Exceeding the recommended light level might suggest there is room for energy savings; however, additional layers or sources of light are used to balance perception of the space and accommodate occupant needs during the day or after dark.

While the design targets presented for light levels are recommendations, LPD allowances and control strategies are prescribed by local energy codes. In the U.S., most jurisdictions have adopted 90.1 or follow the guidance prescribed in the IECC. The current suite of BECP models include information regarding both 90.1 and IECC for several code iterations. The HFMOB was designed to comply with 90.1-2019 for interior lighting power allowances and required control strategies. Compliance requires that the planned equipment wattage be less than or equal to the prescribed lighting power allowance. The lighting power allowance can be calculated according to the building area method or the space-by-space method. 90.1-2019 also defines a simplified building method compliance path for office applications; however, this compliance path is not discussed in this report.

Table 5. IES recommended horizontal illuminance targets and average horizontal illuminance achieved in the HFMOB design, per space type.

Space Type	Minimum Recommended Horizontal Light Level (lx)	Average HFMOB Horizontal Light Level (lx)
Task plane at desktop (30 inches)		
Open Office	300	420
Enclosed office	300	370
Active Storage/Auxiliary	300	320
Conference Room	300	360
Restroom	150	240
Electrical/Mechanical	200	320
Dining Area/Food Prep	100	110
Classroom/Training	300	430
Task plane at floor		
Corridor/Transition	50	120
Stairway	50	170
Lobby	100	160

The interior power allowance for the building area method is determined by multiplying the prescribed LPD by the gross lighted floor area. The gross lighted floor area in the HFMOB is 52,551 ft^2 and the LPD allowance for office buildings is 0.64 W/ft^2, resulting in an interior lighting power allowance of 33,633 W. For the space-by-space method, both the prescribed LPD and the area are assessed for each space type. The interior lighting power allowance is the combined wattage prescribed for each space type. The total interior lighting power allowance is 31,200 W. The space-by-space power allowances are summarized in Table 6. Further LPD analysis is provided in Section 3.2 below; the total connected load for the HFMOB is 26,037 W or 17% less than the space-by-space interior power allowance, thereby complying with the energy code.

Table 6. Application of 90.1-2019 interior lighting power allowances to the HFMOB design, for the building area method and the space-by-space method.

	Space Type	Lighted Floor Area (ft^2)	Prescribed LPD (W/ft^2)	Power Allowance (W)
Building Area Method	Office	52,551	0.64	33,633
Space-by-Space Method	Open Office	22,456	0.61	13,698
	Enclosed office	9878	0.66	6519
	Corridor/Transition	4939	0.41	2025
	Active Storage/Auxiliary	4024	0.38	1529
	Conference Room	2668	0.97	2588
	Stairway	1290	0.49	632
	Lobby	2034	0.65	1322
	Restroom	1958	0.63	1234
	Electrical/Mechanical	1539	0.43	662
	Lounge	829	0.59	489

Table 6. *Cont.*

	Space Type	Lighted Floor Area (ft^2)	Prescribed LPD (W/ft^2)	Power Allowance (W)
Space-by-Space Method	Dining Area/Food Prep	581	0.43	250
	Classroom/Training	355	0.71	252
	Total	52,551		31,200

2.9. Lighting Controls

Regardless of the compliance path selected for determining the interior power allowance, the mandatory provisions for interior lighting controls are implemented on a space-by-space basis and represent the minimum control requirements for a given space type. 90.1-2019 defines 10 control strategies for local control, occupancy and vacancy sensing, dimming, daylight response, and scheduled control. Table 7 summarizes the minimum control requirements for the space types included in the office model. For each space type, all control strategies labeled "REQ" are required. For the control strategies labeled "ADD1" or "ADD2", decision-makers may choose which strategies they implement for code compliance based on the needs and expected use of the space. The bold values represent the control functions included in the model for each space type.

Table 7. Application of 90.1-2019 space-by-space minimum control requirements to the HFMOB design. Bold values represent the control functions applied in the HFMOB.

Control Functions	Open Office	Enclosed Office	Corridor/ Transition	Active Storage/ Auxiliary	Conference Room	Stairway
1. Local Control	**REQ**	**REQ**	**REQ**	**REQ**	**REQ**	
2. Restricted to Manual ON	ADD1	**ADD1**		**ADD1**	**ADD1**	
3. Restricted to Partial Automatic ON	**ADD1**	ADD1		ADD1	ADD1	
4. Bilevel Lighting Control	**REQ**	**REQ**			**REQ**	**REQ**
5. Automatic Daylight Responsive Controls for Sidelighting	**REQ**	**REQ**	**REQ**	REQ	**REQ**	**REQ**
6. Automatic Daylight Controls for Toplighting	REQ	REQ	REQ	REQ	REQ	REQ
7. Automatic Partial OFF			**REQ**			**REQ**
8. Automatic Full OFF	ADD2	ADD2	ADD2	**REQ**	**REQ**	ADD2
9. Scheduled Shutoff	ADD2	ADD2	ADD2			ADD2
10. Scheduled OFF during nonbusiness hours	**ADD2**	**ADD2**	**ADD2**			ADD2

Control Functions	Lobby	Restroom	Electrical/ Mechanical	Lounge	Dining Area/ Food Prep	Classroom/ Training
1. Local Control	**REQ**		**REQ**	**REQ**	**REQ**	**REQ**
2. Restricted to Manual ON				ADD1	ADD1	**ADD1**
3. Restricted to Partial Automatic ON				**ADD1**	**ADD1**	ADD1
4. Bilevel Lighting Control				**REQ**	**REQ**	**REQ**
5. Automatic Daylight Responsive Controls for Sidelighting	**REQ**	REQ	REQ	**REQ**	**REQ**	**REQ**
6. Automatic Daylight Controls for Toplighting	REQ	REQ	REQ	REQ	REQ	REQ
7. Automatic Partial OFF						
8. Automatic Full OFF	ADD2	**REQ**		**REQ**	ADD2	**REQ**
9. Scheduled Shutoff	ADD2				ADD2	
10. Scheduled OFF during nonbusiness hours	**ADD2**				**ADD2**	

Local lighting control for the occupants is required and implemented in all space types except for stairways and restrooms, both of which require full or partial automatic off lighting controls in response to occupancy levels. Daylight responsive controls are required and implemented in all spaces where daylight is present. Although daylight responsive controls for top lighting are required, this control strategy is not implemented in the HFMOB because there are no skylights in the BECP medium office building.

Beyond lighting controls required by code, building-specific decisions related to the everyday occupant experience and interaction with the lighting system influence system performance and efficiency. In modeling and analyzing lighting system energy use, it is important to recognize impacts related to sensor performance, occupant behaviors and location, as well as access to daylight and effects of control zone sizing on a space-by-space basis or even luminaire-by-luminaire basis, for some applications. The control strategy and the sequence of operations will be a primary variable for future research; however, a baseline model is provided in the following paragraphs and Figure 7.

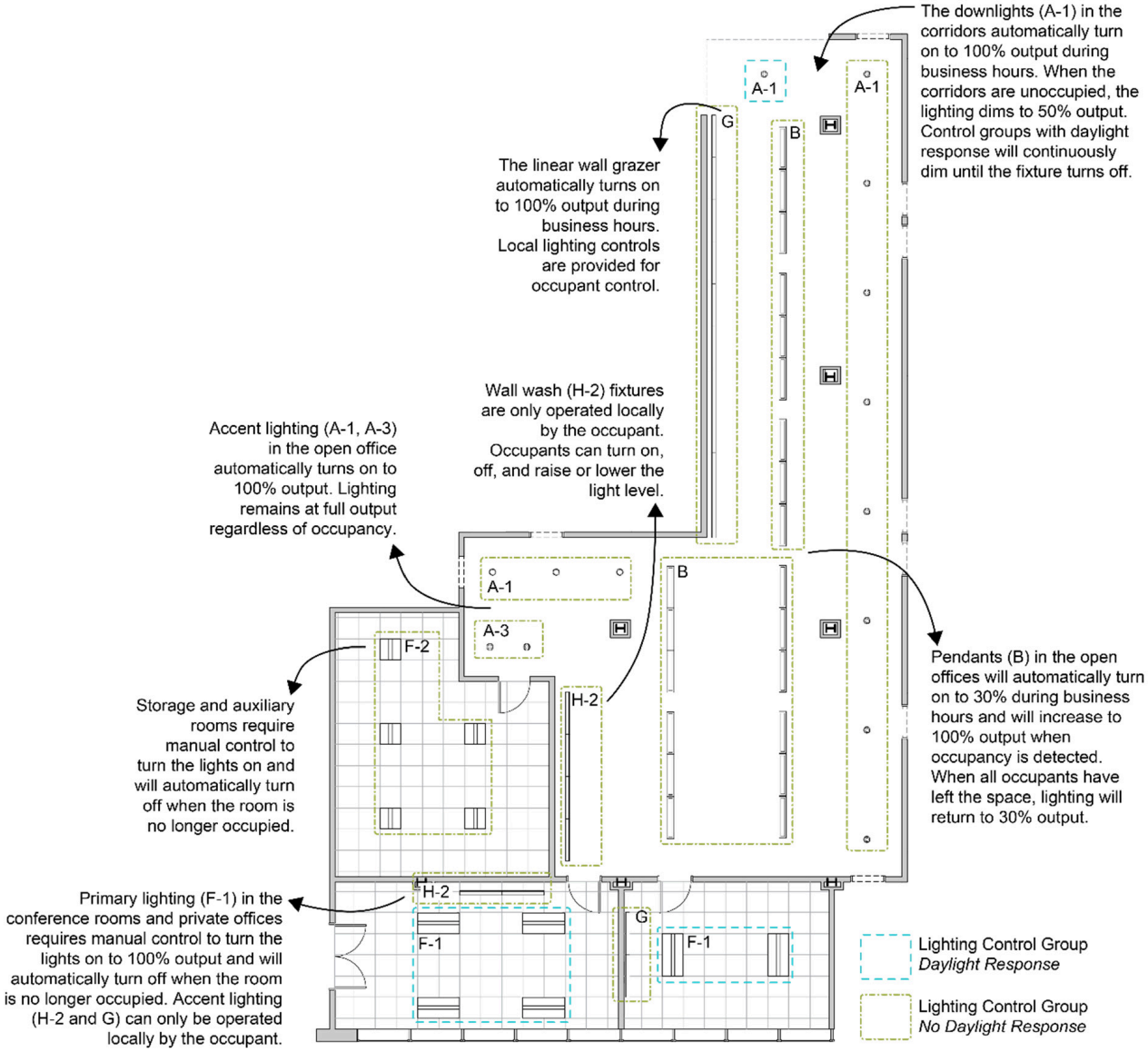


Figure 7. Examples of lighting control groups and typical lighting operation in a conference room, private office, storage room, corridor, and open office space on the first floor of the HFMOB.

In the private offices, the primary and secondary layers of light are controlled separately. Both layers of light require manual operation to turn the lights on and automatically turn off within 20 min of all occupants leaving the space. The conference rooms and classroom follow a similar sequence of operation. In both space types, the secondary layer of light offers increased vertical illuminance, spatial brightness, and accent lighting, but realistically may be used less frequently than the primary troffer lighting.

The sequence of operations and control strategies vary between open office spaces based on daylight availability, size, and specific luminaires in each space. Due to the shared nature of open offices, all pendant lighting will automatically turn on to 30% output during business hours and increase to 100% output when occupancy is detected. Lighting for dining spaces, lounges, lobbies, and corridors will also automatically turn on during business hours and will turn off automatically when the room is unoccupied or at the end of business hours. The general lighting in all daylit spaces will continuously dim in response to available daylight until the fixture turns off. All the lighting is scheduled to automatically turn off outside business hours and allow a 2 h override for lighting control after hours. Figure 7 shows examples of sequence of operations for control groups in a variety of space types. A complete description of lighting control groups and sequence of operations for all space types is provided in Appendix C.

3. Results

The HFMOB builds upon a widely known and commonly used medium office reference model by defining a complete interior architecture, associated space type programming, nominal occupant distribution, and a complete luminaire-level lighting system. Notably, no changes to the structural, envelope, and thermal characteristics defined by the BECP model were required to integrate the lighting system. Fully detailed electrical distribution (e.g., electrical panels, circuit runs), mechanical, and plumbing systems were not developed as part of this work. The following sections quantitively characterize the additional detail provided by the HFMOB by comparing select HFMOB metrics against their counterparts for the BECP model—with the intent of demonstrating the that additional detail is significant, rather than trivial.

3.1. Occupant Load

The architectural detail and luminaire-level lighting layout in the HFMOB model allows for detailed analysis of lighting design choices tied to specific lighting techniques or control strategies. This is especially true for lighting system performance characteristics that are significantly impacted by occupant behavior. The architectural and furniture detail introduced in the HFMOB resulted in a variable nominal occupant density as shown in Table 8 and compared with the uniform occupant density defined by the BECP model. The architectural and furniture detail introduced in the HFMOB resulted in a variable nominal occupant density, as shown in Table 8 and compared with the uniform occupant density defined by the BECP model. A total of 226 occupants have a primary workstation in an open office space, which offer between 59 and 169 ft^2 per person. The five occupants in shared offices have between 143 and 145 ft^2 per person. The remaining 37 occupants in private offices have the most space per occupant, varying between 204 and 355 ft^2 per person. In each office type, the variation is largely due to the architectural layout, size, and particular cubicle arrangement in each space.

Table 8. Comparison of occupant load in the HFMOB and BECP models.

	Space Type	Total Area (ft^2)	Area per Person (ft^2/Person)	Number of People
BECP	Whole Building	53,633	200	268
HFMOB	Open Office	22,456	59–169	226
	Enclosed Office—Individual	9157	204–355	37
	Enclosed Office—Shared	721	143–145	5
	Conference Room	2668	24–36	12 per room
	Classroom/Training	355	19	19
	Total			268

The HFMOB includes 12 space types, some of which are more regularly occupied than others. Figure 8 visually compares the occupant density in BECP model with that of the HFMOB model, where only the office spaces are considered regularly occupied (denoted as blue spaces in the figure). In reality, the rest of the space types, including corridors, lobbies, dining areas, restrooms, mechanical rooms, and storage rooms, are typically not regularly occupied for large portions of the day (denoted as gray spaces in the figure). The blue tint and the density of human figurines in each space visually represent different occupant densities.

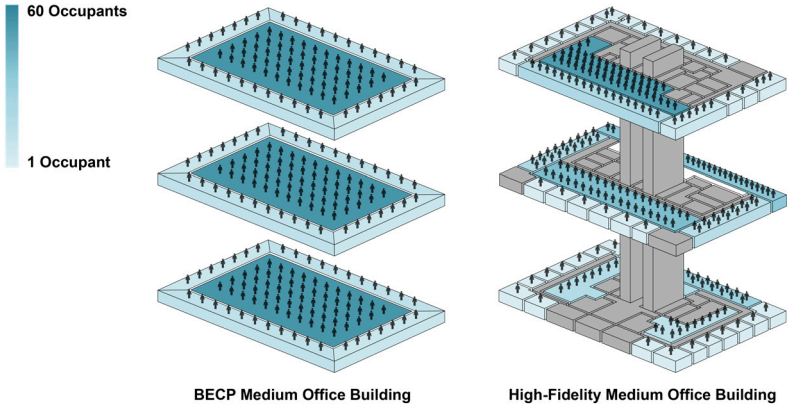


Figure 8. Visual comparison of the uniform occupant distribution in the BECP model (**left**) and the varied occupant distribution in the HFMOB model (**right**).

Uniform occupant density assumptions will significantly misrepresent occupancy-based control strategy performance for lighting and potentially HVAC systems. Realistically, less occupied transition space lighting will be used less frequently than open office lighting, and open office lighting may be used differently than private office lighting due to occupant behavior and the associated control strategies that require lighting to automatically turn on, for example. The interior architecture and occupant workstation model in the HFMOB allow practitioners to evaluate the impacts of detailed lighting control strategies and their dependencies on occupant behavior.

3.2. Lighting Power Density

The lighting design and technology selected for the HFMOB results in a variable LPD, with a range between 0.11 and 0.85 W/ft^2. The stairways, lounges, and corridors typically have lower LPDs, while the restrooms, classroom, and dining areas have the

highest connected load per area, as summarized in Table 9 and compared with the uniform occupant density defined by the BECP model. Notably, the space-by-space method for lighting in 90.1-2019 allows for connected load tradeoffs between space types, as long as the total connected load does not exceed the total interior power allowance.

Table 9. Comparison of lighting power density in the HFMOB and BECP models.

	Space Type	Lighted Floor Area (ft^2)	Prescribed LPD (W/ft^2)	Power Allowance (W)	Connected Load (W)	Actual LPD (W/ft^2)
BECP	Office	53,600	0.64	34,304	34,304	0.64
HFMOB	Open Office	22,456	0.61	13,698	12,669	0.56
	Enclosed office	9878	0.66	6519	5500	0.56
	Corridor/Transition	4939	0.41	2025	1289	0.26
	Active Storage/Auxiliary	4024	0.38	1529	1432	0.36
	Conference Room	2668	0.97	2588	1380	0.52
	Stairway	1290	0.49	632	350	0.27
	Lobby	2034	0.65	1322	905	0.44
	Restroom	1958	0.63	1234	1232	0.63
	Electrical/Mechanical	1539	0.43	662	630	0.41
	Lounge	829	0.59	489	191	0.23
	Dining Area/Food Prep	581	0.43	250	243	0.42
	Classroom/Training	355	0.71	252	216	0.61
	Total	52,551		31,200	26,037	

Although it is not evident in Table 9, LPD also varies for each unique room layout of a given space type. As shown in Figure 9, the LPD across all 10 open office spaces varies between 0.38 and 0.85 W/ft^2 due to the variety of lighting techniques applied and associated luminaire choices. As private offices contain the same lighting equipment, variation in LPD (0.38 to 0.67 W/ft^2) is largely due to the size of each office.

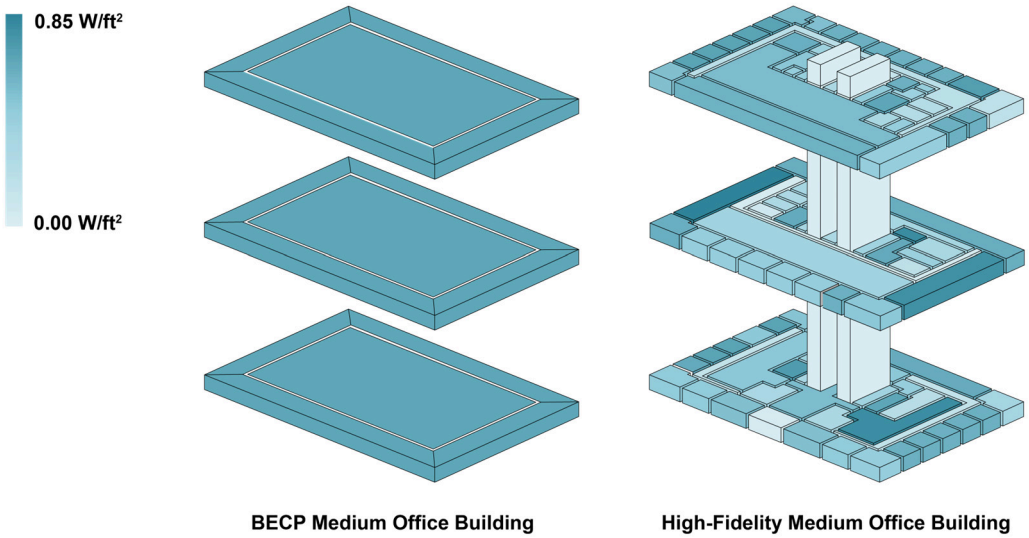


Figure 9. Visual comparison of the uniform LPD in the BECP model (**left**) and the varied LPD in the HFMOB model (**right**). The fill color of each space notes the LPD in each space.

The variation in occupant and lighting densities in the HFMOB may not be representative (e.g., match the statistical mean) for the national office building stock; however, they represent a realistic operating environment that can readily serve as a baseline for the exploration of lighting control strategies, the impact of occupant behavior, and approaches for modeling occupant behavior.

4. Discussion

The HFMOB intends to serve as a common baseline for building designers and researchers—a role similar to the BECP models. However, the HFMOB adds interior architecture, a nominal occupant distribution model, and space-specific lighting and control design that existing reference models do not provide. The HFMOB was shared with colleagues and other researchers during its development, and as a result has already demonstrated this intended utility as a baseline in three published studies. The HFMOB supported analysis of circadian lighting design strategies that quantified the energy impact of meeting design recommendations [23]. This analysis required detailed luminaire specifications and locations as well as occupant locations, as the goal of circadian lighting analysis is to determine how much and what kind of light is entering an occupant's eyes. It was also used to develop a building information modeling to building energy modeling (i.e., BIM to BEM) workflow for designing integrated HVAC and lighting systems [24]. This study demonstrated how the luminaire-level detail and defined space-to-HVAC zone relationships supported coordinated system design. Most recently, the HFMOB was used to evaluate how lighting systems can be integrated into whole-building life-cycle assessments [25]. The study found that lighting energy use assumptions substantially affected the outcome of life-cycle assessments [25] which highlights the need for detailed lighting inputs which are provided in the HFMOB.

We envision that the HFMOB can and will be used for evaluations of lighting control strategies and approaches to occupant modeling, and to develop and demonstrate new tools and workflows for design, configuration, and operation of lighting systems. Supported lighting control evaluations include varying control zone sizing to understand how daylight-responsive and occupancy-based control strategies impact energy use, modeling real-world sensor limitations (e.g., false-positives and false-negatives generated by passive infrared motion sensors) to understand their impact on energy use, and varying how overlapping control strategies (e.g., scheduled, occupancy, daylighting) are implemented to understand their impact on energy use and occupant expectations. Further, the provided control intent narrative represents a realistic, code-compliant baseline; however, the HFMOB could also be used to compare control strategies beyond code compliance.

The occupant distribution model in the HFMOB facilitates the modeling of occupant behavior as a function of both occupant archetype (e.g., manager, regular staff, maintenance staff) and space type, thereby enabling enhanced modeling of occupancy-based control strategies and evaluation of the interdependency of lighting layout, lighting control strategy, and occupant behavior on lighting energy use. Notably, occupant modeling can provide more detailed and realistic analysis of thermal loading and occupancy-based control strategies for HVAC systems. Finally, the HFMOB could be used to understand energy use intensity for open office spaces compared to private office spaces based on occupancy levels. This allows practitioners to evaluate different strategies for managing varying office occupant loads in large buildings.

Many types of practical operational data generated by real-world lighting systems can only be modeled and simulated using a high-fidelity model like the HFMOB—including but not limited to occupancy status (by room and space type), operating hours and light output status (by lighting fixture, room, and space type), and cumulative energy use (by

lighting fixture, room, and space type). Consequently, the HFMOB can support the development and demonstration of design, simulation, energy management, and operational maintenance software tools as well as workflows that share data between tools. Further, the defined relationship between lighting and HVAC zones supports the exploration of coordinated control strategies that leverage lighting-based occupancy data. Finally, the HFMOB can also support research on advanced workflows ranging from AI-based generative design tools to automated processes that configure simulation models and generate semantic models from building information models that are suitable for comparing simulated and operational performance in digital twin applications.

Limitations

Several limitations should be recognized when using or extending the HFMOB. First, the detail added to the HFMOB represents one possible version of interior architecture, occupant distribution, and suitable office lighting design. The model should not be interpreted as broadly representative of the U.S. office building stock. While the model was validated through its adoption of IES lighting design recommendations and 90.1 LPD and control strategy recommendations as a reference model of a representative building, the performance metrics provided for the lighting system were not quantitively validated against real-world performance. Additionally, discomfort glare from lighting was considered during the design of the luminaire layout and fixture selection (e.g., wall washing to provide indirect brightness) but was not simulated and is not reported here. Notably, this approach towards managing glare (i.e., via thoughtful luminaire layout and fixture selection rather than simulation) is the common practice for most (i.e., not high-end or showcase) office buildings. Lastly, detailed, equipment-level mechanical and plumbing systems were not added to the HFMOB model in this work but may be added in future work, as the BECP model contains high-level details about these systems that could be leveraged in the development of a high-fidelity building information model.

5. Conclusions

This paper presents the development and characterization of a high-fidelity reference model of a medium office building (the HFMOB) that can be used for many lighting design use cases that existing reference models cannot support. The additional detail contained in the model is realistic and validated by the use of well-known and adopted lighting industry practices. The definition of variable nominal occupancy by room and space type and support for evaluation of approaches to occupant modeling can be leveraged for other (i.e., non-lighting) use cases, including HVAC and space utilization design. Finally, the HFMOB has already been used as a baseline for published research, demonstrating the utility envisioned by this paper.

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Abbreviations

The following abbreviations are used in this manuscript:

ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
ANSI	American National Standards Institute
LED	Light-emitting diode
IES	Illuminating Engineering Society
HVAC	Heating, ventilation, and air conditioning
BIM	Building information modeling
HFMOB	High-Fidelity Medium Office Building
IECC	International Energy Conservation Code
BECP	Building Energy Codes Program
LPD	Lighting power density
EERE	Office of Energy Efficiency and Renewable Energy
VAV	Variable air volume
ICU	Intensive care unit
ORNL	Oak Ridge National Laboratory
PNNL	Pacific Northwest National Laboratory

Appendix A

The BECP medium office building model has 15 thermal zones, consisting of one core zone and four perimeter zones per floor. The following table associates each room in the HFMOB to the BECP model zone.

Table A1. Summary of the relationship between individual rooms in the HFMOB and the baseline BECP model thermal zones. Each individual room belongs to one thermal zone. The room number is provided on the floor plans provided in Appendix B.

Zone	BECP Area (ft^2)	HFMOB Area (ft^2)	HFMOB Room Number#
CORE_BOTTOM	10,588	10,712	102, 103, 104, 105, 106, 107, 108, 109, 110, 111, 121, 123, 124, 125, 126, 136, 137
CORE_MID	10,588	10,809	201, 202, 203, 204, 205, 206, 207, 208, 209, 210, 211, 212, 213, 214, 215, 216, 227, 229
CORE_TOP	10,588	10,550	301, 302, 303, 304, 305, 306, 317, 319, 321, 323, 325, 326, 327, 331, 333, 334, 335, 336, 337, 338, 339
PERIMETER_TOP_ZN_3	2232	2292	307, 340
PERIMETER_TOP_ZN_2	1413	1237	330, 332, 341
PERIMETER_TOP_ZN_1	2232	2367	314, 315, 316, 318, 320, 322, 324, 328, 329
PERIMETER_TOP_ZN_4	1413	1313	308, 309, 310, 311, 312, 313
PERIMETER_BOT_ZN_3	2232	2098	101, 112, 113, 114, 134, 135
PERIMETER_BOT_ZN_2	1413	1485	128, 129, 130, 131, 132, 133
PERIMETER_BOT_ZN_1	2232	2141	122, 127
PERIMETER_BOT_ZN_4	1413	1377	115, 116, 117, 118, 119, 120
PERIMETER_MID_ZN_3	2232	2055	220, 221, 222, 223, 224, 225, 226
PERIMETER_MID_ZN_2	1413	1065	228
PERIMETER_MID_ZN_1	2232	2421	217

Table A1. *Cont.*

Zone	BECP Area (ft^2)	HFMOB Area (ft^2)	HFMOB Room Number#
PERIMETER_MID_ZN_4	1413	1582	218, 219
UNCONDITIONED SPACE	N/A	154	
TOTAL	53,634	53,658	

Appendix B

The floor plans display the space types, room numbers, and typical furniture layouts developed for the HFMOB based on the BECP medium office building model. The dashed lines represent room boundaries where there are no physical partitions.

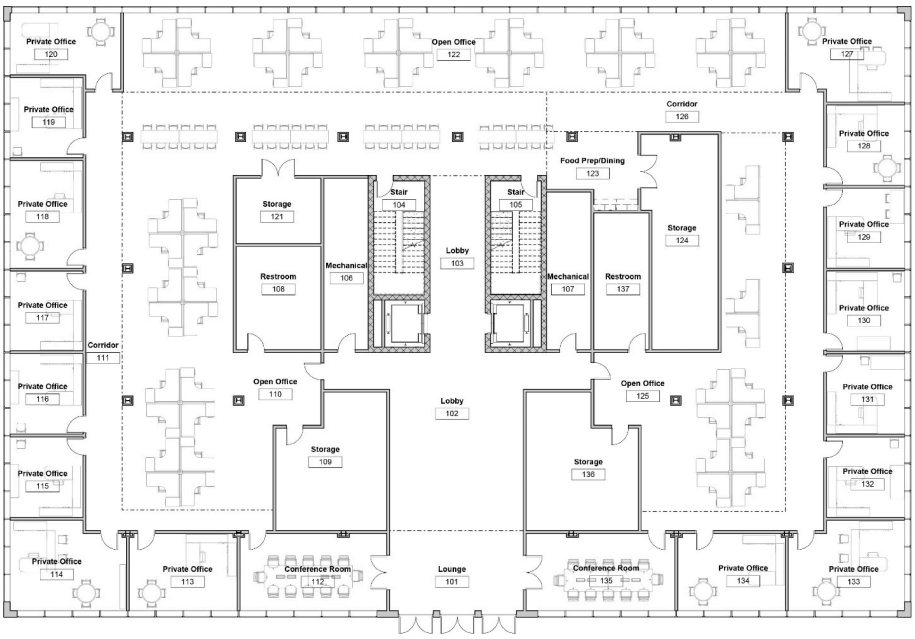

Figure A1. Floor 1 Plan.

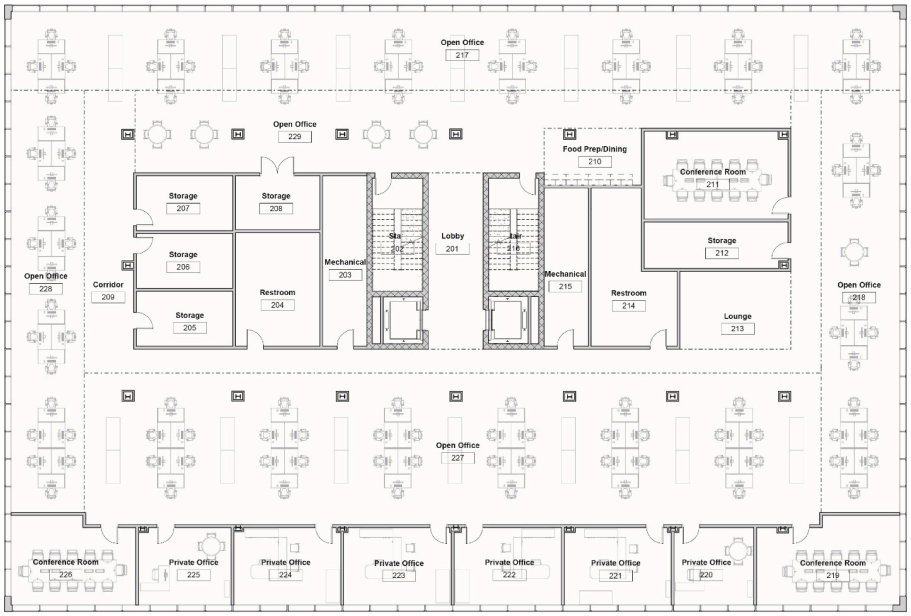

Figure A2. Floor 2 Plan.

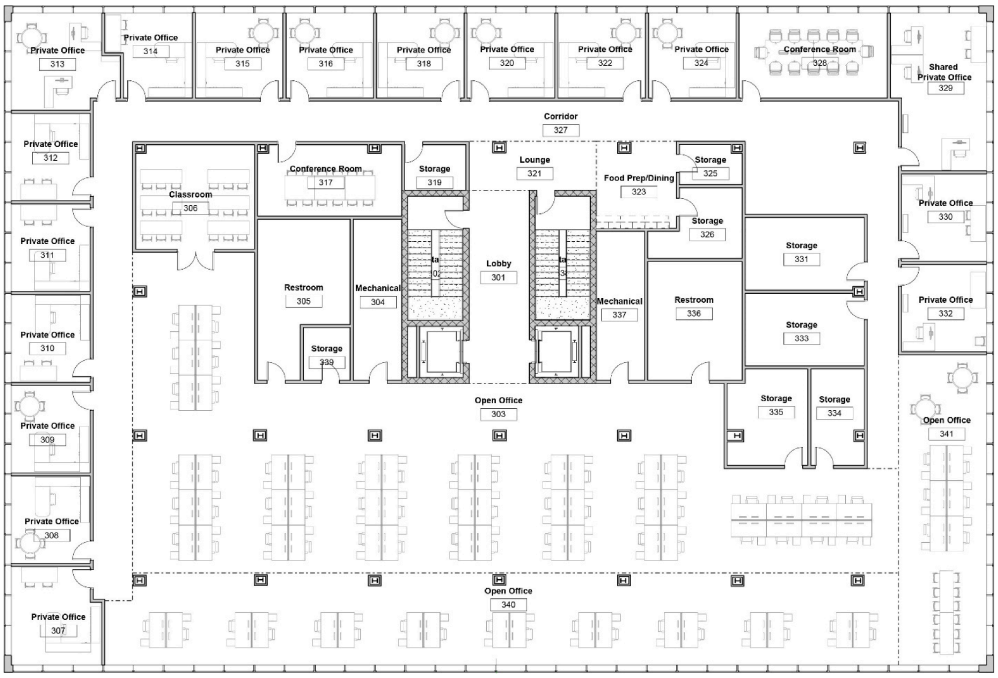

Figure A3. Floor 3 Plan.

Appendix C

The following drawings are lighting layouts that display the luminaire type (e.g., B-1, D-1, H-2, etc.) and the associated control zone identification (e.g., 122-2C). The letter in each control zone ID corresponds to a control scheme in the table below. Control schemes are combinations of individual control functions, such as timeclock control, occupancy or vacancy control, and manual control. The control intent narrative descriptions in Table A1 include both code-required control strategies as well as strategies beyond code compliance to support occupants (e.g., manual dimming).

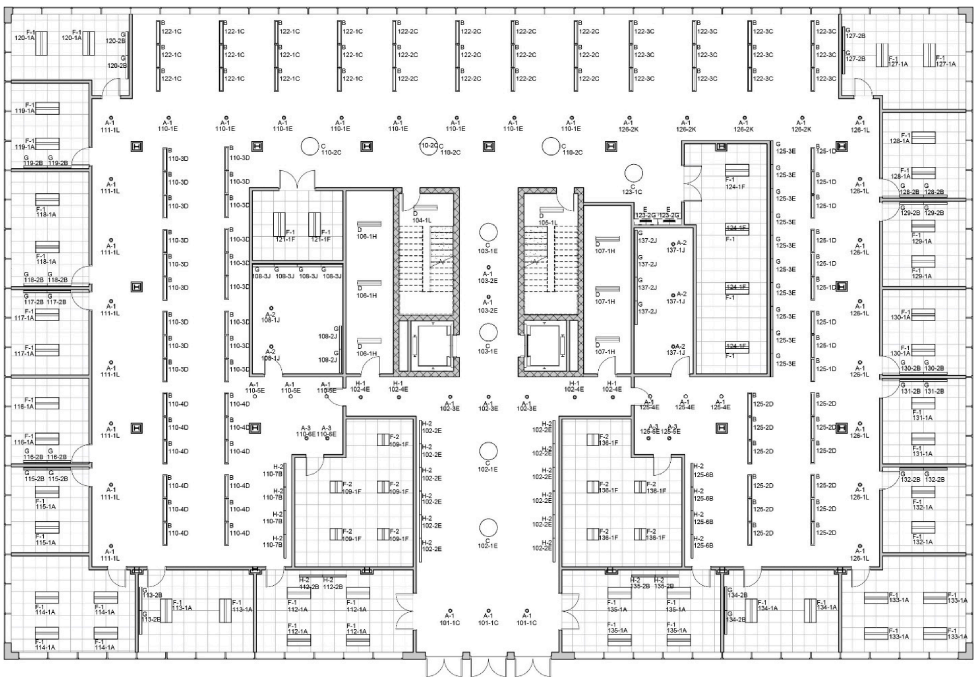

Figure A4. Floor 1 lighting layouts.

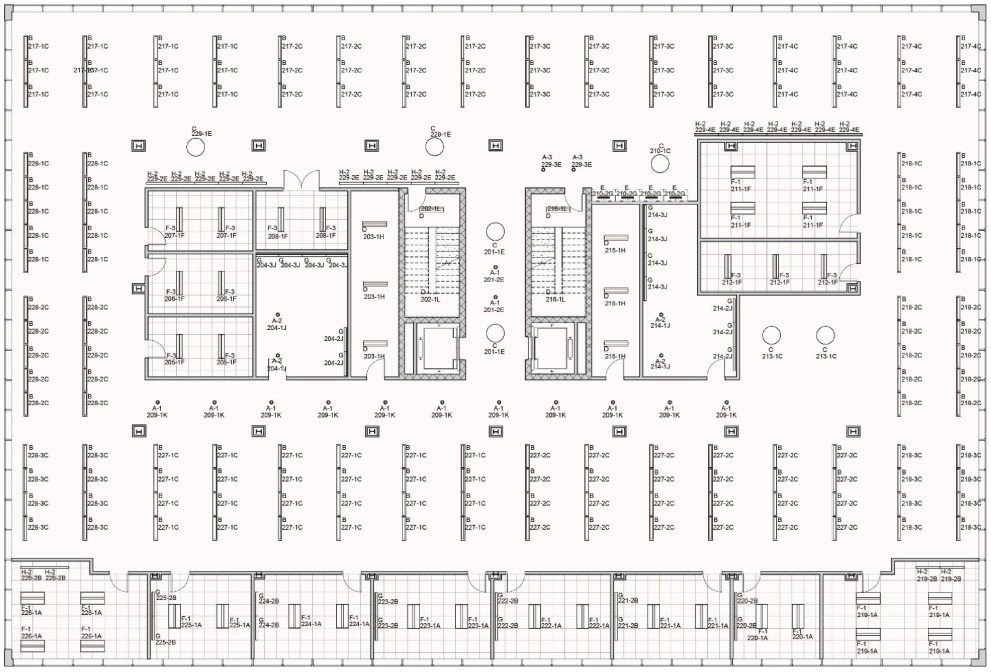

Figure A5. Floor 2 lighting layouts.

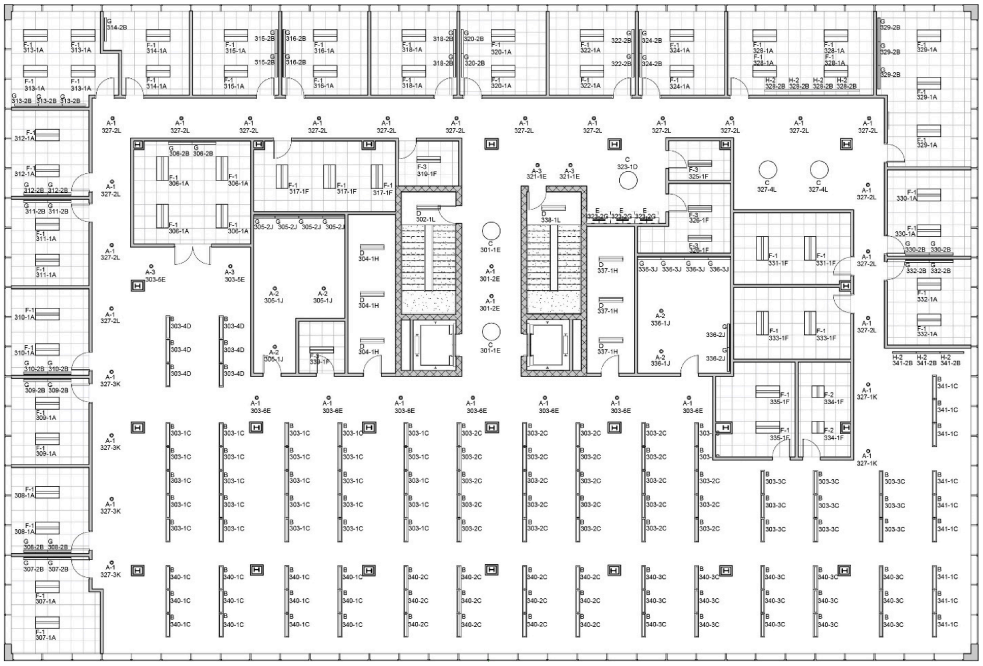

Figure A6. Floor 3 lighting layouts.

Table A2. A description of the control schemes used in the HFMOB. Each control scheme is a combination of individual control functions that may reflect design decisions for occupants or may be required by codes.

Control Scheme	Location	Description
A	Private Offices, Conference Rooms	Local control with on/off and manual dimming shall be provided. Lighting shall be restricted to manual ON to 100%/occupancy sensor OFF within 20 min of all occupants leaving the space. Daylight response shall reduce lighting to OFF. Lighting shall be scheduled OFF outside business hours.

Table A2. *Cont.*

Control Scheme	Location	Description
B	Private Offices, Open Offices, Conference Rooms, Classroom	Local control with on/off and manual dimming shall be provided. Lighting shall be scheduled OFF outside business hours.
C	Open Offices, Lounge, Food Prep/Dining	Local control with on/off and manual dimming shall be provided. ON to 30% via timeclock control. Dim up to 100% when occupancy is detected. Lighting shall dim to 30% within 20 min of all occupants leaving the space. Daylight response shall reduce lighting to OFF. Lighting shall be scheduled OFF outside business hours.
D	Open Offices, Food Prep/Dining	Local control with on/off and manual dimming shall be provided. ON to 30% via timeclock control. Dim up to 100% when occupancy is detected. Lighting shall dim to 30% within 20 min of all occupants leaving the space. Lighting shall be scheduled OFF outside business hours.
E	Open Offices, Lobbies, Lounges	Local control with on/off shall be provided. ON to 100% via timeclock control. Lighting shall be scheduled OFF outside business hours.
F	Conference Rooms, Classroom, Storage	Local control with on/off and manual dimming shall be provided. Lighting shall be restricted to manual ON to 100%/occupancy sensor OFF within 20 min of all occupants leaving the space. Lighting shall be scheduled OFF outside business hours.
G	Food Prep/Dining	Local control with on/off shall be provided. Lighting shall be scheduled OFF outside business hours.
H	Electrical/Mechanical	Local control with on/off shall be provided. ON to 100% via timeclock control. After 6 p.m., lighting shall turn OFF within 20 min of all occupants leaving the space.
I	*Not Used*	
J	Restrooms	Local control with on/off shall be provided. Lighting shall be restricted to occupancy sensor ON to 100%/occupancy sensor OFF within 20 min of all occupants leaving the space. Lighting shall be scheduled OFF outside business hours.
K	Corridor/Transition	Local control with on/off shall be provided. ON to 100% via timeclock control. Lighting shall dim to 50% within 20 min of all occupants leaving the space. Daylight response shall reduce lighting to OFF. Lighting shall be scheduled OFF outside business hours.
L	Corridor/Transition	Local control with on/off shall be provided. ON to 100% via timeclock control. Lighting shall dim to 50% within 20 min of all occupants leaving the space. Lighting shall be scheduled OFF outside business hours.

Table A3. The application of individual control functions in each control scheme.

Control Function	A	B	C	D	E	F	G	H	J	K	L
Timeclock control 7:00 a.m. ON			×	×	×			×		×	×
Scheduled OFF outside business hours (7:00 a.m.–6:00 p.m.)	×	×	×	×	×	×	×		×	×	×
Occupancy sensor ON			×	×					×		
Occupancy sensor OFF	×		×	×		×		×	×	×	×
Automatic daylight response	×		×							×	
Local control	×	×	×	×	×	×	×	×	×	×	×
Manual ON	×	×	×	×	×	×	×	×	×	×	×
Manual OFF	×	×	×	×	×	×	×	×	×		
Manual Dimming	×	×	×	×		×					

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