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Prototype College Building Energy Model: Building Characteristics and Energy Simulation Results

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July 2022

OAK RIDGE National Laboratory

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Electrification and Energy Infrastructure Division

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ABSTRACT

The US Department of Energy supports the development of commercial building energy codes and standards. To support commercial building energy research activities and the development of commercial building energy codes and standards, continuous efforts have been made to convert 16 prototype building models, which cover 80% of US commercial building floor space, to OpenStudio prototype buildings. Additionally, the suite of prototype building models was expanded to include the addition of new building prototype models (e.g., courthouse, college building).

Multiple sources, including databases, documented projects, and personal communications, were used to define the prototype college building, and a 4-story with 69,063 ft^2 building was considered as the prototype college building to represent an average-sized college building in the United States. To represent realistic occupancy schedules and increase the granularity of information, actual class reservation schedules were collected and used.

This report documents the building and system characteristics of the prototype college building model combined with climate-specific and construction vintage–specific requirements for the building envelope and systems from ASHRAE Standard 90.1. The energy simulation results are presented for 4 construction vintages (2004, 2007, 2010, and 2013) and 15 ASHRAE climate zones. The site energy use intensity of the college building was compared with 2012 Commercial Building Energy Consumption Survey (CBECS) and ENERGY STAR data to verify the simulation results. The site energy use intensity of the college building ranged from 60 to 202.4 kBtu/ft^2, and compared with the energy use intensities of Commercial Building Energy Consumption Survey (122.9 kBtu/ft^2) and ENERGY STAR (84.3 kBtu/ft^2) data, the prototype college building results are in a reasonable range.

1. INTRODUCTION

1.1 BACKGROUND

The US Department of Energy supports the development of commercial building energy codes and standards. To support commercial building energy research activities and the development of commercial building energy codes and standards, continuous efforts have been made to convert 16 prototype building models, which cover 80% of US commercial building floor space, to OpenStudio prototype buildings. Additionally, the suite of prototype building models was expanded to include the addition of new building prototype models (e.g., courthouse, college building).

According to the Commercial Building Energy Consumption Survey (CBECS) Building Type Definitions (EIA 2016a), the education building category includes buildings used for academic or technical classroom instruction.[1] The college or university subcategory is under the education building category; other subcategories include elementary or middle school, high school, preschool or daycare, and other classroom education (e.g., adult education, career or vocational training, religious education, training for people who are disabled, health-related training, art school, tutoring).

In particular, the college building model has unique characteristics that contrast with school buildings, which are defined in the OpenStudio prototype building suite. First, the college building includes various space types, such as research, students' working facilities, and other auxiliary areas to support teaching activities. Types and sizes of classrooms are varied depending on the number of students enrolled in different courses and the rate of students enrollment. Furthermore, the college building includes various space types with their own occupancy schedules. Finally, the college building does not include full-scale dining and kitchen facilities and a gymnasium.

To determine the building types and prioritize the model development for this suite, CBECS building type subcategories and relevant survey data were used. For the selected building types, building and system characteristics were researched using a variety of resources to develop building descriptions, thermal zone internal loads, schedules, and other key modeling input information necessary to create a canonical building energy model (Deru et al. 2011).

This study used multiple resources to develop the OpenStudio prototype college building model and presents the research conducted to define the building and system characteristics for the prototype college building, and the final prototype building energy models for the college building.

1.2 COLLEGE BUILDING VERSUS OTHER BUILDINGS IN CBECS

To gauge the share of the college building type in existing US buildings and the energy used in the buildings, the 2012 CBECS data (EIA 2016b) for college buildings was compared with other building types included in the suite of commercial prototype building models (Building Energy Codes Program 2016), including middle school and high school buildings, as well as other building types under the education building category that are not yet part of the suite.

1.2.1 Percentage of Total Commercial Building Floor Space

The 2012 CBECS data represent 27,215 college buildings in the United States. As shown in Figure 1, college buildings occupy a total of 1,883 million ft^2 of floor space, or 2.2% of the US commercial floor

[1] Buildings on education campuses for which the main use is not classroom (e.g., administration building, dormitory, library) are included in the category relating to their use (i.e., office, lodging, and public assembly, respectively)

space, compared with 7% for middle school and 3.5% for high school buildings included in the suite of commercial prototype building models.

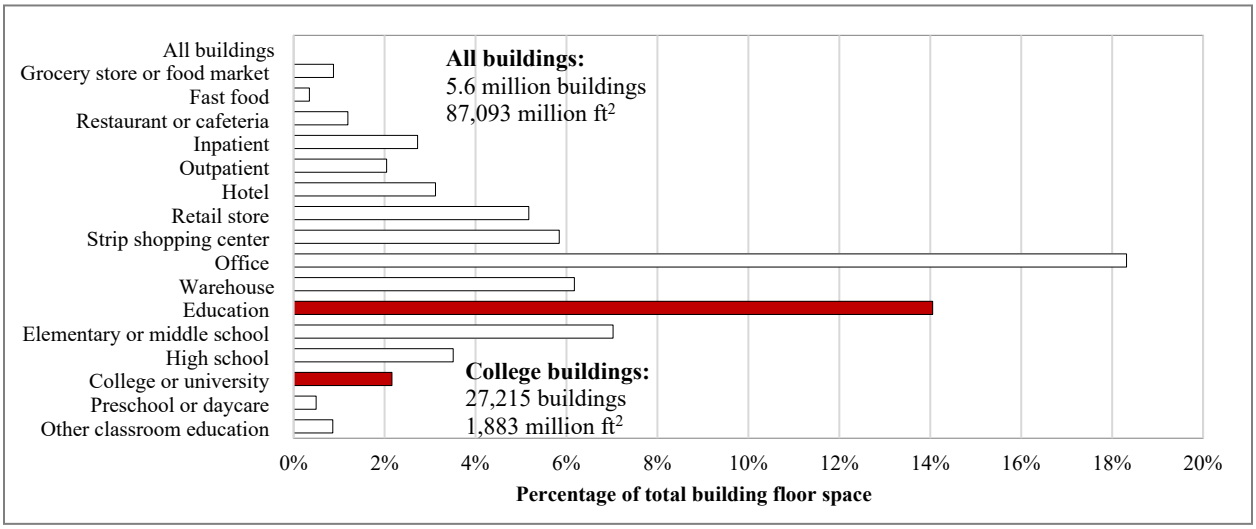


Figure 1. Percentage of total building floor space for college buildings compared with other buildings currently in the suite of commercial prototype building models. Source: EIA 2015.

1.2.2 Building Floor Area

College buildings are large, similar in size to high schools and hotels, with a mean floor area of 69,200 ft² compared with 31,500 ft² per building for the larger education category, 15,800 ft² for office, and 15,700 ft² for all commercial buildings (Figure 2).

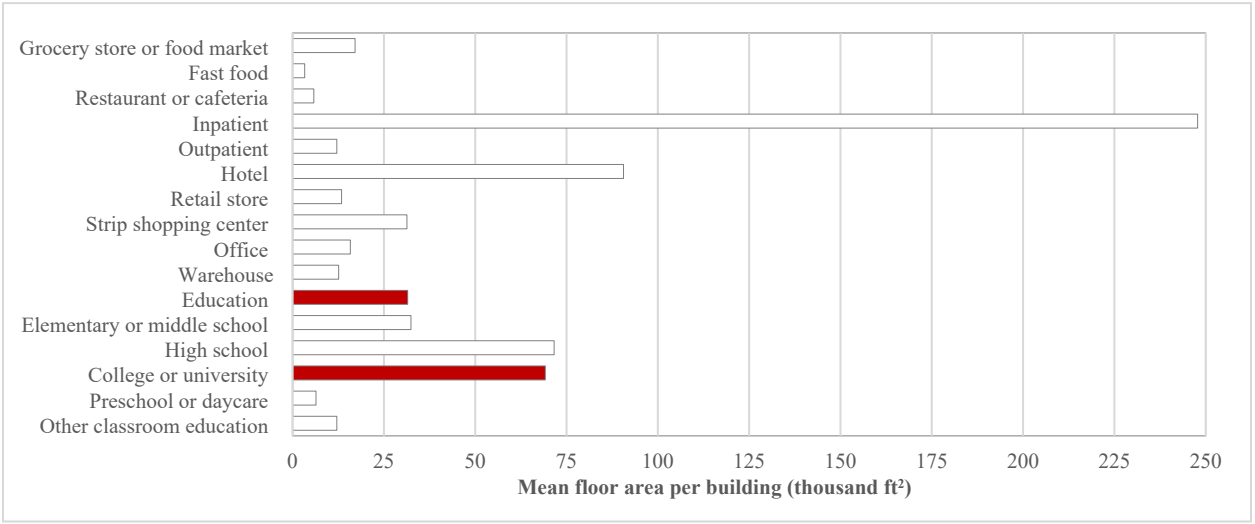


Figure 2. Mean building floor area for a college compared with other buildings. Source: EIA 2015.

1.2.3 Fuel Consumption Intensity

College buildings contribute 3.3% of the total fuel consumption in US commercial buildings, compared with 4.8% for middle school buildings and 2.9% for high school buildings. Accounting for the floor area, college buildings are among the smaller fuel consumption intensity building types with a narrow range of

variation and an average of 122.9 kBtu/ft^2, next to 77.8 kBtu/ft^2 for office and 80 kBtu/ft^2 for all commercial buildings (Figure 3).

Despite having similar average building floor area, the fuel consumption intensity of college buildings is twice that of high school buildings (65.3 kBtu/ft^2) and all other education buildings (54.9–66.4 kBtu/ft^2). The high fuel consumption intensity of a college building is likely due to the distribution and characteristics of spaces and occupancy, which are different from the school buildings.

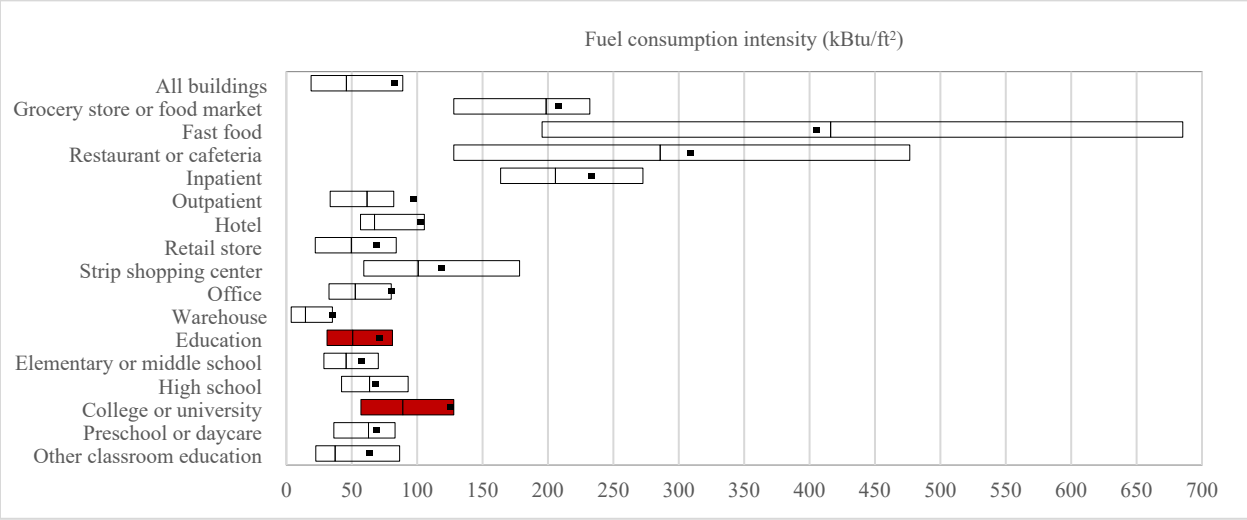


Figure 3. Fuel consumption intensity statistics for college and other buildings. Source: EIA 2015.

Figure 4 plots the fuel consumption intensity against mean floor area of college and other buildings. The clusters indicate building types that are similar in terms of average size and energy use. College buildings are dissimilar to most buildings.

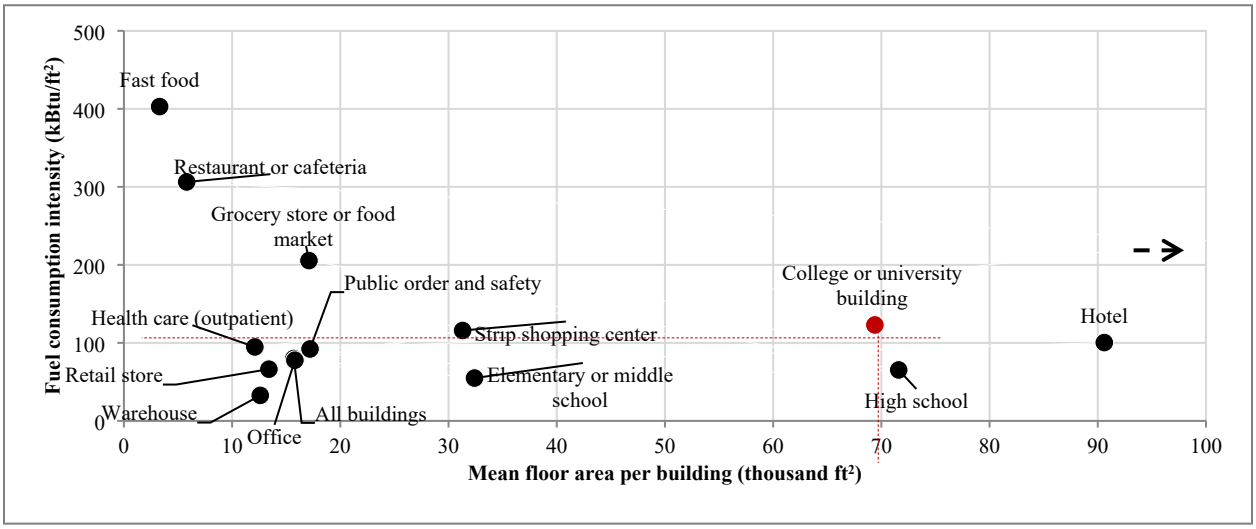


Figure 4. Fuel consumption intensity plotted against mean floor area for college and other buildings. Source: EIA 2015.

2. COLLEGE BUILDING CHARACTERISTRICS

Characteristics of college buildings in the United States vary widely in terms of the spaces, classroom types, and size based on the college type, discipline, and other facilities in the campus. Before researching the building and system characteristics for college building, it is important to recognize the types, operations, and statistics of the colleges that comprise the US higher education system. This information can be used to prioritize and define a narrative for the prototype model to represent most, if not all, types of college buildings. Understanding college operations is important to accurately defining the space types, usage, occupancy characteristics, and use schedules.

2.1 THE US HIGHER EDUCATION SYSTEM

More than 4,500 accredited institutions make up the higher education system in the United States. A variety of institution types offer higher education degrees. Liberal arts institutions, for example, offer courses in the arts, humanities, languages, and social and physical sciences. A majority of liberal arts institutions are private. Private colleges and universities are usually smaller than public institutions and may have a religious affiliation and/or be single-sex schools. Community colleges are another option and provide two-year associate degree programs to prepare students to continue studies for an undergraduate degree or help them gain occupational skills for immediate employment. State colleges and universities, also called *public universities*, were founded and subsidized by US state governments to provide a low-cost education to residents of that state. Public universities generally offer access to research opportunities and classes in a wide variety of fields of study. These universities tend to be very large and generally admit students from wide variety of fields of study than private universities.

2.1.1 Coursework

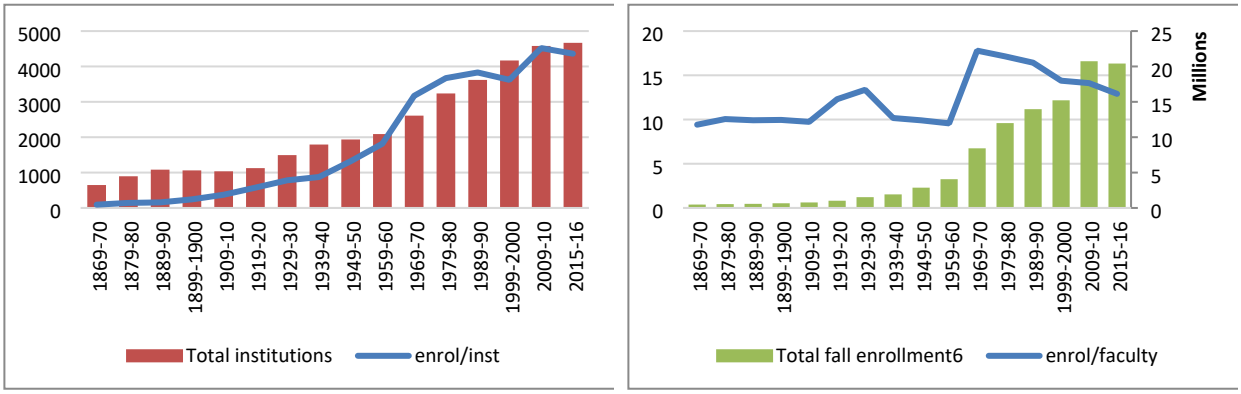
Students' individual interests will guide their choices among the many coursework possibilities. In the United States, students typically earn credits for courses they take, and those credits count toward the completion of a program. Courses are often divided into core subject areas to provide the foundation of the degree program, and major courses to provide specialization in a subject area. Students can also take elective courses to explore other topics of interest for a well-rounded educational experience.

2.1.2 Academic Year

The US academic year usually runs from August/September through May with breaks for holidays. Most universities use the semester system (2 terms of 16–18 weeks), the quarter system (students attend 3 out of 4 total terms), or the trimester system (3 terms).

2.2 ENROLLMENT STATISTICS

To guide the determination of total occupancy (including number of students, faculty, and other staff) in college building, the following data from the National Center for Education Statistics on the historical summary of faculty, enrollment, and staff were used. For the most recent documented year (2015–2016), the average enrollment per institution was 4,583 students, and the student to faculty ratio averaged 12.9.



(a) (b)

Figure 5. (a) Number of institution and average enrollment per institution, and (b) number of enrollments and average number of enrollments per faculty.

2.3 FUNCTIONAL SPACES

College buildings with centralized facilities typically include classrooms of different types (e.g., lecture halls, group study rooms, individual study rooms/cubicles) and supporting spaces, a lobby, and perhaps faculty offices, graduate student workspaces, staff offices, discipline-specific libraries, a cafeteria with vending machines, and meeting rooms. The occupants/users include students, faculty, and other staff. The location, size, and occupancy of these spaces are based on a variety of criteria.

College buildings have several unique characteristics that differentiate them from other educational buildings.

- Unlike a school building, an academic building on a college or university campus does not include full-scale dining and kitchen facilities and a gymnasium. Also, the library and computation center may not be part of the academic building; these facilities are typically provided as all-campus facilities.

- Typically, at a college or university, there is a large variation in the number of students enrolled in different courses, so different types and sizes of classrooms and lecture rooms are required, such as flat floored, slope floored, and auditoriums (for 250 or more students), all equipped with advanced audiovisual facilities (which means higher equipment loads).

- Academic buildings also have faculty offices; discipline-specific teaching, research, and students' working facilities; and other auxiliary areas to support teaching activities.

2.4 BUILDING CHARACTERISTICS IN CBECS DATA

Figure 6 through Figure 10 show relevant characteristics of college building, including floor area, building shape, number of floors, window to wall ratio, construction, and HVAC systems.

- **Floor area**: The 10,000–25,000 ft^2 floor area category is the most common college building size, representing 29% of college buildings.. Meanwhile, 42% of college building floorspace falls under the 100,000–200,000 ft^2 floor area category.

- **Building shape**: Most college buildings have a wide rectangle shape; most buildings under the parent education category have 2.2:1 to 3.1:1 aspect ratios, with an area-weighted aspect ratio of 2.53:1.

- **Number of floors**: In terms of the number of college building and floor space, more than 70% of college buildings are 2- to 4-story buildings. (Figure 7-C).

- **Window to wall ratio**: In terms of the number of college building and floor space, more than 80% of college buildings almost equally fall under the 2%–10%, 11%–25%, and 26%–50% exterior glass categories. 26%–50% exterior glass is the most prevalent in floor space category. (Figure 8)

- **Construction**: Brick, stone, or stucco on stud-walls is the most common wall construction, representing more than 72% of college buildings by number and 73.5% of college building floor space). Plastic, rubber, or synthetic sheeting is the most common roof construction, representing more than 35% of college buildings by number and 31% of college building floor space, followed by built-up roofing and slate or tile shingles.

- **HVAC systems**: District system is the most common system type for heating and cooling, serving more than 5559% of college building floor space, followed by central boiler and chilled water systems, which serve more than 26% of total college building floor space in the United States.

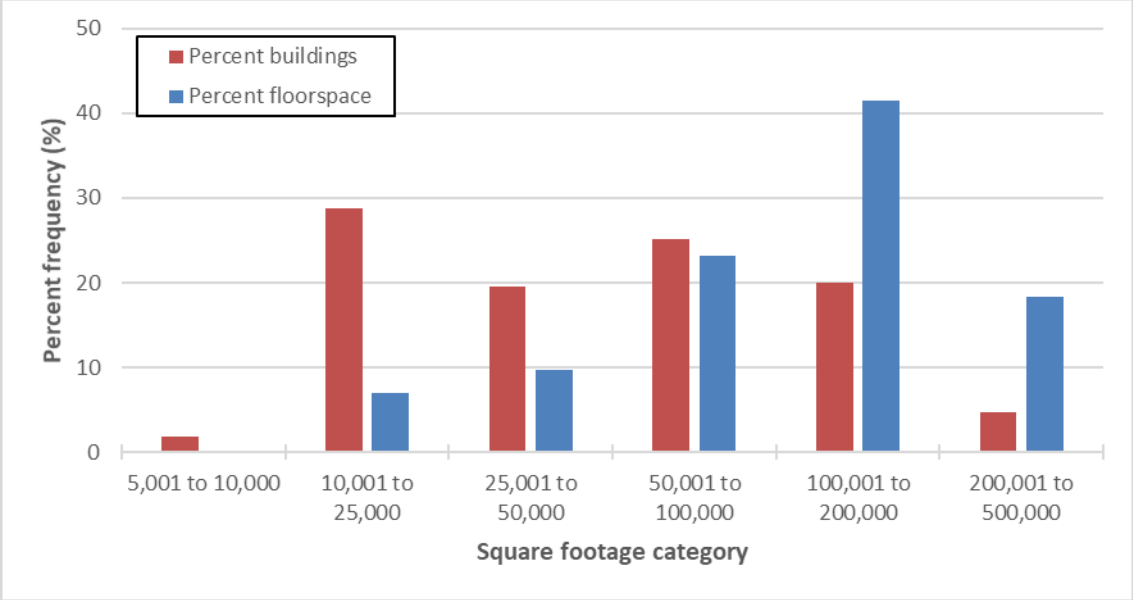


Figure 6. Percentage frequency of college square footage categories. Source: EIA 2015.

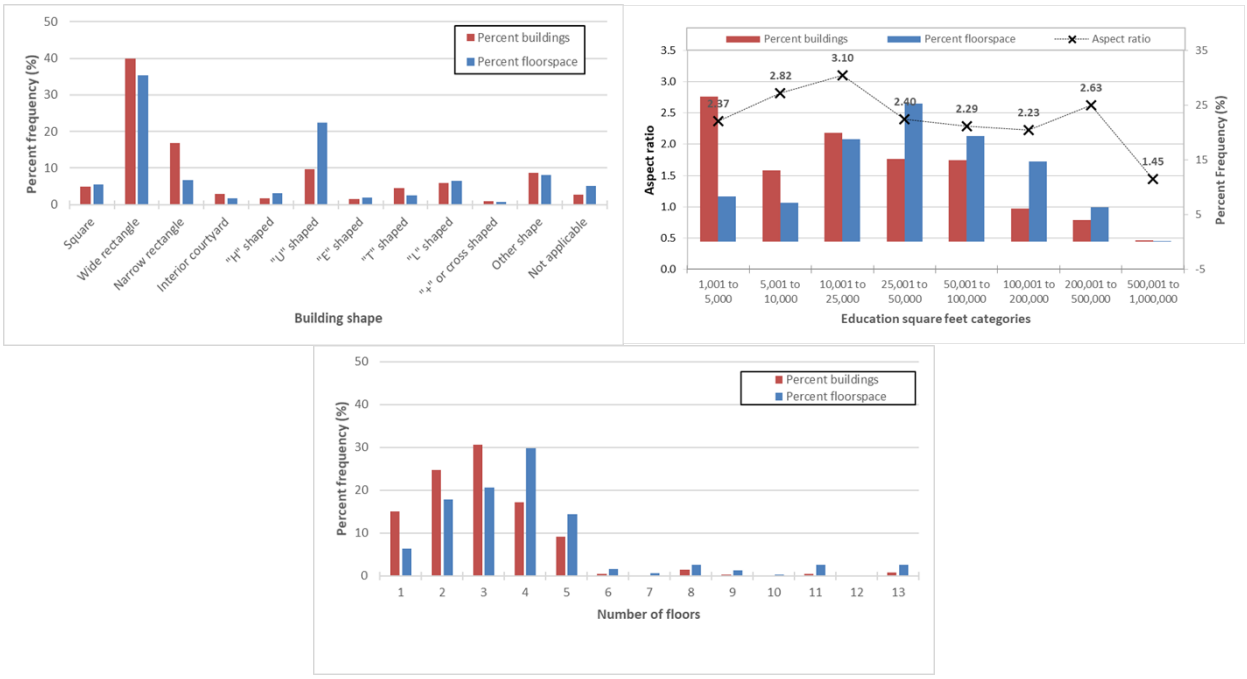


Figure 7. Percentage frequency of (a) college building shape, (b) aspect ratio of education buildings, and (c) number of floors for college buildings. Source: EIA 1996, 2015.

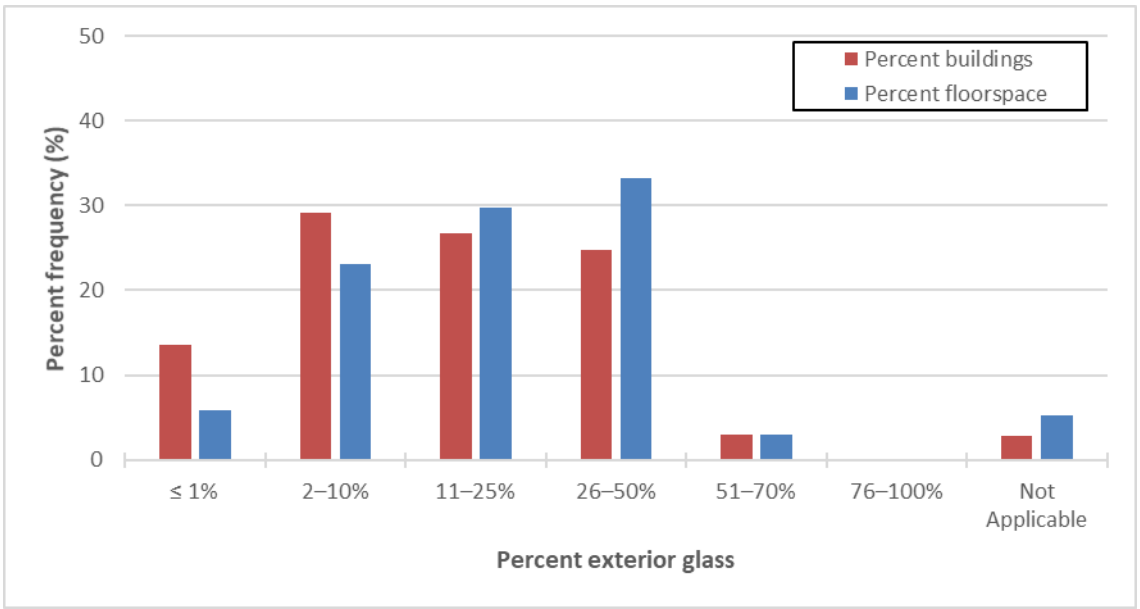


Figure 8. Percentage frequency of percent exterior glass in college building. Source: EIA 2015.

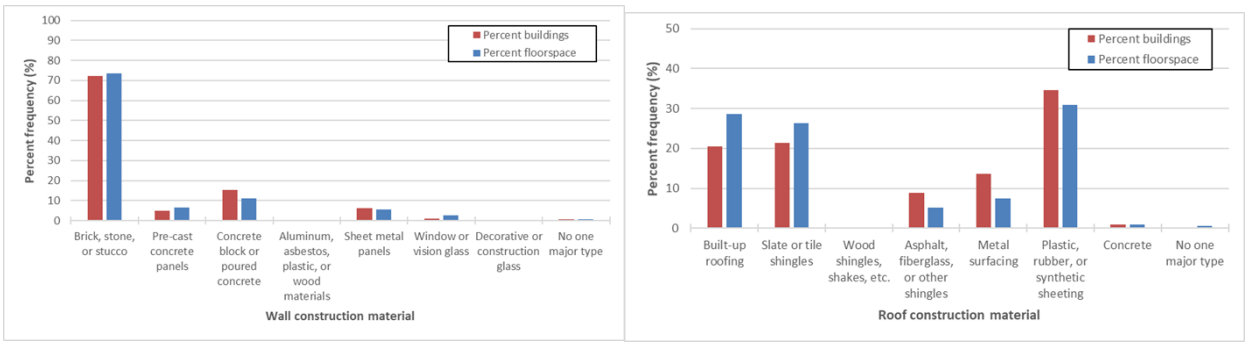


Figure 9. Percentage frequency of construction material for (a) wall and (b) roof. Source: EIA 2015.

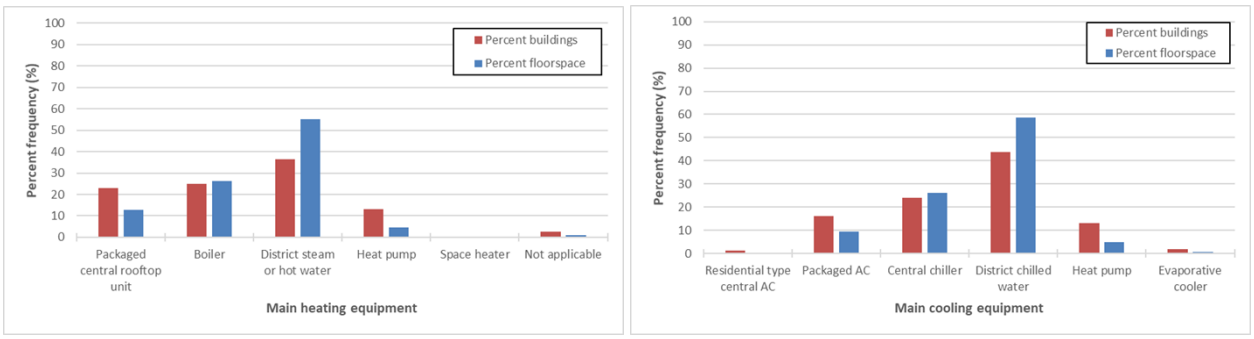


Figure 10. Percentage frequency of main heating and cooling equipment. Source: EIA 2015.

3. PROTYTYPE MODELING CHARACTERISTICS

3.1 BUILDING FORM

The prototype college building energy model is a 4-story building, as shown in Figure 11. The total building area is 6,416 m^2 (69,063 ft^2) and the total conditioned building area is 6,369 m^2 (68,551 ft^2). The floor height is 3.96 m (13 ft) for all floors.

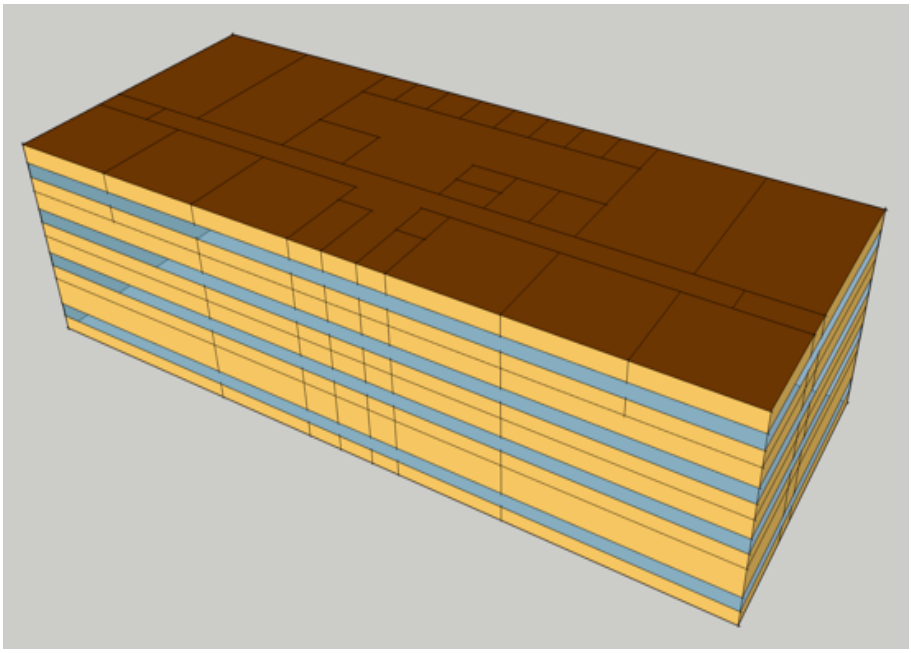


Figure 11. Prototype college building energy model.

Table 1 describes the total window area and window to wall ratio according to the direction of the college building. Regardless of the direction of the building, the window to wall ratio is similar. Depending on the direction of the building, the window to wall ratio is between 30.64% and 30.74%. Total window to wall ratio is 30.69%.

Table 1. Window to wall ratio according to the building direction

	Total	North (315° to 45°)	East (45° to 135°)	South (135° to 225°)	West (225° to 315°)
Wall area (m^2 (ft^2))	2,811.6 (30,263.81)	1,004.8 (10,815.58)	400.97 (4,316.01)	1,004.8 (10,815.58)	400.97 (4,316.01)
Window area (m^2 (ft^2))	862.81 (9,287.21)	308.61 (3,321.85)	123.24 (1,326.54)	308.09 (3,316.25)	122.87 (1,322.56)
Window to wall ratio (%)	30.69	30.71	30.74	30.66	30.64

3.2 SPACE TYPES

Table 2 and Figure 12 describe the floor area and floor fractions of different space types in the prototype college building energy model. The largest portion of the building is devoted to classrooms, studios, and offices. The office consists of a faculty office, open office, and closed office. The restroom consists of a

faculty restroom, student restroom, and staff restroom. Figures 13 to 15 show the prototype college building model layout of each floor. The layout of the second floor and third floor are the same. The media center and cafeteria are located on the first floor, along with a large space type such as a lecture hall and large classroom. Studios are located on the second floor, and laboratories are located on the third floor. Classrooms are located on the second and third floors, and faculty offices are located on the second, third, and fourth floors.

Table 2. Floor area and area fraction of the prototype college building model

Space type	Floor area (m^2 [ft^2])	Percentage of total (%)
Classroom	1,355 (14,581)	21.1
Lecture hall	421 (4,530)	6.6
Laboratory	541 (5,821)	8.4
Art classroom	1,199 (12,901)	18.7
Office	1,215 (13,080)	18.9
Corridor	459 (4,945)	7.2
Conference	138 (1,485)	2.2
Lounge	180 (1,935)	2.8
Media center	270 (2,910)	4.2
Stairs	175 (1,880)	2.7
Storage	75 (810)	1.2
Entrance lobby	75 (810)	1.2
Restroom	233 (2,508)	3.6
Elevator shaft	48 (512)	0.7
Utility	33 (352)	0.5
Total	6,416 (69,063)	100

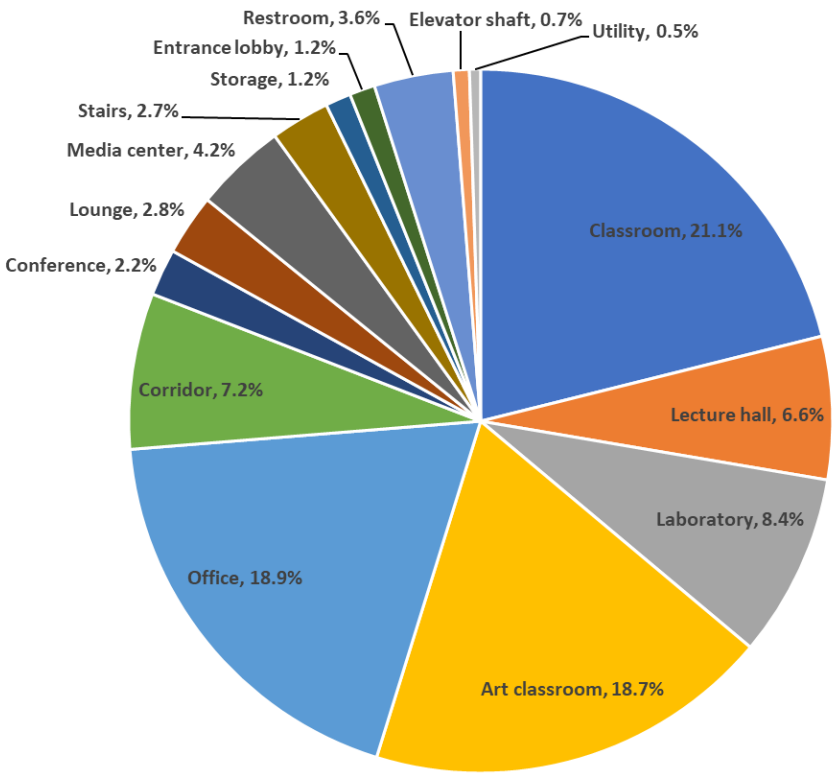


Figure 12. Distribution of the space types of the prototype college building model.

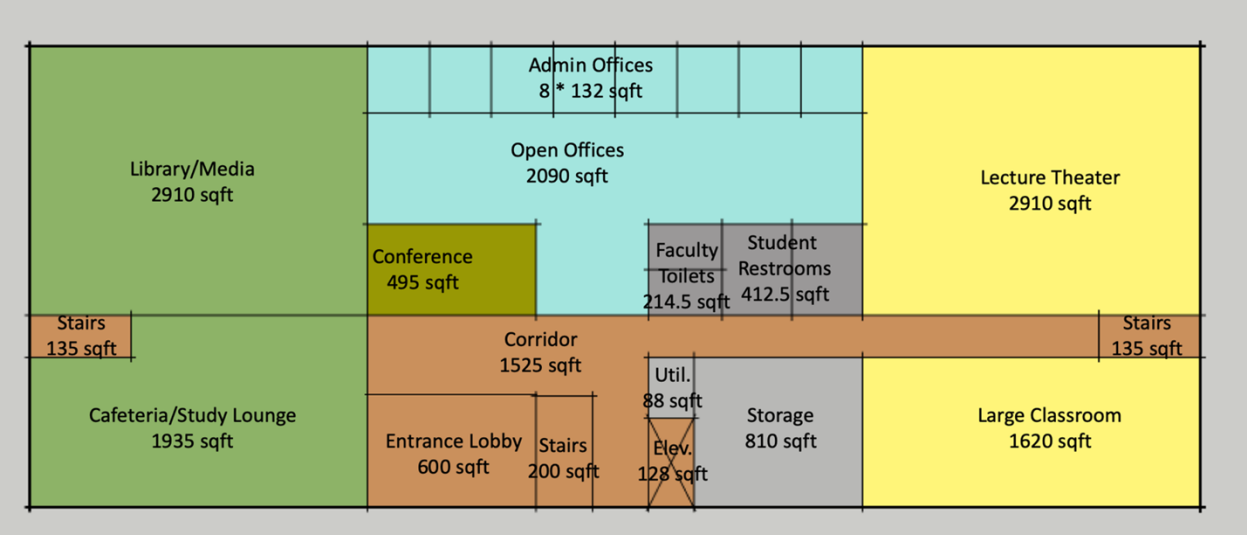


Figure 13. Prototype college building model layout of the first floor.

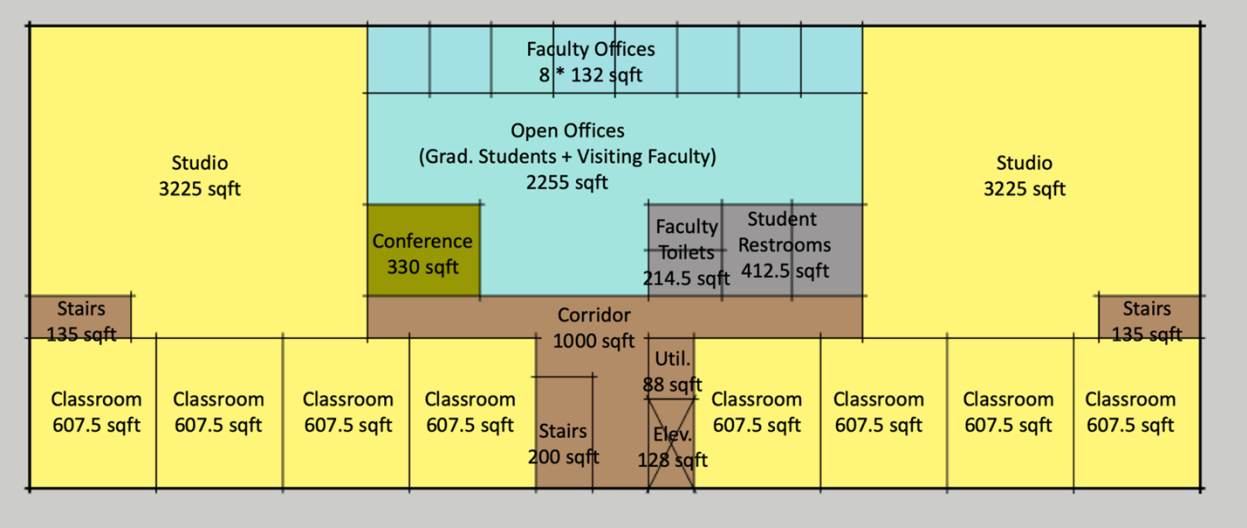


Figure 14. Prototype college building model layout of the second and third floors.

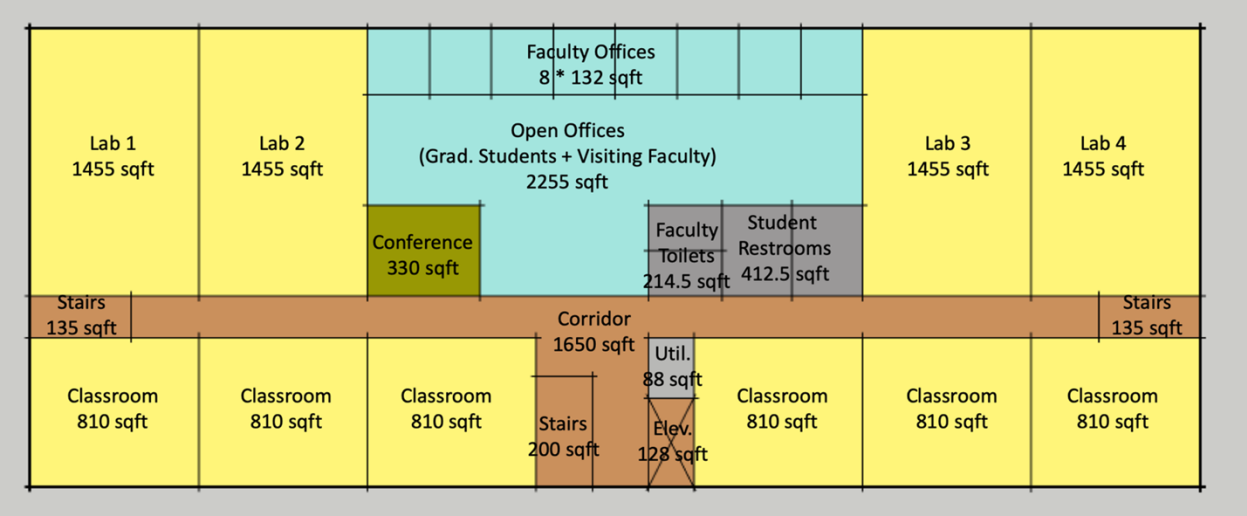


Figure 15. Prototype college building model layout of the fourth floor.

3.3 CONSTRUCTION

The prototype college building was modeled with a mass wall construction, built-up roof, and slab floor. The thermal performance of the building envelope components, including the roof, exterior wall, floor, window, and door, were determined based on the requirements in ASHRAE Standard 90.1. Windows are all metal frame windows in the college building except in the ASHRAE Standard 90.1-2004 vintage, which has 67% of windows as fixed windows and 35% of windows as operable windows.

The design air infiltration was set to 0.2016 cfm/ft^2 of above-grade exterior wall surface area, and door opening infiltration in the lobby was modeled with and without a vestibule based on ASHRAE Standard 90.1 requirements, and they were 6,789 cfm with the vestibule and 9,675 cfm without.

3.4 HEATING AND COOLING SET POINT TEMPERATURES

Figure 16 shows the heating set point temperature for the prototype college building model. In figures, "WD" stands for the weekday, and "WK" stands for the weekend and holidays. During the weekday, the heating set point temperature was 21.1°C (70°F) from 9 a.m. to 9 p.m., and 15.6°C (60°F) from 10 p.m. to 6 a.m. The heating set point temperature was 17.8°C (64°F) at 7 a.m., and 20°C (68°F) at 8 a.m. During the weekend and holidays, the heating set point was constant at 15.6°C (60°F).

Figure 17 shows the cooling set point temperature for the prototype college building model. During the weekday, the cooling set point temperature was 23.9°C (75°F) from 9 a.m. to 9 p.m., and 29.4°C (85°F) from 10 p.m. to 6 a.m. The cooling set point temperature was 27.8°C (82°F) at 7 a.m. and 25.6°C (78°F) at 8 a.m. During the weekend and holidays, the cooling set point was constant at 29.4°C (85°F).

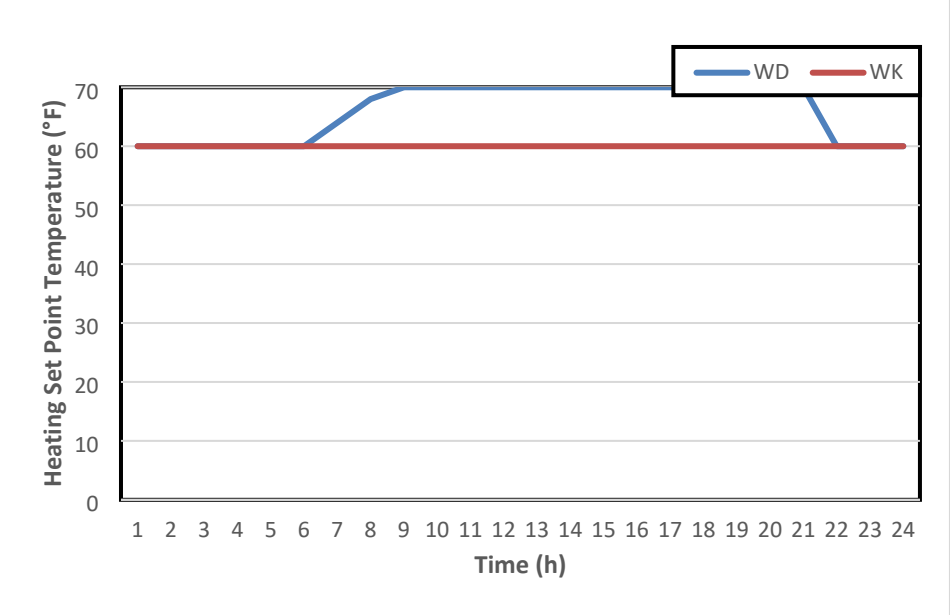


Figure 16. Heating set point temperature for the prototype college building model.

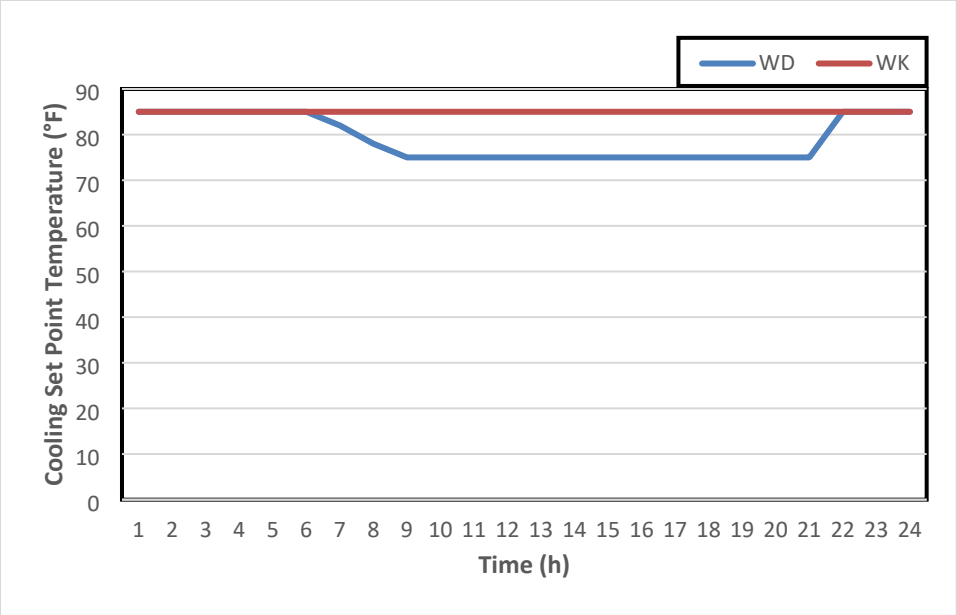


Figure 17. Cooling set point temperature for the prototype college building model.

3.5 OCCUPANCY AND VENTILATION REQUIREMENTS

Figure 18 shows the occupant density depending on the space type. Regardless of the vintage of ASHRAE Standard 90.1, occupancy density was the same. The ventilation requirements on different spaces in the prototype college building was determined from ASHRAE Standard 62.1, as described in Table 3.

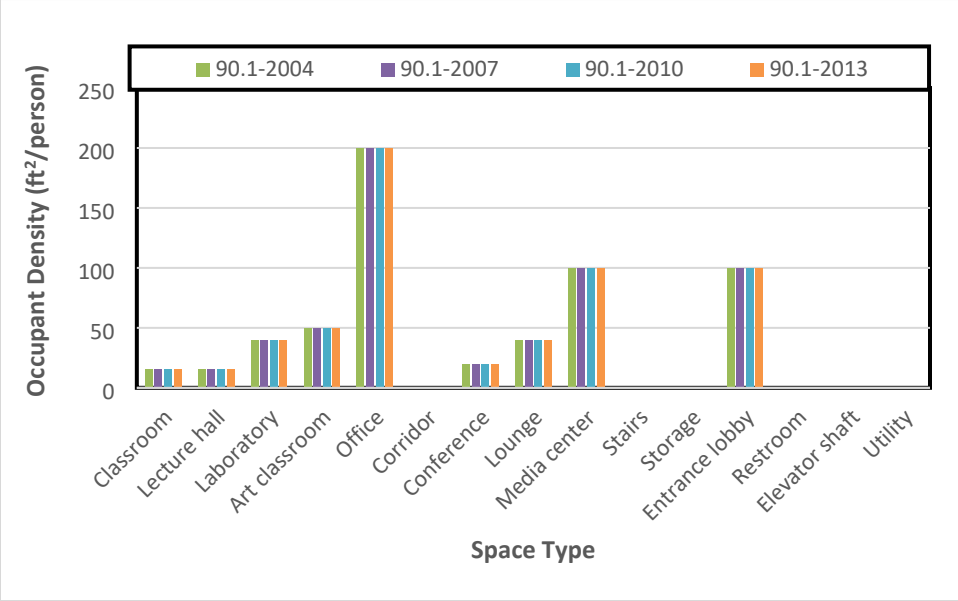


Figure 18. Comparison of space-specific occupant density by vintage.

Table 3. Minimum ventilation requirement by vintage

Zone category	90.1-2004 (based on ASHRAE Standard 62-1999)		90.1-2007 (based on ASHRAE Standard 62.1-2004)		90.1-2010 (based on ASHRAE Standard 62.1-2007)		90.1-2013 (based on ASHRAE Standard 62.1-2007)	
	cfm/person	cfm/ft^2	cfm/person	cfm/ft^2	cfm/person	cfm/ft^2	cfm/person	cfm/ft^2
Classroom	15	—	7.5	0.06	7.5	0.06	7.5	0.06
Lecture hall	15	—	7.5	0.06	7.5	0.06	7.5	0.06
Laboratory	20	—	—	0.43	10	0.18	10	0.18
Art classroom	15	—	—	0.38	10	0.18	10	0.18
Office	20	—	—	0.08	5	0.06	5	0.06
Corridor	—	0.05	—	0.06	—	0.06	—	0.06
Conference	20	—	—	0.31	5	0.06	5	0.06
Lounge	20	—	—	0.37	7.5	0.18	7.5	0.18
Media center	15	—	—	0.17	5	0.12	5	0.12
Stairs	—	0.05	—	0.06	—	0.06	—	0.06
Storage	—	0.15	—	0.12	—	0.12	—	0.12
Entrance lobby	15	—	—	0.11	5	0.06	5	0.06
Restroom	—	0.96	—	0.96	—	0.96	—	0.96
Elevator shaft	—	—	—	—	—	—	—	—
Utility	—	0.05	—	0.12	—	0.12	—	0.12

3.5.1 Occupancy Schedule

As stated in the Sections 1 and 2, college buildings have unique characteristics compared with other school buildings, and it is difficult to benchmark the occupancy schedule of existing school buildings, especially for the space that might have different schedules depending on the enrollment size of the class. Therefore, a need exists to have actual schedules that represent the realistic occupancy schedule classroom, studio, lecture hall, and laboratory.

Researchers at the US Department of Energy's Oak Ridge National Laboratory collected the actual schedules of a classroom, studio, and laboratory and updated the occupancy schedule of the prototype college building. The team received the class reservation schedules of the classroom, studio, lecture hall, and laboratory for a fall semester from 10 universities in the United States, as shown in Figure 19.

Figure 20 shows the process to generate the occupancy schedules. The class reservation schedules from 10 universities were collected. Based on the class reservation schedules, four space schedules—for a classroom, laboratory, art classroom, and lecture hall—were generated.

The following assumptions were made to generate a typical occupancy schedule.

- The fall semester represents a typical semester schedule.
- The summer schedule starts on June 1 and ends on August 31.
- The weekly schedule is defined for Monday through Friday.
- No occupancy schedule is defined for Saturday and Sunday.
- The occupancy schedule is defined based on average classroom reservation schedules of the collected universities' schedules.

Based on the classroom reservation schedule, the classroom operational hours were determined, and the hourly occupancy schedules were calculated by dividing classroom operational hours into 60 min and then generating the daily occupancy schedules of all classrooms based on the hourly schedules. To generate the weekly occupancy schedules, the average daily schedules for Monday through Friday were used.

Figure 19. The location of the 10 universities.

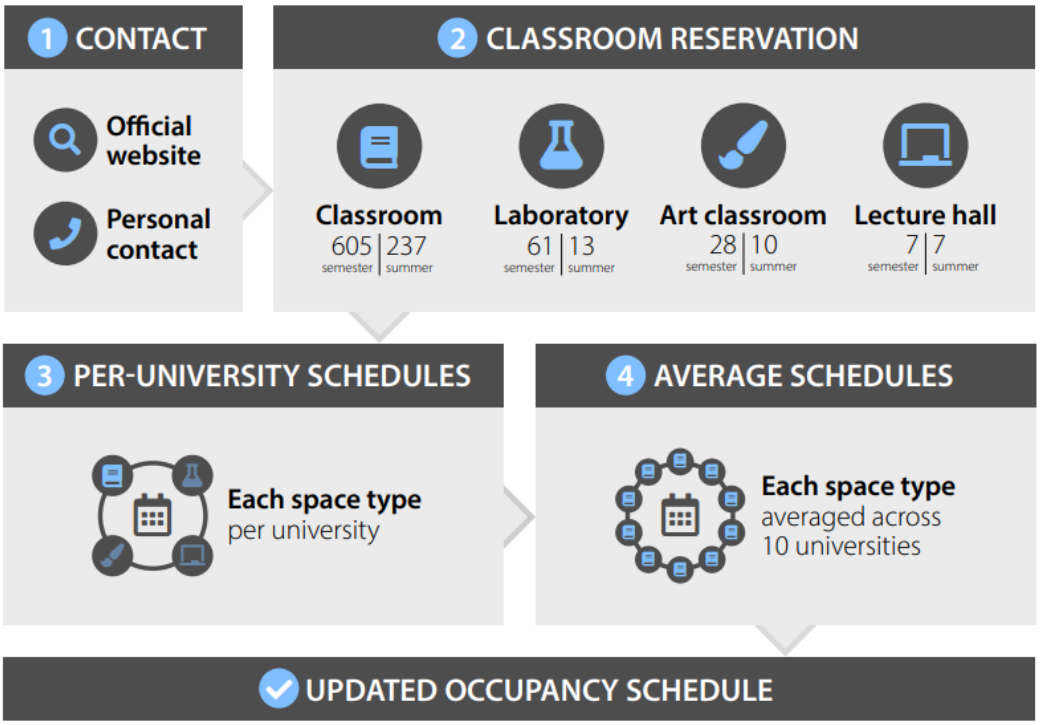


Figure 20. Data process procedure.

Table 4 indicates which types of space are covered by which schedules. Three occupancy schedules were used in a previous version of the whole prototype college building model. However, the current model has six occupancy schedules, which include occupancy schedules for a classroom, laboratory, art classroom, and lecture hall based on actual class reservation schedules. Occupancy schedules for an office, conference room, lounge, and entrance lobby are the same as the previous occupancy schedules. The schedule for the lounge follows a lounge schedule in the secondary school prototype model. All other space types, such as stairs, storage, corridor, restroom, and elevator shaft, do not have occupancy schedules.

Table 4. Occupancy schedules based on the space type

Space type	Previous schedule	Updated schedule
Office	College BLDG_OCC_SCH_Offices	College BLDG_OCC_SCH_Offices
Lecture hall	College BLDG_OCC_SCH_Lecture Theater	College BLDG_Lecture_OCC_SCH
Media center		
Laboratory	College BLDG_OCC_SCH	College BLDG_Lab_OCC_SCH
Classroom		College BLDG_Class_OCC_SCH
Art classroom		College BLDG_Studio_OCC_SCH
Lounge		College BLDG_Cafe_OCC_SCH
Conference		College BLDG_OCC_SCH
Entrance lobby		

Figure 21 shows the general occupancy schedule of the prototype college building model. The occupancy schedules for the conference room, entrance lobby, and cafe study lounge follow this general schedule. Figure 22 shows the occupancy schedule for the office space. In Figure 21 and Figure 22, “Study” indicates the spring and fall semesters, which are from January 1 to June 30 and from September 1 to December 31, respectively. “Summer” indicates the summer vacation, which is from July 1 to August 31.

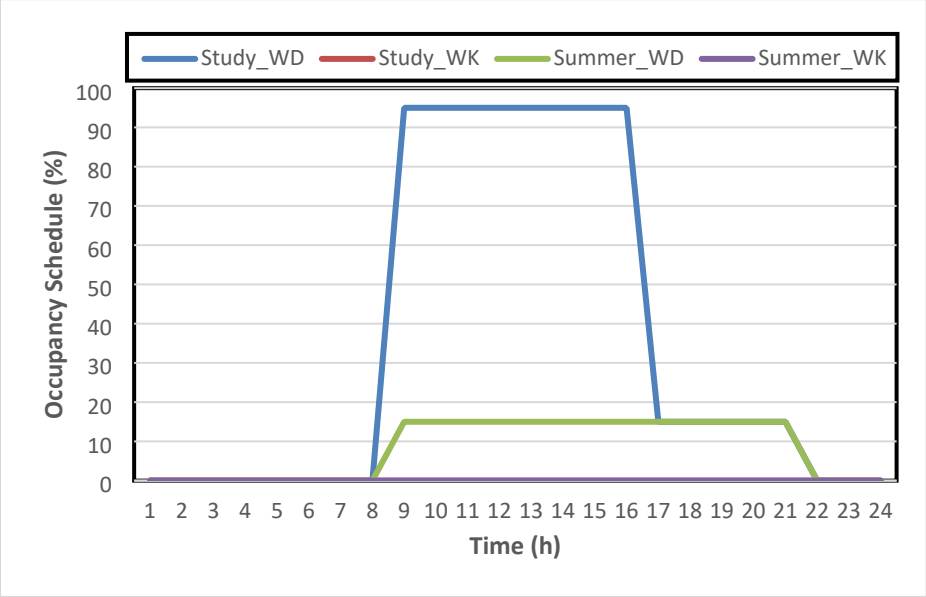


Figure 21. Occupancy schedule for college building.

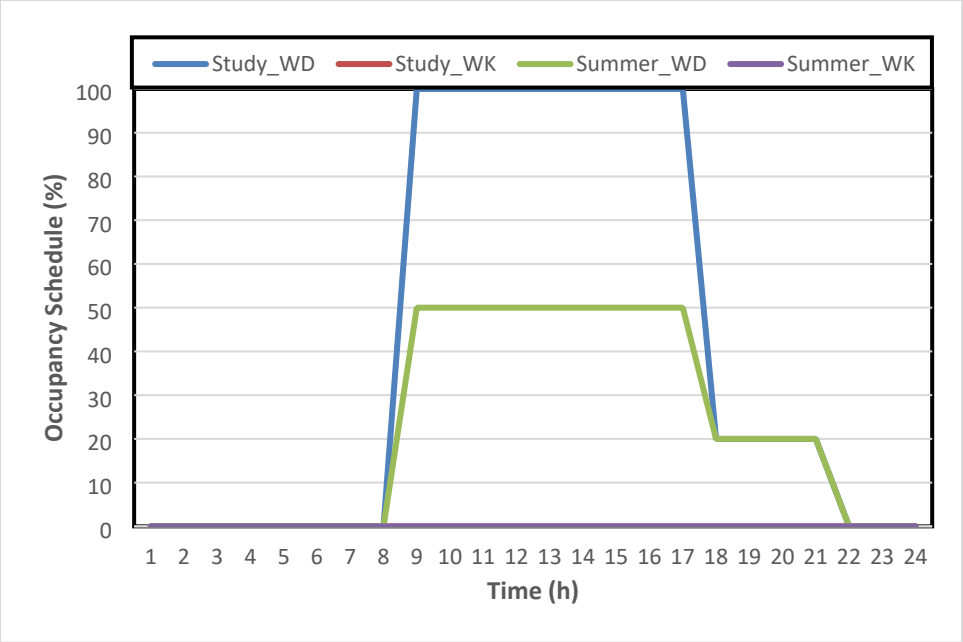


Figure 22. Occupancy schedule for the office.

Error! Reference source not found. shows the box plots of the occupancy schedules in percentages for the classroom, laboratory, art classroom, and lecture hall during the semester, and Figure 24 show box plots of the schedules in percentages during the summer vacation. The boxes in **Error! Reference source not found.** and Figure 24 indicate the first and third quartile. The horizontal line and × indicate the median and mean value of the registration schedule, respectively. In total, 605 classroom reservation schedules, 61 laboratory reservation schedules, 28 art classroom reservation schedules, and 7 lecture hall reservation schedules for the 2021 fall semester from 10 universities were collected.

To determine the occupancy schedules for the summer vacation, the classroom, laboratory, art classroom, and lecture hall reservation schedules for the 2019 summer session, when universities had summer sessions on campus, were collected. In total, 237 classroom reservation schedules, 13 laboratory reservation schedules, 10 art classroom reservation schedules, and 7 lecture hall reservation schedules from three universities, where the universities provide reservation schedules on their official website, were collected. Overall, spaces to support teaching activities were significantly underoccupied during the summer vacation compared with the typical operational hours during the semester. Also, hourly schedules of the classroom, art classroom, and lecture hall showed significant variations during occupied hours, which means the use of rooms is notably different in each space for each university.

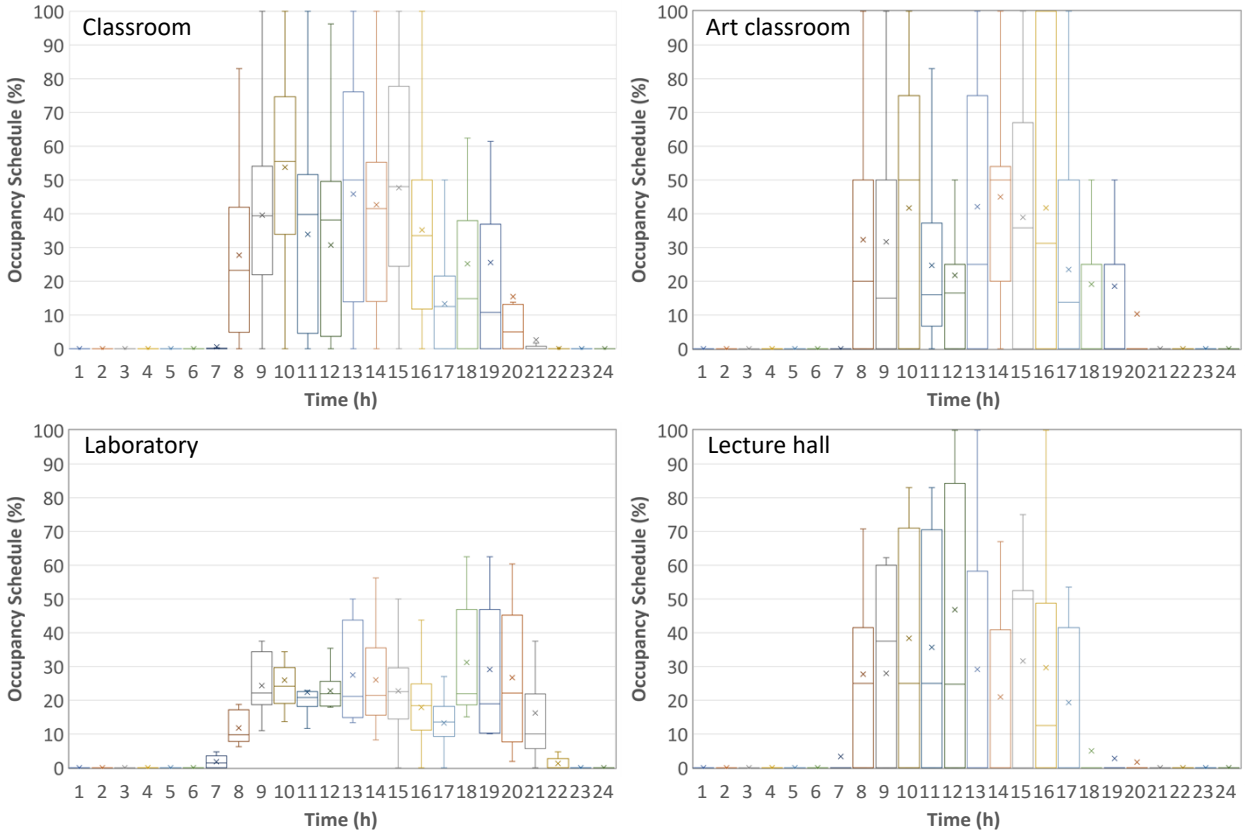


Figure 23. Occupancy schedules during the semester.

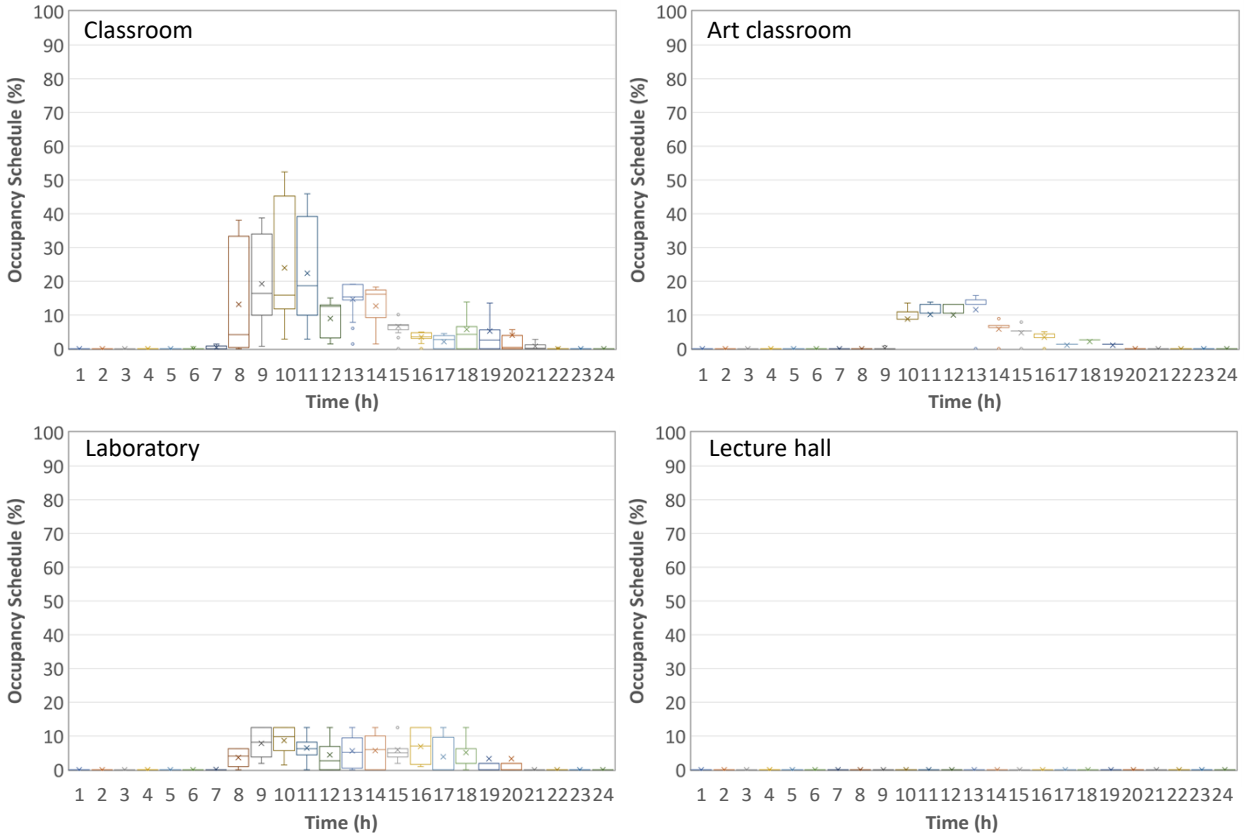


Figure 24. Occupancy schedules during the summer vacation.

Figure 25 through Figure 28 show the updated occupancy schedule for classroom, laboratory, art classroom, and lecture hall. “Up” in Figure 25 through Figure 28 indicates the updated occupancy schedule, “Pre” indicates the previous occupancy schedule, “Sem” indicates the schedule for the semester, and “Sum” indicates the schedule for the summer vacation. Significant differences were observed between the previous and updated occupancy schedules.

The updated occupancy schedule in Figure 25 shows that the classroom was significantly unoccupied (lower than 50% occupancy) compared with in the previous occupancy schedule. Because classes in the college were not all held at the same time, the occupancy of the classroom in the college building during the semester was lower than 50%, which means that fewer than 50% of the classrooms in the college building were occupied at the same time. In addition, the updated schedule showed relatively low occupancy during lunch and dinner times, and the occupancy increased from 6 to 7 p.m. because of classes in the evening. Also, the previous occupancy schedule began at 9 a.m., whereas the updated occupancy schedule began at 8 a.m. During the summer vacation, the updated occupancy for the classroom was 16% from 8 a.m. to 2 p.m. because of the summer session, and only 5% from 3 to 8 p.m.

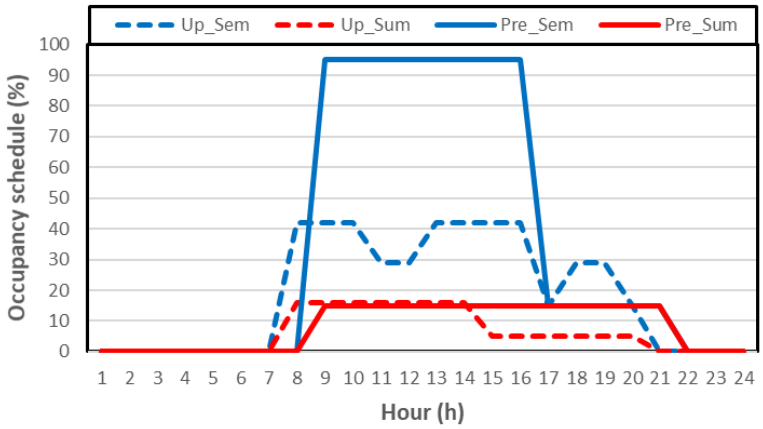


Figure 25. Updated occupancy schedule for the classroom.

Figure 26 shows the updated occupancy schedule for the laboratory. The updated occupancy schedule pattern for the laboratory was similar to that of the classroom. During the semester, the updated occupancy for the laboratory was 25% from 8 a.m. to 3 p.m. and 6 to 8 p.m., which is one-fourth of the previous occupancy schedule, and 16% from 4 to 5 p.m. During the summer vacation, the pattern of the updated occupancy schedule was similar to the previous occupancy schedule; the updated occupancy was 5%, which is one-third of the previous occupancy schedule.

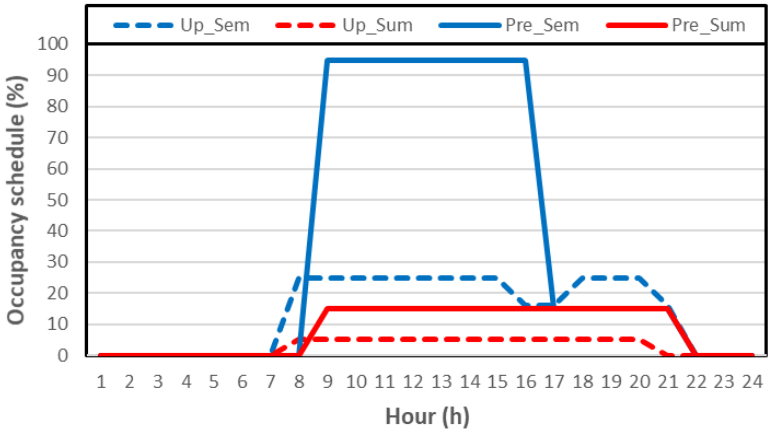


Figure 26. Updated occupancy schedule for the laboratory.

Figure 27 shows the updated occupancy schedule for the art classroom. The updated occupancy was 37% from 8 a.m. to 5 p.m., except for at lunch time (11 a.m. to 12 p.m.). During lunch time and after 5 p.m., the occupancy was 19%. During the summer vacation, the updated occupancy was 6% from 10 a.m. to 7 p.m.

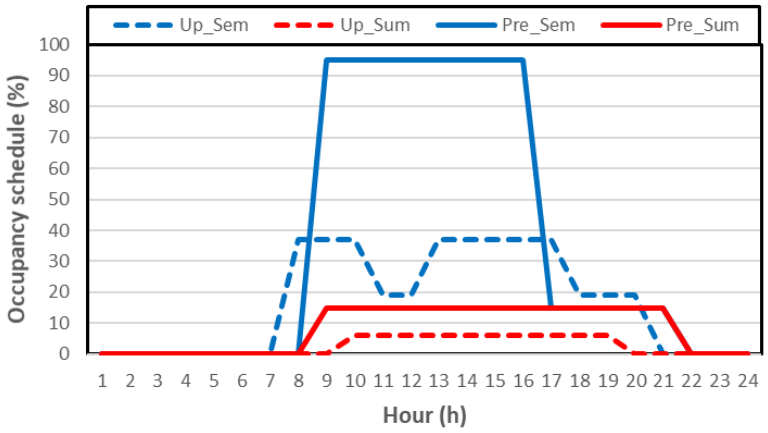


Figure 27. Updated occupancy schedule for the art classroom.

Figure 28 shows the updated occupancy schedule for the lecture hall. The updated occupancy pattern for the lecture hall was completely different from that of the previous occupancy schedule. Unlike the previous occupancy schedule, which had an occupancy peak from 3:00 p.m. to 8:00 p.m., the updated occupancy was 0% after 5:00 p.m., which means that there was no registration after 5 p.m. anywhere in the 7 lecture halls examined in this study. The lecture hall, which is a larger space than the common classroom, is generally used for large classes. Its occupancy was lower than that of the classroom in Figure 25. According to the collected data, the occupancy was 0% during the summer vacation because there was no registration for the lecture hall in the summer session.

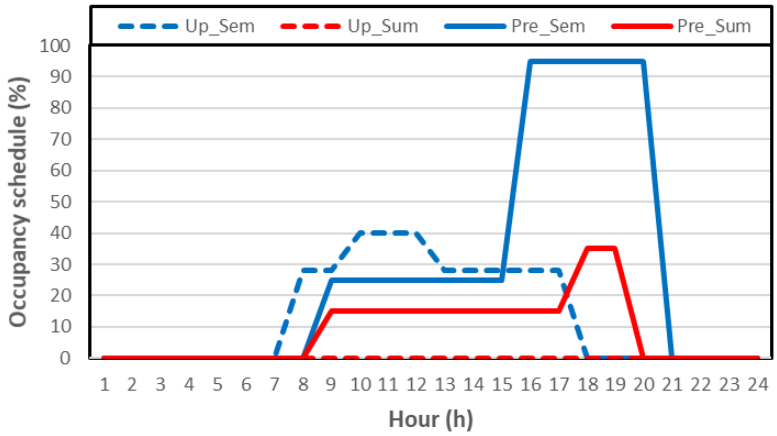


Figure 28. Updated occupancy schedule for the lecture hall.

Occupancy was assigned to the 9 space types—classroom, art classroom, conference room, entrance lobby, laboratory, lecture hall, lounge, media center, and office. Figure 29 shows the maximum number of people in each space type. Figure 30 indicates the average number of occupants in each space type. The classroom had the largest number, with an average of 269 occupants, and the entrance lobby had the smallest number, with an average of 4 occupants.

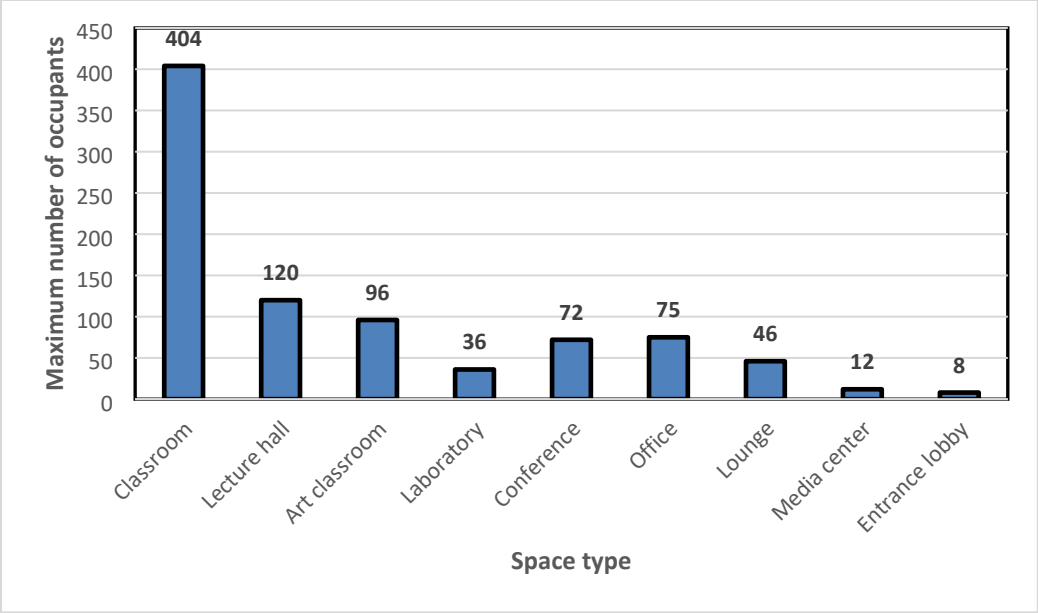


Figure 29. Maximum number of occupants in each space type.

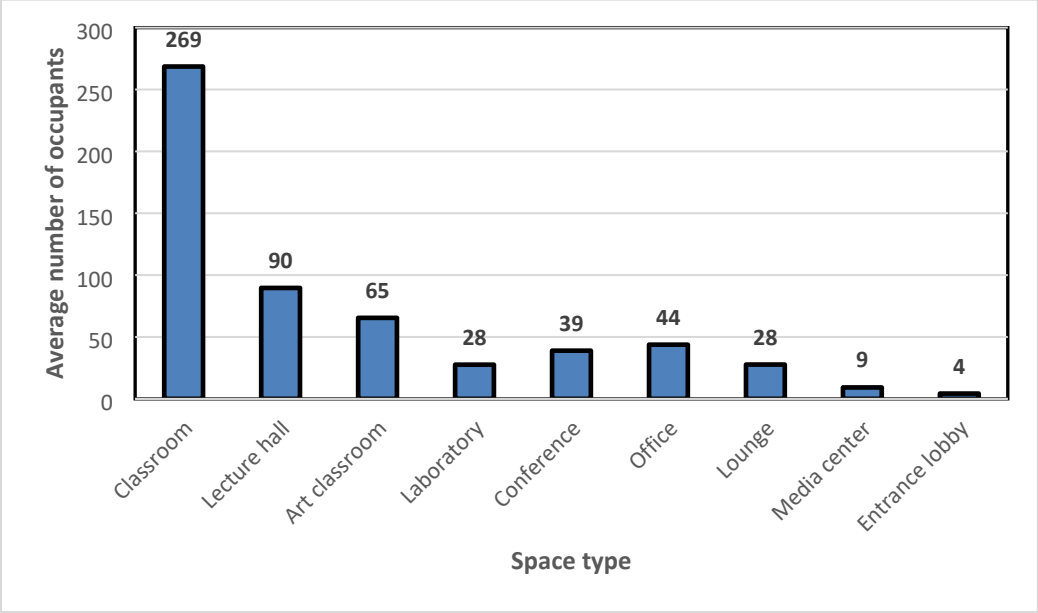


Figure 30. Average number of occupants in each space type.

3.5.2 Mechanical Ventilation

The number of occupants influenced the amount of mechanical ventilation, as described in Table 3.

Figure 31 shows the amount of mechanical ventilation in each space type during occupied hours in climate zone 5A. The weighted value of each space type was used because the floor area of the spaces were varied. In the prototype college building model, there were 22 classrooms, 4 conference rooms, 36 offices, 4 art classrooms, and 4 laboratories. ASHRAE Standard 90.1-2004 had the highest mechanical ventilation, and ASHRAE Standard 90.1-2007 had the lowest. ASHRAE Standard 90.1-2010 and 90.1-2013 had higher mechanical ventilation than ASHRAE Standard 90.1-2007 because, as shown in Table 3,

the cubic feet per minute per person of ASHRAE Standard 90.1-2010 and 90.1-2013 were higher than of ASHRAE Standard 90.1-2007.

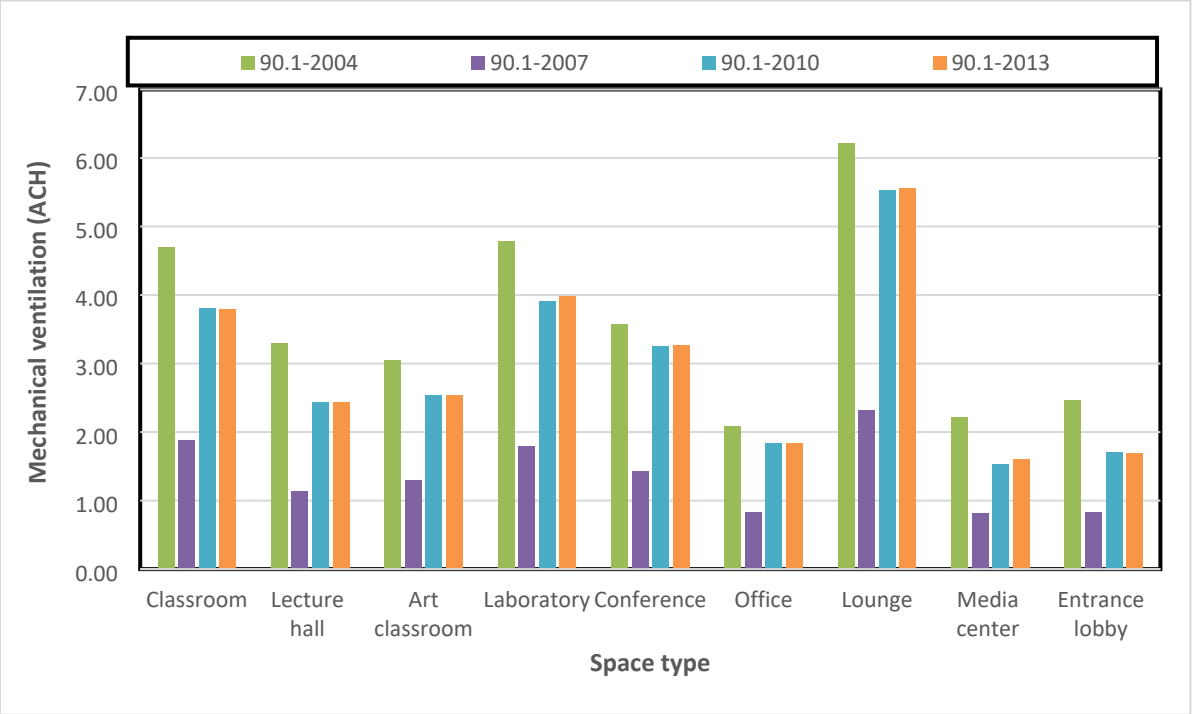


Figure 31. Mechanical ventilation of each space type during occupied hours (climate zone 5A).

3.6 LIGHTING

The lighting power densities were determined from ASHRAE Standard 90.1 and are shown in Table 5. The differences between the vintages are shown in Figure 32. Figure 33 shows the lighting schedule for the prototype college building model.

Table 5. Lighting power density by vintage

Zone category	90.1-2004	90.1-2007	90.1-2010	90.1-2013
	Lighting power density (W/ft^2)			
Classroom	1.4	1.4	1.24	1.24
Lecture hall	1.4	1.4	1.24	1.24
Laboratory	1.4	1.4	1.28	1.43
Art classroom	1.4	1.4	1.24	1.24
Office	1.1	1.1	1.11	1.11
Corridor	0.5	0.5	0.66	0.66
Conference	1.3	1.3	1.23	1.23
Lounge	1.2	1.2	0.73	0.73
Media center	1.2	1.2	0.93	1.06
Stairs	0.6	0.6	0.69	0.69
Storage	0.8	0.8	0.63	0.63
Entrance lobby	1.3	1.3	0.9	0.9
Restroom	0.9	0.9	0.98	0.98
Elevator shaft	—	—	—	—
Utility	1.5	1.5	0.95	0.95

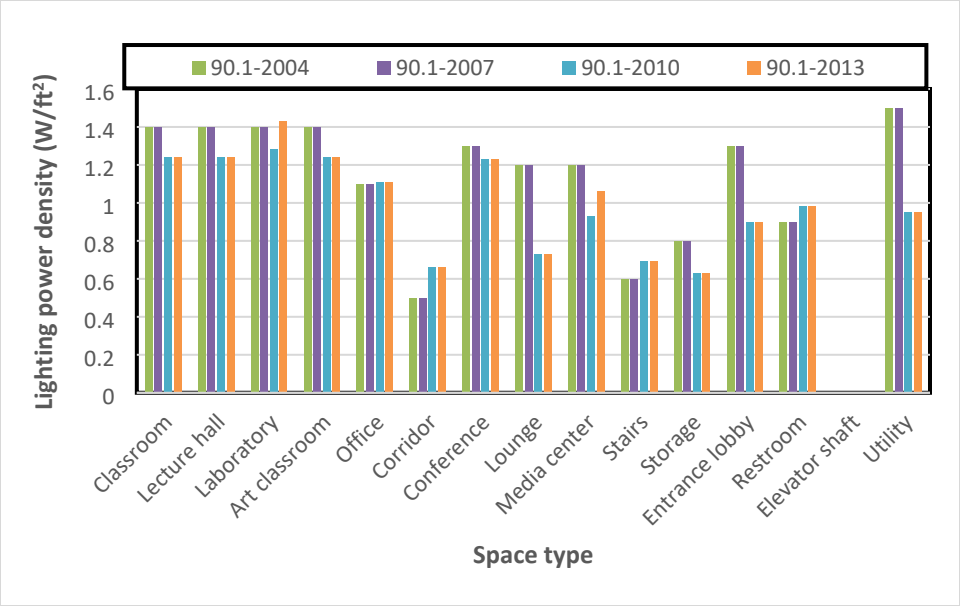


Figure 32. Comparison of space-specific lighting power density by vintage.

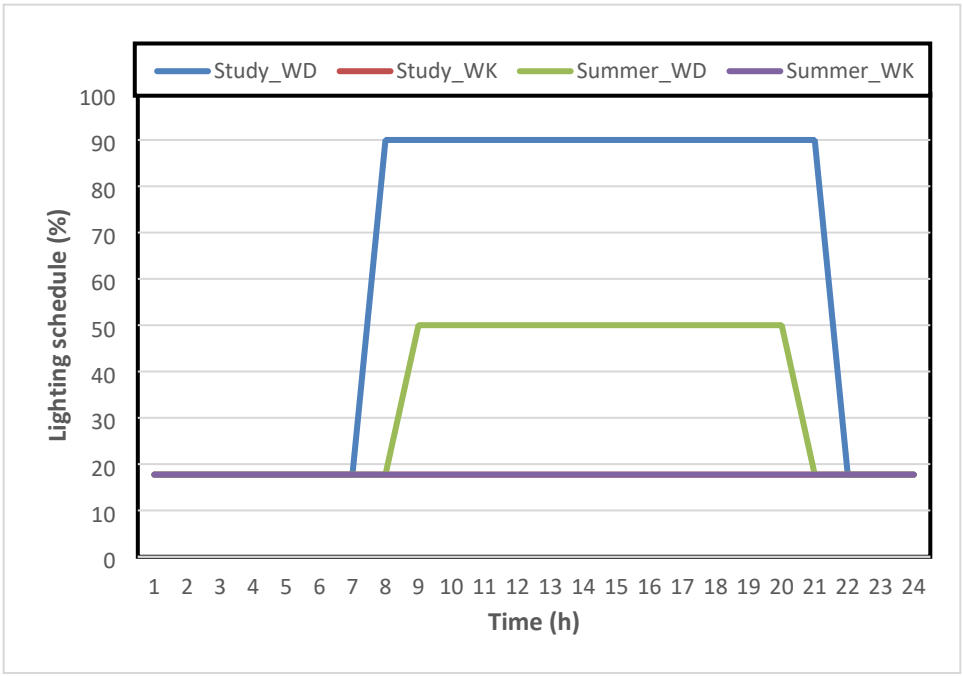


Figure 33. Lighting schedule.

3.7 ELECTRIC EQUIPMENT

The plug and process load was referenced from the OpenStudio prototype model based on the primary use of the space. The space-specific electric equipment loads are described in Table 6. The difference in loads between the vintages is shown in Figure 34. Figure 35 shows the equipment schedule for the prototype college building model. One equipment schedule covers the whole prototype college building model. Two hydraulic elevators were assigned to the elevator shaft, and internal gains of the elevator lift motor, elevator fan, and elevator light were 149.5, 32,110, and 177.9 W, respectively.

Table 6. Plug and process loads by vintage

Zone category	90.1-2004	90.1-2007	90.1-2010	90.1-2013
	Plug and process load (W/ft²)			
Classroom	0.929	0.929	0.929	0.929
Lecture hall	0.929	0.929	0.929	0.929
Laboratory	4	4	4	4
Art classroom	0.929	0.929	0.929	0.929
Office	1	1	1	1
Corridor	0.37	0.37	0.37	0.37
Conference	1	1	1	1
Lounge	7.15	7.15	7.15	7.15
Media center	0.93	0.93	0.93	0.93
Stairs	—	—	—	—
Storage	—	—	—	—
Entrance lobby	0.37	0.37	0.37	0.37
Restroom	0.37	0.37	0.37	0.37
Elevator shaft	—	—	—	—
Utility	0.37	0.37	0.37	0.37

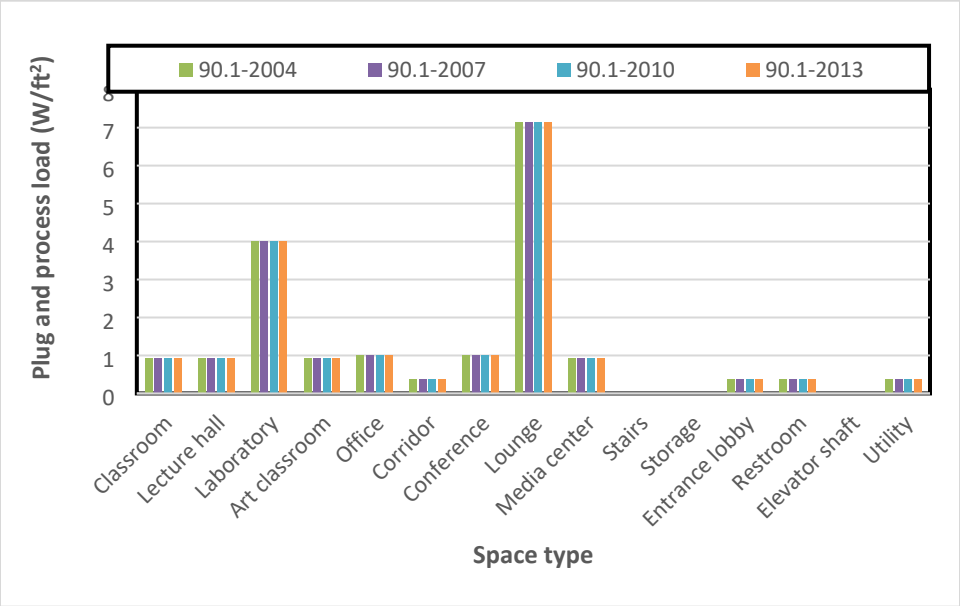


Figure 34. Comparison of space-specific plug and process loads by vintage.

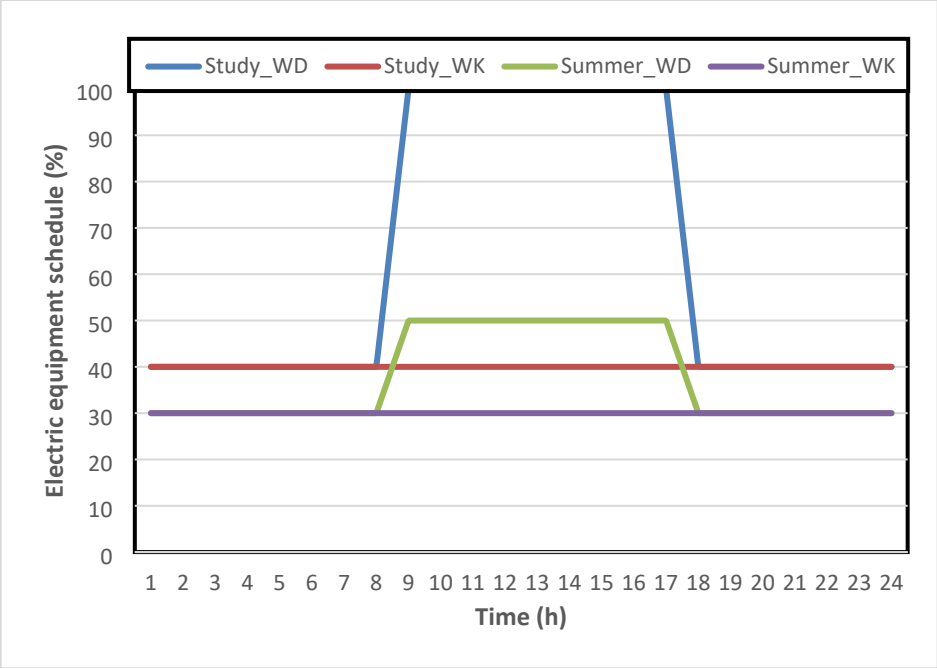


Figure 35. Equipment schedule.

3.8 HVAC SYSTEM

Figure 36 shows the HVAC system diagram of the prototype college building. The HVAC system was based on the requirements of ASHRAE Standard 90.1. An energy recovery ventilator was installed in the HVAC system for the Standard 90.1-2010 and 90.1-2013 models based on ASHRAE Standard 90.1 requirements. There were three water loops—a condenser water loop between the cooling tower and chiller, a chilled water loop between the chiller and cooling coils, and a hot water loop between the gas boiler and main heating/reheat coils. The HVAC system of the prototype college building model comprised 1 gas boiler, 4 main heating coils (water), and 113 reheat coils (water) for heating, and 1 variable speed cooling tower, 1 electric chiller, and 4 main cooling coils (water) for cooling. Also, there were four variable air volume fans for the main HVAC systems. Table 7 lists the components of the HVAC system.

The system efficiency and auxiliary equipment requirements (i.e., economizers, demand control ventilation, energy recovery, and pumps) were determined based on the requirements of ASHRAE Standard 90.1. All the autosized values of the HVAC system were determined by the summer and winter design days. Set points of the supply air temperature, chilled water temperature, and hot water temperature were constant at 12.8°C (55°F), 6.7°C (44°F), and 82.2°C (180°F), respectively. Ideally, the district cooling and heating system will be updated in the future.

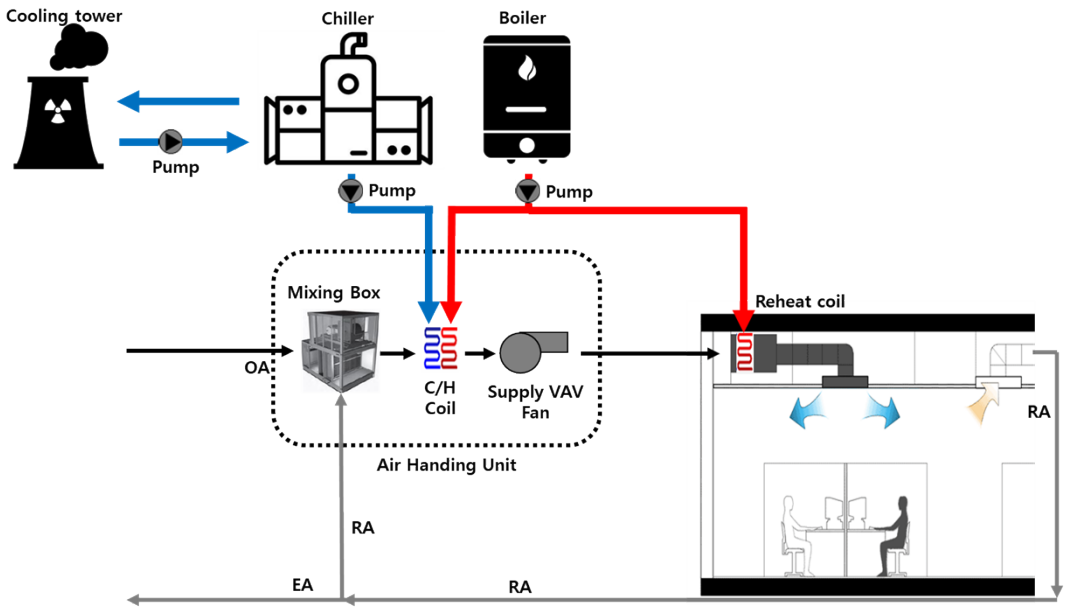


Figure 36. HVAC system diagram. OA: outdoor air; RA: return air; EA: exhaust air; C/H: cooling/heating; VAV: variable air volume.

Table 7. Number of components of the HVAC system

Component name	Number of components
Cooling tower	1
Chiller	1
Boiler	1
Main heating coil	4
Cooling coil	4
Reheat coil	113
Variable air volume box	113
Fan	4 (variable air volume)
Pump	2 variable speed and 3 constant speed
Energy recovery ventilator	0 or 4 (depending on the vintage and climate zone)

Figure 37 shows the HVAC system operation schedule. Unlike other schedules, the HVAC operation schedule has the same schedule during the semester and the summer vacation. The HVAC system turned on at 7 a.m. and turned off 10 p.m. during the weekday. During the weekend and holidays, the HVAC system turned off for the whole day.

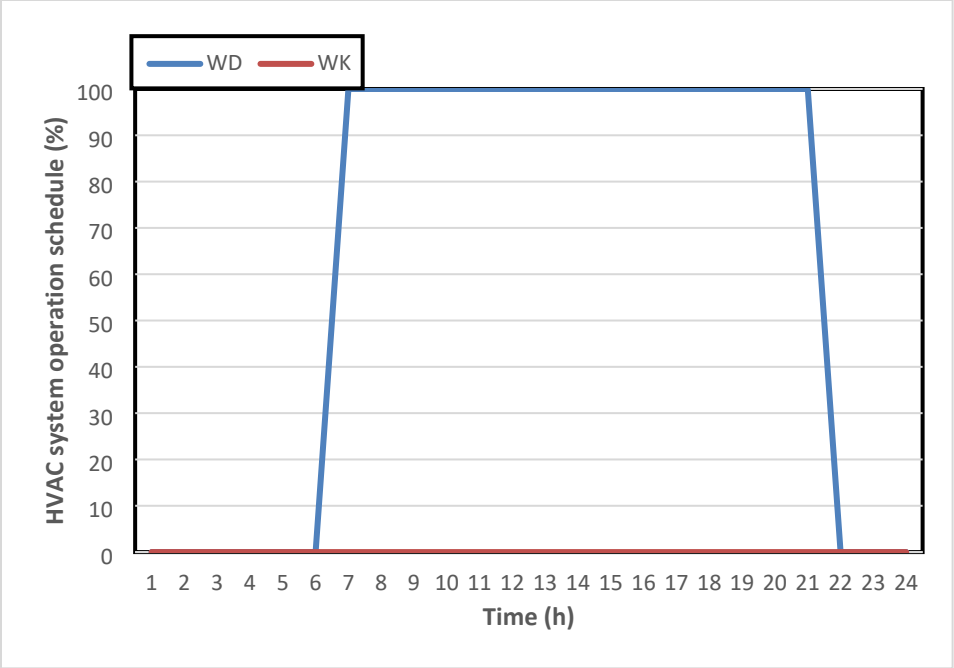


Figure 37. HVAC system operation schedule.

For the service water, a gas water heater was used. The temperature of the service water, which was domestic hot water, was 60°C (140°F). The peak flow rate of the service water was 0.58 GPM, and the pump motor efficiency for the service water was 30%. Figure 38 shows the service hot water schedule. The service hot water service schedule was the same during the semester and summer vacation.

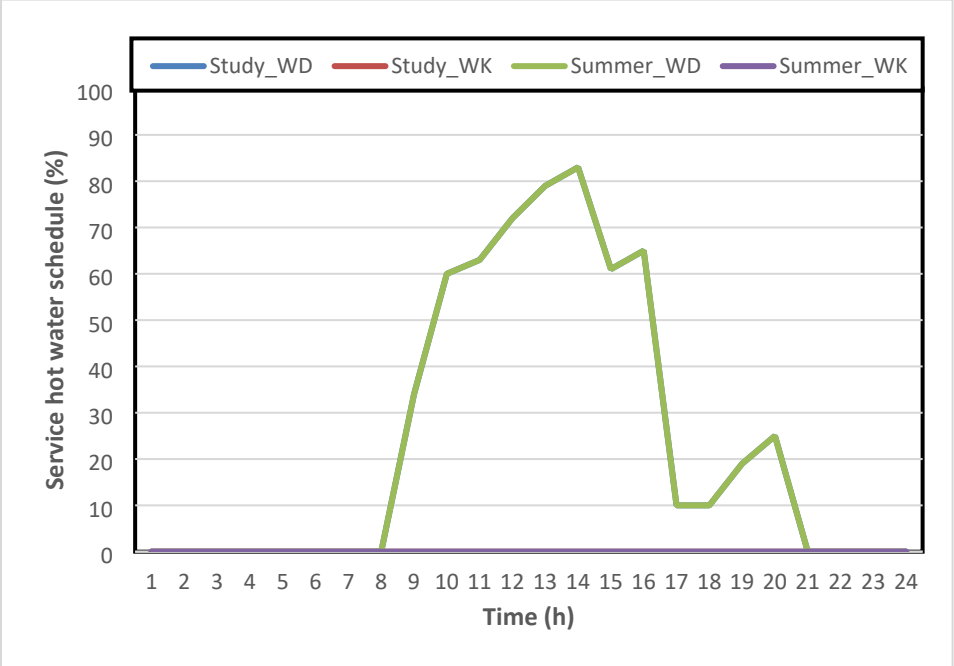


Figure 38. Service hot water schedule.

3.9 ENERGY USE

With the building and system characteristic described in previous sections, the prototype college building model for different vintages was simulated in 8 ASHRAE climate zones. To determine the overall impact of the requirements of ASHRAE Standard 90.1 for different vintages and climate zone on energy use, total energy, cooling energy, and heating energy use are plotted in Figure 39, Figure 40, and Figure 41, respectively. The vertical axis indicates energy use, and the horizontal axis shows the locations and climate zones. Different vintages are represented by different colors. The main reason for the energy use differences depending on the vintages is the mechanical ventilation, which is described in Table 3 and Figure 31.

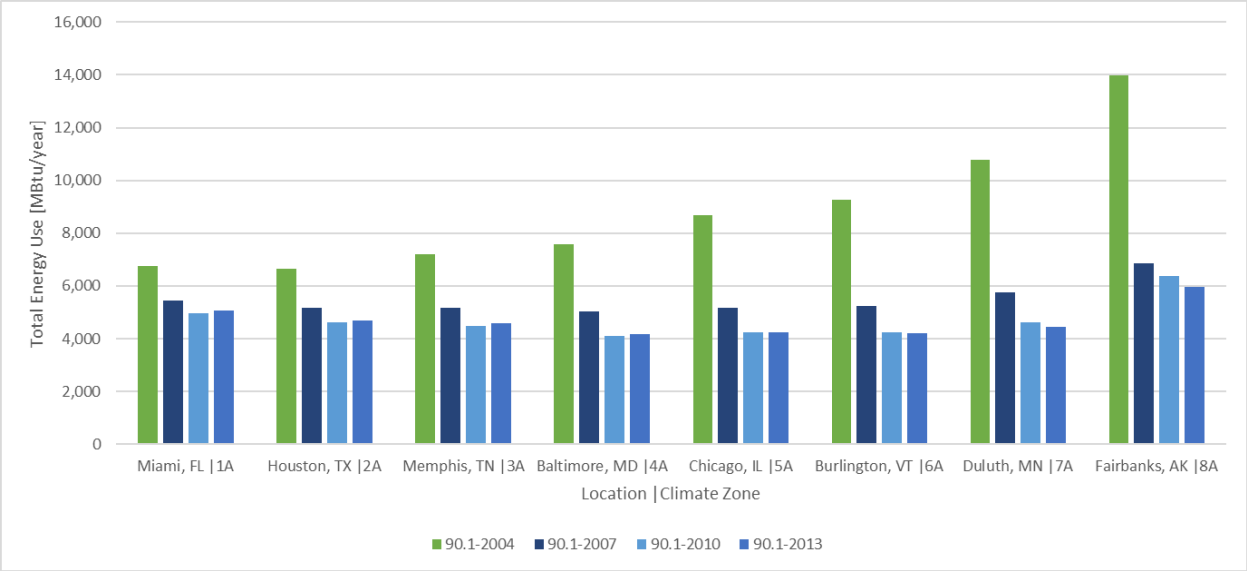


Figure 39. Total site energy use of the prototype college simulation model.

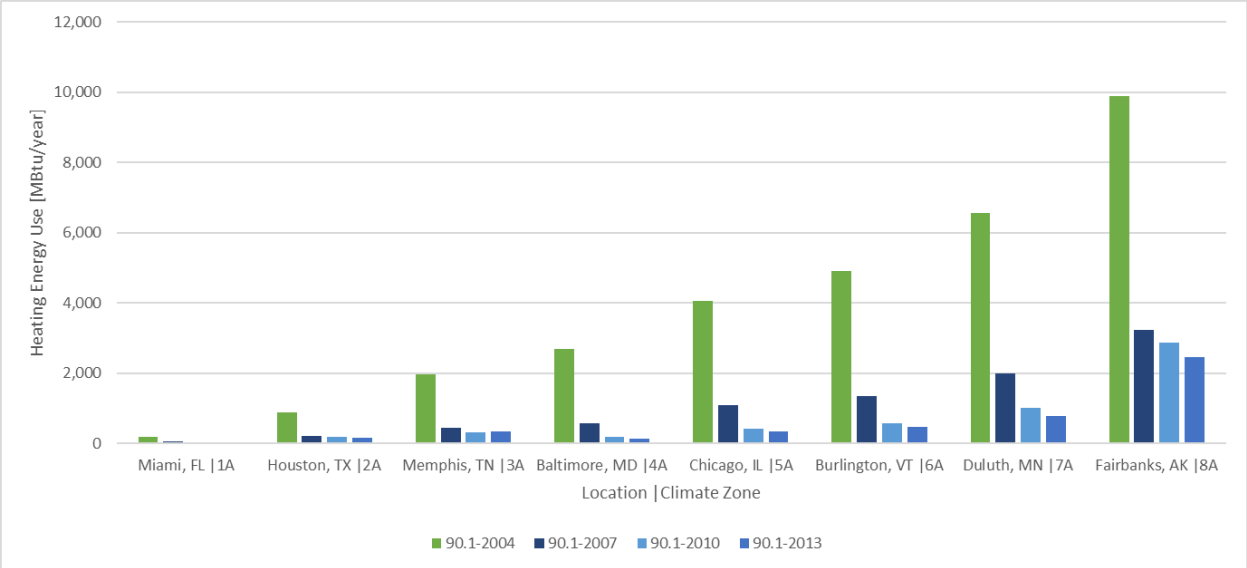


Figure 40. Heating energy use of the prototype college simulation model.

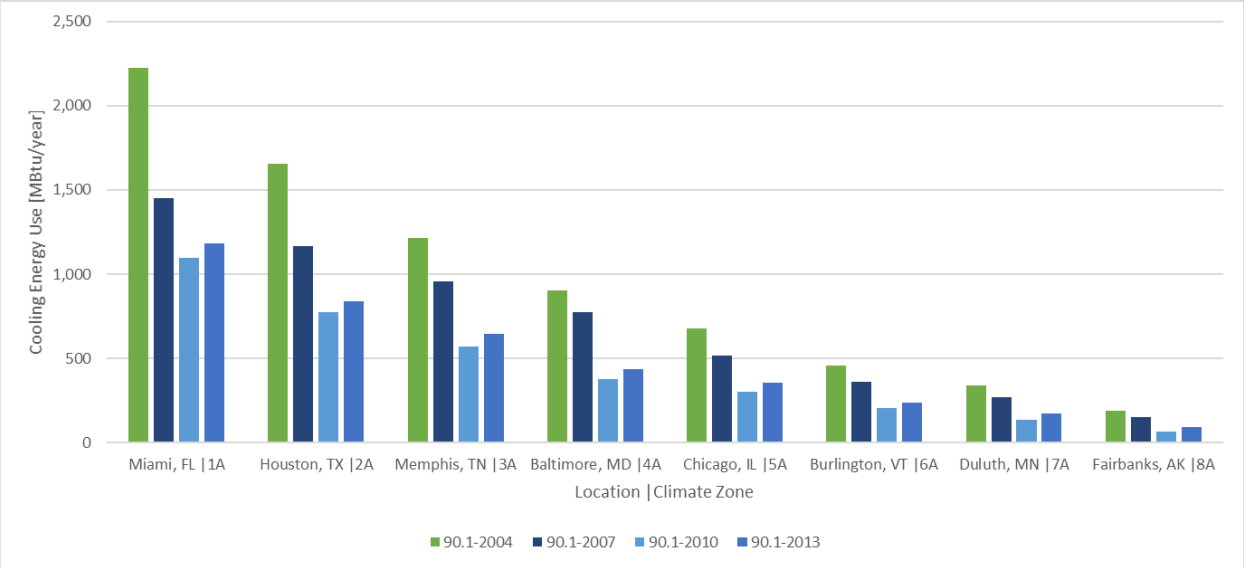


Figure 41. Cooling energy use of the prototype college simulation model.

Overall, compared with the energy consumption for the Standard 90.1-2013 model, the energy consumption for the Standard 90.1-2004 model was 143.1% higher for total energy use, 1,716.9% higher for heating energy use, and 108.1% higher for cooling energy use. For the Standard 90.1-2007 model, the energy consumption was 30.0% higher for total energy use, 297.1% higher for heating energy use, and 78.9% higher for cooling energy use. For the Standard 90.1-2010 model, the energy consumption was 6.8% higher for total energy use, 28.9% higher for heating energy use, and 7.1% lower for cooling energy use. The significantly high ventilation requirements in Standard 90.1-2004 (as shown in Table 3) resulted in increased heating energy use in cold climate zones, and increased cooling energy use in warm climate zones compared with other vintages. The difference among vintages is likely more pronounced in the prototype college building model than in other prototype models. The impact of climate on the energy use is also discernible from the expected trend of heating and cooling energy use in Figure 40, and Figure 41, respectively.

To compare the energy use of the prototype college building with that of existing college building data sets, the site energy use intensity (EUI) was calculated from the simulated total energy use divided by the 69,056 ft^2 gross floor area of the prototype college building model. Figure 42 shows the calculated site EUI for different vintages and climate zones.

The site EUI of the college building was 96.4–202.4 kBtu/ft^2 for the Standard 90.1-2004 model, 73.1–99.3 kBtu/ft^2 for the Standard 90.1-2007 model, 59.5–92.5 kBtu/ft^2 for the Standard 90.1-2010 model, and 60.3–86.5 kBtu/ft^2 for the Standard 90.1-2013 model. Compared with the reported site EUI of 122.9 kBtu/ft^2 based on 2012 CBECS data and 84.3 kBtu/ft^2 by ENERGY STAR (2018), the range of site EUI for the prototype college building is reasonable.

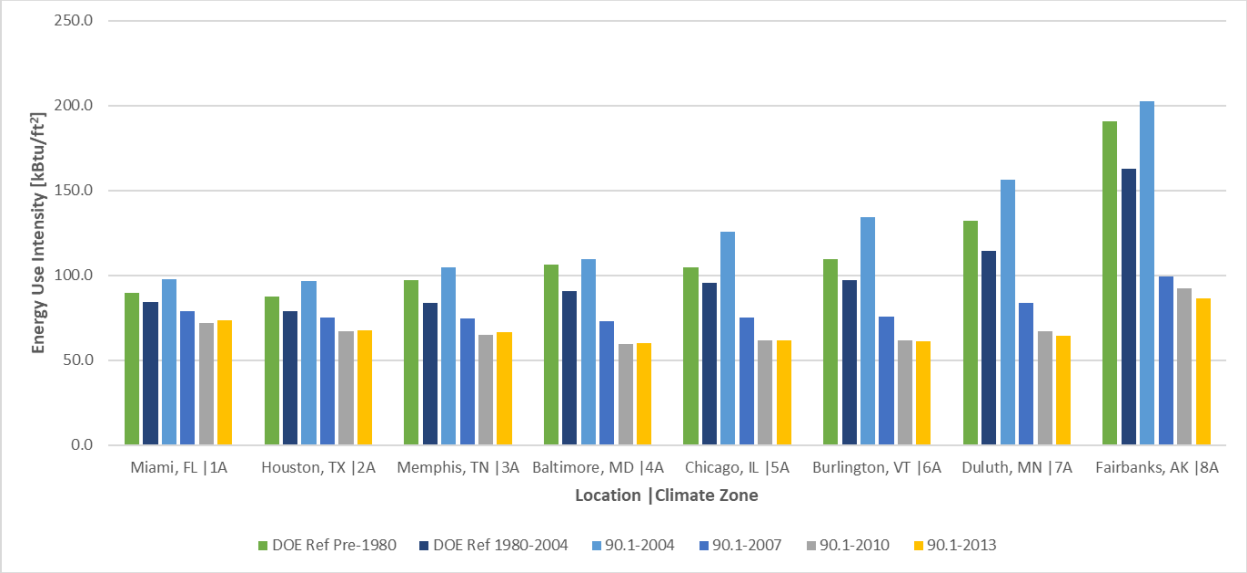


Figure 42. Site EUI of the prototype college simulation model.

4. CONCLUSIONS

As an effort to expand the current suite of commercial building prototype models, this report presents the college building model characteristics, the prototype college energy model, and energy simulation results. To improve the prototype model to represent a realistic college building, actual class reservation schedules were collected and used. The final prototype models include the 60 models for different vintages of ASHRAE Standard 90.1 (i.e., 2004, 2007, 2010, and 2013) and for 15 ASHRAE climate zones, and the modeled energy uses are consistent with existing data from multiple sources. The site EUI of the college building was 96.4–202.4 kBtu/ft^2 for the ASHRAE Standard 90.1-2004 model, 73.1–99.3 kBtu/ft^2 for the ASHRAE Standard 90.1-2007 model, 59.5–92.5 kBtu/ft^2 for the ASHRAE Standard 90.1-2010 model, and 60.3–86.5 kBtu/ft^2 for the ASHRAE Standard 90.1-2013 model. Compared with the reported site EUI of 122.9 kBtu/ft^2 based on 2012 CBECS data and 84.3 kBtu/ft^2 by 2018 ENERGY STAR data, the site EUI for the prototype college building is in a reasonable range.

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