CHAPTER
ONE

INTRODUCTION TO MECHANICAL AND ELECTRICAL SYSTEMS, SUSTAINABLE DESIGN, AND EVALUATING OPTIONS

This book is about mechanical and electrical (M/E) systems in buildings. These systems include:

- Heating, ventilating, and air-conditioning (HVAC)
- Plumbing, consisting of water supply, fixtures, sanitary drainage, sewage treatment and disposal, and storm drainage
- Fire protection, including fire alarm and suppression systems
- Electrical, consisting of power and communications
- Lighting

Over the last 125 years, these systems have been developed and continually improved to make buildings habitable, functional, productive, and safe. In addition, they have allowed flexibility to expand the limits of architectural design. Before modern heating, air-conditioning, and illumination systems, building dimensions were limited due to the need to access windows for light and natural ventilation (see Fig. 1.1). Floors were typically 60 ft or less in depth, or included light wells. Windows were operable and needed to be large and tall enough to allow deep light penetration. Ceiling heights were high to promote stratification of summer heat and to allow the use of operable transom windows over doors for ventilation of interior spaces (see Fig. 1.2).

Air-conditioning and good artificial lighting gave architects the flexibility to design larger floors, and good elevators and life safety systems made high-rise construction possible. These developments occurred when energy to operate buildings was inexpensive by today's standards, and there was very little concern about fossil fuel depletion, dependence on foreign oil, or environmental impact of energy use. As a result, buildings and building systems were designed with little regard for energy efficiency or response to the surrounding environment. With the influence of sustainable design principles, buildings are returning to some of the features which were neglected in recent years, such as daylighting and natural ventilation.

In the early 1970s, the political and economic context of building design changed with the oil embargo, increased energy costs, and the realization that we needed to take care of the environment. Most notably, the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) formulated an energy standard for buildings in cooperation with the Illuminating Engineers Society (IES). Over subsequent years, the standard was updated and made more stringent. The full name of the document is ANSI/ASHRAE/IES Standard 90.1, an it is the basis for energy codes.

Sustainable building design was a simultaneous and complementary development, embracing not only energy but a whole host of environmental, health, and productivity issues related to buildings. Most notably, the U.S. Green Building Council (USGBC) launched the LEED$^{\text{TM}}$ rating system in 2000 and has over subsequent versions defined and developed sustainability in the building industry. The rating system promotes an integrated design approach that involves the cooperation of architects, engineering, owners, building users, and contractors to produce buildings, which conserve resources, reduce environmental impact, and produce a healthy productive place to work. The Nidus Center, a research laboratory building shown in Fig. 1.3, was part of the LEED$^{\text{TM}}$ pilot program.

This chapter defines sustainability qualities in the context of building and building systems design. It also provides tools for evaluating solutions based on qualitative and quantitative criteria. Life-cycle cost analysis is presented using a discounted cash flow methodology. The reader is encouraged to consider not only "hard costs" but also environmental costs and the economics of productivity in the decision process.

1.1 SUSTAINABLE DESIGN

1.1.1 Overview of Sustainability

Sustainability is a concept that applies not only to buildings but also to industry, agriculture, transportation, and all other aspects of societal activity. "Sustainable" can be defined simply as *having an overall beneficial effect on productivity, health, resources, economics, and the environment.* Sustainable design acknowledges responsibility for future as well as current outcomes. Sustainable design decisions are made for their impact not only at the building level but also at the community and global level. Utility, comfort, energy

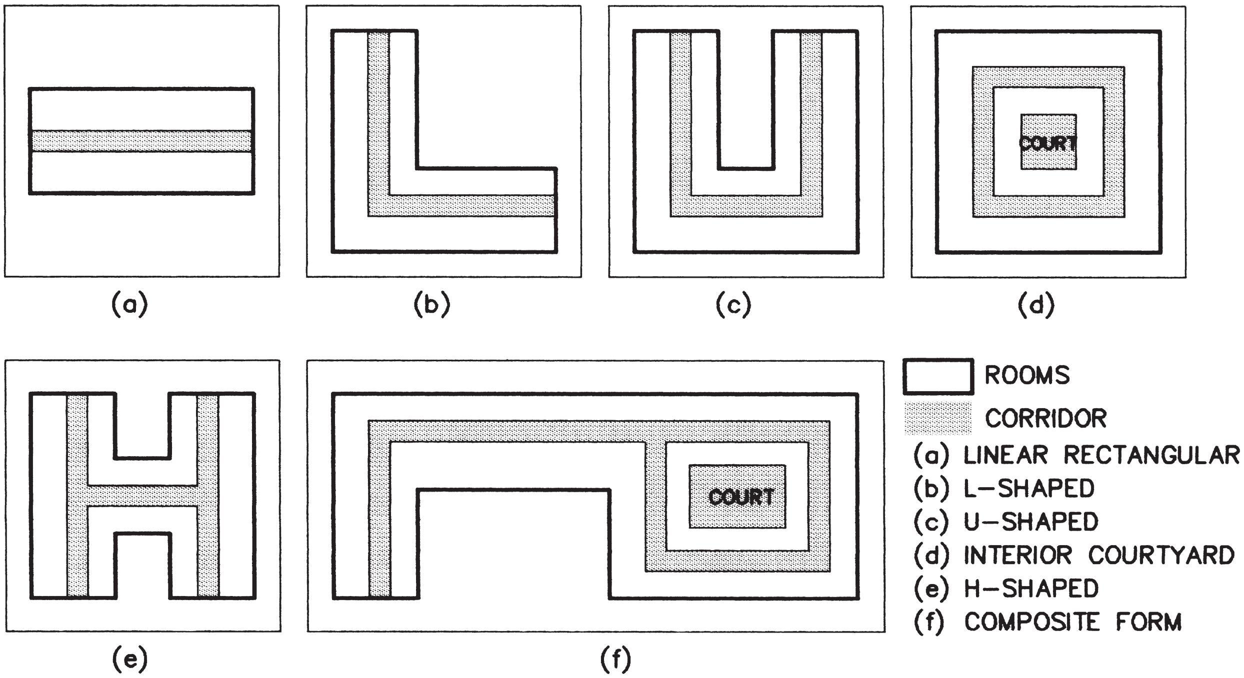

FIGURE 1.1. Common building geometry prior to development of modern M/E systems. With the renewed emphasis on daylight and natural ventilation, these geometries are enjoying a revival.

FIGURE 1.2. Prior to air-conditioning, buildings were equipped with features to take advantage of natural ventilation, such as operable sash, louvered shutters (a), and transom lights (b).

(Courtesy of William Tao & Associates)

FIGURE 1.2. (Continued)

conservation, environmental impact, and appropriate use of technology are basic criteria for mechanical/electrical systems in a sustainable design process.

1.1.2 Design Interactions

Achieving sustainable building solutions requires that many parties work closely together with an understanding of the interactions among building systems and processes. For example, energy usage is affected by architectural form; building materials; lighting; appliances; heating, ventilating, and air-conditioning (HVAC) systems; and even by access to public transportation. There are many participants in the design process who take responsibility for these issues (e.g., architect, lighting designer, owner, consulting engineers, contractors, and suppliers). Too often, each participant makes decisions independent of the others, and opportunities are lost by not understanding the interactions between design factors.

Decisions made by each member of the team will affect systems in which others are also affected. For instance, an architect might design larger windows, which could increase the size of heating and air-conditioning equipment. Or, the lighting designer might design more light fixtures, which would increase the size of air-conditioning equipment.

Interactions also affect health and productivity of building occupants. Daylight and outdoor views, for example, enhance occupants' sense of well-being in buildings, and the effect on performance in the workplace is obvious, though difficult to quantify. Likewise, effective HVAC systems contribute to good indoor air quality to the benefit of occupants' health.

1.1.3 Environmental Impact of Buildings and Building Systems

A building's impact goes beyond the site boundary. Sustainable design must consider how well buildings work to minimize negative environmental impact or even benefit the environment.

Buildings contribute to disruption of storm-water flow, ground erosion, fouling of natural water, light pollution, the growth of landfills from disposal of building materials as construction waste, and, ultimately, demolition. These impacts can be mitigated by good design, and there is potential for well-planned buildings to have zero impact on the environment or even improve the environment.

Buildings account for about 30 percent of overall energy usage in the United States and over 60 percent of electrical usage. This represents not only a depletion of energy resources but also affects the environment by emissions through combustion of fossil fuels, both on the building site and remotely at power-generating stations. Pollution from energy consumption is quantified in Table 1.1.

1.1.4 Water Conservation

Conserving water is a goal of sustainable design. As with most elements of sustainable design, there are economic benefits. Many locations have inexpensive water rates, which alone would not justify significant cost for conservation technology. However, water usage results in sanitary sewer discharge. Sewer charges are generally based on water usage, and are equal or greater in many cases than the water charges. Saving water in buildings will also have a community benefit in reducing the need and cost of constructing, improving, and

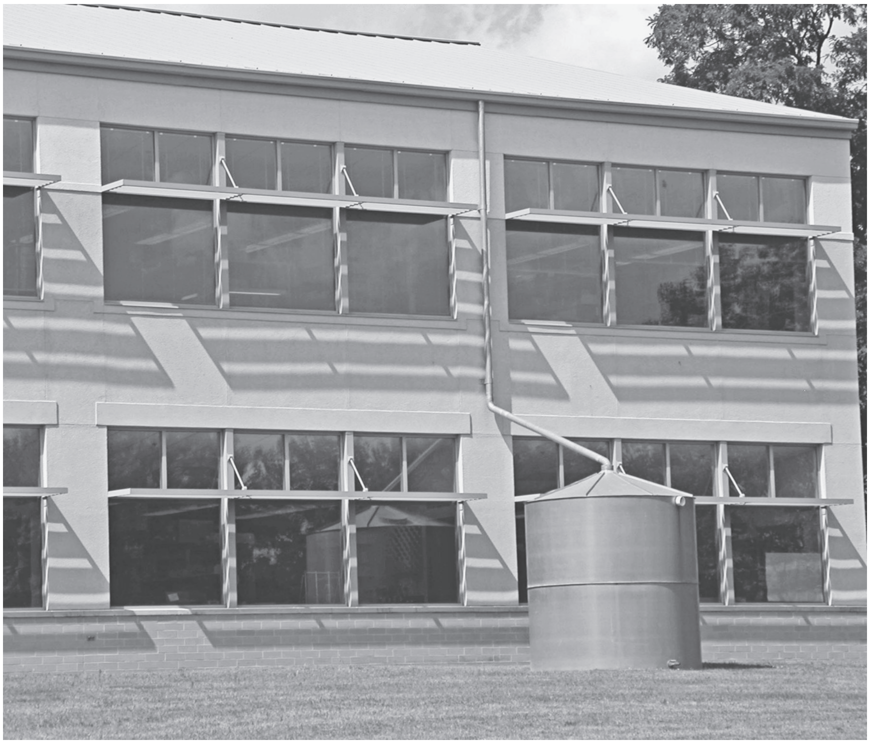

FIGURE 1.3. Nidus Center for Scientific Enterprise, which is among the first LEED^{TM} certified buildings, uses principles of sustainable design to conserve resources, reduce environmental impact, and produce a healthy productive place to work. LEED^{TM} (Leadership in Energy & Environmental Design) is a "green" building rating system administered by the U.S. Green Building Council.

(Courtesy of William Tao & Associates)

maintaining water and sewer infrastructure. EPact (Energy Policy Act of 1992) became effective in 1996 to mandate that manufacturers produce conventional fixtures that flow less water. These mandates still apply and have been supplemented by Environmental Protection Agency's (EPA) WaterSense program, which publishes voluntary standards going beyond the mandate. For instance, EPact requires urinals and water closets to use maximum 1.0 and 1.5 gallons per flush, respectively. To be EPA WaterSense Listed, these values must be reduced to 0.5 and 1.28 gallons per flush, respectively. Sensor controls have also become commonplace in building design. Currently, designers are using alternative products on a limited basis, which use even less water, such as waterless urinals, rainwater collection, and composting

TABLE 1.1 Air Pollutants Produced from Energy Conversion

	Air Pollutants Produced, g (lb)		
Energy Converted or Consumed	**CO_2**	**SO_2**	**NO_x**
1 gallon of fuel oil by combustion[a]	10,500 (23.1)	45.0 (0.10)	18.3 (0.04)
1 gallon of gasoline by automobiles[b]	8,500 (18.8)	37.0 (0.08)	15.0 (0.03)
1 pound of coal by combustion[c]	1,090 (2.4)	9.0 (0.02)	4.4 (0.01)
1 therm of natural gas by combustion[d]	6,350 (14.0)	Nil (–)	24.0 (0.05)
1 kWh of electric energy generated by oil[e]	860 (1.9)	3.7 (0.008)	1.5 (0.003)
1 kWh of electric energy generated by gas[e]	635 (1.4)	Nil (–)	2.4 (0.005)
1 kWh of electric energy generated by coal[e]	1,090 (2.4)	9.0 (0.02)	4.4 (0.01)

[a] Calculated by using fuel oil containing 85% carbon and 12% hydrogen, and 7.4 lb/gal.

[b] Calculated by using gasoline mixture of C_8H_{18} and (C_nH_{2n+2}) having 84% carbon and 15% hydrogen, and 6.1 lb/gal.

[c] Calculated by using bituminous coal containing 65% carbon and 3.8% sulfur.

[d] Calculated by using a mixture of methane (CH_4) and ethane (C_2H_6) and 100,000 Btu/therm.

[e] Data from Green Light Program, Environmental Protection Agency.

toilets. These measures will require acceptance by owners and code officials before widespread usage. LEED has also had a conserving impact, granting points to encourage water savings. Water conservation using fixtures certified by EPA Water Sense program is covered in Chapter 10.

1.1.5 Energy Conservation

Sustainable design approaches for energy conservation include:

- Architectural design to limit HVAC loads by methods recommended in Chapter 4
- Effective HVAC delivery systems as described in Chapter 5
- Efficient heating and cooling production and delivery as discussed in Chapters 6, 7, and 8
- Efficient light sources and controls as described in Chapters 17 and 19
- Using renewable energy sources such as solar thermal as described in Chapter 7 and solar photovoltaic as described in Chapter 13

In addition, building owners should be encouraged to use efficient equipment and appliances such as those with Energy Star ratings.

Designers should be cautioned, however, that energy conservation should not be at the expense of comfort or building productivity. Proper ventilation levels, quality lighting, and thermal comfort are essential for building occupants to operate effectively. Buildings and systems that save energy *and* produce a great environment are truly “high performance.”

There are many energy technologies vying for use in buildings, and choices among options should be made on value at promoting technology as well as life-cycle economics. Solar collectors installed during the “Energy Crisis” of the 1970s could not be justified economically, but were a valuable technology demonstration to develop systems which might someday be commercially viable (see Fig. 1.4). Some energy technologies are fully mature such as the heat recovery wheel shown in Fig. 1.5. The use of proven technologies that require increased investment should be analyzed by economic methods such as discounted cash flow analysis as described in this chapter.

Energy codes have been enacted based on provisions of ASHRAE Standard 90.1, “Energy Standard for Buildings Except Low-Rise Residential Buildings,” which is an industry consensus standard for energy performance of architectural construction, lighting, water heating, and mechanical and electrical equipment. First issued as Standard 90 in 1975, it has evolved to its current version, Std. 90.1-2010, through periodic revisions. LEED’s latest version, Version 3, requires that buildings achieve 10 percent or greater energy savings beyond the minimum compliance with the ASHRAE Standard. Points are awarded to encourage higher savings.

1.2 INDOOR ENVIRONMENTAL QUALITY

1.2.1 Components of IEQ

In addition to environmental benefits and resource conservation, sustainable design enhances health, well-being, and productivity of building occupants. These benefits are achieved by several goals of sustainable design:

- Healthful indoor air quality
- Thermal comfort and individual control
- Good lighting
- Connection with the outdoors

FIGURE 1.4. Solar collectors installed after the 1970s oil embargo were an opportunity to explore new technologies, but could not be justified on the basis of economics or life-cycle cost.

(Courtesy of William Tao & Associates)

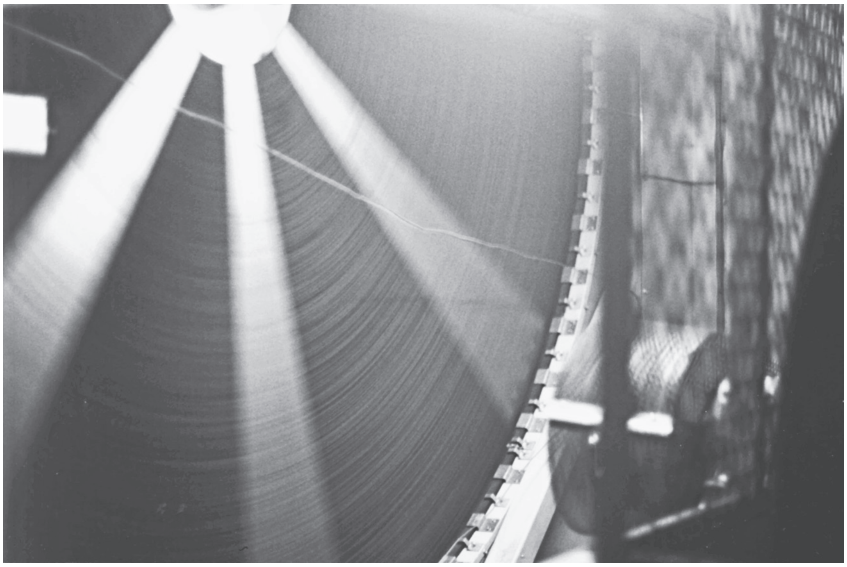

FIGURE 1.5. Heat recovery wheel allows higher ventilation rates without sacrificing economy of operation, exemplifying sustainable design within economic realities.

(Courtesy of William Tao & Associates)

Combined, these factors contribute to "indoor environmental quality" (IEQ), a term used in the LEED^{TM} rating system, described earlier.

1.2.2 Indoor Air Quality

Indoor air pollution is preventable by good architectural detailing, as shown in Fig. 1.6, effective mechanical systems, and proper maintenance. Indoor air pollution in typical buildings, such as offices, comes from chemicals in finish materials, cleaning products, furniture, and fumes from equipment. In addition, biopollutants such as mold can result if humidity is not properly controlled or if there are moisture problems in building assemblies and systems.

Interior chemical pollution and odors can be diluted to acceptable levels with ventilation by liberal quantities of relatively purer outdoor air. Selecting furnishings, interior finish materials, and cleaning products to be nonpolluting will allow lower ventilation rates and save energy. Using local exhaust over offensive equipment is

FIGURE 1.6. Air intakes for Monsanto Research Center in St. Louis are placed high to avoid street-level air pollution as a measure to improve indoor air quality.

(Courtesy of William Tao & Associates)

also effective at preventing chemicals from entering the larger occupied space.

Building occupants themselves are also sources of pollution. They consume oxygen and emit carbon dioxide and body odors. ASHRAE Standard 62.1-2016, entitled "Ventilation for Acceptable Indoor Air Quality," specifies the amount of outside air needed to cover various levels of occupancy. The amount of outside air required in buildings is based on the nature of building usage, floor area, and density of occupancy.

Condensation in roofs or walls can be a problem. Venting, insulation, and vapor barriers can avoid condensation if properly applied, and HVAC design for proper dehumidification is essential. Interior surfaces of HVAC systems can harbor dust, odors, bacteria, and mold. Filters are porous and microorganisms can breed if they are not changed frequently. Acoustical duct liner is also porous and should be avoided or treated with biocide. Condensate pans in air-conditioning systems are continually moist during hot weather and should drain properly.

Indoor air quality has been correlated with employee productivity. Increasing ventilation rates are reported to render 23–76 percent reductions in the incidence of acute respiratory illnesses. Measured data are also available on the relationship between "sick building syndrome (SBS)" symptoms and worker performance. Workers who reported any SBS symptoms took 7 percent longer to respond in a computerized neurobehavioral test. In another test, workers with symptoms had a 30 percent higher error rate.

One study was performed to determine the effects of ventilation rate on absenteeism. Buildings were classified as moderate ventilation (25 CFM/occ) or high ventilation (50 CFM/occ). Absence rate was 35 percent lower in high-ventilation buildings. Even the moderate ventilation rate cited in the study is higher than rates prescribed by ASHRAE Standard 62.1, indicating potential for improvement in current design practices.

1.2.3 Thermal Comfort

In ASHRAE Standard 55, entitled "Thermal Environmental Comfort Conditions for Human Occupancy," comfort involves factors including temperature, air velocity, and humidity. In general, the standard asserts that these quantities must be maintained within reasonable levels and not allowed to change rapidly.

Basically, the standard identifies conditions of temperature and humidity that 80 percent of research subjects will find acceptable. The obvious corollary is that 20 percent may not find conditions acceptable. This implies that there will be a greater likelihood of satisfying everyone if individual temperature controls are provided. Space heaters and thermostat tampering demonstrate the desire for individual control.

Air temperature has been documented to affect worker performance. Small differences in temperature have been reported to have 2–20 percent performance impact in tasks such as typewriting, learning performance, reading speed, multiplication speed, and word memory.

1.2.4 Individual Control

HVAC systems can be designed that offer opportunities for individuals to control their local thermal environment. This simple notion is generally ignored in typical institutional buildings designed with the goal of providing uniform temperature control.

Allowing greater personal control of indoor environments, and allowing temperatures to fluctuate with outdoor conditions, could improve perceived comfort and reduce energy consumption. Individuals will tolerate a wider range of thermal conditions if they have control over their environment, such as operable windows or the ability to adjust airflow. The effect of individual control on productivity has been documented. Providing ±5°F of individual temperature control has been claimed to increase work performance by 3–7 percent.

Individual control is not practical with many HVAC systems. There are, however, several practical options for giving control to individuals. A few furniture manufacturers can integrate local control features into their workstations, which allows the occupant to adjust the quantity and direction of airflow (see Fig. 1.7). Ironically, table fans used before the advent of air-conditioning are similar in concept.

Other options are to deliver air through floor registers, which allows occupants to adjust the airflow from nearby outlets. Operable windows controlled by occupants are appropriate in some climates and/or some seasons. One analysis revealed that occupants of buildings using central HVAC systems were much more sensitive to temperature variation than occupants of buildings that have operable windows. Having control results in higher perceived comfort. People might even be invigorated by the variability of temperature in naturally ventilated buildings (see Fig. 1.8).

Integrating operable windows with conventional HVAC control systems is a challenge. Typical systems, for instance, might place multiple rooms on the same thermostat. If the occupant with the thermostat opens the window, control will be lost for the other spaces. Other potential problems include possible freezing from cold air through windows left open. Security and infiltration of pollen and dust are other problems which need to be considered. Despite these issues, operable windows are highly desired by building occupants and well worth the effort to work out problems.

1.2.5 Superior Lighting Systems

Lighting affects occupant performance and quality of space as well as energy consumption. Uniform illumination by recessed fluorescent fixtures is the most common lighting solution for work spaces, and often results in glare, shadows, and reflections in computer screens. Indirect (all light up toward ceiling) or semi-indirect (a portion up, a portion down) lighting is an alternative, which produces better visibility of tasks at lower levels of illumination. Indirect lighting is theoretically less efficient than direct lighting due to considerable light being absorbed at the ceiling surfaces. However, indirect light is more uniform, eliminates glare, results in less shadows, and can be designed at lower light levels to produce a better environment at lower energy cost (see Fig. 1.9).

FIGURE 1.7. Personal cooling outlet (left) gives individual personnel control of climate at workstation.

(Courtesy of William Tao & Associates)

FIGURE 1.8. Variations in environment are well tolerated when people have a choice; these shoppers prefer an open-air market to the modern climate-controlled grocery store.

(Courtesy of William Tao & Associates)

Daylight Sustainable lighting strategies generally include daylighting. The challenge in using daylight is to control the glare, avoid thermal discomfort, and minimize HVAC loads. Energy interactions must be considered carefully. While one would expect higher air-conditioning loads due to extra window or skylight area, the extra load may be more than offset by reducing the heat gain from artificial lighting which can be deactivated.

No one would question that an attractive, visually interesting environment contributes to occupant satisfaction and higher levels of productivity. Having an outdoor view or a source of natural light is desirable (see Fig. 1.10). The best publicized study on the effects of daylight and view was performed by the Pacific Gas and Electric Company. The following is quoted from their executive summary:

> Controlling for all other influences, we found that students with the most day lighting in their classrooms progressed 20% faster on math tests and 26% on reading tests in one year than those with the least. Similarly, students in classrooms with the largest window areas were found to progress 15% faster in math and 23% faster in reading than those with the least.

FIGURE 1.9. Semi-indirect lighting in this research laboratory is not only comfortable for occupants but also illuminates building services in the exposed ceiling, resulting in better maintenance and safety.

(Courtesy of William Tao & Associates)

FIGURE 1.10. Light well in this classroom building allows daylight to the interior and gives occupants a sense of outdoor weather and time of day.

(Courtesy of William Tao & Associates)

> And students that had a well-designed skylight in their room, one that diffused the daylight throughout the room and which allowed teachers to control the amount of daylight entering the room, also improved 19–20% faster than those students without a skylight. We also found another window-related effect, in that students in classrooms where windows could be opened were found to progress 7–8% faster than those in rooms with fixed windows. This occurred regardless of whether the classroom also had air conditioning. These effects were all observed with 99% statistical certainty.

1.2.6 Connection with Outdoors

Daylight, views outside, natural ventilation, and temperature variation are ways to give building occupants a sense of connection with the outdoors. Occupants feel better and perform better when they have a sense of time of day and outside weather. These connections need not be exaggerated by using large windows, large skylights, or large ventilation openings. Effective placement is more critical in achieving success as shown in Fig. 1.11.

1.3 COMMISSIONING

1.3.1 Scope of Commissioning

Commissioning is an essential feature of sustainable design. It is a prerequisite for LEED^{TM} certification and highly recommended for any new building. Commissioning can generally be defined as the process of proving that systems will operate as intended and implementing adjustments necessary to achieve that goal. Typically, the commissioning process would include the following steps:

1. Review system criteria, including design temperatures.
2. Review and assure that design (load calculations, equipment selections) is able to achieve criteria.

FIGURE 1.11. A simple window at the end of this laboratory corridor provides daylight and view. Lights are rarely turned on during the day in this space.

(Courtesy of William Tao & Associates)

3. Review plans and specifications for consistency with design.
4. Observe construction to assure that equipment and systems are installed per plans and specifications.
5. Verify that contractor has performed prefunctional checkout of systems and equipment (e.g., proper wiring connections, clean filters).
6. Measure system component performance, review test results.
7. Verify control sequences (e.g., thermostat call for cooling starts compressor).
8. Document that these procedures have been performed along with their outcome.
9. Make sure that appropriate owner's staff are trained in operation of the systems.
10. Verify that operating manuals are turned over to the owner.
11. Follow up during the first year of operation to check seasonal performance and address any owner concerns.

Most of the commissioning scope can be performed by the design and construction team; however, the tasks involving review of design are generally done by a third-party commissioning agent.

1.3.2 Benefits of Commissioning

Making sure that systems operate properly will produce better comfort and save energy. In addition, commissioning reduces the need for warranty work and callbacks to adjust systems during the first year. The commissioning report and associated documentation also provide a baseline of performance for tracking the condition of systems and equipment over the life of the building. Commissioning also aids in organizing maintenance materials (manuals and training) for ongoing use by the building's operations staff.

1.3.3 Range of Applications

The scope of commissioning will depend on how simple or complicated the systems are and on the relative importance of proper system operation. A shortened commissioning process might be quite satisfactory for a small commercial building with simple heating and cooling equipment. If system performance is critical, the commissioning process will be extensive. Examples of buildings requiring emphasis on commissioning include museums, data centers, and correctional facilities.

Museums require that systems operate reliably to produce a precision environment with respect to temperature and humidity. Tight control is needed to prevent damage to valuable artifacts. In most climates, systems have extra components and controls for humidification and dehumidification. Systems must be demonstrated to operate properly before valuable artifacts are moved into the building and placed at risk if systems do not operate properly.

Many enterprises rely on continuous operation of data centers for business-critical and safety-critical functions, such as market transactions, air traffic control, and reservations. Systems are designed with redundancy in the event of failure and must transfer load to backup equipment without interruption of service. Commissioning is essential to test failure modes as well as normal operations.

Correctional facilities may have simple HVAC systems, but they are located in facilities that have limited access for correcting systems problems once the facility is put in service. For this reason, a rigorous commissioning process is necessary to make sure the systems are complete and to minimize callbacks. Other systems such as security and alarm require extensive commissioning due to the critical nature of their performance and their complexity in comparison with similar systems for other buildings.

Buildings with less critical functions can generally suffice with the typical start-up and checkout procedures used by conscientious contractors based on manufacturers' recommendations for particular pieces of equipment. For many simple buildings, ongoing maintenance is outsourced, and there is no need for the owner to receive training or operating and maintenance documentation.

1.3.4 Checklists and Forms

Forms are used in commissioning to assist field personnel through the checkout procedure and to record and sign off on results. In most instances, the equipment manufacturers' start-up procedures and forms will be satisfactory with minor modifications for use in commissioning of individual equipment items. Commissioning at the system level (as opposed to individual equipment checkout) requires procedures and checklists customized for the particular system. Control sequences in the specifications or from the control subcontractor's shop drawing submittals are generally the basis for producing system commissioning procedures and forms. Websites of various commissioning organizations and equipment vendors are good sources of standard forms that can be customized for particular projects.

1.4 EVALUATING DESIGN OPTIONS

1.4.1 Subjective Viewpoints

System quality cannot be assessed without defining criteria. Criteria will vary depending on viewpoint. For instance, a contractor might assess a design solely on the basis of ease of construction, whereas a CFO might consider cost most important, and the director of a physical plant might look more closely at maintenance issues. The purpose of the building must also be considered. A developer-built speculative office building might be designed with nondurable, low-cost materials, meet budget, and be economically feasible; whereas a corporate headquarters office building might command a higher level of quality. Building life expectations are also important. For instance, a building for a 5-year research program need not be equipped with 20-year life systems, whereas a long-term, institutional building might be designed for 50+-year systems.

1.4.2 Qualitative Versus Quantitative Analysis

The goal of sustainable design is that buildings be healthy, pleasant, and productive and that they minimize negative impacts on the local and global environment. Achieving this goal with the best solution requires that many factors be considered in the process. Some factors can be quantified economically and some can only be judged qualitatively based on relative importance.

1.4.3 Decision Matrix Method

The decision matrix is a method for evaluating criteria difficult to quantify. The decision matrix can be used to supplement life-cycle cost analyses and weigh options qualitatively. Decision matrix forces the decision makers to assess what is important to them for defining a successful outcome.

A sample decision matrix analysis is shown in Table 1.2. The analysis includes ranking on factors and on qualitative factors for which precise economic quantification is difficult, especially in the early phases of design, when making decisions is most important. The key feature of the matrix method

TABLE 1.2 Decision Matrix Method

A. How a Corporate Owner Might Think About His Options for HVAC of an Office Building

		VAV/Reheat		VAC/Convectors		VAV/Dual Duct		Multizone		VAV/FTU		Fancoils	
		Score	Weighted	Score	Weighted	Score	Weighted	Score	Weighted	Score	Weighted	Score	Weighted
Criteria	**Weight**												
Comfort	8	5	30	8	42	5	30	5	30	8	48	7	42
Flexibility	6	10	60	7	42	8	48	1	4	8	48	7	42
Initial cost	3	10	30	8	24	6	18	4	12	7	21	6	18
Energy consumption	6	7	42	8	48	7	42	7	42	9	54	9	54
Ease of maintenance	6	7	42	8	48	9	54	10	60	6	36	5	30
Longevity	6	9	54	7	42	9	54	9	54	6	36	5	30
Acoustics	5	8	40	8	40	8	40	8	40	5	25	5	25
Total score			**299**		**308**		**296**		**252**		**284**		**255**
% score (normalized)			97%		100%		96%		82%		92%		85%
Grade			A		A+		B		F		B		C

(Continued)

TABLE 1.2 Continued

B. How a Developer Might Think About His Options for HVAC of an Office Building

		VAV/Reheat		VAC/Convectors		VAV/Dual Duct		Multizone		VAV/FTU		Fancoils	
		Score	**Weighted**	**Score**	**Weighted**	**Score**	**Weighted**	**Score**	**Weighted**	**Score**	**Weighted**	**Score**	**Weighted**
Criteria	**Weight**												
Comfort	3	5	15	8	21	5	15	5	15	8	24	7	21
Flexibility	3	9	30	7	21	8	24	1	4	8	24	7	21
Initial cost	10	9	100	8	80	6	60	4	40	7	70	6	60
Energy consumption	2	7	14	8	16	7	14	7	14	9	18	9	18
Ease of maintenance	2	7	14	8	16	9	18	10	20	6	12	5	10
Longevity	2	9	18	7	14	9	18	9	18	6	12	5	10
Acoustics	5	8	40	8	40	8	40	8	40	5	25	5	25
Total score			**213**		**211**		**189**		**151**		**185**		**165**
% score (normalized)			100%		97%		87%		69%		85%		76%
Grade			A+		A–		B		D		B		C

is inclusion of weighting factors which allow quantitative inclusion of real, albeit qualitative, criteria in a comprehensive comparison among alternatives.

This process involves the following steps:

- Define important criteria.
- Score options 1–10 on these criteria.
- Assign weight according to perceived importance of each criterion.
- Multiply weight × score for weighted score.
- Add weighted scores for total score.
- Normalize scores as percent of score of highest ranking option.
- Grade "on a curve."

Note that different constituencies may have various opinions on weighting of criteria, exemplified here by an owner (A) and a developer (B).

1.4.4 Economic Evaluation

The basis for making good business decisions is economics, and two methods are commonly used to evaluate options. They are *simple payback period* and *life-cycle cost analysis*. Payback analysis is a simple tool often used to screen options. It generally considers only the initial cost of implementing the idea and recurring savings in energy. The cost of maintenance and financing are sometimes neglected, and the interactions with other building systems are generally ignored. Life-cycle cost analysis includes maintenance and financing cost, but usually leaves out many important parameters. Virtually never do these analyses include environmental or the impact on occupant productivity. These are considered "soft costs," which are sometimes beyond the realm of defensible quantification. Nonetheless, soft costs can be the most important factors in deciding among options for design.

1. *Payback analysis.* Despite its limitations, payback analysis is often used to evaluate and compare options. Given options with different initial cost and different operating costs, the simple payback period can be calculated to determine which of the options will recoup initial cost most quickly. Simple payback period is calculated by the following equation:

$$\text{Payback Period} = \text{Extra Cost}/\text{Savings}$$

where

Payback Period = the time required for savings between two options to equal the difference in cost

Extra Cost = the difference in initial cost between the two options

Savings = the annual difference in operating cost, generally including utilities and maintenance

Example 1.1 What is the payback period for a hypothetical energy-saving device in a manufacturing plant? It costs $20,000 to install, lasts 5 years, and saves $7500 per year in utilities, consisting of 15,000 therms* of gas at $0.50 per therm. The device will require $500 per year for maintenance and repairs. These costs are assumed for first year of operation.

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* A therm is 100,000 Btu of heating; this unit is used by utilities for billing gas usage.

Solution: Divide \$20,000 by net annual savings, which are \$7500 utilities, less \$500 maintenance, or \$7000.

Payback Period = \$20,000 /(\$7500 − \$500) = 2.9 years

Example 1.2 What is the payback period for installing an improved version of the hypothetical energy-saving device? It is constructed of more durable materials, which will last 10 years and costs \$30,000 to install. Savings are identical at \$7500 per year in utilities, consisting of 15,000 therms of gas at \$0.50 per therm and requires \$500 per year for maintenance and repairs. These costs are assumed for first year of operation.

Solution: Divide \$30,000 by net annual savings, which are \$7500 utilities, less \$500 maintenance, or \$7000.

Payback Period = \$30,000/(\$7500 − \$500) = 4.3 years

Results of payback analysis can be deceiving. A low-investment, quick-payback option (Example 1.1) might appear superior to a higher investment with higher savings and a longer payback (Example 1.2). Over the economic life of the option, the higher investment could produce superior results despite a longer payback period.

2. *Life-cycle cost analysis.* Life-cycle cost analysis is performed by listing the cash flows associated with an option over a given period defined as the life cycle. Initial cost can be accounted for as a single outlay at year zero. Cost could also be treated as payments to amortize a loan or as yearly depreciation of the asset for accounting and tax purposes. The single outlay method is used for simplicity to illustrate the process.

Economics of alternative decisions are best demonstrated by life-cycle cost analysis. Life-cycle cost analysis is an appropriate tool to compare options on the basis of economics, but is often performed solely on the basis of those criteria that are easiest to document. Cost of construction, financing, maintenance, and utilities can be estimated and have a reportable impact on balance sheets and income statements. Life-cycle cost analysis can be more effective if owners, engineers, and architects are willing and convinced to include cash flows attributable to effects on productivity in the workplace. Good indoor environmental quality results in real economic benefit from productivity. These benefits should be included in life-cycle cost analysis.

During the first year and subsequent years of the life cycle, there will be expenses for utilities, maintenance, and repairs. These costs will likely escalate over time.

All future cash flows must be brought back to current value using a discount rate. The discount rate represents the cost of money or foregone return on investment. Using the “foregone return” logic, a dollar invested today at, say, 6 percent investment return will be worth more in the future. Its value will be escalated by 6 percent per year. Conversely, a dollar in the future is worth less today, its value being “de-escalated” or discounted by 6 percent per year. Discount rate can be also considered the expected investment return.

The following examples illustrate life-cycle cost for the same energy-saving device described in the previous section on payback.

Example 1.3 What is the life-cycle cost for the energy-saving device described in Example 1.1. Recall that the hypothetical energy-saving device is being considered for a manufacturing plant. It costs \$20,000 to install, will last 5 years, and will save \$7500 in utilities during the first year of operation, consisting of 15,000 therms of gas at \$0.50 per therm. The device will require \$500 per year for maintenance and repairs during the first year. Assume that energy cost will escalate at 3% per year and that maintenance/repair cost will also escalate at 3% per year. Assume also that the owner expects a 15% rate of return for investment.

Solution:

Life-Cycle Cost Analysis: \$20,000 Energy-Saving Device, 5-Year Life, 3.6-Year Simple Payback

Life cycle of investment (years)	5
Installation cost	20,000
First-year energy saving (utility rates first year)	7500
Annual maintenance/repair cost (first-year value)	500
Energy escalation rate	3%
Repair and maintenance escalation rate	3%
Discount rate (expected investment return)	15%

Year	Install Cost	Energy Saving	Repair and Maintenance	Total Annual Cash Flow	Present Value Total Annual
	Cash Flows in Year of Occurrence				
0	(20,000)	-	-	(20,000)	(20,000)
1	-	7,500	(500)	7,000	6,087
2	-	7,725	(515)	7,210	5,452
3	-	7,957	(530)	7,426	4,883
4	-	8,195	(546)	7,649	4,373
5	-	8,441	(563)	7,879	3,917
Net Present Value of Life-Cycle Cash Flows ($)					**4,712**

Example 1.4 What is the life-cycle cost of the more durable device described in Example 1.2 that costs $30,000 to install. It will last 10 years and will save $7500 in utilities during the first year of operation, consisting again of 15,000 therms of gas at $0.50 per therm. The device will require $500 per year for maintenance and repairs during the first year. Assume that energy cost will escalate at 3% per year and that maintenance/repair cost will also escalate at 3% per year. Assume also that the owner expects a 15% rate of return for investment.

Solution: Note that the $20,000 option in Examples 1.1 and 1.3 has a shorter payback than the $30,000 option in Examples 1.2 and 1.4; however, the life-cycle savings of the $30,000 option are superior.

Installing the hypothetical $30,000 energy-saving device will have a net present value of $8,955, which is considerably higher than the $4,712 for the $20,000 option.

Life-Cycle Cost Analysis: $30,000 Energy-Saving Device, 10-Year Life, 5.5-Year Simple Payback

Life cycle of investment (years)	10
Installation cost	30,000
First-year energy saving (utility rates first year)	7,500
Annual maintenance/repair cost (first year)	500
Energy escalation rate	3%
Repair and maintenance escalation rate	3%
Discount rate (expected investment return)	15%

Year	Install Cost	Energy Saving	Repair and Maintenance	Total Annual Cash Flow	Present Value Total Annual
	Cash Flows in Year of Occurrence				
0	(30,000)	-	-	(30,000)	(30,000)
1	-	7,500	(500)	7,000	6,087
2	-	7,725	(515)	7,210	5,452
3	-	7,957	(530)	7,426	4,883
4	-	8,195	(546)	7,649	4,373
5	-	8,441	(563)	7,879	3,917
6	-	8,695	(580)	8,115	3,508
7	-	8,955	(597)	8,358	3,142
8	-	9,224	(615)	8,609	2,814
9	-	9,501	(633)	8,867	2,521
10	-	9,786	(652)	9,133	2,258
Net Present Value of Life-Cycle Cash Flows ($)					**8,955**

1.4.5 Considering Environmental Emissions in Life-Cycle Analysis

Environmental factors such as "carbon footprint" can be considered in life-cycle cost analysis. Table 1.1 lists pollutants attributable to building energy usage. Various agencies have assigned social costs to the emission of CO_2, ranging from $15 per ton to upwards of $50 per ton. These costs are not directly assessed to the building owner who uses the energy, but are sometimes considered in life-cycle cost analysis by institutions which desire to take a more comprehensive view of their energy operational responsibilities.

Example 1.5 shows a life-cycle cost analysis of the $30,000 investment from Example 1.4 including a value assigned to CO_2 emissions reduction.

Example 1.5 The firm's CEO knows that his board of directors is socially conscious and would appreciate inclusion of the environmental impact of the option. From Table 1.1, we find that 14 lbs. of CO_2 emission will be eliminated for every therm saved. The board subscribes to a governmental agency's opinion that the social cost of CO_2 emission is $25/ton, resulting in a "carbon saving" of (15,000 therms × 14 lbs)/(2000 lbs./ton) = 105 tons per year; 105 tons × $25/ton = $2625.

What is the life-cycle cost of the alternative energy-saving device from Example 1.4 if a value is assigned to reduction of CO_2 emissions?

Carbon cost is assumed to escalate at 3% per year in the analysis presented below:

Solution: Note that the net present value of cash flow is almost three times the value when only energy savings are considered. Considering emissions cost can have a significant effect on the decision process who consider their effect on the environment.

Life-Cycle Cost Analysis: $30,000 Energy-Saving Device, 10-Year Life, Including Productivity and Environmental Values

Life cycle of investment (years)	10
Installation cost	30,000
First-year energy saving (utility rates first year)	7,500
Annual maintenance and repair	500
Cost assigned to CO_2 emissions reduction (gain)	2,625
Energy escalation rate	3%
Repair and maintenance escalation rate	3%
CO_2 emissions cost escalation rate	3%
Discount rate	15%

	Cash Flows in Year of Occurrence					
Year	Install Cost	Energy Saving	Repair and Maintenance	Value of CO_2 Reduction	Total Annual Cash Flow	Present Value Total Annual
0	(30,000)	-	-	-	(30,000)	(30,000)
1	-	7,500	(500)	2,625	9,625	8,370
2	-	7,875	(515)	2,704	10,064	7,610
3	-	8,269	(530)	2,785	10,523	6,919
4	-	8,682	(546)	2,868	11,004	6,292
5	-	9,116	(563)	2,954	11,508	5,722
6	-	9,572	(580)	3,043	12,036	5,203
7	-	10,051	(597)	3,134	12,588	4,732
8	-	10,553	(615)	3,228	13,167	4,304
9	-	11,081	(633)	3,325	13,773	3,915
10	-	11,635	(652)	3,425	14,408	3,561
Net Present Value of Life-Cycle Cash Flows ($)						**26,628**

1.4.6 Energy Usage in Perspective with Other Operating Expenses

This section examines the components of building operating cost and the relative importance of energy in comparison with other costs associated with building operations, especially labor costs for personnel working in commercial buildings. An office building is used for example. Office buildings in temperate climates use energy for HVAC, water heating, lighting, office appliances, and vertical transportation. The table here shows how a typical low-rise building might use energy for these functions.

Energy Use	Percent
HVAC	53
Hot water	1
Lighting	28
Appliances	18

Generally, a Midwest office building will experience energy bills of \$1.50 to \$2.50 per year for gas and electric.

To place the cost of energy in perspective, here is an example of operating costs for a typical office building in a temperate climate:

Facility Expenses, Typical Office Building

Expense Component	Expense (%)	\$ per Year
Investment return	59	8.35
Repairs and maintenance	5	0.73
Preventative maintenance	4	0.60
Janitorial	7	1.01
Site maintenance	0	0.06
Gas	**1**	**0.19**
Electric	**13**	**1.84**
Water	1	0.09
Sewer	0	0.05
Environmental	1	0.13
Life safety	1	0.11
Security	5	0.73
Space planning	2	0.29
Total facilities expense	**100**	**14.18**

Energy (highlighted in the table) is about \$2.00/ft^2 per year, representing less than 15 percent of the overall cost of owning and operating a facility, exclusive of personnel costs. This value might be higher or lower depending on climate and utility rates, but the general relationship will be fairly consistent with these values.

1.4.7 Energy Cost Compared with Personnel Cost

A typical office building will likely have an occupancy density of 200 gross square feet per workstation, including circulation, toilets, and lobby. Personnel cost can be expressed in terms of \$/ft^2 per year for comparison with other operating costs, including energy:

Analysis of Personnel Cost in \$/ft^2 per Year

Occupancy density	200 ft^2/employee
Salary (example)	\$50,000/yr
Fringes @ 30%	\$15,000/yr
Personnel annual cost	\$65,000/yr
Personnel annual cost per ft^2	\$325 ft^2/yr

1.4.8 Economics of Productivity and Energy

Relative to energy cost at \$2.00/ft^2 per year, employee cost is a very large number! Energy conservation is a key issue in sustainable design, but considering the purpose of buildings, saving energy at the expense of occupant well-being and performance is not advisable. Here are a few arithmetic scenarios to make the point.

Suppose that a facility manager changes thermostat set points and reduces lighting levels to effect a 20 percent reduction in utility bills. Savings would be about \$0.40/ft^2 per year. Suppose further that these reductions in building service quality reduced employee productivity by 1 percent. The loss in productivity would be 1 percent of \$325/ft^2 per year, or \$3.25. The energy savings of 20 percent, or \$0.40/ft^2 per year, sound impressive and would likely win praise from the CFO, but such a program is not a good idea if there are harmful side effects on productivity.

Conversely, suppose that a facility manager installs better temperature controls and increases lighting levels at the expense of a 20 percent *increase* in utility bills. Extra cost would be about \$0.40/ft^2 per year. Suppose further that these improvements in building service quality increased employee productivity by 1 percent. The gain in productivity would be 1 percent of \$325/ft^2 per year, or \$3.25. Obviously, the extra cost for energy, though considerable, would be a great investment considering the beneficial side effects on productivity.

These examples are not intended to detract from the importance of energy conservation, but rather to point out that energy should be used or conserved with an eye toward *overall* building performance. A high performance building uses energy effectively and enables high performance personnel.

1.4.9 Considering Personnel Productivity in Life-Cycle Analysis

Example 1.6 shows a life-cycle cost analysis of the \$30,000 energy investment from Example 1.4, including an assessment for productivity changes on the plant floor.

Example 1.6 At the last minute the plant foreman was told about the installation of the energy-saving equipment described in the preceding example problems. He was pleased with the potential energy savings and enthusiastic about the reduction in carbon footprint. Unfortunately, he was familiar with a similar installation in a competitor's shop and knows that the device will cause a decrease in temperature and considerable breezes on the plant floor. The foreman of the plant estimates that this will cause extra “warm-up” breaks during the winter for the plant’s 20 \$15/hour fork truck drivers. Assuming a loss of half hour per day for 12 cold weather weeks (60 days), the productivity impact will be \$9000 annual loss.

Productivity cost is assumed to escalate at 3% per year in the analysis presented below:

Solution:

Life-Cycle Cost Analysis: \$30,000 Energy-Saving Device, 10-Year Life, Including Productivity as well as Environmental Values

Life cycle of investment (years)	10
Installation cost	30,000
First-year energy saving (utility rates first year)	7,500
Annual maintenance and repair	500
Productivity loss	9,000
Cost assigned to CO_2 emissions reduction (gain)	2,625
Energy escalation rate	3%
Repair and maintenance escalation rate	3%
Labor (productivity) escalation rate	3%
CO_2 emissions cost escalation rate	3%
Discount rate	15%

	Cash Flows in Year of Occurrence						
Year	**Install Cost**	**Energy Saving**	**Repair and Maintenance**	**Value of CO_2 Reduction**	**Productivity Gain (Loss)**	**Total Annual Cash Flow**	**Present Value Total Annual**
0	(30,000)	-	-	-	-	(30,000)	(30,000)
1	-	7,500	(500)	2,625	(9,000)	625	543
2	-	7,875	(515)	2,704	(9,270)	794	600
3	-	8,269	(530)	2,785	(9,548)	975	641
4	-	8,682	(546)	2,868	(9,835)	1,170	669
5	-	9,116	(563)	2,954	(10,130)	1,378	685
6	-	9,572	(580)	3,043	(10,433)	1,602	693
7	-	10,051	(597)	3,134	(10,746)	1,842	692
8	-	10,553	(615)	3,228	(11,069)	2,098	686
9	-	11,081	(633)	3,325	(11,401)	2,372	674
10	-	11,635	(652)	3,425	(11,743)	2,665	659
Net Present Value of Life-Cycle Cash Flows (\$)							**(23,457)**

This hypothetical example shows that so-called “soft costs” can make a difference in the economic performance of concepts. Inclusion of even small changes in productivity of building occupants can have a very large effect on the decision process. In this case loss of productivity makes the energy saving feature ill-advised.

QUESTIONS

1.1 What are the benefits of buildings with shallow floor depths?

1.2 How much CO_2 will be liberated to the atmosphere in a year’s time due directly to a lighting system consuming 300,000 kWh per year?

1.3 If a corporation is concerned with its carbon footprint and accepts a value of \$25 per ton to account for societal costs, what is their perceived economic impact of this much CO_2?

1.4 What will the relative impact be on CO_2 for heating and for cooling, assuming the buildings in Question 1.1 are located in the Midwest (hot summers, cold winters)?

1.5 How does “sustainable” design differ from energy-effective design?

1.6 What factors should the architect and engineer consider to produce a high performance environment for building occupants?

1.7 How does saving energy help to protect the environment?

1.8 What is the role of maintainability in sustainable buildings?

1.9 How could building site selection affect the environment?

1.10 What factors should interior designers consider in terms of indoor air quality? Architects? HVAC engineers?

1.11 What design features would you suggest to allow personal climate control in a single-story residence? A high-rise office building? A classroom building?

1.12 Compare the importance of commissioning for a data center versus a classroom building.

1.13 What sustainable design issues should architects consider in deciding window materials and locations?

1.14 Name a few quantitative factors involved in the analysis of a building HVAC system. Name a few qualitative factors.

1.15 Is there ever a time when energy conservation is unwise? If so, give examples.

1.16 Prepare three decision matrices to evaluate operable windows versus fixed windows in an office building. Use the process described in Section 1.4.3. Fill out the matrices as an occupant, a maintenance staffer, and a building owner.

1.17 Will a commercial building developer use a higher or lower discount rate than an institutional building owner? Why?

1.18 An energy conservation option has a first cost of $50,000. It requires $4000 per year maintenance and saves $10,000 per year in utilities. What is the simple payback period for the option?

1.19 The system in Question 1.18 will last 15 years with no salvage value. What is the 15-year life-cycle cost assuming energy cost escalation of 4% annually, maintenance cost escalation of 2% annually, and a 5% discount rate? What if the discount rate is 15%?

1.20 Assume the option in Question 1.18 is installed in a building with 200 occupants, with average personnel cost of $60,000 per year. If the device interferes with temperature control, resulting in a 2% decrease in productivity, what would the simple payback be?

1.21 What would the payback be if the option in Question 1.18 improved temperature control and resulted in a 2% increase in productivity?

1.22 Calculate the life-cycle costs for the two cases (2% decrease, 2% increase in productivity) using data from Questions 1.19 and 1.20 for a 5% discount rate and a 15% discount rate.