STRATEGIES FOR INTEGRATED DESIGN OF SUSTAINABLE TALL BUILDINGS

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This research paper examines the process of integration of tall building systems with special emphasis on sustainable buildings. The design of tall buildings warrants a multidisciplinary approach and requires the integration of architectural components, structure, vertical transportation, fire safety, energy conservation, and communication systems.

A major component of this research entails the development of an "Integration Web" that illustrates the relationships and inderdependence of the physical systems of tall buildings. It is a tool that can be used by architects, engineers, and planners to facilitate coordination. Similar to a "food web," the Integration Web is related to each major function of the AIA contract including Architecture, Structure, Mechanical Electrical, and Plumbing (MEP), as well as municipal services. The Integration Web can be linked to LEED criteria for integration of sustainable and high-performance building features.

Lastly, case studies of buildings are mentioned, which represent a new generation of sustainable high-rise buildings that are challenging conventional high-rise building practices and setting trends for such future projects incorporating innovations in materials and smart building systems. These buildings are seemingly well-tuned to their climate; and they provide a major portion of their own energy requirements through integrated passive design, daylighting, and intelligent control systems.

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I. Introduction

Until recently, tall buildings have been viewed as mega-scale energy consumers with little regard for sustainable architecture. However, this is changing with a new generation of high-rise buildings that have been designed with energy conservation and sustainability as their principal criteria. Cities throughout the world are growing rapidly, creating unprecedented pressure on material and energy resources. According to the World Commission and Environmental Development or Brundtland Report, *Our Common Future*, sustainable design is an effort to meet the requirements of the present without compromising the needs of future generations by encouraging the wise and prudent use of renewable resources, alternative strategies for energy production and conservation, environmentally friendly design, and intelligent building technology. It adds that, "Sustainable development is not a fixed state of harmony, but rather a process of change in which the exploitation of resources, the direction of investments, the orientation of technological development, and institutional change are made consistent with future as well as present needs" (WCED, 1989).

Two crucial elements are addressed in this definition of sustainable development. First, it acknowledges the concept of "needs," especially with regard to disparities between rich and poor, such as food, clothing and shelter essential for human life, as well as other "needs" to allow a reasonably comfortable way of life. Second, it accepts the concept of "making consistent" the resource demands of technology and social organizations with the environment's ability to meet present and future needs. This includes both local and global concerns and has a political dimension, embracing issues of resource control and the inequities that exist between developed and developing nations. In this way it endorses the notion of sustainable development as improving rather than merely maintaining the quality of life within the limits of the carrying capacity of supporting ecosystems. (Williamson, et al., 2003).

While the concept of sustainability is becoming accepted by architects and planners as well as by relevant private and public institutions, there is little worldwide consensus on what specific actions should be taken. In their search for models that incorporate sustainable principles of design, many designers and planners have looked to history and vernacular architecture in particular. For example, passive systems of climate control used by builders of vernacular architecture in the past, such as shading and increasing the thermal mass of walls, and using natural ventilation and plantings, are being incorporated into many "green" buildings that reduce their need for costly, mechanical environmental control systems.

However, while such lessons can and have been readily transferred from vernacular buildings to small modern building types such as houses, schools, community buildings, and the like, they are less easily transferable to large modern building types for which there are no historical precedents, either of scale or complexity (Abel, 2003). This is especially true for tall office buildings, since the large internal spaces they require make it difficult to achieve levels of natural lighting or ventilation in the deeper parts of the building. Strong winds or driving rain on the higher parts of very tall structures mitigate against keeping windows open all the time, further complicating the problem.

Integrated design is different than conventional design in its focus on active collaboration within a multidisciplinary team. Hypothetically speaking, it is possible to design and construct a building made of totally independent components designed in isolation. This approach, however, will not yield a harmonious or beautiful building, and it is not practical. Architects tend to take the opposite approach by starting with carefully considered ideas about the complete and constructed building, and then exploring inward, working through intricate relations between parts and functions. According to Leonard Bachman, integration among the hardware components of building systems is approached with three distinct goals: Components have to share space, their arrangement has to be aesthetically resolved, and at some level they have to work together or at least not conflict with each other (Bachman, 2003).

In sustainable tall buildings especially, an integrated process is necessary because of their scale and the fact that green design affects so many different elements of a building, such as daylighting, which in turn concerns siting, orientation, building form, facade design, floor-to-floor heights, interior finishes, electric lighting controls, and cooling loads, among other things. Green or vegetated roofs, with their impact on storm water runoff, building structure, building form, thermal insulation, and plantings, are another example where integration must be considered (Malin, 2006).

2. Integration and Sustainability

Bachman lists three types of *integration*: physical integration, visual integration, and performance integration.

Physical integration is fundamentally about how components and systems share space, that is, how they fit together. The floor-ceiling section of many buildings, for example, is subdivided into separate zones for lighting, ducts, and structure to support the floor above. These segregated volumes prevent "interference" between systems by providing adequate space for each system. Sometimes these systems are meshed together or unified, which requires careful physical integration. Connections between components and among systems in general constitute another aspect of physical integration.

Visual integration involves development of visual harmony among the many parts of a building and their agreement with the intended visual effects of design. This may include exposed and formally expressive components of a building that combine to create its image. The Hong Kong and Shanghai Bank Building in Hong Kong is an example where the visual expression of the physical systems and components of a building to create a powerful visual and aesthetic result.

Performance integration has to do with "shared functions" in which a load-bearing wall, for instance, is both envelope and structure, so it unifies two functions into one element. It also involves "shared mandates" - meshing or overlapping functions of two components without actually combining the pieces. In a direct-gain passive solar heating system, for example, the floor of the sunlit space can share the thermal work of the envelope and the mechanical heating systems by providing thermal mass and storage.

Since the beginning of the industrial age in 1830, building technology has advanced from monolithic structures with marginally controlled passive environments to glass-enclosed skeletal frames with intelligent robotic servicing. Much of this change occurred after 1940 with the proliferation of mechanical, electrical, and plumbing systems (Bachman, 2003). The most obvious influence of industrialization has been first, the progression of advanced materials that performed better and lasted longer; and second, the standardization of building components that could efficiently be produced by machines. Modern technical solutions now may come as well-ordered or totally preconfigured systems designed by other professionals.

While many architects of the nineteenth century were concerned with rational building design and monolithic exposed construction, they did not consider it a prerequisite of good building (Ford, 1990). Julien Gaudet, the chief theoretician of the Beaux-Arts in the late nineteenth century, recognized that both an unfinished monolithic and layered system of discreet elements were possible, and that the expressed components themselves contained their own aesthetic integrity (Gaudet, 1901).

The idea of using industrial mass-production building systems as a basis for design has its origins in the 1920s with Walter Gropius and the New Architecture of the Bauhaus in the Weimar Republic of Germany. Frank Lloyd Wright's design for the S.C. Johnson and Son Office Building in Racine, Wisconsin of 1939 is an example of design integration versus standard practices of construction. Wright, like many architects, thought that a functional building should be tightly integrated and, therefore, would be less expensive. In an integrated building, in which the separate systems are tightly interlocked, more functions can be performed by each element. In modern construction, elements tend to be independent and specialized rather than monolithic, integrated, and multifunctional. This is especially true in large-scale buildings like high-rises where specialization of labor and materials in the building industry requires a high level of organization and coordination among the suppliers and fabricators.

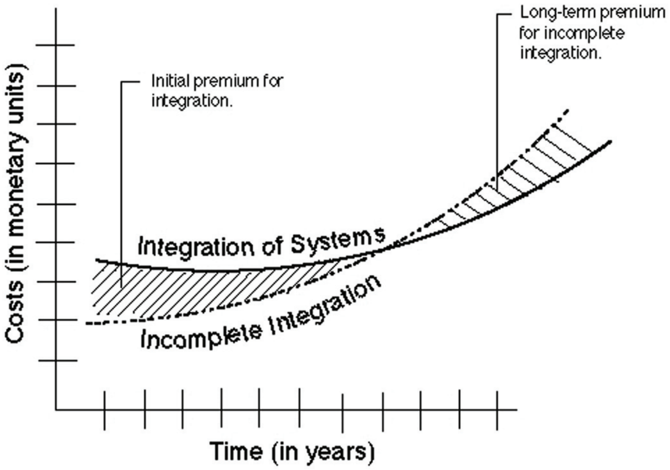


Figure 1: Cost-Effectiveness of Integration

Integration, resulting in simplicity, yields not only order but long-term economy. The break-even point of intersection in Fig. 1 between the two curves depends upon the size and complexity of the building. Integrated innovative design does not necessarily represent high additional costs, although as shown in Fig. 1 the initial costs may be higher than that of conventional design with incomplete integration. However, its benefits are immense in that operating costs are lower and energy costs could be substantially lower compared with conventional solutions. With continued implementation of integration techniques even the intial cost will eventually level off. In a well-run integrated design process, the additional time that a team spends developing a schematic design is offset by a reduction in the number of meetings needed later to work out conflicts among systems that were not integrated from the start. An internal study at the large A/E firm Hellmuth, Obata & Kassabaum (HOK) found that sustainable design projects were, on average, 25 percent more profitable for the firm than conventional projects (Malin, 2006). The Rocky Mountain Institute, a non-profit think tank and consultancy that pioneered many of the practices now known as green building, has identified four key components of an integrated design process (Malin, 2006):

1. Whole-Systems Thinking: taking interactions between elements and systems into account, and designing to exploit their energies.
2. Front-Loaded Design: thinking through a design early in the process, before too many decisions are locked in and opportunities for low-cost, high-value changes to major aspects for the design have dwindled.
3. End-Use, Least-Cost Planning: considering the needs of a project in terms of the services (comfort, light, access) the end user will need, rather than in terms of the equipment required to meet those needs.
4. Teamwork: coming up with solutions as a group and collaborating closely on implementing those solutions.

Teresa Coady, of Bunting Coady Architects in Vancouver, helped create the Canadian Government's Commercial Buildings Incentive Program, set up specifically to promote integrated design. Some factors include (Malin, 2006):

1. Shape and Shadow: massing and orientation of the building as related to function, daylight, and structural considerations.
2. Site Opportunities: location of building and its effect on the immediate context;
3. Envelope: types of walls and locations of windows;
4. Lighting Design: daylighting and electrical lighting;
5. How the Building Breathes: natural ventilation and passive heating and cooling;
6. Comfort System: heating and cooling loads and mechanical systems design;
7. Materials: selection and composition; and
8. Quality Assurance: review of building as a system.

For example, to optimize costs and performance, many sustainable designers have proved that high-performance facades work just as well as conventional methods of perimeter heating to provide comfort at the edges of a building on cold days. Other benefits include reduced energy use, less noise, and fewer maintenance demands. Teamwork among professionals is essential to maximizing integration opportunities in sustainable buildings. Judith Heerwagon, of J.H. Heerwagon & Associates in Seattle, has identified several important components of good teamwork on design projects (Malin, 2006):

1. Strong support from the client;
2. Mutual respect;
3. Effective communication; and
4. An ability to deal constructively with conflict.

3. “Systems Thinking” and Integration of Systems

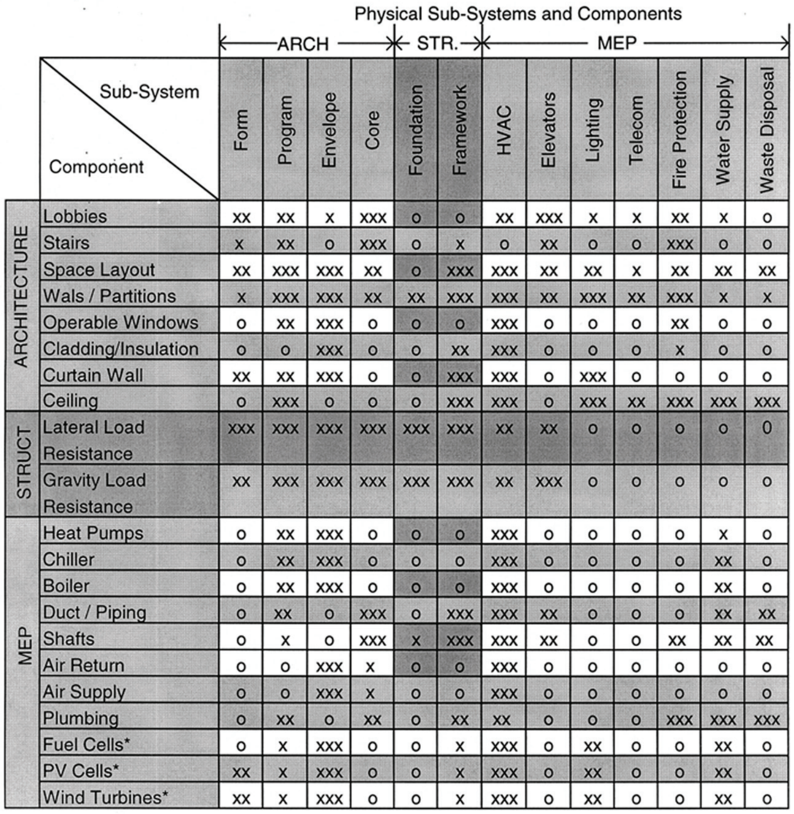
Often the definition of integration gets confused with the idea of having systems or components to do the work of multiple systems or components. This is more related to a combination of functions and not the true nature of integration, which involves the coordination and design of building systems to work together in a holistic manner. Not all systems necessarily integrate with each other. For example, in systems such as fire suppression and security, the desire is often for their complete separation so as to isolate them from other systems in order to prevent possible accidents that would cause overall system failures. When these systems are integrated into the whole, back-up systems are generally provided to create redundancy within the desired systems.

While all physical systems are essential for the complete functioning of the tall building, the most important are the structural systems and the mechanical systems. These systems are discussed below with regard to how they function independently and in conjunction with other interdependent systems and the architecture of the building.

3.1 Structural Systems

Structural invention and the expression of tectonic strategies have continued to be neatly integrated into architectural significance by centuries of formal experiment. Until the advent of the computer, the reticulated frame remained the most widely used structural solution for high-rise buildings. However, as buildings exceeded 40 stories in height, new innovative structures had to be developed. In the first reticulated frame buildings in Chicago designed in the late nineteenth and early twentieth centuries, wind as a force acting on the building could not be represented analytically. Masonry was used on its exterior to stabilize the building as whole, and the interior was resolved by using a metal frame of posts and beams. In their design of the Masonic Temple of 1892 in Chicago, Burnham & Root offered the first resolution with crossed wrought-iron bars used to brace the building against wind (Abalos, et. al., 2003). Corydon T. Purdy and the firm of Holabird & Roche used a rigid framework located in the first bay perpendicular to the façade of the Old Colony Building of 1894 in Chicago. These methods were also used in the construction of the Woolworth Building built in1913 and the Empire State Building of 1931 in New York (Condit, 1974).

The “tectonic order” is “the visual expression of the building structure and its intentional integration with other major systems” (Frampton, 1995). Vertical pipelines and ducts occasionally run through floors resulting in perforations. From the perspective of physical integration, structure is often made to contain the service systems. Conventionally, the interstitial space between floor and ceiling layers normally carries the horizontal distribution of HVAC, electrical, and lighting services. Hollow structural members, which are stronger in bending than solid members of the same mass, are also appropriate conduits for the distribution of service elements. Structural systems selection generally involves the choice of the lightest-weight members of the most economical material, allowing the most efficient configuration that is appropriate to the anticipated loads.



Physical Sub-Systems and Components

	Sub-System / Component	ARCH				STR.		MEP						
		Form	Program	Envelope	Core	Foundation	Framework	HVAC	Elevators	Lighting	Telecom	Fire Protection	Water Supply	Waste Disposal
ARCHITECTURE	Lobbies	xx	xx	x	xxx	o	o	xx	xxx	x	x	xx	x	o
	Stairs	x	xx	o	xxx	o	x	o	xx	o	o	xxx	o	o
	Space Layout	xx	xxx	xxx	xx	o	xxx	xxx	xx	xx	x	xx	xx	xx
	Wals / Partitions	x	xxx	xxx	xx	xx	xxx	xxx	xx	xxx	xx	xxx	x	x
	Operable Windows	o	xx	xxx	o	o	o	xxx	o	o	o	xx	o	o
	Cladding/Insulation	o	o	xxx	o	o	xx	xxx	o	o	o	x	o	o
	Curtain Wall	xx	xx	xxx	o	o	xxx	xxx	o	xxx	o	o	o	o
	Ceiling	o	xxx	o	o	o	xxx	xxx	o	xxx	xx	xxx	xxx	xxx
STRUCT	Lateral Load Resistance	xxx	xxx	xxx	xxx	xxx	xxx	xx	xx	o	o	o	o	0
	Gravity Load Resistance	xx	xxx	xxx	xxx	xxx	xxx	xx	xxx	o	o	o	o	o
MEP	Heat Pumps	o	xx	xxx	o	o	o	xxx	o	o	o	o	x	o
	Chiller	o	xx	xxx	o	o	o	xxx	o	o	o	o	xx	o
	Boiler	o	xx	xxx	o	o	o	xxx	o	o	o	o	xx	o
	Duct / Piping	o	xx	o	xxx	o	xxx	xxx	xx	o	o	o	xx	xx
	Shafts	o	x	o	xxx	x	xxx	xxx	xx	o	o	xx	xx	xx
	Air Return	o	o	xxx	x	o	o	xxx	o	o	o	o	o	o
	Air Supply	o	o	xxx	x	o	o	xxx	o	o	o	o	o	o
	Plumbing	o	xx	o	xx	o	xx	xx	o	o	o	xxx	xxx	xxx
	Fuel Cells*	o	x	xxx	o	o	x	xxx	o	xx	o	o	xx	o
	PV Cells*	xx	x	xxx	o	o	x	xxx	o	xx	o	o	xx	o
	Wind Turbines*	xx	x	xxx	o	o	x	xxx	o	xx	o	o	xx	o

** Sustainable Components.*

KEY: Degree of Influence

xxx	Major
xx	Moderate
x	Minor
o	N/A or Rare Influence

Figure 2: Influences of Physical Sub-Systems and Components

Prior to 1965, the design of structural systems for skyscrapers was done in a conventional way by fastening together beams and columns to create a stiff structural grid for resisting wind forces. Fazlur Khan was the first structural engineer to question this approach and to tackle the entire issue of structural systems for tall buildings by devising a whole range of structural systems: framed tubes; braced tube; mixed steel-concrete systems; and superframes (Ali, 2001). The DeWitt-Chestnut Apartments of 1965 in Chicago, designed by Bruce Graham and Fazlur Khan of Skidmore, Owings & Merrill (SOM), was the first attempt to construct a high-rise building in which the structural tube in the perimeter frame acts as a "punched wall" reintroduced the concept underlying the traditional load-bearing wall as an active element in the building's response to wind loads. Tube buildings – particularly the bundled tube system that was used for the Sears Tower and One Magnificent Mile buildings in Chicago – offered a new architectural vocabulary through different massing possibilities (Ali, 1990).

Until about 1970 the skyscraper's structural behavior could be analyzed three-dimensionally by using estimates based solely on experimental or simplified analytical models. Today the critical mathematical aspect of indeterminate structural problems can be tackled by the computer by which alternate schemes can be analyzed, and the structural members can be optimized. Computers have simplified the process of making complex calculations so that more structural options can be explored and more precise solutions can be readily achieved.

Recently, the need for openness in the exterior facade desired by architects and owners resulted in the location of primary structural elements resisting lateral loads within the core rather than at the perimeter. Most supertall buildings (Petronas Towers, Jin Mao, Taepei 101, etc.) use this concept in the form of outrigger-and-core systems or a variation of it employing belt trusses or mega-columns at the perimeter. In some cases, mixed steel-concrete construction is used to draw on the advantages of both materials.

Physical Sub-Systems and Functions

	ARCH				STR.		MEP						
Sub-System / Function	Form	Program	Envelope	Core	Foundation	Framework	Elevators	HVAC	Lighting	Telecom	Fire Protection	Water Supply	Waste Disposal
Life Safety	o	xx	x	xxx	xxx	xxx	x	x	x	xx	xxx	xx	o
Structural Stability	xxx	xx	x	xxx	xxx	xxx	o	x	o	o	o	o	o
Waste Disposal	o	o	o	o	o	o	o	o	o	o	o	xx	xxx
Electrical Supply	o	x	o	o	o	o	xxx	xx	xxx	x	x	o	o
Water Supply	x	o	o	o	o	o	o	o	o	o	o	xxx	xxx
Indoor Temp. Control	xx	o	xxx	o	o	o	o	xxx	x	o	o	o	o
Vertical Transport	x	xx	o	xxx	o	x	xxx	o	o	o	o	o	o
Interior Illumination	xx	x	xxx	o	o	o	o	o	xxx	o	o	o	o
Water Infiltration Control	xx	o	xxx	o	o	o	o	o	o	o	o	o	o
Day Lighting	xxx	xx	xxx	o	o	o	o	o	o	o	o	o	o
Organization	xxx	xxx	x	xxx	o	o	xx	o	x	o	xx	o	o
Energy Conservation	xx	xx	xxx	o	o	o	x	xxx	xxx	o	o	o	o
Communication	o	xx	o	o	o	o	xxx	xxx	x	xxx	o	o	o

KEY:

Degree of Performance	
xxx	Major
xx	Moderate
x	Minor
o	N/A or Rare Performance

Figure 3: Influences of Physical Sub-Systems and Functions

Architects and structural engineers generally collaborate during the early stages of tall building design. The owner wants the least expensive way to find and do things. This is done by "value engineering" studies and cost analysis by cost consultants. Site selection is driven by market forces. The evolution of design proceeds with programming and mass modeling. Since September 11, 2001, perception by the public has become an important consideration in making tall buildings structurally sound and secure from terrorist acts. Studies on floor-to-floor heights, lease spans, core plans, floor plate modules, façade glass area, etc. are carried out by the architect to optimize floor space in conjunction with marketing analysis. Since tall buildings cannot be tested as full-scale models, structural engineers carefully study the structural systems at this stage keeping in mind the constructability of the structure. The engineers and architects communicate through computer-based drawings and sketches to offer their design intents. Many major decisions are made through this schematic design phase. A good working relationship between the architect and the engineer is important for effective collaboration, although occasional adversarial conflicts are necessary in order to develop an optimum design from both view points. Local regulations and infrastructure constraints must be researched before commencement of the design process for all disciplines including the mechanical, electrical, and plumbing systems. The matrix in Figure 2 shows the interrelationships of Physical Sub-Systems and Elements.

3.2 Mechanical Systems

In tall buildings, horizontal distribution of mechanical networks is not the main issue or even the only one at the level of structure. Other factors linked to the technical aspects of the heating, ventilating, and air-conditioning (HVAC) systems include centralization of the equipment on mechanical floors and adequate placement of the vertical service columns, which require integrated solutions. Figure 3 shows the interrelationships of Physical Sub-Systems and Function.s

Beginning in 1960, the concept of the office landscape emerged. This model was based on an unobstructed, continuous, deep, and air-conditioned volume supplied with uniform energy services. These changes in planning also led to the further integration of mechanical systems, as floor-to-floor distances decreased. In a similar vein the invention of fluorescent lighting changed the architectural planning of office and commercial buildings dramatically. The building width could be much deeper so the reduction of sunlight in the interior was no longer a problem.

In tall buildings, horizontal distribution of mechanical networks is not the main issue or even the only one at the level of structure. Other factors linked to the technical aspects of the HVAC systems include centralization of the equipment on mechanical floors and adequate placement of the vertical service columns, which require integrated solutions. In the United Nations Secretariat of 1950 in New York, for example, the skyscraper's section is zoned into floors for mechanical equipment in which groups of 15 to 30 floors are served by a mechanical floor located in the middle of each group, thus avoiding power loss along the length of the conduits.

The skyscrapers of the 1920s used a central core that helped to stiffen the buildings against the lateral forces of wind, housed the energy management and vertical transportation systems, and provided mechanical services to each floor. The core occupied space that was still considered unusable and not in proximity to the façade plane. The RCA Building and the Seagram Building, both in New York, with usable depths from the outside wall to the core of around 24 ft. (7.3m), are typical examples of this method of distributing space. The development of artificial climate control systems introduced the possibility of achieving deeper usable space.

The Inland Steel Building in Chicago completed in 1958 and designed by Bruce Graham, Walter Netsch, and Fazlur Khan of SOM, relegated the structural system to the periphery of the building and concentrated the service elements in an autonomous core. This solution maximized the concept of flexibility in office spaces in the form of completely unobstructed floors of 10,333 sq. ft. (960 sq. m), which were appropriate for open-plan offices, executive offices (at the 19th floor), meeting rooms (at the 13th floor), or any other form of administrative organization. This organizational principle made explicit the existence of two spatial systems and, by locating the service areas at the periphery, freed usable space from any form of interior obstruction (Abalos, et. al., 2003). This concept was first used by Louis Kahn in the Alfred Newton Medical Research Building of 1959 at the University of Pennsylvania, Philadelphia and later in the laboratories at the Salk Institute of 1965 at La Jolla, California.

Centralized computer spaces, which appeared in the early 1970s, became models for a new form of integrated technology. The densely packed cables and wires required by computers and the need to dissipate the heat they produce led to the widespread development of raised access floors to facilitate equipment repairs, alterations, and replacements.

As the flexibility of the layout of workspaces increased, the workplace itself remained physically linked to energy systems and the work environment became progressively individualized or compartmentalized. This had a profound effect on the design of tall buildings. For example, in the 1950s through the 1970s, ceilings, floors, walls, and the structural frame were parts of a complete system that included among its components partition walls, storage areas, and furnishings. The design of the Sears Tower of 1973 and other tall office buildings by SOM rested on the division of the ceiling into a 6-foot (1.8-meter) grid that acted as a guide for interior subdivisions. This measurement coincided with the largest desk dimension, and when duplicated, with the smallest office unit. Each unit contained its own services (lighting, ventilation, electricity, telephone, etc.), so that each occupied portion of the office was technically autonomous. The recommended minimum depth for the office landscape was 60 ft. (18.5m) but some plans were deeper, around 120 ft. to 150 ft. (37m to 46m). The suspended ceiling, which supplied consistent uniform energy, became the primary modular planning element for the layout of the office.

Well-integrated applications of advanced facade technology together with innovative HVAC systems results in significant energy savings and improves indoor air comfort. If the facade and HVAC systems are engineered as two components of the same solution, not only will the performance be better – both initial and operating costs may be significantly reduced. This suggests that there is a need for a change of approach bringing together facade specialists and mechanical and electrical engineers during the early stages of the design process.

4. Technology Transfer

“Technology transfer” refers to the process whereby the techniques and materials developed in one creative field, industry, or culture are adapted to serve another (Pawley, 1990). New developments in aeronautical engineering, production and assembly methods, and new materials often find their way to the building construction industry. The design of a jumbo jet, for example, can be compared to a building in terms of scale, integration of complex systems and intellegent technology, structural engineering to resist wind loads and create and efficient, aerodynamic design, and the development of new materials to increase strength and reduce weight and drag. Like tall buildings, aircraft are self-contained environments with their own micro-climates. Because they often fly at high altitudes, their interiors must be pressurized to withstand external air pressures and to maintain comfortable pressure levels within for occupants to maintain proper sensory response. Like a tall building, they are designed and assembled at a large scale, which requries careful planning, coordination, and integration of complex systems. This integration begins at the earliest stages of design to avoid costly mistakes during fabrication and assembly.

One example of technology transfer that applies directly to the structural system of tall buildings is the application “Finite Element Analysis.” Until the 1970s, structural engineers did not have the tools to analyze the structural behavior of a tall building with precision with regard to applied forces, such as gravity and wind loads, and earthquakes. They were limited to considering the tall buildings holistically as a monolithic structure-as in the case of buildings of limited height-or to break taller buildings into component “sections” that could be analyzed approximately. Consequently, tall buildings were generally over-structured to allow for a margin of safety that would compensate for any degree of error that might be present in the calculations.

The same problem of the effect of aerodynamic forces on structure is encountered in the design of an airplane fuselage where pressure differences induced by air pressure and wind turbulence at high altitudes must be factored into the design. Since structural weight and mass must be optimized to achieve effiecency, approximate calculations are unacceptable. Finite Element Analysis provides a tool for the engineer to calculate precisely the stresses in any part of the structure, resulting from an accurate three-dimensional analysis of the entire structure element-by-element.

Another example applies to composite materials that have been developed to increase strength and reduces weight. Carbon fiber is light-weight material that can be laminated to produce an extremely strong cladding material for the exterior surfaces of jumbo jets. The manufacturing process of carbon fiber is very expensive, however, and involves nano-scale technology. Hence, there is only one major manufacturer of carbon fiber materials in the world today. The aircraft industry has recently used carbon fiber reinforced composite material for the latest 777 jumbo jets. Although carbon fiber composite material have not been widely used in tall buildings to date, they hold great promise in reducing the weight and mass increasing the structural strength of columns, girders, trusses, and beams of supertall buildings in the future. A 40-story multi-use “carbon tower,” designed by architect Peter Testa, has been proposed as a visionary project.

Architects also have been applying software developed for the aerospace industry to the design of their buildings. Frank Gehry uses the Catia software system developed by the French aerospace company, Dessault Systemes to transulate the complex geometries of his famous museums form three-dimensional working models into construction drawings. However, the Catia system was primarily designed as a manufacturing system, and is generally put into action after a design or building shape has already been determined (Abel, 2004).

New computer modeling techniques are being used to test the effect of different environmental systems on a building's energy-efficiency. Foster and Partners has used computer models, such as computational fluid dynamics or CFD, in shaping the office tower for Swiss Re, London, and the new headquarters for the Greater London Authority (GLA). The helical structure of Swiss Re creates a more aerodynamic from that minimizes the effect of wind forces. It also allows for a series of "sky courts" that spiral along the inside facade of the building that contribute to its social character and help to regulate its internal microclimate. The GLA design was morphed from a pure sphere-the most efficient geometric form for enclosing a given volume-based on the impact of the sun path and other environmental considerations.

The greatest challenges and most advanced technology in the construction of the Swiss Re and GLA involved the production of the cladding systems. Schmidlin, the Swiss-based company who made the cladding for both London buildings, created their own detailed computer 3D model of the cladding system for the Swiss Re tower, bridging spreadsheets and production line. Parametric modeling, orginally developed by the aerospace and automobile industries for designing complex forms, enabled both Foster's architects and Schmidlin's fabrications to make changes right up to the last moment and automatically updated the project data as needed (Foster, 2005). The design team used software from Bentley Systems to rapidly explore design options. The parametric approach and scripting interface allowed them to quickly and accurately generate in minutes complex geometric models that once took days to generate manually. Schmidlin also wrote their own special software linking the 3D model directly to the Computer Numerically Controlled (CNC) machines on the production line, so doing away with conventional programming. The software manufacturer AutoDesk has recently introduced Revit which offers similar parametric capabilities to the architect in coordinating the production of construction documents with product specifications offered by manufacturers.

4.1 "Power Membranes."

The invention of mechanical air-conditioning by Willis Carrier in America in 1939 and its widespread use in the post-war years effectively shaped vertical architecture in the latter half of the twentieth century. During the 1950s and 1960s suspended ceilings and molded floor slabs of concrete and steel were developed as a "multi-purpose power-membrane" in which technical rationality and economy emerge as new architectural objectives consistent with the mechanized environment (Banham, 1990). Eero Saarinen achieved the first integrated structure/mechanical solution in his General Motors Technical Center in Warren, Michigan in 1950 by combining structural thickness with space for the horizontal distribution of mechanical conduits by using boldly angled triangular structures (Abalos, et. al., 2003). His solution demonstrated how the related concepts of climate-controlled space and building depth could come together in the ideal of a space that was free from physical obstructions. By creating large bays in which thickness was needed more for purposes of stiffening than for loads, Saarinen was able to span 49 ft. 3 in. (15m) without using intermediate columns (Abalos, et. al., 2003). Although Saarinen's solution was aesthetically pleasing, it failed to fully integrate the other artificial climate control systems of the building.

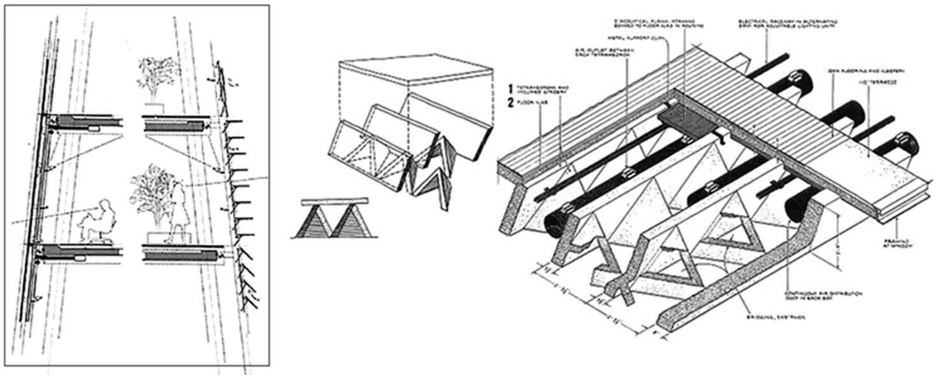


Figure 4: London Bridge Tower, 2009 (left) and Yale University Art Gallery, 1954 (right). Details of integration of mechanical risers in floors and structure.

Louis Kahn's Yale University Art Gallery in New Haven, Connecticut, constructed in 1954, was the first building that incorporated a ceiling that functioned as a stable architectural element that could contain the various mechanical systems without concealing the structure (Fig.4). Kahn's approach was to replace the redundant mass of accumulated layers with a concrete tetrahedral structure whose cavities contained the technical ducts and conduits (Abalos, et. al., 2003).

In sustainable skyscrapers, priority has been given to passive systems of heating and cooling over active and mixed-mode systems because this is the best way to achieve the ideal level of servicing for ecological design and because it represents the lowest level of consumption of energy from renewable sources. Passive design is essentially low-energy design achieved by the building's particular "morphological organization" (Yeang, 1999).

The London Bridge Tower proposed for 2009, designed by the Renzo Piano Building Workshop with Ove Arup & Partners, uses a floor structure that is a carefully integrated system of raised floors, slabs, tapered steel beams, and mechanical ventilation systems (Fig. 4). This reduces the ceiling-to-floor height to a very efficient 2.5 ft. (0.77m) and adheres to Piano's dictum that a modern building must be "human, technological, energetic, and economic" (Riley, et. al., 2003).

4.2 Intelligent Building and Systems Automation

Intelligent building refers to a building that has certain intelligent-like capabilities responding to pre-programmed stimuli to optimize its mechanical, electrical, and enclosure systems to serve the users and managers of the building (Yeang, 1996). The Intelligent Building has evolved into advanced integrated subsystems, which in varying degrees are part of most buildings today. It includes the Building Management System (BMS), Security System, Fire and Safety System, Communication System, and Office Automation.

An intelligent building is dynamic and responsive and requires continuous interaction among its four basic components:

- Places (fabric, structure, facilities);
- Processes (automation, control systems);
- People (services, users); and
- Management (maintenance, performance in use).

It has the ability to "know" its configuration, anticipate the optimum dynamic response to prevailing environmental stimuli, and actuate the appropriate physical reaction in a predictable manner. Intelligence can be used to improve the performance of the building fabric by integrating smart building design features into new construction, which can significantly increase the energy efficiency of the building while also providing enhanced human comfort.

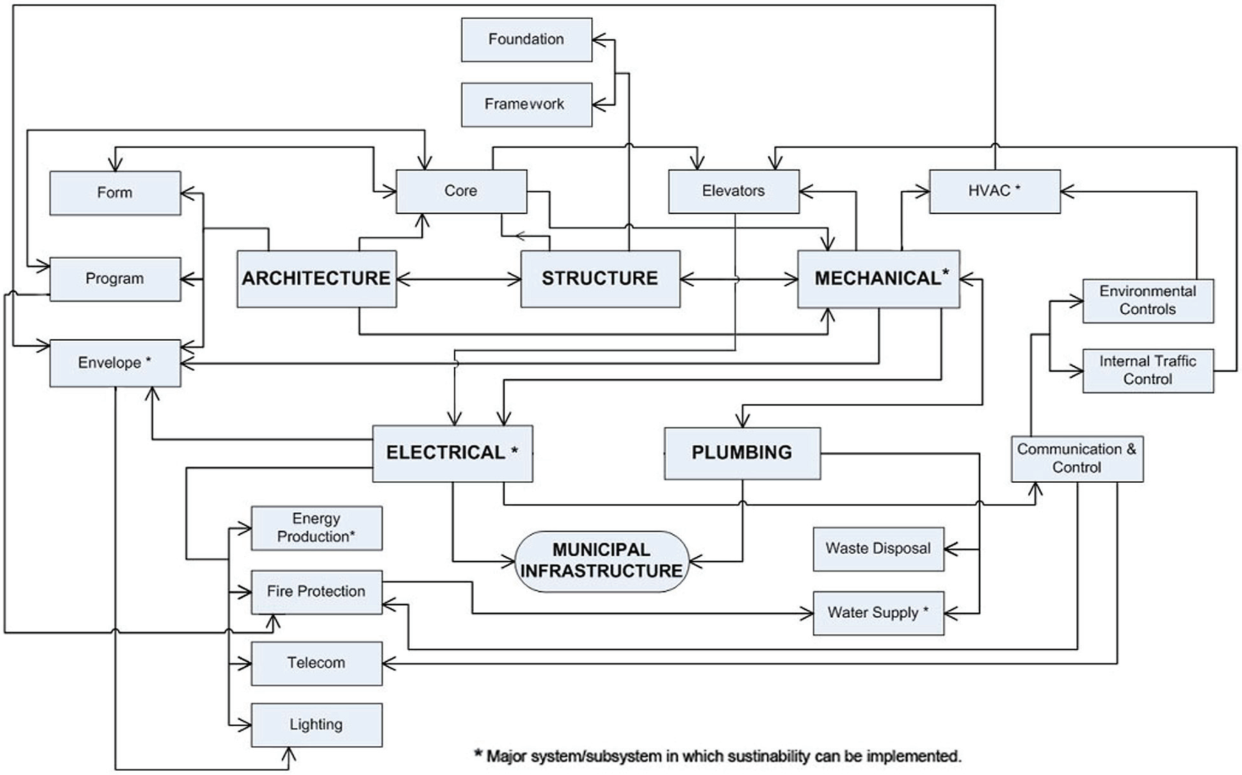


Figure 5: Tall Building System Integration Web.

5. Development of Integration Web

The development of a Tall Building System Integration Web as a tool to assist architects and engineers in the decision-making process for sustainable tall buildings has been a primary focus of this research (Fig. 5). While all buildings require integration, sustainable tall buildings require a greater level of integration at the early stages of the design process because they require coordination of complex, interdependent systems. However, overemphasizing integration at the conceptual phase of a project can also be a drawback especially when considering LEED credits. The checklist of LEED points can be helpful in identifying measures to pursue, many of which benefit from an integrated approach. But focusing on individual credits too early in the design process can also get in the way of design integration producing a “point-chasing mentality,” which drives up project expenses by causing people to forget how the points work together. During initial meetings, it is more useful for a team to focus on sustainable goals and opportunities on a broader level (Malin, 2006).

The challenge is getting all members of a design team on board with the design process in a sustainable high-rise, especially if they have never done it before. Among the strategies that leaders have used to get a buy-in from consultants, client groups, and other team members are team-building exercises, tours of existing green buildings, and collective visioning sessions. By exploring the underlying aspirations for building, the team may come to see that the real goal is not the building per se, but the services and benefits it can offer to the client and the community at large.

Figure 6: Swiss Reinsurance Headquarters, 2004, London, Foster and Partners.

The Tall Building System Integration Web will facilitate the decision-making process at critical stages by clearly defining the relationships of each major physical system and subsystem of a tall building. It can also lead to the development of a methodology for performance evaluation of an integrated sustainable building in comparison to a conventional building designed without a focus on sustainability. The Integration Web is not time dependent. However, one other objective is to develop a Critical Integration Process (CIP) that will automatically hyperlink each aspect of the building's component systems as related to goals and objectives of sustainability. The CIP can alert designers, engineers, manufacturers, and building operators to issues that require integration at critical times during the design and commissioning process and facilitate coordination. In this respect, it is analogous to the Critical Path Method (CPM) used in construction which charts the responsibilities of contractors and subcontractors organized along a time line. Since design decisions are time-dependent, it will be desirable to construct the CIP to function in a time-dependent manner. It should also be noted that the Web reflects the general case for the integration of physical systems in a tall building. Since sustainable design impacts almost every system, it must be examined relative to each system. Specific LEED criteria can then be addressed.

6. Case Study Examples

Buildings such as the Swiss Reinsurance Building in London, the Menara Mesiniaga Tower in Malaysia, the Conde Nast Building, and the Solaire Building in New York City are just a few examples that represent a new generation of sustainable high-rise buildings that are challenging conventional high-rise building practices and incorporate a powerful visual expression with smart building systems. The Conde Nast and Solaire buildings have been thoroughly investigated by the authors.

Tall buildings conceived as "vertical garden cities" can use urban space and resources more efficiently and, at the same time, create more user-friendly and habitable buildings. Consequently, future sustainable high-rise buildings will need to be even more energy-efficient and functionally diverse with emphasis on multi-functional tall buildings that consolidate living, working, retail, and leisure spaces into a single building.

6.1 The Swiss Reinsurance Headquarters

For the Swiss Reinsurance Headquarters building, constructed in 2004 in London, Foster and Partners developed innovative technological, urban planning, and ecological design concepts (Fig. 6). The steel spiral "diagrid" structure creates an aerodynamic form that provides the lowest resistance to wind. The shape of the building also diminishes demands on the load-bearing structure, as well as the danger of strong downward winds in the area around the building. The office spaces are arranged around a central core with elevators, side rooms, and fire escapes. The net-like steel construction of the load-bearing structure lies directly behind the glass facade and allows support-free spaces right up to the core. The most innovative element in the inner structure is the inclusion of triangular light shafts behind the facade, which spiral upwards over the whole height of the building. These light and air shafts are interrupted every six stories by an intermediate floor to minimize the development of drafts and noise.

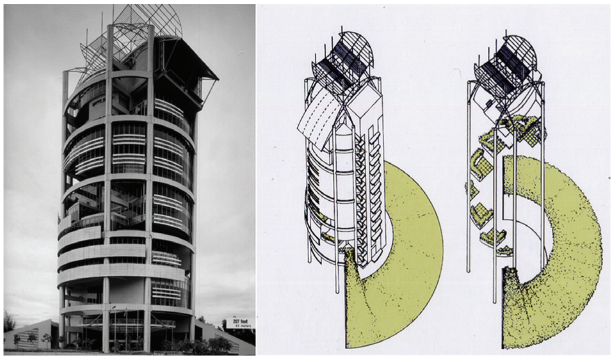


Figure 7: Menera Mesiniaga, 1992, Subang Jaya, Malaysia, T.R. Hamzah and Yeang.

The Swiss Re Tower has a circular plan that widens as it rises from the ground and then tapers toward its apex. This form responds to the specific demands of the small site and reduces its apparent bulk as compared to a conventional rectangular mass of equivalent floor area. The slimming of the building's profile at its base reduces reflections, improves transparency, and increases daylight penetration at ground level. The floor plates at mid-height offer larger areas of office space, and the tapering form of the tower at its apex minimizes the extent of reflected sky. The aerodynamic form of the tower encourages wind to flow around its face, minimizing wind loads on the structure and cladding, and enables the use of a more efficient structure. Natural air movement around the building generates substantial pressure differences across its face, which can be used to facilitate natural ventilation within the building.

The 590-foot (180-meter) tall tower is supported by an efficient structure consisting of a central core and a perimeter "diagrid' - a grid of diagonally interlocking steel elements. Unlike conventional tall buildings in which the central core provides the necessary lateral structural stability, the Swiss Re's core is required to act only as a load-bearing element and is free from diagonal bracing, producing more flexible floor plates (Foster, 2005).

6.2 The Menara Mesiniaga

The Menara Mesiniaga in Subang, Malaysia, designed by T.R. Hamzah and Yeang in 1992, presents an early model building for the physical translation of ecological principles into high-rise architecture (Fig. 7). The fifteen-story tower expresses its technological innovations on its exterior and uses as little energy as possible in the production and running of the building. Instead of a continuous facade, the building opens and closes in sections arranged in stages around the tower. It has an exterior load-bearing structure of steel with aluminum and glass, and a crowning superstructure for the roof, planned as a future support for solar cells. The interior and exterior structure of the tower is planned around climatic considerations and its orientation toward the daily path of the sun. The massive core of the building, with elevator shafts and staircases, faces east and screens off the penetrating heat up to midday. Deep incisions and suspended aluminum sunscreens on the south facade ward off the direct rays of the noon and afternoon sun into the interior. Most of the office space faces west and north. Around the base of the tower lies a semicircular, steeply sloping garden, which continues into the building itself in the form of spiral terraces planted with grass. This visibly brings the natural environment into the architecture.

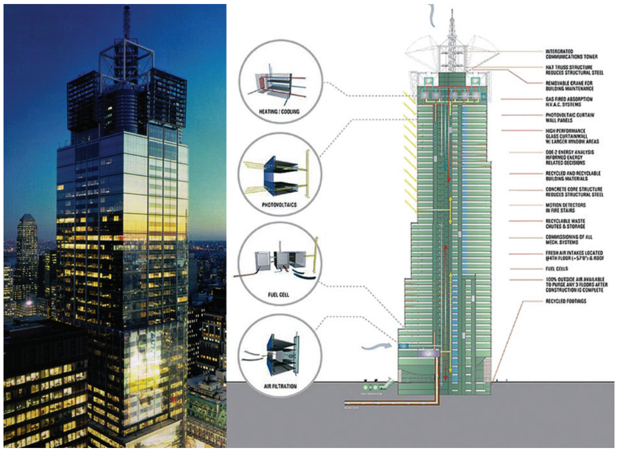


Figure 8: Conde Nast Building, 4 Times Square, 2000, New York City, Fox & Fowle Architects.

6.3 The Conde Nast Building

The Conde Nast Building at 4 Times Square in New York City (Fig. 8) is the first ecologically designed North American skyscraper (Riley, et. al., 2003). Completed in 2000, it rises 48 stories up out of Times Square and comprises 1.6 million sq. ft. of lease space for commercial offices and retail. The Durst Organization, in conjunction with Fox & Fowle Architects, developed the project with the aim of instituting indoor ecology, using sustainable materials, implementing responsible construction, prescribing sustainable maintenance procedures, and building an energy-efficient building. Many of its innovations are considered standard for office buildings today. The facades of the building address the Times Square entertainment district to the west and the corporate Midtown area of Manhattan to the east.

Critical Issues. According to the U.S. Department of Energy (DOE) Annual Energy Review (DOE, 1999), office buildings consume more than 24.8% of all U.S. electrical supply—more than any other building type. Several issues influenced the design process (Kaplan, 2001). High-rise buildings typically have a large core-to-wall depth and a corresponding low ratio of perimeter envelope to interior space, which creates special mechanical and lighting challenges. There is also a limited amount of roof space for mechanical equipment. There is an economic penalty for multi-story spaces, thick exterior walls, and additional floor-to-floor height. Energy and space are required for elevators, without which the building cannot function. A considerable amount of time was also spent educating the tenants about the benefits of sustainable design and the use of the building's infrastructure to reduce operating costs.

Design Tools. The design team relied on the expertise of many organizations including Cosentini Associates, the project's engineer, the Natural Resources Defense Council, and the Rocky Mountain Institute (RMI), among others. DOE-2 computer modeling was used for energy analysis and was recommended to tenants for further lighting consultation along with use of the RADIANCE lighting design program. ALGOR and CFD2000 were used to simulate fluids and air movement.

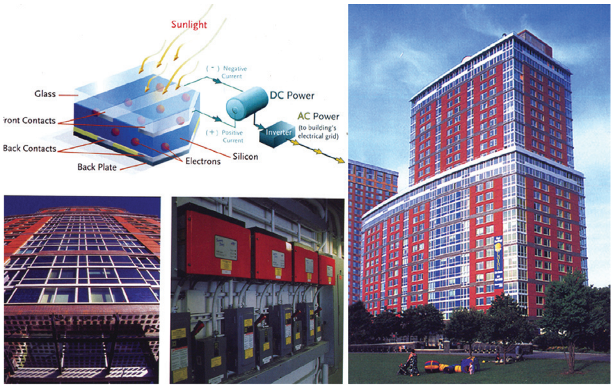


Figure 9: The Solaire, 2003, Battery Park, New York City, Cesar Pelli and Associates.

Sustainability Features. The large areas of glass curtain wall maximize daylight penetration into the office floors and incorporate low-E glass coating to filter out unwanted ultraviolet light while minimizing heat gain and loss. Photovoltaic panels have been integrated in spandrel areas on upper floors of the east and south facades, generating a meager but symbolic amount of electricity by day. Sophisticated mechanical systems ensure high indoor air quality by introducing filtered fresh air into the office environment. Tenant guidelines produced by the architects established environmental standards for living, power usage, furniture systems, carpets, fabrics, finishes, and maintenance materials to ensure indoor air quality and also as a comprehensive strategy to maintain environmental sustainability for the life of the building.

While sustainable technology can be cost-effective if it is well-integrated with other building systems, it can also be costly if done through processes that are not well-integrated. The designers admit that the fuel cells of Conde Nast were added too late in the process for the designers to properly integrate them, so the heat they produce when generating electricity is wasted (Malin, 2006).

Results. According to studies conducted by the National Renewable Energy Laboratory (2001), Conde Nast uses 40 percent less energy that a comparable conventionally-designed building built according to the New York State Energy Code. This has resulted in lower energy usage and costs, and a reduction in CO2 emissions.

Annual energy cost savings:	$1,760,000
Annual energy use savings:	20,841,269 kWh/year
CO2 emissions reduction:	9,191 tons/year

6.4 The Solaire

The Solaire, located at Battery Park on the Hudson River in New York City, is a 27-story, 293-unit luxury apartment building developed by the Albanese Organization and designed by Cesar Pelli & Associates (Fig. 9). Completed in 2003, it is the first residential high-rise building in the U.S. to integrate green features in a comprehensive way. Its sustainable features include photovoltaic panels incorporated into the building's facade, a planted roof garden, and fully operational blackwater treatment system. It is based on guidelines developed by the Battery Park City Authority (2000), which address five areas of concern:

1. Enhanced indoor air quality;
2. Water conservation and purification;
3. Energy efficiency;
4. Recycling construction waste and the use of recycled building materials; and
5. Commissioning to ensure building performance.

In addition to the Solaire, seven other sustainable high-rise buildings are planned for Battery Park City and will be designed using the guidelines.

Guidelines. The Battery Park City Authority (BPCA) Residential Environmental Guidelines were developed specifically for the design of residential apartment buildings to augment Leadership in Energy and Environmental Design (LEED) standards developed by the U.S. Green Building Council. LEED is a voluntary program in which building owners can apply to have their building rated for environmental impact ranging from regular certification to silver, gold, or the very highest, platinum. In return, owners receive tax credits prorated according to the level of certification. These guidelines have become a model for green high-rise residential buildings throughout the world.

Critical Issues. The BPCA determined that the first costs for a sustainable residential high-rise building would be 8 to 12 per cent higher than for a conventional building. As an incentive to the developers to go green, the New York State Energy Research and Development Authority (NYSERDA) was willing to pay up to 70 percent of the incremental cost of energy efficiency measures that would reduce the use of electricity and assisted the developer in materials sourcing for the project. The design team tried to find the right balance between indoor air quality and energy efficiency, weighing cost and availability issues in material selection, and calculating additional space required for some of the systems. By looking at the systems as a whole in terms of energy efficiency at the earliest level of the design process, the team determined that it could reduce energy consumption by 35 percent over the New York State energy code.

Sustainability Features. The team discovered that if they used a blackwater treatment system to collect all of the wastewater in the building instead of a graywater recovery system as originally planned, they would eliminate the initial cost of a double-pipe system. Photovoltaic (PV) panels were used both as a cladding system and as an energy producer. Half of the PV panels are on the front facade and half are installed on the roof. Cost reductions were achieved by having the panels for the facades installed at the factory by the window manufacturers, thereby avoiding possible labor issues between the glaziers and electricians.

The gas-fired absorption chillers selected for the HVAC system reduce electrical demand by 65 percent during peak hours, which in turn helps to reduce overall CO2 power plant emissions. In addition, they contain no chlorofluorocarbons or hydrochlorofluorocarbons, so they won’t damage the ozone layer. Sensor controls and high-efficiency lighting fixtures in The Solaire resulted in lighting that was 70 percent more efficient than a standard code-compliant building. The planted roof helps to insulate the building from thermal gain, absorbs carbon dioxide and generates oxygen, and alleviates the heat island effect common to most urban environments. The Solaire’s daily operation in monitored by its Building Management System (BMS), a single computerized system that coordinates and controls HVAC, fire, lighting, security, and other systems. It also supplies a steady and immediate stream of information ensuring the quick response of building staff to system problems.

Results. The Sustainable Task Force, a group composed of 40 state agencies in California, released a study based on 33 completed green buildings. It found that while it costs nearly two percent more on average to construct a green building than one using conventional methods, the green building can be expected to yield a savings of more than 10 times the initial investment during the life of the building. It also found that an integrated design and commissioning process—training operational staff in building systems performance monitoring and operation—was most cost effective.

Approximately 67 percent of the building materials (by cost) were manufactured within a 500-mile radius of the building. Approximately 50 percent of these materials also contained raw materials extracted from the local area. And 85 percent of the construction waste was recycled.

The Solaire project team also found that existing models used to score the quality or success of a green building do not always acknowledge important design and construction achievements, such as its innovative use of gas cooling technology which is inherently energy efficient.

7. Conclusion

According to Buchanan (1995):

> The significance of seeking a scientific basis for design does not lie in the likelihood of reducing design to one or another of the sciences...Rather, it lies in a concern to connect and integrate useful knowledge form the arts and sciences alike.

Technology transfers have fostered developments in materials, engineering, and systems design from fields such as aeronautics and the automotive industry and applied them to the building construction industry. Like the aeronautics industry, integration of building systems and components is integral to achieving the most efficient, cost-effective, and sustainable buildings. In the case of tall sustainable buildings, integration involves the coordination and design of building systems to work together in a holistic manner in order to maximize energy efficiency and reduce life-cycle operations and maintenance costs

However, before an Integration Web is finalized, more research must be conducted on the sustainable tall buildings included in this paper as case study examples. The lessons that can be learned from these buildings will be an invaluable resource to the developers, planners, and designers of future sustainable high-rise buildings. Europe is leading the way currently, because energy costs and zoning regulations have required tall buildings to meet stringent guidelines relative to sustainability and "green" architecture, including daylighting, natural ventilation, energy consumption, water usage and treatment, and other sustainable goals.

Finally, research from the case studies needs to be incorporated into the planning and design of tall buildings that will provide a comprehensive approach to understanding and predicting the life cycle costs, energy use, and performance of tall buildings and their impact on their urban habitats as applied to sustainability—both from the viewpoint of energy and resource consumption as well as socio-cultural factors.

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