
AC 2011-2741: INTEGRATION OF ARCHITECTURE AND SUSTAINABLE ENGINEERING PRINCIPLES TO ACHIEVE AN ENERGY-EFFICIENT DESIGN

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Integration of architecture and sustainable engineering principles to achieve an energy-efficient design

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The design of commercial office buildings is a complex process, in which various designers from different perspectives involving the architects, mechanical and structural engineers, lighting designers and specialist simulation modelers contribute to an integrated approach. The integrated approach may involve the use of local weather conditions, such as wind-driven ventilation and daylighting, as well as the characteristics of the building shape, materials and space planning needs.

In this paper, a methodology presented to our students in the framework of this course is presented. This methodology is based on using actual buildings, where local weather conditions as well as engineering considerations and architecture are used in an integrated approach to achieve a successful design.

We discuss the course program from the students' point of view, and the experience earned in design, integration, and methodology and also in written and oral communication skills. Methodology used to evaluate the effectiveness of this integrated course in terms of learning outcomes is also described.

1. Introduction:

A typical building is a complex system in which each discipline's design proposals have an impact on all of the other disciplines in a cascading fashion. Also, integration is a concern at different levels of the design process. In particular, an integrated design between the functionality of the mechanical systems and the desirability of the architectural design has been recently considered comprehensively in the development of commercial buildings; although this integration has always been a concern in the airplane and automobile industry (Mc Conahey et al., 2002).

The integration of architecture and sustainable engineering principles has many benefits, including improving energy efficiency of the building while maintaining a reasonable level of thermal comfort. The creation of office environments that influence the productivity and health of the working population through natural ventilation, operable windows, and daylight interiors is of concern as well.

However, a number of issues arise because of the interdependence and interaction between various disciplines. For instance, one decision about glazing that allows more

light into the building might also simultaneously increase the solar gain to the point where the cooling from natural ventilation alone will not be sufficient to maintain acceptable indoor conditions in terms of temperature and relative humidity. The solar gain may serve to diminish the cooling effect of the thermal mass during the earliest hours of the day because of long-wave radiative exchange between the warmed low level surfaces exposed to the sun and the night-cooled thermal mass above. This would cause the necessity of the introduction of an air-conditioning system, which would then add electrical load to the building. Consequently, the decision of using clearer glazing should be accompanied by other considerations, such as the placement of exterior shade not only to provide solar protection but also to allow for a form-based visible architecture with a standard repeatable floor plan (Allard, 2005). Also, fins have to be introduced on appropriate façades to intercept direct solar radiation during the afternoon hours when the sun would otherwise fall on the glazing at the same time outdoor air temperatures peak.

The objective of this paper is to address some issues regarding the integration between the building's systems and the architecture through actual project design. A methodology presented to our students in the framework of this course is presented. This methodology is based on using actual buildings, where local weather conditions as well as engineering considerations and architecture are used in an integrated approach to achieve a successful design.

2. Natural Ventilation and an integrated design of natural ventilation in high-rise buildings

Natural ventilation systems rely on pressure differences to move fresh air through buildings. Pressure differences can be caused by wind or the buoyancy effect (chimney or stack effect) created by temperature differences or differences in humidity. In either case, the amount of ventilation will depend critically on the size and placement of openings in the building. The natural ventilation used in the integrated approach is usually wind-driven. The use of natural ventilation for commercial buildings has been demonstrated for daytime and off-hour applications. The use of natural ventilation for nocturnal pre-cooling and the factors influencing performance are discussed by Martin and Fletcher (1996), and by Kolokotroni (2001). The investigation of the feasibility of off-hours accelerated ventilation has been also discussed (Megri et al., 1999).

The majority of ancient buildings are ventilated naturally. With an increased awareness of the cost and environmental impacts of energy use, natural ventilation has become an increasingly attractive method to reduce energy use and cost and to provide acceptable indoor environment quality and to maintain a healthy, comfortable, and productive indoor climate rather than the more prevailing approach of using mechanical ventilation. In favorable climates and buildings types, natural ventilation can be used as an alternative to air-conditioning plants, saving 10% - 30% of total energy consumption (Allard et al., 1998).

The integration of natural ventilation which is translated by the façade optimization, in terms of shape, orientation and exposure to wind and solar radiation, cause difficulties related to space allocation and planning to enhance the natural ventilation cross-flow potential. In particular, in the case of a San Francisco building all of the individual enclosed offices are located along the central spine of each floor plate rather than at the perimeter (Mc Conahey et al., 2002). Also, the design characteristics of the office furniture will have a direct bearing on the performance of natural ventilation.

Integrated design between the functionality of the mechanical systems and the desirability of the architectural design, which is an old consideration in automobile and airplane industry, has evolved recently in building industry, especially with the development of new computer programs such as Airpak by Fluent, AGI, DOE and EnergyPlus. The integrated design approach is an integration between the principles of various areas, such as passive ventilation, energy absorbing materials, daylighting and interior space planning, considering both the architectural aspect and the mechanical aspect simultaneously when creating a concept for a building.

The use of natural ventilation in the integration process is a decision that has to be assessed, since achieving thermal comfort under natural ventilation is quite challenging and requires extensive study under different conditions using predictive simulations. Various strategies that include different window configurations have to be tested. These strategies include: wind only, internal stack, internal and external stack, internal stack and wind, internal and external stack and wind. On the basis of this analysis of the results of the simulation, the design team decided upon appropriate measures, such as the selection of the type of glazing on the appropriate façade of the building to minimize the heating and cooling loads while maintaining reasonable thermal comfort conditions.

3. Case studies:

Design of Argonne National Laboratories:

As an example, the Argonne National Laboratories, designed by OWP/P (architecture and MEP design and consulting company), includes a passive ventilation system created by using wind towers all along the building to the top. The wind tower works by creating a pressure differential. The wind blowing over the top of the tower creates a lower pressure than the atmospheric pressure inside the building. This difference in pressure causes the air to flow naturally up and out of the top of the building. Stack effects created with wind towers is an old concept that has improved over the years with better technology and electronic controls. Modeling systems have further enhanced the usefulness of natural ventilation through the use of a wind tower.

In addition to this, an open atrium area is used in the center of the building mass to create an area for air to flow freely. By using this design, the objective is a building which is architecturally interesting with an energy conscious ventilation system, and which includes day-lighting.

Incorporating an open atrium in a building allows greater flexibility in planning. While not used in the design of this building, a closed atrium can act as a buffer zone between the interior climate and the outside climate. More control over the temperature of the used space is gained when using a closed atrium and the cost is lower.

Another system used to create natural ventilation is the hollow flooring used on the second, third and fourth floors. These flooring systems allow additional natural airflow through the mass of the building. Also used in buildings are materials that absorb energy when the temperature exceeds human comfort levels and expels energy when the temperature drops. This building uses concrete to absorb and expel the heat. Concrete is used because of its ability to collect and hold energy more efficiently than other materials such as metals. This is another way that the HVAC system may be integrated into the architectural design of the building.



Fig 1a. Natural ventilation: cool and warm air Fig 1b. Day-lighting reflections (OWP/P)

The rendering of Figure 1a shows the flow of cool air in through the windows and up through the open atrium. The cool air is exchanged for the warm air that leaves through the wind tower. Also seen in this figure are the heat sinks made of concrete on the ceilings of each level. The concave design allows for a greater surface area to absorb and expel energy when needed.

This building also uses the same system that is used to allow for passive ventilation to allow for natural lighting to enter and reflect in the building and atrium. The dual use of the system allows for savings in initial cost and ongoing costs through energy conservation. Visual comfort is also increased by the implementation of this system by allowing the people inside the building to use more natural lighting than electric fluorescent lighting. Fig 1b shows the daylight penetration and the use of reflective light.

Design of Foxconn Building:

These concepts are also followed in the design of the Foxconn building project in China (OWP/P), in which a similar passive ventilation system was implemented, used in conjunction with a forced air system. However, the passive ventilation was drawn upward through hollow walls and flooring alone rather than by means of an open atrium. The architectural design of the building allowed for the mass to be wider at the base and taper toward the top. This design permitted pressure difference to be used more effectively at the bottom where it is greater and as the building goes up, the pressure difference decreases, diminishing the supply of natural air changes. Again, this shows the integration of the mechanical aspect of the HVAC system and the physical side of the architectural design. As in the Argonne building, relative humidity is controlled by using hybrid ventilation. The ventilation is not controlled entirely by passive or forced ventilation thus allowing humidity to be controlled in the building.

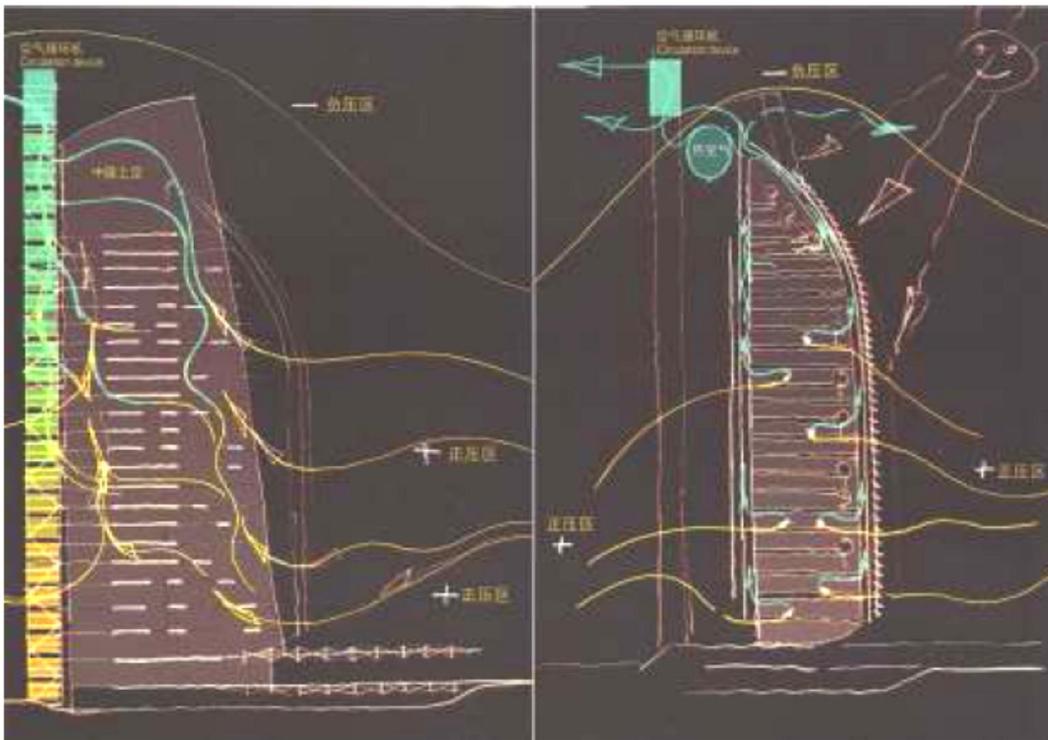


Fig 2. – Building section showing airflow up and out of the building through the wind tower and the hollow walls and floors (OWP/P).

Choices in integrated design are based on many factors. The first of the factors is based on the owner's needs, wants and support. The owner determines the budget, massing, orientation and operating costs of the building among many other features. Another factor is the systems that were used in the past. An owner may be more inclined to use what has been chosen in the past, rather than selection a more innovative building.

The designs presented depend upon the climate concerned. The buildings would not perform the same way in different local weather conditions with different temperature, relative humidity, and wind velocity and direction. The buildings are also oriented according to the availability of natural airflow as well as natural lighting. The physical setting of the building may also influence the size and shape of the building as in the Foxconn building in China. Each building has to be designed to be lower than the building behind it in relation to the river at the center of the city. This constraint creates a challenge for the architect.

Additional considerations:

Glazing: The glazing used can differ based on the needs of the building. General glazing can be a simple double pane window with a low-e coating. Factors that change what glazing is used can be the aesthetics needed or the light and heating that needs to be allowed or reflected from the building. Heat gain versus heat loss can change the coating options or insulating gap of the glazing.

Control of Climate: Integration can be controlled automatically, manually or a hybrid of the two. If it is controlled automatically, the system is monitored by a computerized detection system. This system monitors a building according to zones and can open and close vents and windows according to ventilation needs. A manually controlled system allows freedom of those inside to open and close windows freely. A hybrid system can have controls such as a display showing when the windows can be opened and closed yet still allows for the inhabitants to override the suggestions made by the computer.

Control of Humidity: Relative humidity can be controlled by these computerized systems. By monitoring the humidity in the building, the system can control natural ventilation somewhat while controlling the forced ventilation HVAC system. These systems are also designed with climate considerations. Hot and humid climates would be treated differently than cold and dry areas.

Cultural Factors: Cultural differences also lead to different designs. In American culture, a majority of the public is used to closed buildings and controlled climates. Other countries around the world have varying preferences according to the way building have been historically designed.

Pollution as a Factor: Other factors included with the design of naturally ventilated buildings include pollution and dust. In an area where pollution is higher, the use of natural ventilation would be detrimental to the well being of the occupants. Noise pollution can also be a factor in deciding whether or not natural ventilation is beneficial in designing an HVAC system.

Sustainability in Design: Natural ventilation and day-lighting, as well as high performance HVAC systems and the use of renewable energy can be part of a sustainable design. Owners choose to use this feature as part of their building for a number of reasons. One of the reasons can be a decrease in cost. This decrease in cost can be in the

initial cost or in the long term operating costs. While one system may be more expensive in the beginning, by using more natural ventilation and lighting it may save costs for the owner over time.

These variables can be used to find the balance between energy consumption and performance. In other cases, the owner is concerned about other issues such as pollution and the protection of the environment.

4. Assessing students learning

In the capstone presented here, the learning approach was composed of project based learning combined with continuous discussions between the students, team leaders and the instructor (the instructor is the main author of this paper and the two other authors are the team leaders). Two approaches have been used to evaluate this teaching approach, the direct technique in which students are asked to give their opinion about the course and the indirect way through surveys. The approach we adopted in this particular course and in the architectural engineering education, in general, has been used and refined over years and has proved popular with the vast majority of students over that period. In this course, the students emphasize different aspects of the design process.

The evaluation on how this turned out is based on the instructor and team leaders perception, the work and reports produced by students and the results from student course surveys. Statements in the course evaluation showed that students enjoyed learning and were learning about what they believed to be necessary for future workplaces.

Assessment was made up of a combination of oral and written examination. Towards the end of every semester, the Interprofessional Projects Program organizes an event called IPRO Day, which is a culmination of all the work teams have done during the semester. On that day, all IPRO teams and even guest teams from other universities compete for cash prizes and recognition by giving formal presentations and showcasing their projects in the form of an exhibit. Some of the past guest teams include participants from Auburn University, California State University-Fresno, Michigan Technological University, and more. During the IPRO Day, students have the opportunity to observe other projects and discuss them with their colleagues.

Oral presentations are a common feature of project-based learning courses. The oral presentation assessment scheme is based on: presentation skills, relevance of material, depth of research, comprehension and the response to questions. A weight vary from zero to a maximum number is given for different aspects of the presentation.

Project reports are always used as part of project-based learning. The assessment scheme for a project report is based on: presentation skills (references, language, etc.), methodology and understanding, comprehension, analysis synthesis, organization of ideas, and the content information evaluation, fieldwork, and creativity.

Course surveys were performed periodically twice every semester, mainly to access the feedback from the students. The course questionnaire was used at the end of course in written form. The five parts of the questionnaire related to the student opinions and suggestions for improvements on the performance of faculty, learning objectives, work load, student responsibility and independence for learning and, in the final written evaluation, also about assessment.

Based on assessment, we found in almost all cases that the students performed very well and the reports were of an acceptable quality. We also found that this kind of courses give more freedom to students. The students are overwhelmingly positive and in general. They identify the course as very different. These students usually complain about the difficulty of starting the project and request more attention from the instructor. Students have ample opportunity to discuss their ideas with the instructor. Extensive time involvement is needed to satisfy some students. Adjustment is needed to meet the expectation of certain category of students.

5. Course evaluation:

In parallel with the self-evaluation of each course by the instructor, we also conduct a course evaluation by students. The course objectives introduced earlier in the course are again provided to the students at the end of the semester. The students' input on whether the materials offered have met the objectives is then compiled and used in the program outcome assessment process. Results of instructor course evaluations (conducted by students) are reviewed by the Department Chair and the Dean and shared with the faculty.

Each faculty member also conducts an evaluation of performance of students in his/her courses as part of the Program objectives and outcome assessment process. A summary report on the performance of students (to meet the Program objectives) and compliance with the Program outcomes is prepared and submitted to the Department Chair for the assessment purposes.

Future plans to evaluate the effectiveness of the capstone in term of learning outcomes:
Actions that will be implemented to improve the effectiveness of the curriculum in term of learning outcomes:

- We expanded on the instructors' self-evaluation such that more direct assessment of students' learning outcomes is obtained. A set of standards for instructor's self-evaluation will be prepared by the faculty and the Board of Advisors and will be implemented with the annual assessment cycle. The main point of these standards is that the evaluation of students' performance will be based on samples of work in three categories of students: those in the upper 75 percentile, those in the 50 – 75 percentile and those below the 50 percentile populations. Thus the assessment results compiled are based on course performances and grades, exams, projects, presentations of students, and writings as required in some courses. Furthermore, each course specifically addresses the learning outcomes and relation between the course and the Program outcomes, the methods used for the evaluation of

students' performance and the relevance of the course materials to the Program outcomes following the standards adopted for the assessment process.

- Students will be provided with the course descriptions including learning objectives and outcomes. Students also will provide their input on the Program outcomes. The results from this instrument are used along with those from the instructors' self-assessment of courses as a means to ensuring compatibility in results obtained.
- A more rigorous process in assessing the learning outcomes of this capstone course will be implemented, which are in parallel with the Program outcomes. The following outlines process will be used for this capstone course assessment.
 - Individual instructor evaluation of the degree of learning achievement of individual students on a capstone team, which includes consideration of the collective achievements of the team.
 - Peer evaluation (optional by instructor).
 - Grading of deliverables by the instructors (project plan, mid-term review, final report, exhibit (and abstract), oral presentation, team minutes, web site if applicable).
 - Teamwork survey.
 - Self-assessment.
 - Senior Design Symposium judging (with evaluation criteria explicitly indexed to the learning objectives and articulated via rubrics for all measures).

6. Conclusions:

Integrated design refers to the use of multiple building systems working together. In our case the integrated design refers to the functionality of the engineering aspect working in conjunction with the architectural appeal and usefulness of the building. Both of the examples showed the use of the architectural design as a passive ventilation system. This appears to be a forerunner in designing new and desirable structures while helping to create sustainable designs. The designs presented are reliant on the climate they were designed for. The buildings would not work as well in a different temperature, humidity, etc. The buildings are also oriented according to the availability of natural airflow as well as natural lighting.

The architectural engineering firms use many different software systems to analyze the designs used in creating a building. Usually DOE2, eQuest, EnergyPlus as well as TRNSYS/COMIS, TRNSYS/CONTAM are used to determine energy use and cost along with AGI for daylight analysis. Other CFD models are also used, such as FLUENT. These software programs allow architects and engineers to determine what the impact of each of their designs would have on the overall effect of the HVAC system.

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