The use of analyses for a better environment in early design for a Stanford University Building

Isabelle Lavedrine[1], Cole Roberts[1] and Tom Bauer[2]

[1] Arup, 901 Market Street, Suite 260, San Francisco, CA 94530, USA
[2] BOORA Architects Inc, 720 SW Washington Street, Suite 800, Portland, OR 97205, USA

ABSTRACT: The Stanford Environment and Energy (E&E) Building has ambitious targets set as parts of Performance Criteria defined for the Stanford University Campus. These criteria are based on several standards, one of them being the LEED rating system. Thanks to great cooperation between the architects and the engineers, the Stanford E&E Building will combine a look which fits within the existing campus, a large amount of interior daylighting and will make use of the principle of adaptive comfort. Most of the building consists of laboratories and offices. All offices on the North- and East-facing façade will be naturally ventilated. As part of the comfort study, several numerical analyses were performed, which linked with each other to enhance the design. A thermal analysis was carried out, as well as an analysis to determine the flow rate for the naturally ventilated offices. To complete the study, a Computational Fluid Dynamics analysis of one of the atria was performed to verify temperatures at high level. Finally, an energy analysis was carried out to demonstrate that the Performance Criteria were met.

Keywords: natural ventilation, energy, comfort, CFD

1. INTRODUCTION AND BACKGROUND

The Stanford Environment and Energy (E&E) Building is the first of four buildings that will make up the new Science and Engineering Quad at Stanford University. The Quad will be the most ambitious building project on campus since the University completed the iconic historic quad in 1898.

The Environment and Energy Building is the first building on the Stanford campus to conform to the Stanford Performance Criteria for High Performance Buildings and the first to be subject to the Stanford Guidelines for Life Cycle Cost Analysis. As such, it has established performance targets that meet or exceed the LEED™ Platinum benchmark.

The building will house the recently named Wood's Institute for the Environment, a broad coalition of environmental initiatives representing a wide cross section of academic and professional disciplines currently spread across campus. Research scientist, engineers and policy specialist are coming together to accelerate the creation, application and integration of sustainable technologies. The performance of the building itself is thus essential to the mission and program of the Institute.

2. THE ARCHITECT'S INTENT

The master plan for the Science and Engineering Quad, completed in 2004, was founded on the following mission statement: "*The Quad will function as an interdisciplinary connection for the Science and Engineering communities at Stanford. As such, the high performance buildings must blend the best of the past, the proven innovation of the present, and the needs of the future.*"

Embedded in the University's vision statement above are the primary elements and challenges that define the design intent of this project.

- *The building must be compatible with the historic campus vernacular.* The design of the project must meet the high performance building criteria established as part of the Master Plan, while respecting the treasured aesthetic vernacular of the core campus. Incorporation of certain high performance strategies such as rooftop photovoltaics, atria skylights and vents, exterior sunshades and an overall emphasis in transparency present a vernacular challenge that must be carefully balanced.

- *Provide an open interior environment that will promote goals for academic collaboration and enhance the high performance strategies.* The natural ventilation and day lighting strategies both suggest an interior planning concept that is open and permeable between the perimeter and interior spaces of the building. This open planning concept challenges conventional use patterns for the building's stakeholders, including privacy and security needs. Their willingness to embrace a more open environment is directly related to the magnitude of savings in energy and operational costs that their perceived compromises will yield. While the users are appreciative of the potential of enhanced comfort and productivity in their interior environment, it is the quantifiable savings that is most persuasive. The modeling and lifecycle analysis has been essential to this process.

- *The design process must give the stakeholders confidence that the high performance strategies and systems will work.* Many of the future occupants have experienced life in other campus buildings where earlier generation examples of similar high performance strategies were employed and failed. The design process for this project has had to overcome these negative precedents. A thorough educational process has been required, based in large part on the results of the modeling and analysis in order to prove that these systems are being thoughtfully and thoroughly designed.

- *The design should set the standard for future projects.* The strategies that are being employed in this project are expected to establish a precedent for the next three quad buildings, as well as all future construction on the Stanford Campus. And, in keeping with the mission and goals of the Institute for the Environment, the Environment and Energy Building should inspire and affect positive change that is applicable throughout the marketplace – this will be the ultimate measure of this project's success.

In keeping with its mission: "*The vision for E&E is that of an internationally recognized high performance building that does more than simply bring further accolades to the campus. Pushing the envelope of technology and our relationship to space; itself designed and intended to be a teaching tool, the E&E building will inspire faculty, staff, students and visitors to take the next steps toward a sustainable future*."

3. ENGINEERING CHALLENGES

An important basis of the design intent was to maximize the use of natural ventilation wherever possible in the building. Spaces where such ventilation strategy could be applied were identified based on their usage (i.e. laboratories were evidently omitted) and their orientation. Hence all North- and East-facing offices are going to be naturally ventilated, and all the atria. Additionally, to enhance interior conditions, maximum use of natural daylight was advocated. This in turn leads to an increase in glazed areas with potentially negative effects on comfort.

To maintain comfortable conditions in these naturally ventilated and day-lit spaces, the ventilation strategy had to consider hot summer conditions when outside temperatures exceed 82°F (27.8°C) and also winter conditions when heating is required.

Meeting the energy reduction goals of a 50% net reduction and net carbon neutrality reflected a significant design challenge made all the more onerous by budgetary limitations, a high energy use density reflected in a 25% laboratory program, and an architectural aesthetic that had to remain consistent throughout the four buildings of the engineering quadrangle.

Challenges however became opportunities as the team uncovered multi-faceted solutions that addressed budget, performance, and aesthetic in a synergistic fashion.

By maximizing naturally ventilated areas, simplifying design, educating occupants, and deleting equipment (through reduced load), the high performance HVAC system first cost is actually less than that of a conventional design.

By focusing on the loads of the laboratories, energy savings that dwarf a non-laboratory building are resulting. The team has successfully reduced the design air change rate to 6ACH, systems have been "right sized" through comparison space metering, re-heat has been eliminated through distributed cooling, and all air streams incorporate low pressure energy recovery. Additionally, the University is planning to establish preferential purchasing for all future buildings in order to limit the non-regulated energy use stemming from receptacle loads.

Lastly the team leveraged the architecture to provide both aesthetic comfort and energy savings. High mass arcades and punched stone clad windows serve a dual purpose of allowing for naturally ventilated spaces while fulfilling a need to consistently reflect the vernacular of the Stanford main quadrangle. The slanted red-tile roofs had an unforeseen benefit as not only do they effectively shade the rooftop equipment, but they allow for the exhaust stack velocity to be reduced by 50% yielding as much as a 75% reduction in system external static pressure.

To support the design intent and help devise a ventilation strategy, several modeling exercises were undertaken. Finally, the Stanford Guidelines for Life Cycle Cost Analysis required the project team's to identify systems that should undergo analysis and to fund those systems that are shown to realize a payback in less than 10 years.

4. NUMERICAL ANALYSES

4.1 Ventilation analysis

The Oasys proprietary software package VENT was used to perform ventilation analysis for one typical atrium and adjoining offices. The analysis focused on external conditions corresponding to summer design day with no wind. The aim of the analysis was to verify that enough air movement occurred through the offices and then through the atrium driven only by stack ventilation. The model assumed that offices had external operable hoppers, internal operable hoppers opening into the atrium, and that operable openings were situated as high as possible in the skylight of the atrium. The analysis showed that on average, 10 air changes per hour can be achieved through the offices.

However, the analysis also raised further points, such as the risk for third floor and/or localized areas being inadequately ventilated or overheating if air cannot leave the atrium fast enough. In turn, a Computational Fluid Dynamic analysis was carried out to address this issue and is presented in Section 3.3.

Natural ventilation modes were derived for the E&E building, and include some of the following guidelines:

- The atrium louvers function to control the overall pressure differential and hence airflow through the atrium. The louvers are to be greater than 480ft² (44.6m²) total net free area per atrium, with equal dispersion between the four faces of the atria. A wind speed and directional indicator mounted on the building will allow the building management system to close louvers that face into prevailing winds when wind speed exceeds 10 mph (16.1km/h). At no time shall more than two sides of the atria (windward facing) be closed due to concern over wind. In so doing, the atrium conservatively allows for wind conditions to aid the flow of air through the atrium by negatively pressuring (hence drawing air from the atrium) the leeward face.
- The motorized window actuators on the north and east facing naturally ventilated offices occur at the upper awning window only. The actuators allow the building management system to passively flush the building during cool evening hours. In this mode, air flowing in through the 1st -3rd floor actuated windows passes through acoustical boots high in the enclosed office, then into the accompanying hallway, and then into the atria.

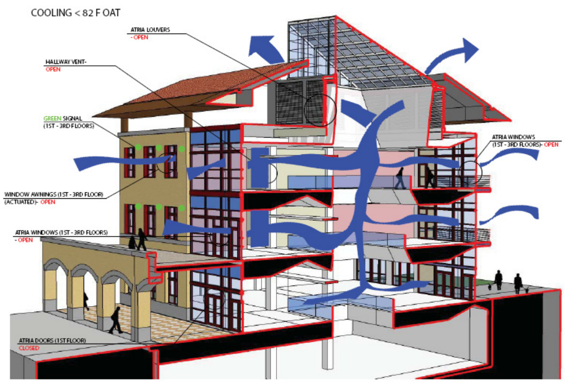

Figure 1: Natural ventilation through building when external temperature is less than 82°F (27.8°C)

4.2 Thermal Comfort

The Average Hourly Statistics of Palo Alto, California, where Stanford University is situated, clearly highlight the almost continuous need for heating for most of the year, and minimal cooling requirements for the months of June, July, August and September. As the high temperature for those summer months does not go above 82°F (27.8°C), this gives some indication that natural ventilation might work for those months in providing adequate cooling supplemented by the introduction of sufficient draft.

By definition, Thermal Comfort is the condition of mind that expresses satisfaction with the thermal environment. The thermal environment is comprised of those characteristics of the environment that affect a person's heat loss or gain:

- Air temperature,
- Relative humidity
- Air velocity
- Radiation (mean radiant temperature),
- Metabolic rate
- Clothing insulation.

In addition, *Adaptive Comfort* requires:

- Sense of control
- Naturally ventilated spaces.

The principle of adaptive comfort was adopted to set comfort criteria, which enables to reduce the cooling and heating requirements and hence the energy consumption of the building.

The Oasys proprietary software package ROOM was used to perform the Thermal Comfort analysis on various spaces on all four orientations. For each orientation and space, several ventilation options were analyzed and their respective influence on the space dry-bulb temperature. These options included:

- Size of window opening
- Thermal mass
- Radiant floor cooling
- Supplemental mechanical cooling (for the South and West orientations).

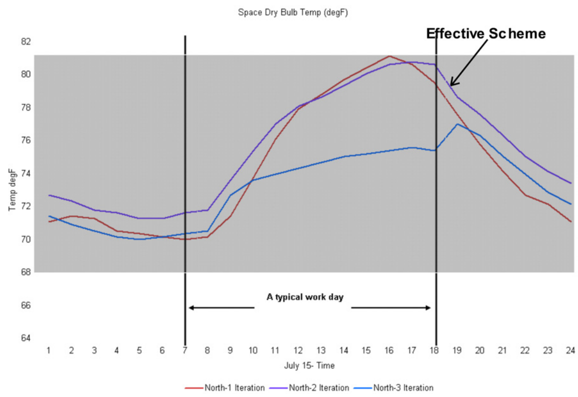

Figure 2: Results for a North-facing office space

The following conclusions were reached:

- North office: Natural ventilation requires BOTH awning windows at top and BOTH awning windows at the bottom to be operable. It also requires thermal mass in the floor, night flush, and ceiling fans for additional air motion.
- South Studio: Natural ventilation requires BOTH awning windows at top and BOTH awning windows, in addition to operable casement windows with thermal mass at both floor and roof. Ceiling fans are also recommended. A suggested alternative is to have BOTH operable awnings at high and low level and radiant cooling via the floor.
- South office: Natural ventilation requires SINGLE operable awning at high and single operable awning at low level with supplemental radiant cooling or chilled beam.
- West office: Natural ventilation is possible for significant number of hours during the year but later afternoon is a significant concern. A mixed mode system with ventilation air conditioning and supplemental radiant ceiling or chilled beam is recommended.

4.3 Computational Fluid Dynamic (CFD) Analysis

A CFD analysis of one atrium of the E&E Building was performed to provide a better understanding of the air movement and temperature variation inside the space and permit the design team to review the system performance before it was built. The aim of the study was to help the design team have a better understanding of the comfort level provided to the occupants at all levels in the atrium and its adjacent hallways, especially on the third floor.

The simulations were carried out using the CFD code STAR-CD v3.24. The computational domain represented one atrium and part of its adjacent hallways. The study looked at summer conditions, a warm day at 82°F (27.8°C) and design day at 86°F (30°C).

The computational domain consisted of approximately 333,000 cells. The mesh was refined close to the air exhausts from offices (both naturally ventilated and air-conditioned), the louvers in the skylight and close to the glazed surfaces in the atrium. The maximum cell dimension was 11in (0.28m) (in parts of the model where flow gradients are small), the smallest cell dimension is about 1.25in (0.03m).

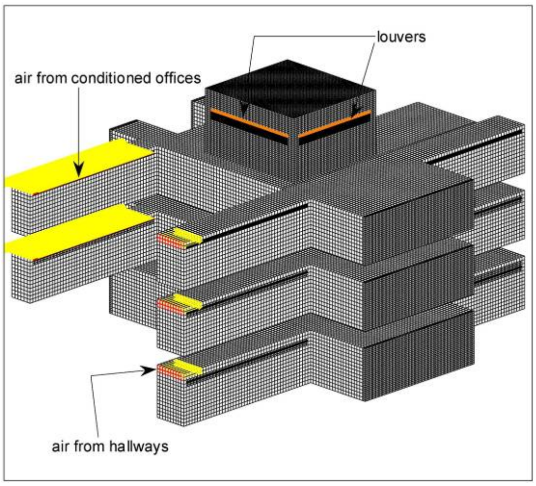

Figure 3: Example of CFD mesh

The CFD model was run for five different cases combining different skylight heights, outside air temperature, ventilation scenarios, and surface temperature assumptions (to represent the influence of thermal mass).

Some of the assumptions made for the simulations were as follows:

- Flow was assumed to be steady-state, i.e. it represented a fixed moment in time at which conditions are estimated to change very slowly and/or remain constant for a long period of time.
- The total number of occupants was assumed to be 6 people per floor, corresponding to the ASHRAE 90.1-2004 [1] density of 600ft² (55.7m²) per person in both the atrium and the hallways. The convective load per person was set to 255Btu/hr (75W) per person.
- The exhaust air coming from the conditioned offices was set to 74°F (23.3°C), with a flow rate of 40cfm (0.02m³/s) per office.
- The exhaust air coming from naturally ventilated offices, when appropriate, was set to 82°F (27.8°C), and the flow rate was obtained from the Oasys VENT analysis.
- The air supplied in the hallways was set to 65°F (18.3°C) with 125cfm (0.06m³/s) coming from each hallway into the atrium.
- When the atrium was assumed to be naturally ventilated, there were:
  - 4 openings on the first floor (2 on the North side, 2 on the South side
  - 3 openings on the second floor, one on the North side, 2 on the South side
  - 3 openings on the third floor, with identical areas to the ones on the second floor
- Exhaust from the atrium happened through high-level louvers.
- The comfort range for dry bulb temperatures was such that the maximum temperature in the atrium was not to exceed 82°F (27.8°C).
- The temperatures predicted by the CFD model represent dry-bulb temperatures, not the mean-radiant temperature. This means that the effects of radiant heating from warm glazing, or radiant cooling from the effect of thermal mass (cooler floors) were not represented directly in this study.

The CFD analysis demonstrated that predicted temperatures in the atrium and adjacent hallways can be maintained below 82°F (27.8°C) with adequate air movement under warm or hot summer day conditions. For this to be achieved, the following is recommended:

- Thermal mass was deemed to play a critical part in achieving comfort levels with outside air temperature of 86°F (30°C).
- Additional supply of cooler air inside the hallways (derived from minimum hallway ventilation requirements) was also important. Without this ventilation air, comfort was not achieved on the 3rd floor of the atrium.
- It is possible to naturally ventilate the atrium when outside temperatures are less than 82°F (27.8°C). It is recommended that the openings be as large as possible at the atrium occupied level, with great flexibility in their opening and closing, and potentially be placed either at high level or, as close as possible to the floor in order to prevent high velocities from causing discomfort.

Additionally, the CFD analysis showed that the skylight height could be reduced without negative effects on the predicted temperatures on the 3rd floor.

4.4 Energy Analysis

The energy analysis for Stanford University was conducted using a modified ASHRAE 90.1-2004 [1] energy modeling protocol that allowed credit for naturally ventilated spaces and receptacle load reductions. Unlike most energy analyses undertaken to date, all loads (both regulated and non-regulated, including all process and receptacle loads) were included.

The simulation was conducted using eQuest v3.55 running on a DOE-2 calculation engine.

Meeting the energy reduction goals of a 50% net reduction and net carbon neutrality hinged on a six-step process of:

1. Demand Reduction
2. Use of Passive Strategies
3. Use of Efficient Active Strategies
4. Recovery of Energy
5. Self Production of Energy through Photovoltaics
6. Green Power Purchasing

The results of the energy modeling demonstrated a 51% energy use reduction and 34% energy cost reduction. These reductions were exclusive of the benefits garnered from reduced receptacle loads and distributed cooling, both of which are expected to further improve the comparative energy performance of the building.

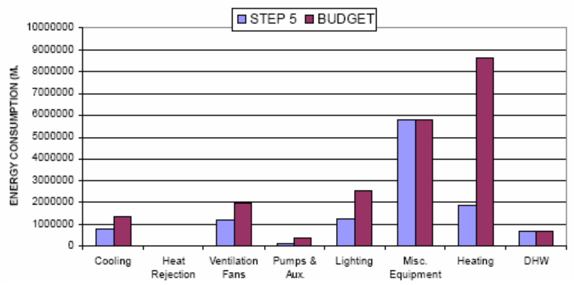

Figure 4: Step 5 of the energy modeling process demonstrated significant savings in heating and cooling energy use as well as ventilation & pumping. Some of the greatest savings were derived from lighting power reductions through an extraordinarily well day-lit environment.

4.5 Daylighting Analysis

The integrated passive daylighting design became a priority for the E&E building not only due to the benefits associated with energy savings, but the visual comfort benefits as well as psychological and health benefits.

- Design considerations

Initial goals for the daylighting as set forth by the Stanford Performance Criteria indicating that the daylighting design should conform to the LEED™ EQc8.1 requirements. The EQc8.1 goal was superseded by the Stanford Performance criteria, which set a goal of 75% of critical task areas meeting the 25 footcandle minimum at noon on the equinox. Impromptu meeting areas, such as the atria lobbies, that received 15 footcandles or more could be attributed to this criterion. This design goal epitomized the emphasis of reducing the energy consumption of the lighting systems within the building.

In order to meet the goal of reducing overall energy consumption within the building, it was imperative to consider the thermal implications of the daylighting design. The glazing selection for daylighting affects the thermal performance of the building. Therefore, the amount of daylight allowed into the building had to be tempered by the associated thermal load added. Glazing selection was key to this by specifying the correct visible light transmittance, as well as correct thermal properties. The thermal properties of the glazing were then integrated into the energy modeling, to provide a comprehensive analysis.

Further considerations for the daylight design included architectural aspects of the building, as it relates to the people inside, and the campus as a whole. From inside the building, the daylight design was optimized for visual comfort, striving to eliminate discomfort glare and maximize useful daylight. The views to the outside were also a priority as to allow the occupants of the building the connection to the outdoors. Furthermore, the E&E architecture was to remain consistent with the established campus aesthetic, and significant deviations were not an option.

- Design implementations

Implementation of the daylighting design manifested itself into two primary design components: perimeter wall window design, and central atria design. These two design elements account for the majority of the daylight entering the building.

The perimeter of the E&E building is primarily designed as office, meeting, and some laboratory space. Since many of these spaces are enclosed, a method of delivering the daylight through that perimeter space and into the interior space was needed. On the south and west walls, interior light shelves combined with exterior shading devices were recommended. The shading device and light shelf isolate an upper portion of the window to receive direct incident sunlight, through high visible transmittance glass. This illumination reflects off the light shelf, and scatters indirectly off the ceiling to light the room. For the offices lining the perimeter, transom glazing near the ceiling allows this light reflected from the light shelf to penetrate deeper into the building core.

Below the light shelf and shading device, the window glazing has tinting reducing the amount of direct illumination, but allowing the views to campus to remain clear and unobstructed.

The central building atria were also analyzed and designed to maximize the utilization of daylight entering these spaces. The four atria provide a significant amount of daylight to the core of the building, along with significant views and a connection to the outdoors.

In order to mitigate the intensity of the illumination entering the atria, the glazing for each atrium was designed to include a thin film photovoltaic laminate, which reduced the visible light transmittance to around 15%, while maintaining the view, and generating electricity.

Figure 5: Rendering of office with light shelf

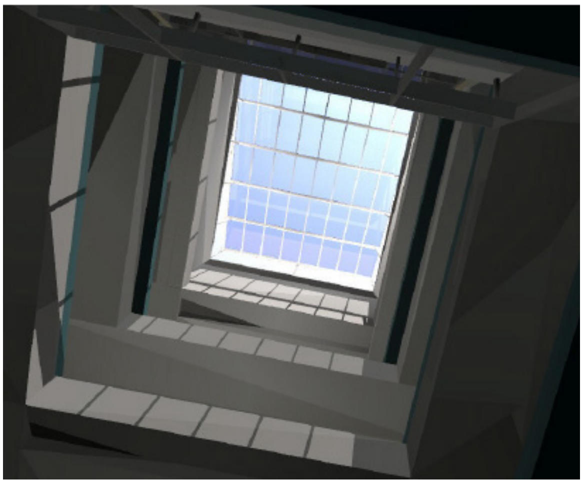

Figure 6: Rendering of Atrium space

4.6 Life Cycle Cost Analysis

Although no code is in place, Stanford has adopted a life cycle analysis guideline that requires teams to fund any energy conservation measure that yields a 10 year or better payback.

Table 1: Generic criteria for many of the project Life Cycle Analysis

Study life	45 years
Nominal Stanford Discount Rate	7%
Inflation – Far Term Value (Years 6+)	3%
Real Stanford Discount Rate – Far Term Value (Years 6+)	3.9%
Escalation Rates	
*Maintenance, Labor, and Materials	1%
*Energy & Water Utilities	1%
Electricity (per kWh)	$0.1205

The energy modeling and daylighting simulation output was incorporated into the Life Cycle Cost Analysis.

In many, but not all cases was the 10 year (or better) payback horizon realized.

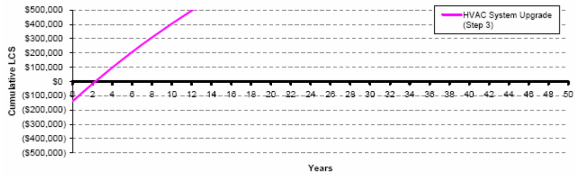

Figure 7: Sample results for daylighting and energy systems

4. CONCLUSION

The design team and University stakeholders have consistently relied on the modeling and analysis to guide decision making throughout the design process. It was crucial that the analysis began early in the project and was continually updated and refined. The academic and research focus of many of the occupants of this building is rooted in computational modeling and analysis enabling them to be engaged and interactive at a detailed level. In this integrated design strategy, almost every decision had some impact on building performance. The data and analysis has been essential to expedite the formulation and evaluation of options and ultimately inform the owner's direction to the design team. The integrated process has given the design team and the University the confidence to follow through on the lofty performance goals and aggressive sustainability agenda for this project. The life cycle analysis has helped identify the most cost effective means to accomplish these goals.

The Environment and Energy Building will establish the performance benchmark for a nine building campus initiative that will be realized over the next decade. The Stanford Board of Trustees is looking closely at the return on investment of this project in order to establish the goals, scope and budget priorities for the next eight. This building must meet its functional goals, and provide an outstanding and productive environment for the significant work that is being done within its walls. Its success is essential in building the momentum of Stanford's sustainability initiatives. The modeling and analysis have enabled the Environment and Energy Building to embrace this responsibility and opportunity to the fullest extent.

ACKNOWLEDGEMENT

The authors would like to acknowledge the help of several of their colleagues who contributed to this study: Shruti Narayan, Jason Edling, Jake Wayne. The authors would also like to thank Maggie Burgett from Stanford University.

REFERENCES

[1] ANSI/ASHRAE/IESNA Standard 90.1-2004 – Energy Standard for Buildings except Low-Rise Residential Buildings.
[2] STAR-CD version 3.24, CD-Adapco.