Carbon Footprint in the Design Studio, a Paradigm Shift

Abby Brandvold[1], Khaled Mansy[2], John Phillips[2], Tom Spector[2], and Jerry Stivers[2]
[1] Walter P. Moore, Dallas (USA)
[2] Oklahoma State University, Stillwater (USA)
khaled.mansy@okstate.edu

Abstract

This paper reports on investigative academic work of the authors employing evidence-based design tools to teach students how to optimize their design for the combined impact of operational and embodied energy. An approach that recognizes the fact that at day zero of building operation, it has already contributed to energy consumption and carbon generation. Being aware of the optimization problem and their responsibility for training the new generation of designers, the authors integrate energy performance as a primary design goal in teaching a Comprehensive Design Studio that is required for senior students in Architecture and Architectural Engineering. The paper discusses life cycle carbon analysis, in association with other tools, as a means to evaluate design alternatives based on overall contribution to carbon footprint due to both operational and embodied energy. Minimizing operational energy, however, may be at odds with minimizing embodied energy. For example, a high window-to-wall ratio can be ameliorated by exterior aluminum shading devices, but these shading devices may actually have high embodied carbon. Therefore, energy performance and life-cycle carbon reductions must be treated as an optimization problem. To make this point clear, a case study in a student's evaluation of envelope design alternatives is presented.

Keywords: Carbon footprint, operational energy, operational carbon, embodied energy, embodied carbon.

1. Introduction

In 2019, four of the authors co-taught the Comprehensive Design Studio at the OSU School of Architecture. The studio has a long tradition of success in addressing integrative design and collaboration with professional practice. Continuously, the studio enjoys dedicated support from Oklahoma's architects and engineers, as well as design firms and professional societies that sponsor student awards. In 2004, the studio was awarded the National Council of Architectural Registration Boards (NCARB) Grand Prize for Creative Integration of Practice and Education in the Academy. In 2020, for its plans to address global warming, the studio was awarded the Association of Collegiate Schools of Architecture (ACSA) Course Development Prize for Architecture, Climate Change, and Society. One of the primary educational goals of the studio is to introduce students to performance-based design. In 2019, the authors explored expanding the scope of the studio to address performance not only to include operational energy, but also to include embodied energy, in a way that students may evaluate their design iterations based on carbon footprint as the primary measure of performance. This holistic approach to performance evaluation should help students make well-informed design decisions and better understand the interrelationship between architecture and national and global environmental issues.

2. Performance in the design studio

Driven by the emphasis on performance-based design, performance is addressed in the Comprehensive Design Studio in a multi-faceted fashion, i.e., in terms of structural performance, energy performance, and cost performance. Being the capstone studio for the architectural engineering students and the required studio before last in the architecture program, it is taken by well-prepared senior students towards the end of the curriculum when they have already taken all prerequisite architectural science and structural courses.

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2.1 Preparation in lecture courses

In the program's technology track, students entering professional school are introduced to the universal concept of sustainability and the three economic sectors that consume energy, i.e., the industrial, transportation, and building sectors (residential and commercial) as shown in Fig. 1a (EIA, 2018), with building operation consuming around 38% of the total primary energy resources. Follow-up architectural science courses primarily focus on the building's operational energy, with less emphasis on the impact of the industrial and transportation sectors. Students become aware of the profession's relative success in capping energy consumption at 2005 levels and its more challenging task to reach zero-energy by 2030 as shown in Fig. 1b (Mazria, 2019). In the required structural courses, students are introduced to engineering science and design of timber, steel, and concrete structures, with less emphasis on the embodied carbon in structural materials due to manufacturing processes, transportation, and on-site construction. In the required professional practice courses, students learn the principles of project management and cost estimating. Indeed, there is a limited opportunity to introduce the concept of holistic performance in rather fragmented lecture courses. It is arguably a much better opportunity to do so within the design studio context where students can address all building systems (structural, mechanical, electrical, and the building service systems) and cost estimating in the same design project.

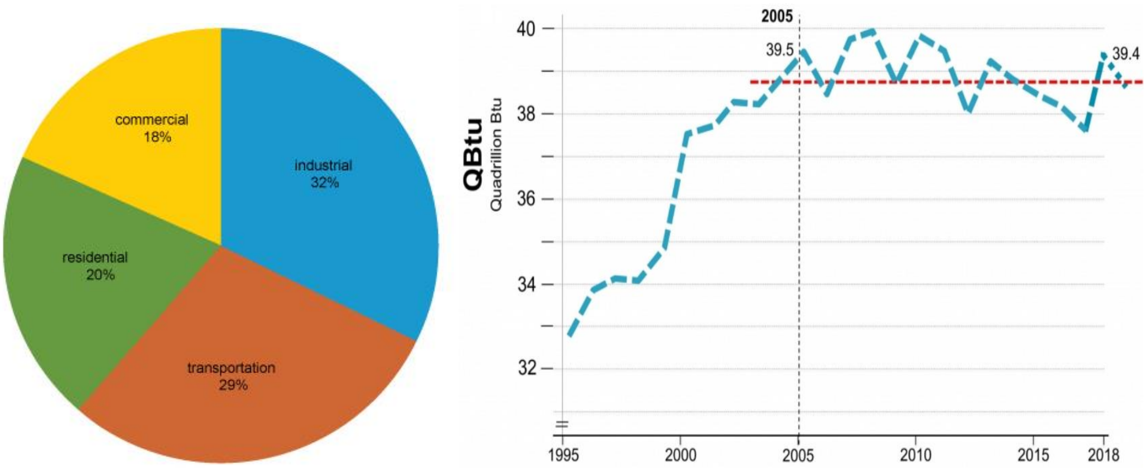

Fig. 1: (a) Shares of total US energy consumption by end-use sectors in 2017, and (b) US building sector operational energy consumption

2.2 Performance in the design studio

Understandably, most design studios in undergraduate architecture programs are limited in scope to just schematic design (SD). Usually, only one or two studios in each program extend beyond schematic design to cover design development (DD) and construction documents (CD). Only in upper level design studios the students become prepared to address DD design problems and systems integration. Indeed, students usually have limited opportunity to improve their skills in terms of performance-based design (Mansy, 2017).

In the Comprehensive Design Studio, the faculty articulate the scope and learning objectives to maximize students' exposure to building efficiency, structural performance, energy performance, and cost performance. During the second semester of the fourth year of the architecture curriculum and fifth year of the architectural engineering curriculum, students enroll in a 12-credit hour block of three interconnected courses, i.e., 6-hour comprehensive design studio, 3-hour concurrent technology seminar, and 3-hour project management course. In studio, the 15-week semester is divided into five weeks of SD when students work in teams and ten weeks of DD and CD when each student works on his/her own DD of a significant space within the building, which we call DD focus space.

For structural performance, during SD each student team is responsible for developing two structural schemes for their project, then selecting the better performing system. During DD, each student is expected to develop structural details necessary for the building envelope and foundations. Architecture students use simple rules-of-thumb and architectural engineering students use computer programs.

For energy performance, during DD, in addition to proving the building's code compliance with the International Energy Conservation Code (IECC), each student is expected to make sound performance-based decisions to design efficient mechanical, lighting and daylighting systems in his/her DD focus space. Course requirements include the four following tasks.

- Code compliance with IECC, either based on the code prescriptive values or based on performance (minimum of 15% energy cost saving)
- Electric lighting design in the DD focus space: verify performance in terms of recommended illuminance in foot-candles (fc) and light load in Watt/sf. Students may use hand calculations, online calculators, or an illumination design software.
- Daylighting design in the DD focus space: verify performance based on average illuminance and distribution when testing physical models under the artificial sky dome, or in terms of spatial daylight autonomy (sDA) and annual solar exposure (ASE) when using a daylighting simulation software.
- Cooling load: verify performance in terms of the building's energy use intensity (EUI), and peak cooling load in the DD focus space. Students may only use verified energy simulation programs.

For cost performance, at the end of DD, each student is expected to estimate the total construction cost of his/her building using RSMeans. While typically there is no predetermined construction budget, this requirement greatly helps students to better understand the cost implications of their design decisions.

2.3 How to evaluate overall performance?

It can be claimed that the Comprehensive Design Studio addresses performance in a comprehensive fashion since it helps students to understand the performance implications of their design decisions regarding building design, structural design, energy design, and quantities of specified materials. The key observation, however, is that students' experience remains dissected into three different performance measures with no reasonable way to combine them into an overall quantitative measure. Due to the same disconnect between individual measures, another source of concern is the tendency of students to design buildings with a high to very high window-to-wall ratio (WWR). An overwhelming majority of students end up with a much higher WWR than what is allowed by IECC, which also results in higher EUI than what is permitted in order to comply with code. To bring the building into code compliance, a popular solution is specifying a better-than-code glass that is also more expensive and/or adding external shading devices that come with an added cost and embodied carbon. The apparent dilemma here is: is it a good idea to reduce operational energy at the expense of a higher embodied energy?

3. Life cycle analysis

In order to establish one measure of performance that combines all three performance measures in a meaningful way, carbon footprint seems to be a reasonable candidate. Life cycle analysis of the building can combine all factors affecting structural, energy, and cost performance. It is also capable of combining both operational and embodied energy, to calculate operational and embodied carbon, and estimate the building's global warming potential. Global warming potential per square foot of the building can be considered the primary measure of its environmental performance. The apparent dilemma here is that in professional practice design decisions are, understandably, made to optimize the cost as dictated by the client. Future research may investigate how cost may align with global warming potential. The next section (section 4), reports on the investigative case study performed in order to find the pros and cons of establishing global warming potential as the primary measure of performance in the design studio, and to explore the possibility of using life cycle analysis as a design-assisting tool during DD and not only at the very end of the design process.

4. Case study

In an independent study that is tied to the design development phase of her project, we helped one of our architectural engineering students (Abby Brandvold) conduct a comparative analysis of the performance of three alternative designs of the envelope of a significant space in her project (the DD focus space). The objective of this study was to investigate the possibility of conducting more comprehensive analysis than what is so far regularly required in studio, precisely, to assess performance of design iterations based on the overall impact of both operational and embodied carbon, a new approach in which the design's carbon footprint is considered the primary measure of its environmental performance. Instead of only meeting the regular studio requirement of developing a baseline and one code-compliant envelope design, she developed a baseline and two code-compliant design iterations (Fig. 2) and estimated the overall carbon footprint of each of the two alternative designs. Below is a detailed description of the steps of the case study.

4.1 Step one: establishing the baseline and alternative envelope designs

Since the objective is to evaluate the impact of proposed design improvements compared to a reasonable baseline, the student developed energy models for the minimum code-complying design and two design iterations intended to reduce the cooling load in the focus space. For the purpose of this case study, this energy model is for a south-facing 20ft-high lobby for a museum in Oklahoma City (climate zone 3A). As for occupancy loads, all input data comply with relevant requirements in IECC-2018 and ASHRAE Standard 62.1-2016, as well as data available in ASHRAE Handbook of Fundamentals (ASHRAE, 2017). Below is the description of the three energy models.

- Standard reference design building

  As defined in IECC-2018, this energy model (model #1 in Fig. 2) is a version of the proposed design (of the envelope design in the student's DD focus space) that meets the minimum requirements of the code, which is used to determine the maximum annual energy use requirement for compliance based on total energy performance (IECC-2018). Input data comply with all relevant prescriptive values required by IECC for a metal-framed building. Glass ratio is 40%, assuming compliance with requirements for increased vertical fenestration area with daylight responsive control. Thermal properties of all envelope components (fenestration, exterior wall, roof, and slab-on-grade) comply with tables C402.1.4 and C402.4 in IECC. Refer to Table 1 for a detailed list of input data.

- Proposed envelope design without external shading

  This design iteration proposes a 90% window-to-wall ratio (WWR) of the envelope in the same focus space (model #2 in Fig. 2). The glass used is a high-performance glass having the thermal properties listed in Table 1. Using such glass is intended to reduce solar heat gain in order to reduce cooling loads. The lower-than code U-factor should help reduce both heating and cooling loads. However, because of the larger area of glass (compared to the standard reference design building), this design results in an increase of total length of the aluminum frame and mullions.

- Proposed envelope design with external shading

  This design iteration proposes adding a horizontal external shading device (louvers) in front of the 90% glass in order to further reduce solar heat gain and, in turn, further reduce cooling loads (model # 3 in Fig. 2). Like the first design iteration, the lower-than code U-factor should help reduce both heating and cooling loads. Glass thermal properties are listed in Table 1. Adding the aluminum louvers does not only increase the quantity of aluminum used, but also requires additional structural support for the louvers.

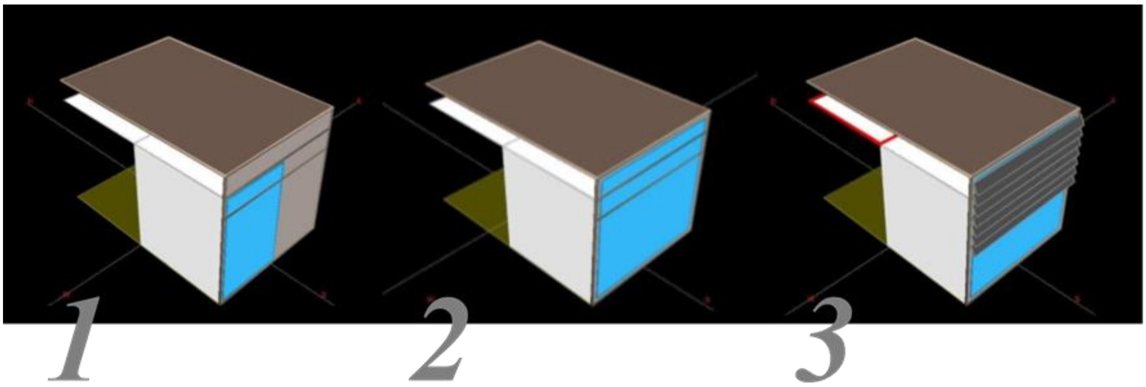

Fig. 2: Energy models of the standard reference design and two design iterations

4.2 Step two: energy performance (operational energy)

Energy modeling was performed using eQuest, which is an energy simulation program that is validated by the US Department of Energy (DOE, 2020). eQuest performs accurate hourly load calculations and produces both of the energy use intensity (EUI) and the peak load in every thermal zone. Based on the results of energy simulation, the

EUI of the standard reference design building (baseline for comparison) was 133.7 kBtu/sf.yr. The 90% WWR envelope design with high-performance glass resulted in EUI of 111.6 kBtu/sf.yr., achieving 16.5% energy savings compared to the baseline, while the partly-shaded 90% WWR envelope resulted in a lower EUI of 108.6kBtu/sf.yr., achieving 18.8% energy savings compared to the baseline (refer to Table 1). In conclusion, since both alternative design improvements result in energy cost savings greater than 15%, they both comply with the IECC based on performance (IECC-2018). In conclusion, based on EUI only, adding external shading results in higher environmental performance.

Although not related to code compliance, an interesting result that is worth-mentioning here is that while the two proposed design iterations resulted in considerable energy savings, only the partly-shaded envelope design reduced the peak cooling load in the perimeter thermal zone, which resulted in further cost savings due to downsizing of mechanical equipment.

Tab. 1: Input data and results of energy simulation, cost estimating, and carbon life cycle analysis

	Standard reference design	**Design iteration without external shading**	**Design iteration with external shading**
IECC climate zone	3A	3A	3A
Space use	Lobby	Lobby	Lobby
Exposure	South-facing	South-facing	South-facing
Floor-to-floor height	20 ft	20 ft	20 ft
Window-to-wall ratio	40%	90%	90%
Wall U-factor (Btuh/ft^2.^{o}F)	0.064	0.064	0.064
Roof U-factor (Btuh/ft^2.^{o}F)	0.039	0.0314	0.0314
Slab on-grade U-factor (Btuh/ft^2.^{o}F)	0.73	0.4545	0.4545
Glass properties			
- U-factor (Btuh/ft^2.^{o}F)	0.46	0.26	0.25
- Shading coefficient	0.29	0.14	0.195
- Visible Transmittance	0.275	0.06	0.21
External shading	None	None	Aluminum louvers
Occupancy loads			
- Lighting power (W/sf)	1.0	1.0	1.0
- Ventilation, CFM per person	5.0	5.0	5.0
- Ventilation, CFM per SF	0.06	0.06	0.06
- Set point temp in cooling (^{o}F)	75	75	75
- Set point temp in heating (^{o}F)	72	72	72
- Density (sf/person)	100	100	100
- People sensible load (Btuh/person)	250	250	250
- People latent load (Btuh/person)	200	200	200
Results of Energy Simulation			
- EUI (kBtu/sf.yr)	133.7	111.6	108.6
- Peak cooling load (CFM/sf)	1.25	1.52	1.24
Cost comparison			
- Cost estimate ($/sf)	baseline	+165.67	+239.67
- Return on investment	NA	baseline	-3.57%
Global warming potential (kgCO_2eq/sf)	NA	24.98	156.30

4.3 Step three: cost performance

Cost analysis was performed by summing the cost of each individual component of each envelope design and determining the overall cost per square foot for that wall assembly. Cost data were collected from manufacturers and the most current RSMeans. Cost of the 90% WWR design improvement adds $164.67 per square foot, while cost of the partially shaded 90% WWR adds $239.67 per square foot. After factoring in the energy savings due to the use of external shading (18.8% > 16.5%), using the current rates of natural gas and electricity from the OG&E (Oklahoma Gas & Electric Company), adding the external shading results in negative return on investment of 3.57%. In conclusion, based on financial analysis only, adding external shading is not economical over the useful life of the building.

4.4 Step four: embodied + operational carbon

Life cycle analysis was performed using Athena, the Impact Estimator for Buildings, which is developed by Athena Sustainable Materials Institute (Athena, 2019). The same input data used to perform cost analysis was used to calculate embodied carbon due to manufacturing and transportation of materials, on-site construction, operation, de-construction, demolition, disposal, and waste processing of the two design improvements. The global warming potential of the 90% WWR is 24.98 kgCO_2eq, while due to the added aluminum louvers and increased use of materials to attach them to the structure, it is 156.30 kgCO_2eq for the partially shaded 90% WWR. In conclusion, adding the aluminum external shading results in surprisingly high global warming potential, which should eliminate it as a possible design improvement.

4.5 Step five: case study conclusions

Apparently, the different measures of performance do not favor the same design iteration. While the aluminum external shading results in lower EUI and a smaller mechanical system, it is not cost effective (negative return on investment) when compared to the design without external shading. Furthermore, it results in a significant increase in global warming potential. In situations when different measures conflict, the design team may need to decide based on the client's highest priority. However, if carbon footprint is considered as the primary measure of environmental performance, then the decision is clearly to eliminate the aluminum external shading.

5. Conclusions

In conclusion, this investigative study sheds light on several issues that relate to performance-based design, climate change, architectural education, and professional practice. These issues can be explained as follows:

It is important to correct the practice of saving operational energy at the expense of embodied energy. It is counterproductive to design high performance buildings with high window-to-wall ratio. Increased glass ratio (than what is allowed by code) requires the use of more expensive glass that is also most likely of a higher embodied carbon (compared to other materials such as brick and gypsum board) and/or the use of external shading devices that also come with high embodied carbon.

Disagreement is possible between different measures of performance when considered in isolation. Conflicting feedbacks render a real challenge to students in making well-informed performance-based design decisions based on quantitative evaluation. In such situation, they will have to subjectively choose to follow the direction of one feedback and ignore the other(s). For example, design an envelope that yields higher energy savings although it is more expensive to build, or to design an envelope that is less expensive to build although it does not achieve the lowest energy consumption.

In light of the urgency of climate action and the quest to fight global warming, the carbon footprint, expressed as global warming potential per square foot, may be considered the primary measure of performance, which replaces the need for looking at different aspects of performance, e.g., structural, energy, and cost performance. The key advantage of using carbon footprint as the primary measure is that it takes into account structural materials, both of operational and embodied energy, and all specified materials to be used in construction. Furthermore, building performance expressed in global warming potential should provide students with more comprehensive understanding of the relationships to the other economic sectors, i.e., industrial and transportation (Fig. 1a).

In the sake of supporting pragmatic professional practice, future research is needed to test the correlation between design driven by climate action and the least cost design often desired by clients.

Using life cycle cost analysis as a design-assisting tool in studio faces several challenges. Such challenges are due to the lack of necessary information needed to quantify carbon during some of the cradle-to-grave stages, namely, building material production and transportation, on-site construction, and end of life (disposal, reuse, and recycle).

High performance buildings are the reason behind the profession's success in capping operational energy at 2005 levels. However, achieving zero operational energy by 2030 is impossible without reliance on renewable energy technology, which comes with its own high embodied carbon. In the future, a paradigm shift will happen when zero operational energy has been achieved and the environmental impact of buildings becomes solely due to embodied carbon. At that point, performance-based design will be all about the stages before and after the occupancy stage of buildings.

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