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METHODS

A design workflow for integrating performance into architectural education

Ulrike Passe[1]

Abstract

Sustainable design for carbon-neutral buildings requires a thorough understanding of environmental building performance. The urgent need to reduce greenhouse gas emissions radically creates additional demands for architectural education and practice. These demands challenge conventional educational building design and architecture programs. A new pedagogical approach to the architectural studio is presented that specifically responds to this challenge. A highly structured 10-stage workflow for architectural design equips students with knowledge, tools, and processes to integrate and predict dynamic performances of light, sun, heat, and air movement in their design decisions. This pedagogical approach has been used in ARCH 601, a required sustainable design studio in the second year of the professional Master of Architecture program at Iowa State University, US. A specific emphasis is placed on the iterative feedback between daylighting, natural ventilation, and the building's enclosure. In an effort to understand the impact of this pedagogical approach on the career of former students, a survey was sent to the graduates of the past five years. A majority reported the positive learning outcomes and importance to their current career.

Practice relevance

The architectural profession is moving toward the creation of carbon-neutral buildings. A new approach to architectural education is shown to equip architecture students to meet this challenge. An architectural studio approach allows students to integrate and predict the dynamic performances of light, sun, heat, and air movement, based on using an innovative, highly structured workflow method. An alumni survey provides insights into the relevance and impact of this approach on their career. Learning these skills made architectural students better equipped to address sustainable design in their career. The workflow can be easily adopted by other architectural courses and practices. This can help to accelerate the education of architectural students towards carbon neutrality.

Keywords: architects; climate change; design methods; design studio; education; energy; pedagogy; zero carbon

1. Introduction

> Through exclusively social contracts, we have abandoned the bond that connect us to the world, the one that binds the time passing and flowing to the weather outside, the bond that relates the social sciences to the sciences of the universe, history to geography, law to nature, politics to physics, the bond that allows our language to communicate with mute, passive, obscure things—things that, because of our excesses, are recovering voice, presence, activity, light. We can no longer neglect this bond.
>
> (Serres 1995: 48)

The United Nations' (UN) Brundtland Report (Brundtland 1987) defines sustainability as a social, economic, and environmental and cultural goal of societies to meet the needs of today without compromising the needs of future generations. The goal of carbon neutrality is one of a group of goals that brings sustainable communities and environmental justice together (Agyeman 2005).

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Buildings exist at the interface between the social and the new natural contract. The impact of buildings on the changing climate and resource depletion leads to the demand for carbon-neutral buildings as one major aspect of the 17 United Nations' Sustainable Development Goals (SDGs) (UN 2020). A rapid reduction in carbon emissions (both embodied and operational) are needed to achieve the Paris Agreement's goal to limit global warming. Since 1990, 'the negawatt revolution' (Lovins 1990) has been promoted for the economic and environmental benefits arising from a significant reduction of building energy/carbon. However, buildings are complex socio-technical entities, embedded in a social–cultural–economic–climatic context, and carbon or energy cannot be considered in isolation. Therefore, carbon-neutral buildings need to be embedded within a holistic education towards sustainable architecture and cities.

A key question that arises is how can architectural education respond to providing graduates with new knowledge and skills to create low- or zero-carbon buildings? Given the very short amount of time to implement change and reduce the negative impacts of existing and new buildings, there is an imperative to connect the social contract with a natural contract as proposed in the above quotation by Michel Serres.

This paper presents an approach that uses the structure of the existing architectural curriculum and adapts one of the key courses: the design studio. A design studio in US academic architecture education is both a space and a learning experience, as noted by Schoen (1983). Typically, it is a space in which about 10–30 architectural students spend most of their time, talking and interacting, but also working silently in parallel on their design project. The architecture studio model as practiced today as a learning environment and the integration of supporting knowledge into a comprehensive whole is based on the Boyer Report (Boyer & Mitgang 1996). This report grounded the accredited professional architecture programs. The National Architecture Accreditation Board (NAAB) (2020) student performance criteria amended over the past two years now specifically include climate action and performance metrics.

This paper presents a pedagogical method based on a new workflow for the architectural studio. This method has been developed, applied and refined in a required semester-long (17 weeks) second-year graduate sustainable design studio (ARCH 601) within an accredited 3.5-year professional US based Master of Architecture program.

The goal of ARCH 601 is to prepare students with the skills to design carbon-neutral buildings as one criterion within the wider scope of sustainable design using mainly passive design strategies, passive solar, passive cooling, natural ventilation, and daylighting, which are inherently spatial architectural strategies using space for the conversion, distribution, and storage of solar energy already promoted by Lyle (1994), but refined by Passe & Battaglia (2015), amongst others. This paper presents a unique workflow based on the data-driven post-occupancy evaluation (POE) of a solar house designed, constructed, and operated for net-zero energy (Passe *et al.* 2017). The POE conducted by the author's research center and its students (ISU CBER 2020, n.d.) supports modeling prediction for passive solar and natural ventilation strategies with actual measurements.

The projects laid out by the ARCH 601 studio are real-world problems as could be found in a professional setting. These types of studio projects have been set in US schools for decades, so there is nothing particularly innovative in the setting. However, the goal of this particular studio course is to creatively address challenges to design buildings, which once built will meet carbon neutrality (Jankovic 2012) as part of a set of sustainable performance metrics for design excellency (AIA 2020), which is novel. The author developed its program of study to better equip students during the early design phase with the knowledge and tools to integrate and predict the interaction of their design with the physical world, and the impact of the dynamic performances of light, sun, heat, and air movement on their design, when especially natural ventilation and daylighting are complex and dynamic phenomena.

This studio challenges students to develop integrative design projects, a major requirement of a professional architecture program (NAAB 2020) that explores the relationship between buildings, climate, socioeconomic factors, and environmental forces. The outcomes are building designs that are predicted to be efficient and non-wasteful with energy, water, material, and other resources. Projects include investigations of the impact of solar energy, airflow, daylighting, building materials, and assemblies, thus mainly passive systems, on spatial quality and to validate decisions quantitatively through energy modeling and performance simulation and life-cycle analysis. The studio usually has 12–16 graduate students enrolled and they collaborate in teams of two or maximum three. An emphasis is placed on designing for a regional site, and its socioeconomic conditions, which is representative of similar situations throughout the US Midwest. The projects stress interdisciplinary research, engagement with local community stakeholders, building owners as well as, at times, Extension specialists to develop responses to the specific climate and site conditions.

Design pedagogy relies heavily on 'learning by doing,' as introduced by Dewey (1916). Designing is learned by mocking-up a virtual real-world project. Therefore, ARCH 601 directly integrates the performance simulation of the technical predicted functioning of the projects into the workflow so that the simulation drives the process (Oxman 2008: 107):

> Current theories and technologies of digital design suggest a shift from analytical simulation to simulation for synthesis and generation. These approaches identify generative processes with performance. This distinction is very significant. Instead of analyzing the performance of a design, and modifying it according to results, performance-based simulations can directly modify designs.

ARCH 601 is also dedicated to integrating teamwork as a mode of practice. Teamwork is about granting responsibility to individual team members and sharing work, which does not necessarily correlate with the traditional understanding of the designer as a sole creator. However, teamwork demands respect and compromise and is essential in professional practice. Unfavorable group dynamics cannot always be avoided and may lead to conflicts among students and between students and faculty. The most common conflicts are related to personal working modes, personal life issues, and unevenly balanced workloads within the group. Teamwork in the design studio needs to be carefully monitored and the role of the instructor is to help balance out personal conflicts. Team composition is facilitated via a team-building exercise (Brncich *et al.* 2011).

ARCH 601 also places a significant emphasis on human comfort and occupation, which is highlighted in the analysis and visualizations of activities. The workflow presented here is based on a 2016 studio project for one of the Iowa Lost School sites (a term coined by the *Des Moines Register* 2016).

The paper is structured as follows. This introduction frames the context and challenge to be addressed. The following section covers the theoretical framework for the presented workflow method and introduces the detailed workflow developed over the past 10 years. Next, the results of an alumni survey conducted in 2019 are given. The conclusions consider the viability of this method for wider architectural education and the rapid transition of the architectural profession.

1.1 Site context: The community dimension

Sustainable development in architecture and urban development (UN SDG 11) demands the integration of societal issues with the environmental and economic. In ARCH 601 the social is introduced via deliberate selection of site context. Without this, the ability to achieve zero carbon targets is undermined by lack of consideration of societal issues which impact environmental design. A thorough study of the selected site and its socioeconomic and demography context provides the students with the basis to develop their own program for the project. All these sites were selected to include considerations of the impact of place on social dimension of sustainability. Project sites are located either in an urban context, which provides challenges to the ideal relationship with solar orientation or are adaptive reuse projects. In all locations, the students are charged with the development of a mixed-use program including some form of residential use, an environment for working, and an aspect of community, which address the socioeconomic situation through density.

From 2014 to 2020, sites were carefully selected in Old North St. Louis (ONSL) (n.d.) in Missouri, at the 6th Avenue Cultural Corridor in Des Moines (Des Moines 6th Avenue Corridor 2015), and at either Greene Square Downtown Cedar Rapids, 324 South Front Street Midtown Memphis, Tennessee, or Pershing Crossing (C40 Cities 2018), City of Chicago. Three ‘Lost Iowa Schools’ were used to develop a viable adaptive reuse project towards carbon neutrality.

2. The workflow for a performance-based design pedagogy

The conceptual design workflow (**Figure 1**) (first two-thirds of the semester) was tested and developed over 10 years. It presents three phases starting with climate and radiation analysis leading to decisions on orientation, massing, and geometry, followed by an iterative process that includes daylight and glare analysis, thermal energy balance, natural ventilation, and spatial composition as well as early integration of a detail interlude. This interlude strengthens the students’ understanding of material and assembly processes in relationship to data inputs in the modeling tools. The iterative circle can be repeated multiple times until a final synthesis can be drawn.

2.1 Theoretical background

Given these critical demands for sustainability, it is clear that architecture technology and design pedagogy should be better integrated (Architecture 2030 n.d.; SBSE 2019; AIA 2019). Technology, sustainability, and carbon literacy cannot

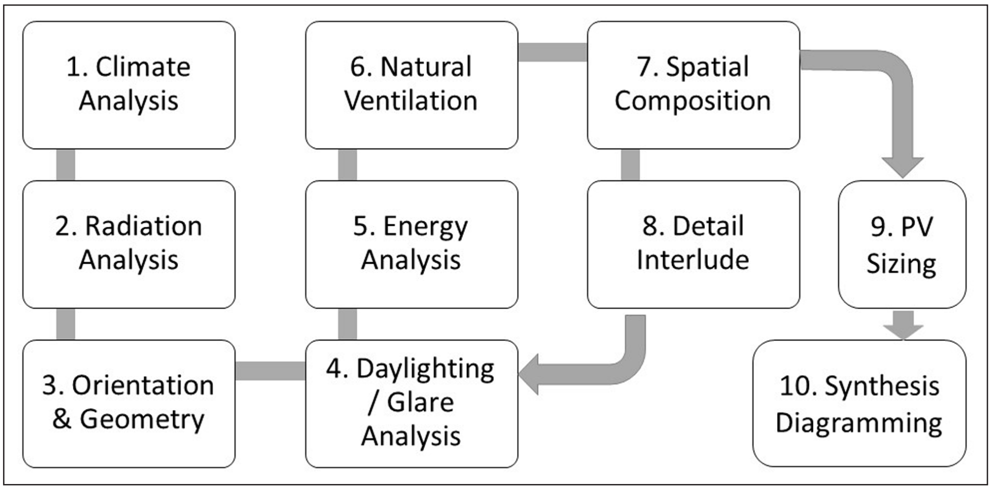

Figure 1: Workflow in 10 stages: stages 1 and 2 lead to massing *partis* (stage 3), followed by an iterative process during stages 4–8, which leads to a conclusive final project, for which the energy production system can be developed in stage 9 and synthesis diagrammed in stage 10 stages 9 and 10.

continue to be taught as theoretical knowledge separate from the studio design project. Instead, form and performance need to be based on a holistic conceptual understanding of space and materials with all their complex environmental, phenomenological, and sensual properties. An awareness of all sensual qualities of space is thus the crucial starting point towards a holistic and integrative architectural education. Architectural environmental technology and design are related through holistic thinking, such as theorized by Bachman (2012).

By enhancing technology pedagogy through hands-on laboratory work in all three major technology fields (structures; materials and assembly; and environmental forces and control systems), students gain hands-on learning experience needed in the fast-evolving profession. This integrative approach provides the basis for the ARCH 601 studio pedagogy. In opposition to most current textbooks for energy-efficient, net-zero design, which introduce and provide practice examples of important technical parameters, such as daylight, energy, passive, and active systems (Jankovic 2012; Hemsath & Bandhosseini 2018; Kwok & Grondzik 2018), ARCH 601 follows Passe & Battaglia (2015) where the design of spatial sequences connecting public and private spaces as well as inhabitable, socially just spaces, is the major goal of sustainable design.

Therefore, the pedagogical approaches to architectural design and environmental forces, systems and controls integrated in this studio are intrinsically related, and taught as part of the other. Architectural design is a comprehensive and synergistic activity. Building technology is thus an integral part of the whole, as theorized by Bachman (2012: 43):

> ....a building is conceptually an ordered set of many sorts of organized flow. Working backwards from organized flows to their channels through material and space, we can thereby reconceptualize a building, not as an every-day physical object, but as conceptual circulation systems composed of conduits, reservoirs, barriers, valves, switches, transformers, and other modulating elements. This non-local scale of reality is what has been described here as the strategic sphere of architecture: intelligent, insightful, responsive, and performative.

Building technology is considered here as the materialized relationship between built form and history, culture, and the environment, in particular climate, location, and topography (Lechner 2014). This relationship can be clearly analyzed in the comparison of traditional vernacular building types of different regions of the world (Oliver 1997). Humidity, dryness, heat, cold, and light intensity have left their marks on the roof types, surfaces, materials, and incorporated openings. They position themselves in relationship to the direction of the sun, the prevailing winds, and temperatures. As already noted by Banham (1969), the concepts for heating, cooling, and lighting are based on the interrelationship of the exterior climate and the internal needs and the control of both. Their provision is strongly related to design principles and spatial practices (Shove & Walker 2014). Designing is a critical inquiry based on many, sometimes conflicting, parameters. Design is an iterative thought process that integrates various parameters and forces into an inextricable relationship of space and form. New digital tools make this more visually accessible to designers (Oxman 2008).

In order to enhance student learning of environmental technology as designerly ways of knowing (Cross 1982), ARCH 601 stresses the notion that physical relationships expressed in mathematical formula can be translated into architectural and spatial proportions, phenomena, and sensations, and are thus inherent design principles (Groak 1992). This approach leads to an interrelationship between geometry, material, space, color, and atmospheric conditions. Spatial and architectural qualities are stressed rather than mere calculations and pure physical quantifications to understand the physical concepts and to be able to calculate basic performance metrics. Using state-of-the-art research findings in the humanities, the sciences, and engineering (Hays 2010), the workflow methods used in ARCH 601 provides an integrative learning experience for students to become architectural professionals, researchers, or scholars with knowledge of sustainable design concepts, theories, and practices.

2.2 The role of precedents

Based on literature research, the students select a precedent project, which shares some distinct parameters with their studio project. This could be the climate zone, the adaptive reuse program, and certainly the goal to use as few resources as possible, and thus incorporates renewable energy onsite, or all the above. The casting of a wider net results in a catalog of approaches for all students. It is also important that the students find the precedent projects themselves not to bias them with instructor preferences. The project goal is to understand and communicate how each of these projects achieves net-zero energy or low-energy performance and works with the climate it is situated in, and how it has performed over time. Students gain a thorough and increased understanding of how spatial and programmatic design concepts relate to energy performance by conducting a brief paper-based POE of the precedent. This also helps to develop students' performance simulations skills. All precedent projects have to be studied with the simulation tools. At this moment, the key metrics are introduced, such as energy-use intensity (EUI) (EnergyStar 2020a, 2020b), daylight autonomy (DA) (Reinhart & Walkenhorst 2001; Reinhart *et al.* 2006), and the goals of the Architecture 2030 Challenge (2020) to reduce demand. Passive strategies are developed first and prioritized to reduce the loads on any kind of active systems. As strikingly noted by Umberto Eco in *Map of the Empire* (1995), a one-to-one map of the world is impossible, therefore the relationship of a dynamic performance with varying 8760 hourly data points across the year and thus the necessary abstraction of a metric such as EUI or DA is an important learning objective to mitigate and accept uncertainty.

This teaching philosophy was very much influenced by the author's experience leading the 2009 Iowa State University Solar Decathlon team (US DOE 2020). At that time, no studio existed that educated the students to use performance metrics as a driver for design decisions. Such an integrative studio environment had to be development anew (Passe 2011; Brncich *et al.* 2011).

The Solar Decathlon House Database (ISU CBER n.d) developed by the author provides an important and unprecedented learning tool for ARCH 601 to understand that net-zero-energy buildings are possible with existing technology for the hot, humid, and extreme cold climates of Iowa and much of the US Midwest.[1]

While there are rules and best practices related to the physics of environment, responses in the built world are *always* varied. The evaluation of case studies as a method *opens up the student mind* to the diverse field of approaches to integration of energy performance prediction into the design concept. Through case study analysis, students gain the ability to critically evaluate the success of a case study project by using basic energy performance-prediction measures and developing models of the case study to understand the performance baselines.

2.3 Computer models in architecture pedagogy

Performance-based design is closely related to evidence-based design, which has long been established in healthcare (Ulrich *et al.* 2010) using health research as evidence for design decisions. Scenarios provide insights into the future operation of the building when the success of a design strategy relies in the proper control of air movement, control of daylight, and sunlight penetration or blockage leading to the control of energy flow in the building (Groak 1992).

The first step to computer-based performative design is the creation of a computer model of the proposed building. As the project to be designed does not exist yet, this stage is per se an iterative process to analyze the opportunities of the site. The studio follows the definition by Jankovic (2012: 7):

> the term modelling is defined as making a logic machine, which represents the geometry and material properties of the building and the physics processes in it. Simulation is then defined as numerical experimentation with the model so as to investigate its response to changing conditions inside and outside the building.

As with physical models, digital computer models require a significant degree of abstraction. Not all geometric details are necessary and not all physics processes need to or can be simulated. There is always a function of time limitation involved. This is an important learning objective of the studio that often goes unnoticed when working with digital tools. Models are abstract representations of an aspect of the world where mathematic (numerical) equation are used to simulate the physics in the real world (Winsberg 2010).

The account of climatic variability in performance-based design depends on the science behind computer simulation. Thus, the students make decisions based on predicted performance with experimentation conducted using the computational model. To understand the relationship between the mathematical inputs for physical relationships into the computer model all students in the course are required to first take the Environmental Forces and Control Systems (ECS) module of the required Building Technology sequence, where they conduct the calculations by hand and learn to understand the impact of each variable on the overall outcome (see Figure S1 in the supplemental data online).

2.4 Iterative process: decision-making process in a team

Given the multitude of variables, it is essential to develop an iterative workflow (Stotz *et al.* 2009; Kensak & Noble 2014) to experiment with the computer model and appreciate how the model reacts to the various parameters affecting performance. The majority of time in the workflow is spent on how much does the energy consumption increase or decrease with changes in orientation, windows size, *etc.*, and how does massing onsite influence heating and cooling load as well as daylighting. This process towards optimization can also be called a sensitivity analysis (**Figure 2**).

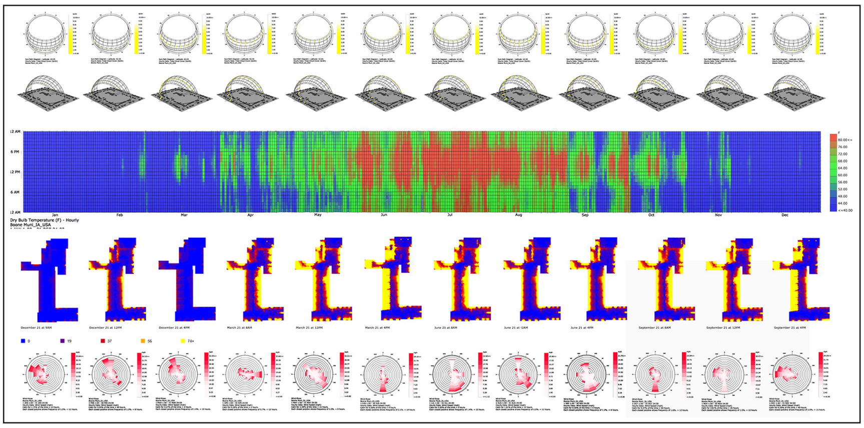

Figure 2: Evaluation of seasonal environmental and solar radiation data (January–December, from left to right) (Apicenter project, 2016, by Shawn Barron and Saranya Panchaseelan).

3. The workflow: The sequence of design parameters

3.1 Stages 1 and 2: Climate and radiation analysis

To develop volumetric concepts, the students study the relationship of space and environmental forces first. (The 2016 project was in Ogden, Iowa, the site of a 1954 elementary school building that was under threaten of decommissioning.) The energy performance of buildings depends on their potential to use solar radiation onsite in winter and sheltering the interior from solar radiation in summer while still providing sufficient daylighting and ventilation. Thus, at least three volumetric *parti* diagrams are developed to evaluate solar radiation, daylight, and ventilation strategies for an aperture to optimize for orientation. During the warmest period of the year reducing solar radiation needs to balance daylighting, while during winter, maximizing passive solar needs to balance heat loss during the very cold nights. In the US Midwest, passive cooling in summer is as important and as challenging as passive heating in winter.

Figure 3 shows the composite panel of the Apicenter project for the Ogden site, highlighting the analysis for its spatial interaction and daylighting strategy throughout the year. Given that the complexity anticipating the use and performance in operation leads to an array of assumptions that have to be tested for their separate performance aspects before being put together to evaluate trade-offs.

The second set of *parti* diagrams addresses the potential to use natural air movement for ventilation and passive cooling. Natural ventilation potential largely relates to the relationship of the building's position and orientation to the prevailing winds in summer and sheltering the building or group of buildings from those same forces in winter. The rarely well-understood concept of stack ventilation is introduced at this point as well, based on Passe & Battaglia (2015). A good ventilation strategy requires the connection of vents via a flow path, which can be challenging in a deep building. This exercise highlights the importance of a shallow floor plate, optimizing the relationship between spatial composition and the prevailing wind directions and using space to channel and block air to create form (**Figures 3** and **4**). Software entitled Climate Consultant (Milne & UCLA 2020) provides suggestions for passive design strategies that students can start exploring in the next steps using more refined computational tools.

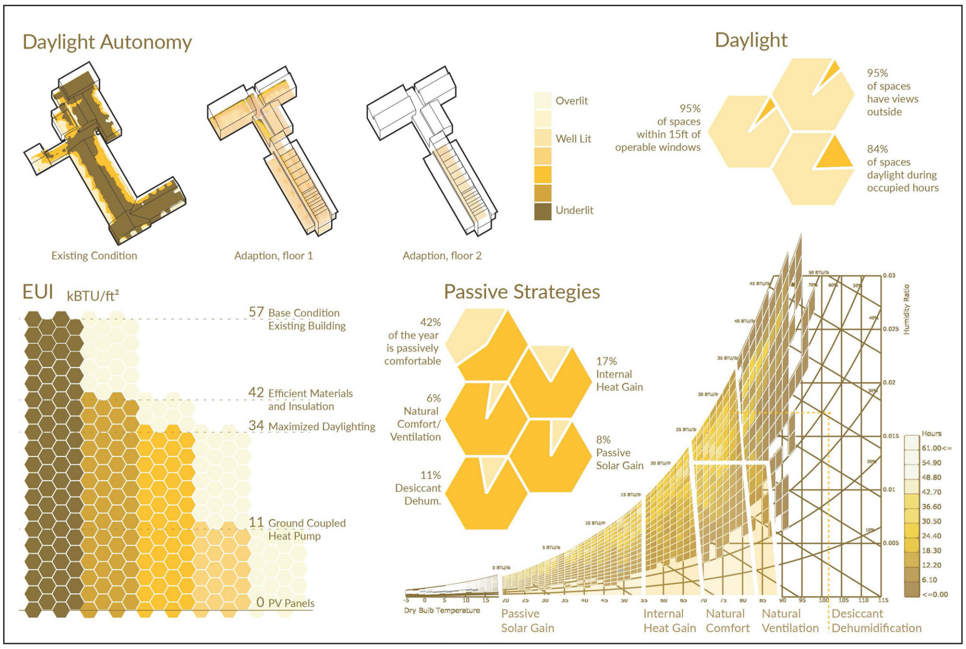

Figure 3: Design responses to climatic conditions using innovative environmental performance diagrams (Apicenter project, 2016, by Shawn Barron and Saranya Panchaseelan).

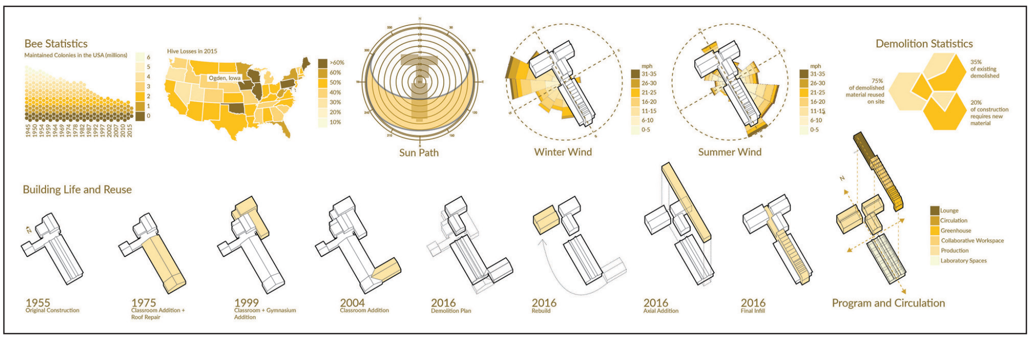

Figure 4: Massing development and passive climate response. (Apicenter project, 2016, by S.B. and S.P.).

3.2 Stage 3: Developing massing geometry and orientation to reduce energy loads

The massing studies resulting from stages 1 and 2 are then tested with Sefaira software for REVIT (Trimble, Inc. 2020) for their potential annual EUI to meet the Architecture 2030 Challenge (2020). Keeping program variables constant at first, the most promising massing schemes are iteratively tested with a variety of window-to-wall ratios and enclosure strategies. At this point the student teams move forward in parallel with at least two *partis* derived from stage 2. The site and *parti* review is conducted right after the site field trip (if it is not local) in order to validate the massing with local experience. **Figure 5** shows how these early studies developed into design decisions.

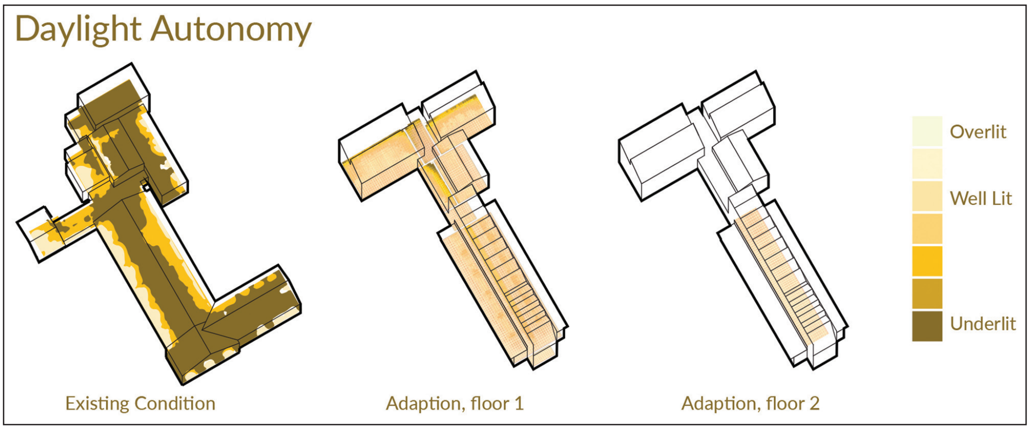

Figure 5: Daylight Autonomy simulation of the current existing condition and improved condition with two floors (Apicenter project, 2016, by S.B. and S.P.).

3.3 Stages 4 and 5: Energy load reduction versus daylight and views

Solar radiation and parametric daylighting tools within Sefaira for REVIT (Trimble, Inc. 2020) or DIVA for Rhino (Solemma 2020) are used in this two-week session to determine window-to-wall ratio, extend the time of year when no active systems are needed, and to integrate daylight targets of at least 50% DA and natural ventilations strategies into the overall spatial layout. **Figure 5** studies the detailed spatial DA in a studio project as the adaptive reuse approach revives the original composition of the building and adds new volumes on the roof.

3.4 Stages 5 and 6: Ventilation versus energy versus daylight to form a spatial sequence (stage 7)

Introducing natural ventilation into a project is often the largest challenge for the learning-sustainability designer as the resource to facilitate natural ventilation (wind) is erratic and volatile, especially in an urban context of the Midwestern climate. Opening windows will often just not be sufficient to provide the required air change rate and cooling capacity. Thus, during these workflow stages the students alternate iteratively between daylight simulation for 50% autonomy and natural ventilation studies comparing flow path, window-to-wall ratio, and aperture strategies to achieve the most possible annual time for natural ventilation. This stage provides the most opportunities for spatial exploration. MIT Coolvent (2020) has proven to be the best and robust investigation tool, even if not using computational fluid dynamics (CFD) such as in IES-VE (2020), because it is quick and provides sufficient information to make an informed decision. The Java-based computational tool allows input for spatial schematics based on five sectional typologies (atrium, cross, single sided, shaft, and chimney) and provides results of the time of year and day when the given strategy provides sufficient air-change rates based on ANSI/ASHRAE 62.1-2019 (2019) and ANSI/ASHRAE 62.2-2019 (2019) and the percentage of comfortable time based on the adaptive comfort standard (ANSI/ASHRAE 55 2017). For an example of student work, see Figure S2 in the supplemental data online.

3.5 Stage 8: Detail interlude: Material consideration for carbon neutrality and beauty

Architectural design concepts manifest themselves in the way the building is constructed and detailed by separating, layering, or joining architectural elements according to the intended spatial and formal composition and according to technical necessities to achieve a functional whole. This conceptual notion gets elevated to a new level of complexity when energy efficiency needs implementation into the actual construction of a building. Conceptual questions to address are: How might the building need to change (like a chameleon) from summer to winter? Or does it just put on its thick winter coat? Clothing acts as a metaphor to discuss the new (and old) necessity and questions the modern dogma of structural honesty as critically investigated by Passe & Nelson (2013). Therefore, half way through the 16-week semester, after the schematic design review when the students presented the outcome of their iterative process from stages 3 to 7, a weeklong exercise challenges the students to develop a large-scale detailed section (highlighting also the respective elevation) at ½ inch to the foot scale (equals roughly 1:25) following the path of the sun and air in summer and winter.

Students engage in a critical drawn discourse on the need to design more airtight buildings with high *R*-values and high-performance windows reconciling appearance and aesthetic with environmental, building physics, and structural concepts. This is a very challenging moment for the students as very few previous studios have requested them to develop detailed investigations of their assemblies. They need to understand that these drawings/models represent a space and its materiality and atmosphere, and are not just concerned with technical assembly. At this point a variety of material choices is discussed based on their embodied carbon using available carbon calculators such as EC3 (Building Transparency 2019). For an example of integrative student work from this stage, see Figure S3 in the supplemental data online.

The detail interlude also requires the students to consider the urban–landscape integration and access related to the site's topography and thus the integration into the site and urban context, while developing interior spatial connections from the urban exterior to the unit and back. The detailed sectional drawings are reviewed as scaled prints and redlined and discussed in collaborative sessions, where students also provide feedback to each other. The detail interlude provides the basis for the development of one of the most important final drawings: the integrative section in stage 10 (see Figure S5 in the supplemental data online).

3.6 Stage 9: Meeting reduced energy demand with renewables

Once the students have refined their design proposal and reduced the required electrical and thermal energy demand significantly via massing, envelope, daylight, solar heating, and passive cooling strategies, embodied carbon towards a net-zero carbon potential in stages 1–8, the photovoltaic (PV) array is sized on and around their built volumes. The opportunities for using PV for previously developed shading strategies and window-integrated technologies are also explored to synergistically use shading elements which reduce heat gain and produce electrical energy. This occurs three months into the semester. The placement and integration of the renewable energy source is treated as a major design integration challenge using the PV tool within Sefaira for REVIT or basic hand calculations based on solar radiation data from the US Solar Radiation Database (US NOAA 2018). Students will be introduced to the most innovative current development in the PV manufacturing realm based on Lueling (2009). All prior design decisions have contributed to reducing the energy use, which needs to be produced by the PV array. (Figure S4 in the supplemental data online shows a visualization of this student work.) Bringing this balance to a net-zero-energy balance is the first step to carbon neutrality; the second is the consideration of embodied energy and carbon; this final goal is met by the reuse of an existing building.

3.7 Stage 10: Final design synthesis and diagramming

Based on multiple iterations of the first nine steps of the workflow, all performative aspects are integrated into a built form and correlated with the desired program for the building based on a critical reflection of envelope material and construction type, with a determination of the window-to-wall and floor area ratios to improve the understanding of the depth of enclosure assemblies selected in the energy simulation tool. The goal for a low or zero-carbon emission building is thus also an exercise in composition, space planning, and aesthetics. To communicate the results with reviewers and/or clients, multiple iterations of diagrams are developed parallel to the design development, as visualized in Figure S6 in the supplemental data online.

4. Impact on practice survey results

In order to understand and analyze students' ability to integrate the workflow into their design career, a survey was conducted with students who completed the course over the past 5 years.

This 10-minute anonymous confidential Qualtrics survey was sent to all graduate students who used the described workflow. The study complied with Iowa State University's Institutional Review Board (IRB) requirements (a committee that reviews and approves human subject research studies). **Table 1** lists the 12 survey questions.

A total of 82 former students received the survey via email, representing about 90% of students who took the class. A total of 27 completed the survey (a response rate of 33%). A total of 48% of respondents were female and 52% of respondents were male. Further demographics are presented in **Figure 6**. The majority of alumni considered knowledge acquired in ARCH 601 important to their current position (**Figure 7**).

The word cloud in **Figure 8** visualizes the weight of noted concepts in response to question 7. **Figure 9** tabulates the responses of importance to the workflow for their current career, while answers to question 11 reveal that even with comprehensive training the changes in the workplaces are slow.

When asked about the possibility to use actual environmental performance analysis in their current work, only 59% used environmental performance tools in their current position. **Figure 10** shows the detailed response about which tools are currently used. Of all the tools they encountered, climate analysis and daylight simulation were the most used in practice.

In the open-response section, respondent A noted a reason for this issue, beyond their control: liability issues related to code compliance documentation, which seems to be assigned to specialists and outside consultant.

Respondent B noted, that in the current state that they practice, the firm helped write legislation that made it a requirement to meet a minimum standard of sustainability in all buildings. However, these are all standards that do not require testing or analysis at the architect's end. The mechanical and electrical engineers conduct the modeling towards the EUI. The architect really just provides tighter wall assemblies with more insulation. Yet, respondent C noted that while they might not use the tools directly in their current job, they might be the firm member to evaluate those drawings which are made by an energy modeling consultant and are able to understand them, thus noting how crucial ARCH 601 was for their current positions.

Table 1: The 12 questions posed in the alumni survey.

1	What is your current professional position?
2	What is your age?
3	What gender do you identify with?
4	When did you graduate?
5	What is your current employment status?
6	Was the knowledge you gained in ARCH 601 important for obtaining your current job?
7	Please recall the learning outcome with regards to your design skills you obtained in ARCH 601?
8	What importance do you place of sustainable design in your current work?
9	Looking back, please evaluate the importance of the learning experience of ARCH 601 in your overall professional architecture curriculum?
10	Please rate the importance of using environmental performance evaluation software in your current career?
11	Do you use environmental performance tools in your current job a. Daylighting yes/no b. Energy modeling yes/no c. Natural ventilation simulation yes/no d. Climate data visualization yes/no e. Solar Geometry charts/plots yes/no f. Other
12	Lastly, please provide any further feedback and information which you might find valuable to report about your learning outcome from ARCH 601 in your current practice position in architecture or related field.

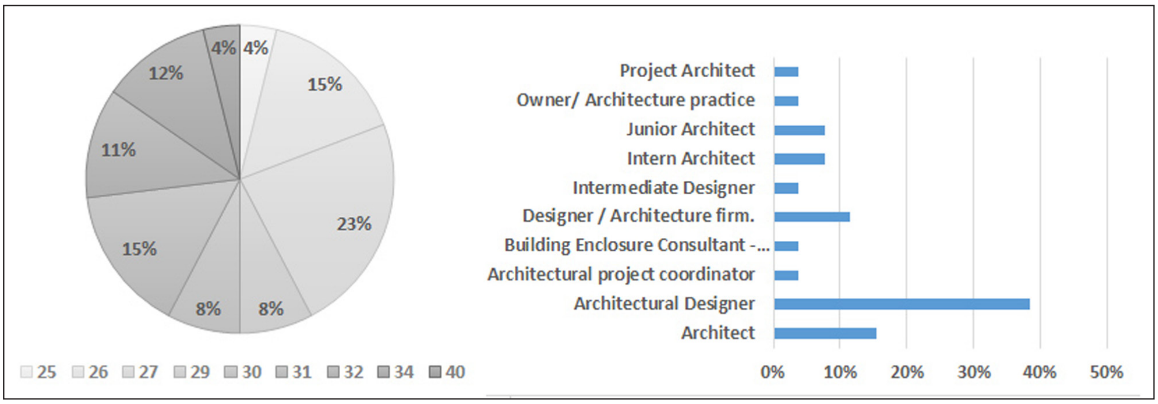

Figure 6: Age distribution of respondents (question 2) and their professional position (question 1).

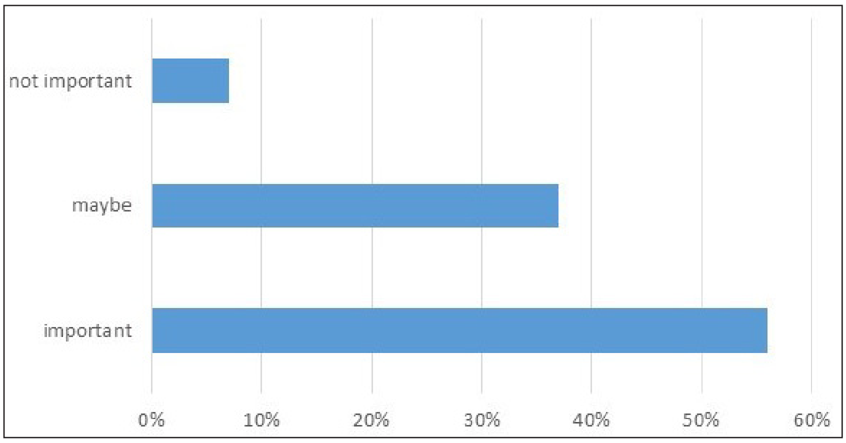

Figure 7: Responses to question 6: What is the importance of the knowledge gained in ARCH 601 to your current job?

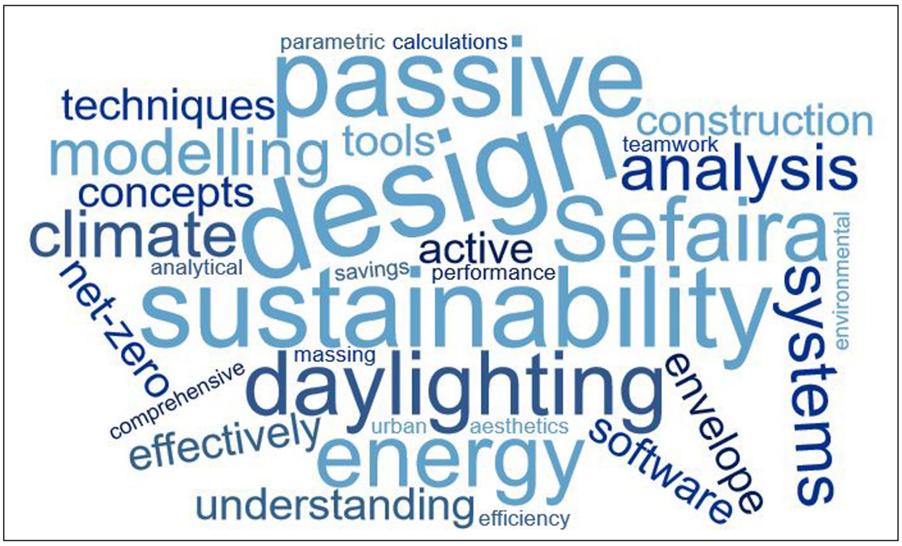

Figure 8: Word cloud of the importance of respondent recollected learning outcomes (question 7).

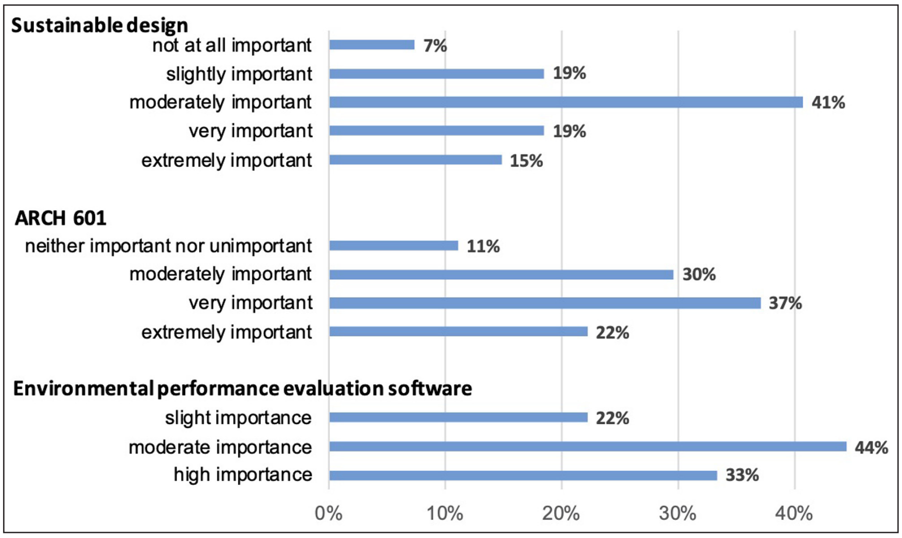

Figure 9: Responses to question 8 (top) on the importance of sustainable design, question 9 (middle) on the importance of ARCH 601 in the overall professional curriculum, and question 10 (bottom) on the importance of using environmental performance evaluation software in your current career.

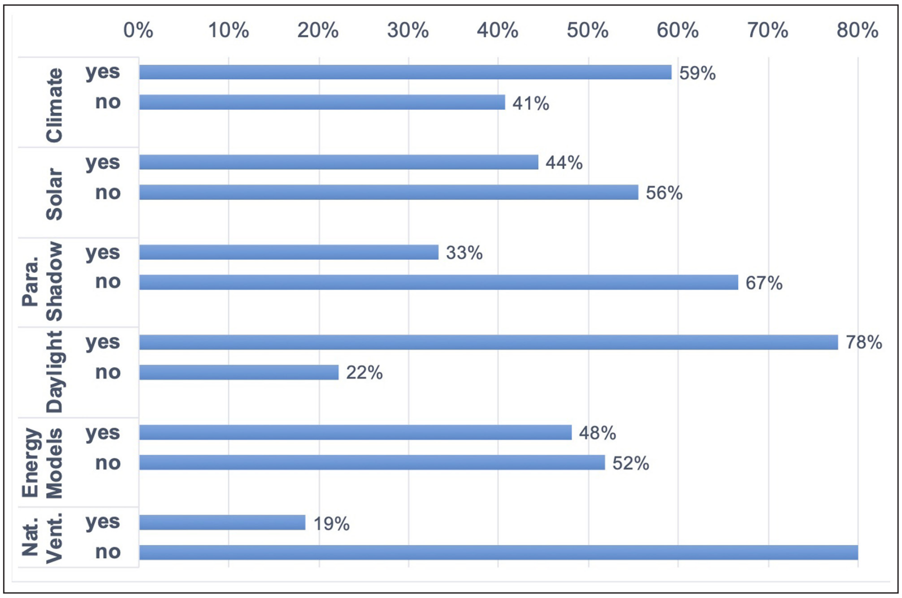

Figure 10: Responses to question 11: Do you use environmental performance tools in your current job?

Respondent D noted that Arch 601 provided a rich foundation for general building sciences. It was an advanced introduction for multiple environmental performance criteria in buildings including energy performance, sustainability issues, and daylighting. Therefore, respondent E applauded the useful technical information compacted into one semester. All 13 respondents who provided open-ended feedback noted the useful resources and concepts they had learned:

- The general concepts and principles around sustainability and environmental design have been the most useful so far as a working designer (more than digital tools and performance data).
- Arch 601 is a comprehensive design exercise for learning and practicing design that is environmentally conscious.
- ARCH 601 is especially helpful in making students realize the importance of advocacy for sustainable methods and how to effectively communicate data and graphics that support such design.

Respondent F stated that their current firm considers sustainable strategies such as environment friendly building products/materials, or heating, ventilation and air-conditioning (HVAC) systems and light fixtures that are more energy efficient, yet in the end it all depended on what the client wanted and the role of the architect often becomes the educator of the clients regarding sustainable design. Therefore, the workflow offers a great resource for practices to start thinking and learning about sustainable design. The studio reassured this respondent that practicing within the field of architecture was a goal that they wished to pursue. This particular respondent is now involved with USGBC's (2020) LEED certification discussions and material health in ways that would have not been possible had the earlier interests not been jump started by this course.

A final comment from respondent G summarizes the current state of practice. Their company has designed some of the earliest net-zero buildings in the country, and sustainability is a huge emphasis across the board for them, but most of the actual energy performance analysis and modeling is done by the engineers/consultants. Therefore, the architects on the team continually design around the feedback from the engineers from pre-design to POE, but the designers themselves are not directly involved with the energy software. They need to know enough to have a conversation with the engineers, and understand metrics and data, and be familiar with the main tools, but most of the deep performance modelling is done by the engineers. Yet, this informed discussion relied on the knowledge learned through the workflow and their design team has generally made net-zero the target for every new project embedded in everything the firm does.

5. Conclusions

The paper detailed the outcome of a novel pedagogical process involving 10 stages. The outcome of the alumni survey provides important data on how the outcomes were later recalled and applied within an architecture firm. The integration seems to work best when the design team is comprised of sustainability-educated architects and engineering consultants, and the firm culture enables deep integration.

A design studio can allow exploration and integration of complex social, cultural, environmental, and technical considerations. The presented workflow process for the architectural design studio shows it is feasible to create significant changes in student capabilities for the creation of low- and zero-carbon buildings. However, a highly structured process for achieving this seems necessary. It is possible for other design instructors to rapidly deploy and adapt this structured process. Moreover, this can be done within the confines of an existing architectural curriculum—without triggering the bureaucratic changes and consents that might accompany a change to the structure of architectural education. The agency of the studio leader means that a transition to a low-carbon curriculum can be implemented quickly.

Climate analysis and daylighting are clearly the most prominent tools with 75% of the respondents still using those tools. Energy performance simulation is still mainly conducted by consultants, but the majority of alumni noted that the workflow method helps them in their communication and decision process between client and consultant. Half the respondents noted that the visualization potential of tools such as Sefaira support their discussion about energy savings with clients in the workplace.

Unfortunately, the topic that is least used in practice is natural ventilation, despite the emphasis in the workflow method. The American romance with air-conditioning (Ackerman 2010) and the complexity and volatility of the reliability of this important energy-saving strategy is most likely the reason why natural ventilation is not yet better included in practice. Going forward, the knowledge gained from the alumni feedback surveys will enforce the position of ARCH 601 in the curriculum, and help to refine the workflow methods by including the challenges faced in practice. The 90 alumni have been well equipped to establish the change needed to enable build environment professionals to decarbonize the built environment.

The reflections on more than five years of educational practice presented here are further strengthened by the supportive and encouraging response of nearly 40% of the surveyed alumni. The development of the digital tools for this unique workflow method has strongly supported them. The environmental performance simulation tools are at a stage and organized in such a way through the workflow for students to be able to pick up the concepts in a meaningful way. The student feedback shows that the concepts they learned are the most important skill set they can currently implement in the workplace.

Note

[1] The project was an integrative, interdisciplinary cross-campus collaboration to design and build a 800 ft^2 (74 m^2) free-standing, solar-powered dwelling. The Interlock House showcased new practices in construction that use less energy and create less waste. A data-acquisition system tracks and monitors performance to verify its net-zero prediction. Several POE results on daylighting strategies, human comfort parameters for natural ventilation in the humid summers, as well the multiple-year database and live interface are available to the students (Leysens & Passe 2014; Passe *et al.* 2016, 2017; Jeanblanc *et al.* 2016).

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Competing interests

The author has no competing interests to declare.

Ethical approval

This project was reviewed by Iowa State University's Institutional Review Board (IRB). The survey and survey administration methods were approved.

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Supplemental data

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