Integrating Energy Simulation in Design and Construction Studios: experiences from two undergraduate courses

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Abstract
Given the increasing importance of data-driven approaches for optimizing design and construction choices, industry professionals must understand how to evaluate building performance simulations. Still, few construction programs teach building optimizations in their undergraduate curriculum. To address this gap, students in a newly developed design and construction integration major are taught to use and interpret energy simulations in two design studios, while they work on semester-long building design projects. Literature review and case-study methods are presented, followed by a brief explanation of context. Experiences in the delivery and development of both studios are provided and include the main topics taught, assignments and projects, technology implemented in the classroom, and a summary of our impressions of the taught iterations. Finally, we conclude with four main lessons learned and recommendations to other programs and instructors looking to integrate energy analysis in their construction and design related programs.

Keywords: energy analysis, design and construction, undergraduate education, case study

1 Introduction
Understanding the life-cycle impact of design and construction decisions is extremely important to the built environment, given that most buildings are made to last several decades. With the raising awareness about buildings' impact on the environment, accrediting bodies for architecture, engineering and construction (AEC) undergraduate programs in the United States have included outcomes that are directed at addressing this gap (NAAB, 2020; ABET, 2019; ACCE, 2019). However, the level of knowledge required by accrediting bodies on this matter varies per AEC discipline. For example, while design and engineering students are required to factor the impact of their proposed design to the environment into decision-making processes (ABET, 2019; NAAB, 2020), construction students are only required to have a basic understanding of sustainable construction (ACCE, 2019). This difference may help explain the divergence in how AEC disciplines perceive the importance of sustainability seen in the research by Becerik-Gerber, Gerber and Ku (2011) – with sustainability courses being much more prevalent in architecture programs than engineering and construction.

And though construction professionals are not usually involved in major design decisions, the rise in use of collaborative delivery methods, such integrated project delivery, design build and public-private partnerships (PPP) indicate that this might change, and construction professionals may actually be increasingly more participative in design discussions and decisions. This trend combined with the general public's increased awareness towards the impact of buildings on the environment have contributed to push clients to demand that construction stakeholders "to adopt sustainable policies in construction processes" (Tan, Shen, & Yao, 2011, p. 225) Therefore, it is important that construction professionals understand how principles of sustainability affect not only the construction phase of a project, but also its design and operations.

Within sustainability, we are specifically focused on energy consumption, knowing that residential and commercial buildings accounted for 28% of the total United States end-use energy consumption in 2019. End-use energy consumption does not include energy system losses. When energy system losses are accounted, then the combined share of residential and commercial sectors is 39% of the total energy consumption in the United States in that same year (US-EIA, 2021). Furthermore, it is known that most of the energy in a building is consumed during the operating phase of a building (Ramesh, Prakash & Shukla, 2010). Therefore, it is important that all AEC stakeholders understand the importance of making energy-efficient decisions that have long term impact in buildings, which includes not only mechanical, electrical and plumbing system definitions, but also efficient building envelope design. Brncich, Shane, Strong and Passe (2011) have indicated the lack of integration of AEC disciplines as a hindering factor for teaching sustainable design and construction. Answering the call for more integration, Purdue University has launched a major in Design and Construction Integration (DCI) with the goal of bridging the communication and flow of information between AEC disciplines.

In the present paper we present our efforts into integrating energy simulation in two design studios designed specifically for DCI undergraduate students using a case-study approach. To this point, we will first present a brief background literature on the BIM based energy analysis in construction education and Project-Based Learning. Then, we present information about how the DCI curriculum is organized and specific teaching context at the School of Construction Management Technology (SCMT) at Purdue University. Each of the design studios – CM 33000 (Design and Construction for CM I) and CM 33100 (Design and Construction for CM II) is presented in general terms, including course learning objectives and class structure. Then, for each course, we provide information specific to the teaching of building science and energy simulations and how that is integrated with students' semester long design project. Finally, we conclude with lessons learned and future directions for other instructors who are looking to integrate energy simulations in their construction-based curriculum.

2 Background Literature

In the present paper, we will refer to energy analysis as the process of evaluating software results that simulate the energy consumption of a building during its occupancy phase. Some similar terms include building energy simulation (BES), building energy performance (BEP) and building performance simulation (BPS). Previous studies in construction education often include energy analysis as a part of students' training on sustainability, therefore background information in teaching about both topics to construction students is provided. Additionally, the authors will provide a brief background literature on project-based learning and its application to construction education

2.1 Teaching Sustainability and Energy Analysis in AEC programs

With recent advances in software for the AEC industry and given the importance of making certain design decisions early on, several software related to energy modeling have been developed. Many of those energy analysis tools work through as plug-in to modeling software, to facilitate the exchange of information. For example, Krygiel and Nies (2008) describe the benefits of BIM and automated calculations to facilitate sustainable building practices such as dimensioning for rainwater harvesting, solar access and recycling of materials. Therefore, the teaching of these building science concepts in AEC education can be integrated with using Building Information Modeling (BIM) tools. In fact, slightly over 40% of programs surveyed by Becerik-Gerber, Gerber and Ku (2011) indicated that they use BIM to teach sustainability concepts, though the level of teaching varies per AEC discipline, with designers being much more frequently exposed to energy analysis software, such as Ecotect, than other AEC disciplines (Becerik-Gerber, Gerber, & Ku, 2011). Interestingly, in the same research Becerik-Gerber et al (2011) indicated that architecture students are frequently exposed to at least one sustainability focused software, while engineers and construction students are less frequently exposed to software that can help with the understanding of those sustainability concepts.

Despite the importance of sustainability in the built environment, few studies have been published about academic experiences in teaching energy analysis to construction students. An example from Australia shows the importance of selecting the adequate modeling tool for architecture and construction students to evaluate the impact of their decisions (Rajagopalan, Wong & Andamon, 2016). Software choice was also a challenge presented by Lewis et al. (2015) while teaching energy modeling using a BIM-based tool, because the capabilities of the software can be overwhelming, and because some software and computer issues that can arise when using new technology.

Using a similar framework to the present study, Shen, Jensen, Wentz and Fischer (2012) proposed a standalone, elective course in BIM and energy-efficient buildings to construction management graduate and undergraduate students. A large part of the course was dedicated to improving building energy performance through energy analysis and modeling iterations. Their experience show that most students found it helpful to use a BIM as they were learning about sustainability (in their case building energy analysis). Another example is provided by Kim (2013), though the focus in this case was more on understanding and interpreting the data yielded in energy analysis, such as evaluating factors that contribute to improve energy performance in buildings, than the impact those energy analyses could have in the design of the building. Therefore, the present study fills a gap by sharing a recent experience in two courses that have integrated energy analysis in current design projects in an integrated design and construction course.

2.2 Project Based Learning

Another aspect of the current study is its use of project-based learning (PBL) in the cases. Project-based learning engages students in proposing a solution to a problem and results in the production of artifacts (Blumenfeld et al., 1991). . Another important aspect to increase students' motivation to participate in PBL is maintaining the problem broad enough to allow for students "…to develop their own approaches to answering the question" (Blumenfeld et al., 1991, p. 372). Additionally, using real world problems and shifting the focus from instructor to student-center help to engage students and increase learning (Chinowsky, Brown, Szajnman & Realph, 2006).

Pertaining to the AEC disciplines, project-based learning is often a key aspect of studio education architecture students often experience during their training (Kuhn, 2001). Other features of PBL within a design studio environment is that most projects in design studios are semester long and work is subject to multiple formal (and informal) critique sessions that help improve projects' iterations (Kuhn, 2001).

The use of PBL to teach design and construction integration has been documented in several universities in the United States and abroad (Chinowsky et al., 2006). Specifically to construction education, results from Barlow (2011) and Siotiak and Walters (2009, 2013) indicate positive results in the use of PBL in their programs. PBL can be used in small projects throughout the curriculum or can drive curriculum decisions, such as in the authors' institution (for more information see Benhart et al., 2017 and Metzinger et al., 2019)

3 Methodology

The present study is a self-report of the experiences of two instructors (and authors of this paper) in teaching energy analysis to groups of design and construction integration (DCI) students in sophomore and junior level design studios. The first author is the lead instructor of CM 33000 (sophomore level design studio), while the second author is the lead instructor for CM 33100 (junior level design studio), but both co-teach in both courses, working together in development, instruction and assessment (see Debs & Hubbard, 2020). We will start by providing an instructional context section, with the specifics of the School of Construction Management Technology (SCMT) at Purdue University and cover major specific information. Then, we will report our experiences particularly in teaching energy analysis in each of the studio courses, including:

- Learning objectives
- Instructional units
- Weekly Assignments
- Software use
- Assessment
- Lessons Learned from the two iterations of each course

And, while each author contributed more towards the description of the course they lead, lessons learned were discussed and agreed by both of us prior to their inclusion in the conclusion.

4.1 Instructional Context (University and Major Specific)

The two design studios covered in the present study are part of a new major called Design and Construction Integration (DCI) and are offered by the School of Construction Management Technology (SCMT) at Purdue University. It is important to know that the programs taught at SCMT have gone under a significant curricular restructuring in the past years, with the goal of incorporating more active learning experience, including Project Based Learning (PBL), as well as to incorporate concepts of spiral learning (Harden, 1999). To do this, courses that were previously divided in content topics (such as Estimating or Scheduling) are now combined into larger courses (usually 6 or 9 credit hours) that cover multiple topics around common projects. For more references, see Benhart et al., 2017 and Metzinger et al., 2019).

The DCI curriculum utilizes many of the same courses as the construction management program, with a few additional courses specific to design, and a building systems course which is taught mainly for DCI and interior design students (and is required before students take CM 33000). The design studios depicted in the present study are the two required design studio courses DCI students must take. The first studio, CM 33000 is a pre-requisite to the second studio, CM 33100. A basic construction graphics course is required for students to enter CM 33000, and a more advanced, BIM-based construction graphics course is required before students take CM 33100. Both studios last for 16 weeks and are structured to have 50 minutes lectures twice per week and 4-hour studios also twice per week. Lectures are meant to provide topical content and support the development of semester-long projects developed during the studio. To minimize instructor load and improve peer learning, when possible CM 33000 and CM 33100 studios (but not lecture) are scheduled during the same location and time. CM 33000 was offered Fall 2019 and Spring 2020, and CM 33100 was offered Spring 2020 and Spring 2021.

4 Case Study 1 – Energy Analysis in CM 33000

The first studio, CM 33000, is taught at the sophomore level and focuses on introducing students to the concept of built environment design and communication tools. The course learning outcomes are:

1. Develop basic projects, sketches and pre-projects related to the built environment using appropriate design conventions
2. Exercise criticism in relation to built-environment design disciplines by taking user needs, aesthetics and technical demands into consideration at the same time
3. Analyze relevant precedents in order to make informed design choices
4. Explain the feasibility analysis, supervision and coordination of integrated projects
5. Demonstrate professionalism by analyzing proper communication, team work, rules & regulations, and level of detail required within an integrated approach to the design and construction of the built environment

The energy component is included in objective 2, by considering technical demands into consideration during the design process. Students achieve this goal by working on a semester-long residential (single-family home) design, during which they have to work with peers (who act as clients of their project) to develop a reasonable program. Their projects should be individually-designed small homes (with a target size between 500 and 650 square feet). Their semester-long project is split into four deliverables:

(1) site selection – working as a group of 3 to 5, students present and defend their choice of site selection for the homes. Students' semester long projects are developed in communities. In this deliverable, students must provide a neighborhood and site analysis to justify their choice;

(2) conceptual design – students present and defend the design concept for their proposed homes (individual assignment). Examples of items they present in this deliverable are program, estimated cost, preliminary sketches and design references;

(3) schematic design – In this deliverable, students refine their concept and explore technical aspects that affect their design. Deliverables include the plans, sections, elevations and perspectives, updated cost and this is the first deliverable that students are required to expand on the energy analysis and passive options for the home. Energy-analysis specific deliverables include:

- Daylight analysis
- Information on ideal R-value for exterior wall;
- Peak Heating and Cooling loads;
- Explanation of passive architecture strategies used in the home.

(4) design development – in this deliverable, students are required to present updated plans, sections, elevations and perspectives, updated cost, renderings, building systems plans (mechanical, electrical, and plumbing plans and schedules), a detailed exterior wall section, and updated energy assessment, including yearly and monthly consumptions and energy saving options used in the project.

For the first deliverable, students use hand sketches, but then transition to design their buildings using SketchUp. Students actively work in the project during studio sections, while in the lecture, they are exposed to the principles of architectural design. Two 50-minute lectures during the semester are directly focused on sustainability principles – one by the main instructor and another by an invited guest, who describes his experience integrating those principles in design. Most of the information taught on both lectures focuses on passive design strategies.

Because the focus of this course is getting students familiarized with the complexity of factors influencing design decisions, students are only introduced to energy analysis and related software (Sefaira) in preparation for their third deliverable. Two studios in week 7 are dedicated as work-sessions to get students familiarized with Sefaira, including importing model to the web application, obtaining response curves to aid design decisions, and interpreting energy analysis results. Students have a 30-minute presentation on how to work with Sefaira and how to interpret the results, and then are encouraged to run it by themselves, with the supervision of the instructor and a teaching assistant. For CM 33000, students are not required to have a target Energy Use Intensity (EUI) goal during this design studio and are graded in their inclusion of the information requested, referring to the energy analysis, for deliverables 3 and 4.

During this studio, students also have 13 weekly assignments that help them further develop several aspects in their design. Among the 13, only three have components that directly are related to energy analysis, which include a report on the ongoing energy analysis efforts (week 7), defining their mechanical, electrical and plumbing (MEP) equipment and explaining how it relates to their buildings' sustainability (week 9), and detailing their wall layers (including definition of the R-value for the whole assembly) (week 10).

4.1 Results from Fall 2019 and Spring 2020 iterations:

Though energy analysis is not the focus of the class, we believe the introduction of the concept and a software about the topic at this level helped the students think about factors that could influence the building's energy consumption during the occupancy phase. However, because Sefaira was only introduced after their concept design presentation (deliverable 2), we believe students were very fixed in moving forward with their original concept, instead of revising more energy efficient, passive architecture alternatives.

Additionally, due to the small size of the project, the energy consumption of each home was already low (mostly under $500 annually), therefore many students were not particularly motivated to revise their model with more passive design approaches. And, in terms of building mechanical systems, many opted for split system HVAC and tankless water heater (though size of home certainly was the main driving factor) and only one opted for using solar panels.

In terms of usability, the fact that Sefaira was a plug in to SketchUp made analysis very user friendly for students. The web application for Sefaira, however, was sometimes overwhelming to students, presenting them with many options that they did not understand without instructor guidance. The vast majority of students only worked with the definition of mechanical systems, and manipulating the initial screen of Sefaira, specifically R-value, U-value and some materials' definitions as data inputs, and the heat and cooling peak loads, annual and monthly consumptions as data outputs. Sefaira web application was especially helpful during the end of Spring 2019 semester, when CM 33000 had to be taught remotely due to the ongoing pandemic.

5 Case Study 2 – Energy Analysis in CM 33100

The second studio, CM 33100, is taught at the junior level and focuses on introducing students to the net-zero energy design of commercial buildings. The organization of the course is greatly inspired by the Solar Decathlon Design Challenge by the United States Department of Energy (U.S.-DOE) (U.S. DOE, 2020). The course learning outcomes are:

1. Exercise criticism in relation to built-environment design disciplines by taking user needs, aesthetics, cost, schedule, safety and technical demands into consideration at the same time
2. Identify sustainability, efficiencies and resource conservation principles to be applied in the built environment
3. Elaborate sketches, two-dimension drawings or three-dimension models using standard design conventions to aid in the design and construction coordination
4. Demonstrate the skills associated with making integrated decisions across multiple systems and variables in the completion of a design project
5. Demonstrate professionalism by analyzing proper communication, team work, rules & regulations, and level of detail required within an integrated approach to the design and construction of the built environment.

The learning component for energy is identified in the second learning objective and is a major portion of the design process for their semester long project. Students achieve this objective by working on a semester-long development of a small commercial lot with multiple buildings. Each student determines a suitable business for the location based on surveys of potential stakeholders. The size and type of building are based on building use and required needs for the facility. The students work as a team to develop their site and then individually to design their building. Their semester-long project is split into four deliverables:

(1) building selection and site development – Faculty identify a location for commercial business development and students determine the type of commercial businesses for the location and develop the site. The location may be an existing commercial site that will be re-developed or a green field site. Working as a group of 3 to 5, students provide a rationale for their commercial building selection based on stakeholder feedback and present initial schematics of their building locations. Students also develop a transportation plan how people access the site (pedestrian, vehicle, bus, bike, etc.) as well as a neighborhood and utility analysis. Students present and defend their choice of commercial business and the overall site development plan.

(2) conceptual design – students present and defend both their building design for their proposed commercial business (individual assignment) and their updated site plan (group assignment). Students are provided with the "Solar Decathlon Design Challenge Guide" (U.S. DOE, 2020) to assist in understanding important energy design features in their building and to assist in formatting their final report. Examples of energy related items that are required for this deliverable include initial plans for MEP system to reduce energy, locations that consider passive strategies, and an initial Energy Use Index (EUI) based on square footage and building type.

(3) schematic design – In this deliverable, students refine both their building and group site concept utilizing additional energy information. Main energy deliverables include:

- Summarizing the energy design goals the team considered when creating and developing the design.

- Providing an energy analysis and detail sustainable design features. Students note how EUI has evolved over the design. They also provide both energy usage estimates and power estimates from renewables. Information on how much offsite power will be needed to the operate facility is also included in this deliverable.
- Financial information on solar panel installation including Life Cycle Costs (LCC) are required for the deliverable.
- MEP preliminary plans:
    - Mechanical plans – location of mechanical rooms, system layout
    - Plumbing – location of mechanical room and piping runs
    - Electrical – electrical closets, schedule of both AC and DC ports

(4) design development – in this deliverable, the students are required to submit detailed design plans and include the following energy information:

- Summary of calculations for onsite or off-site renewable energy (e.g. photovoltaic, geothermal, wind turbine, etc.) to offset the annual energy consumption of the building.
- Final EUI for the building with supporting documentation
- Summary of major inputs for the energy model, including envelope characteristics, lighting power densities, plug load densities, HVAC sizing capacities, and HVAC system efficiencies

Similar to the CM 33000 class, the development of the design is mainly done during the studio portion of the course utilizing Autodesk Revit. The lecture periods are focused on passive and active design strategies to reduce energy consumption and methods to calculate the energy reduction. During the course of the semester there are thirty 50-minute lectures of which eleven are devoted solely to energy design. The course utilizes the book “Net Zero Energy Design: A Guide for Commercial Architecture” (Hootman, 2012) to support lecture topics. Lecture topics include: net zero design concepts, passive energy design, integrated design methods focused on energy usage, establishing energy targets and baselines, design fundamentals of net zero buildings, energy efficient building systems, renewable energy options, and building envelope design for high efficiency. Other lectures topics tie into the concept of energy design such as economics evaluation of building construction and operation.

As students progressed through their design, they continually are updating their building’s energy usage. In order to determine energy usage during the various stages of the design process a number of energy calculations and software programs are introduced. The programs utilized include:

1) Energy Start Target Finder (Energy Star, 2021). This web-based program can be utilized in the preliminary design phase to determine both baseline EUI values and target EUI values. The program will provide baseline EUI calculations with as little information as the location, building type and building square footage. More advanced EUI calculations are also available with additional building information.
2) PVWatts Calculator (NREL, 2021). This web-based program provides the amount of energy the site would gain from a solar panel installation either on the roof of a building or as a solar farm near the building site.
3) Ekotrope Wall, Floor and Roof Calculator (Ekotrope, 2021). This web-based program provides information on insulation R values for different wall, roof, and floor designs. As their design progresses these design values are important for other software systems that need this information to correctly calculate energy usage.
4) Sefaira (Trimble, 2021). Similar to CM 33000, Sefaira is used to determine final EUI calculations. The software program is an add on used in Autodesk Revit. Once the students have a model of their building they can start to run the Sefaira software to see updated EUI information and specific energy usage data. An important input for the Sefaira model is the R values for walls, floors, and roofs. The Ekotrope software is used for this input.

During this studio, students also have 13 weekly assignments that help them further develop several aspects in their design. Components related to energy analysis include:

- Week 3 – report on design challenge criteria and setting goals. The Solar Decathlon Design Challenge provides design challenge criteria for a number of building design attributes. Students set goals for: Energy Performance, Engineering, Financial Feasibility and Affordability, Architecture, Market Potential Operations, and Comfort and Environmental Quality.
- Week 5 – Report on student review of potential passive architecture technology to reduce energy consumption in your design.
- Week 6 – Students prepare and present a short lecture (15 minutes) on a renewable energy system and how it could be implemented in their particular site.
- Week 7 – The students perform a cost benefit analysis of the photovoltaic system. The costs, maintenance, salvage values and other costs of the system operation are taken into account to come up with a Life Cycle Cost (LCC) and other economic data such as simple paybacks and Return on Investment (ROI).
- Week 8 – Students provide and initial landscape plan for thier building and immediate surroundings. Students discuss how landscaping will play a role in building/site energy performance and/or water conservation.
- Week 11 – Students provide an update on their design challenge goals from the week 3 assignment.
- Week 12 –Students develop a pro-forma of one of the businesses that occupy their building. This provides an opportunity to relate business income with cost of the building and the proposed energy systems.

5.1 Results from Spring 2020 and Spring 2021 iterations:

The focus on energy usage throughout the class supported student understanding of building systems and the importance of considering energy usage throughout the design process. The Spring 2020 class was limited in the amount of 3D modeling and energy software implementation due to the Covid-19 Pandemic making it difficult for them to utilize Revit and other university software. The Spring 2021 did not have those restrictions and the class proceeded as planned. While both semesters covered the same general material the observations for this section are more focused on Spring of 2021. The student building design and overall site designs incorporated many energy efficient features that were both passive in nature such as shading and daylighting and active systems focused on HVAC. The students were able to calculate EUIs during multiple phases of their design, determine photovoltaic power production, and implement low energy systems such as geothermal heating/cooling.

Many of the building energy design features were straightforward to determine energy savings while some systems were challenging. For the more challenging systems only basic energy savings information was calculated. For example, solar power was relatively easy to calculate the projected annual electricity output and determine the reduction in energy consumption for the building. For the Spring 2021 semester, the students used a geothermal heat pump (Commercial Reversible Chiller) coupled with radiant floor systems for heat and chilled beans for cooling which is more difficult to determine the overall impact due to the complexity of the system. Fortunately, Sefaira coupled with their Revit model had options for these types of systems. Students could update EUIs of their proposed HVAC system based on the Revit model of their building and the R-values for their building envelope. While students were able to get energy performance data from Sefaira there tended to be program errors and it was difficult to confirm the accuracy of the numbers. In Spring 2021 a DC grid system for the building sites was incorporated. The DC grid system links directly to a portion of the solar power system and was designed to charge electronics, power lights, and use for other low voltage applications.

One teaching tool that helped the energy design process in Spring 2021 was a set of construction documents from an existing university building that used a geothermal system and incorporated many active and passive energy strategies. Students and faculty used these construction documents to better understand many design details such as geothermal systems, implementation of radiant heating and cooling, and daylighting techniques.

6 Lessons Learned and Recommendations

Our experiences echo some of the findings by Lewis (2015), in that we had some technical issues while running the energy analysis software, some issues with number accuracy and the fact that the many options given by the software may sometimes overwhelm students. In addition to that, in a process of consensus, we as both instructors of the courses and authors of this paper agreed on the following four lessons learned related to the use of energy analysis in both our design and construction studios:

- By performing energy analysis into an integrated design project, students can better visualize the long-term impact of equipment choice and building components in the lifecycle of a building. This benefit is strengthened by the possibility to assess and compare construction and operating costs, which also gives students a better understanding of the life cycle cost of a building.
- The use of energy analysis software is helpful to students, however, the lack of transparency about the analysis sometimes makes it challenging for novice learners to interpret and assess the accuracy of the results. We recommend that an introduction to software for energy analysis be done at the undergraduate level with close scaffolding by instructors, who can help students navigate the software and interpret results.
- Defining the right moment of when to introduce energy analysis remains as a point of improvement. Because if analysis is done too early, the information might be too vague for students to directly apply to their project. On the other hand, if given too late, students may already be set into their design and not be willing to make alternative design options incorporating more passive architecture strategies.
- Specifically for the more advanced studio (CM 33100), we are still debating how much in depth to discuss about the design of mechanical building systems for commercial facilities. Our goal is to include enough so that students understand how advanced renewable systems work without exceeding the scope of the course.

And, for future studies, we recommend: (1) obtaining student feedback through survey or interviews, to determine students' understanding of energy analysis and its importance on the built environment; (2) evaluating other energy analysis software that can be used in the course; and (3) determining the optimal point in which energy analysis should be introduced in each studio.

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