# 103 Lessons Learned from a Multi-year Initiative to Integrate Data-Driven Design Using BIM into Undergraduate Architectural Education

J. Benner and J. J. McArthur

**Abstract**

The question of how to best integrate BIM into the curriculum is one of significant debate, especially at the university level. This paper presents the ongoing development of a third-year BIM integration curriculum within an Architectural Science undergraduate program, with a specific focus on a project designed to introduce students to data-driven design. This project has students create a series of massing models in Autodesk Revit, which are analyzed for both initial cost and life-cycle energy performance and these iterations guide studio project development. This paper presents the pedagogical approach developed to introduce students to advanced BIM use cases such as cost analysis and energy simulation and evaluates the first three years of integration of these topics into an architectural curriculum. From 2015 to 2017, over 300 students participated in this project, creating and evaluating over 1000 model iterations. Student feedback obtained through surveys and course evaluations demonstrates that this project is effective not only to provide students with increased BIM capabilities, but also encourage them to synthesize a broad range of data generated through simulation to refine and develop their designs.

**Keywords**

Pedagogy • Energy simulation • BIM • Data-driven design

## 103.1 Introduction

The last few years have seen an increasing interest by the architectural profession in the integration of simulation into the design process, frequently referred to as “data-driven design”. Within a pedagogical context, there is similarly significant debate regarding the best way to integrate BIM into curricula, particularly in the design disciplines (architecture and engineering) at the university level.

Several educators have developed approaches for integrating into the architectural curriculum, through studio/design courses [1, 2], construction applications [3], or capstone projects [4]. The systematic review by Abdirad and Dossick [7] provides an excellent summary of BIM pedagogical approaches through March 2015 and provides a comprehensive reference for readers, while Poirier et al [6]. provide further insight and a summary of recent industry-academic workshops on this topic. Of particular interest to this work was the application of Bloom’s taxonomy to BIM education outcomes by Sacks and Pikas [5], who recommended that Levels 1–3 (Knowledge, Comprehension, and Application) be the objectives of undergraduate education and that Level 4 (Analyze) constitutes best practice at the graduate level.

This paper presents the ongoing development of a third-year BIM integration curriculum within an architectural science program, with a specific focus on a project designed to introduce students to data-driven design, particularly the use of BIM-based building performance simulation and cost analysis as an iterative design tool. This mirrors increasing industry adoption of similar practices, whereby BIM is increasingly integrated with energy simulation and other analysis tools, allowing designers to more comprehensively consider building performance as a part of the design process. The objective of

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the research presented in this paper is to develop a pedagogical approach to introducing students to advanced BIM use cases such as cost analysis and energy simulation, and to evaluate the first three years of integration of these topics into an architectural curriculum. This pedagogical research was undertaken in parallel with a technical study investigating the relative accuracy of BIM-based energy simulation with industry standard tools at the schematic design stage [8].

## 103.2 BIM Integration Toolkit

The BIM Integration Toolkit was initially developed in 2015 to introduce third-year undergraduate students to intermediate and advanced BIM concepts and forms an integral part of Ryerson's digital curriculum integration strategy, building on first-year virtual reality (VR) use in studio, second-year introductory BIM tutorials focused on design authoring and the use of augmented reality to engage with real site conditions, and supporting fourth-year advanced digital design and fabrication activities. This approach follows experiential learning principles, and is described in detail by Hui et al. [9].

Rather than focusing on *how* to use the software, which was introduced in the first half of the undergraduate program, the BIM Integration toolkit focuses on *why*, discussing the impact of BIM on lifecycle project delivery and how it can be used to integrate simulation and analysis to improve building design, construction, and operations. This focus on practice implications and holistic understanding aligns well with the recommendations made by Sacks and Pikas [5]. The objectives of this toolkit are to:

1. Prompt reflection and critical thinking on the fundamental shift in how buildings are designed and visualized between CAD and BIM design paradigms.
2. Explore how multi-disciplinary coordination can be facilitated or hindered by the use of BIM.
3. Understand how BIM is used by various parties for analysis, cost estimating and scheduling, and operations management, and what the key requirements are for architectural BIM models to facilitate this use.
4. Understand how building systems are integrated by exploring a complete, multi-disciplinary BIM model of a campus building and comparing it to as-built conditions.
5. Gain experience in simple BIM-based energy simulation and cost analysis and apply this knowledge to refine a design.

The toolkit consists of a set of elements designed to supplement project management and design studio courses, including real project case studies, question and answer interviews with both practicing architects and general contractors, video tutorials guiding students through BIM techniques such as energy modeling and cost estimation, and a comprehensive multi-media literature review including peer-reviewed literature, online lectures, relevant industry blogs, and technical resources. This toolkit is supported by an instructional guide for professors, including recommended in-class and assigned activities. A key element of this toolkit—and the focus of this paper—is a project linking the integrated design studio building form development (massing) activity with the Project Economics course and using simulation to test design alternatives. This toolkit was rolled out in the fall of 2015/16 and adopted in the Project Economics (project management) course, and Integrated Design Studio I and II, and repeated in 2016/17 and 2017/18. This project was refined over this period based on lessons learned.

## 103.3 Case Study Methodology

A total of 310 students participated in the data-driven design project between 2015 and 2017, creating and evaluating over 1200 model iterations. In each year, these students completed this project as part of a third year mandatory core course.

The data-driven design project was initially introduced in 2015 and was completed by 101 students. In this first iteration, students undertook a $2 \times 2$ factorial study considering two potential building shapes ("massings"), each tested with two different building envelope approaches. In the first year, these envelope approaches were prescribed as one of: (1) two dramatically different envelope types, noting that opaque facades must include a reasonable amount of glazing for daylighting and views; (2) the same cladding material but dramatically different window-to-wall ratios (WWRs), with WWR consistent on each facade; or (3) consistent WWR but comparing even distribution (e.g. 40% glazing on each façade) to a distribution with the majority of glazing on the south facade and limited glazing on the east and west. Figure 103.1 shows a sample set of massing and envelope combinations generated in this initial project using the third option described above. Once these four models had been created, students undertook two investigations. First, a simplified capital cost estimate was created

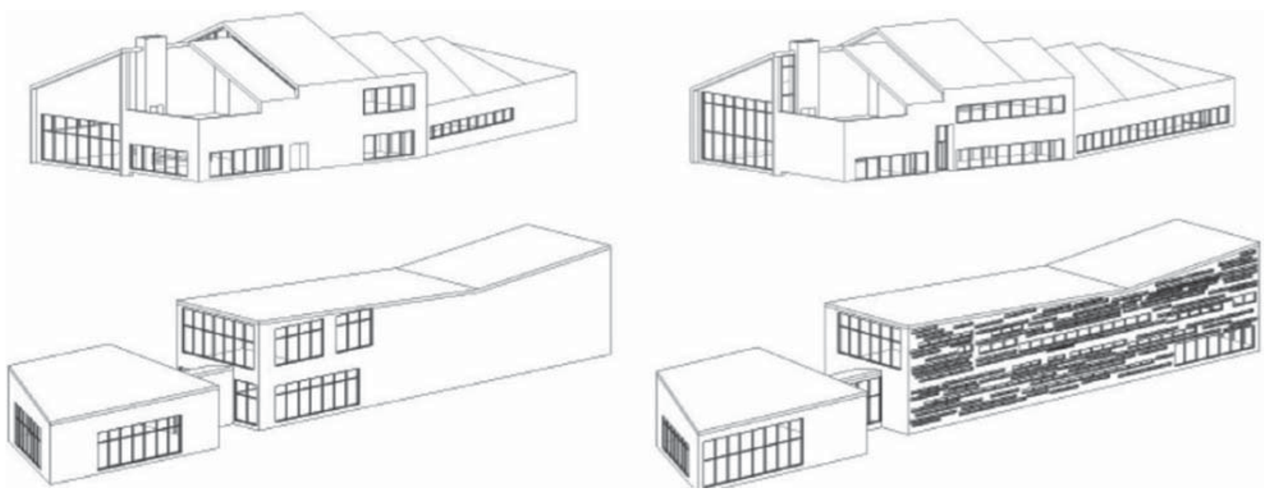

**Fig. 103.1** Sample massing and envelope concept combinations (Fall 2015) (used with permission)

considering only building envelope quantity take-offs; due to the level of development of this project in the studio (conceptual massing) only the form had been developed and more detailed costing was not feasible as was discovered early in the first year of implementation. The second analysis was that of building lifecycle energy. Using Green Building Studio, each student performed an energy simulation using energy settings provided in the project brief. Students synthesized their results into a memo summarizing their justification for each envelope and massing considered, the results of the cost and energy analysis and their recommendations for the most cost-effective design. This pushed the students to achieve Level 4 (Analysis) and begin to achieves Level 5 and 6 (Synthesize and Evaluate) of Bloom's taxonomy as defined for BIM education [5].

Based on the best results from these two years, the 2017 project was revised to guide students to engage more fully with data-driven design concepts. In this new iteration, students analyzed their studio project massing and investigated design iterations to try to improve energy performance. Having performed this preliminary evaluation alone, they teamed with a second student to compare results from these initial explorations. Students then worked together to create a fifth iteration to further reduce the life-cycle cost of the better-performing massing and documented their findings in a poster.

Autodesk Revit [10] was used for quantity take-offs, while Green Building Studio (GBS) [11] was used for building energy modeling. A comprehensive set of tutorials was created to guide students through the mechanics of this process.

Model results from both 2016 (representing the first iteration) and 2017 (second iteration) were reviewed by a Professional Engineer with energy simulation expertise, who reviewed relative end use ratios, simulated energy use intensities (EUIs in ekWh/$m^2$/yr), and the energy end-use breakdown to identify modeling errors and evaluate design refinements. Note that in Years 1 and 2, students were primarily using Revit 2015 or 2016, whose GBS plug-in provided detailed heating and cooling load breakdowns, for example *window conduction* and *infiltration*, as standard outputs. In Year 3, many students used Revit 2017, which no longer provided these breakdowns, making specific modeling issues more difficult to diagnose. Instead, students were able to export end-use breakdowns, for example *space heating*, which was used for model result checks to inform the statistical analysis presented.

Learning outcomes were evaluated primarily through qualitative evaluation of the student projects. In iteration 1, the grading rubric equally weighted the correct execution and documentation of quantity take-offs and energy simulation (25% each) with the students' analysis and discussion of the results obtained (50%), which was focused on whether these results were realistic and the appropriateness and value of using the GBS plug-in for energy simulation at this stage of design. In iteration 2, the rubric equally valued four elements: energy analysis and cost estimates (individual mark), the refined design (group), and presentation (group). Within each category, comprehensive and correct execution as well as depth of critical analysis formed the basis for the grade assigned. The complete rubric is provided as supplemental material to this paper.

## 103.4 Case Study Results

Over the first two years, 206 students completed this project, resulting in 824 models. In the third year, the pairing of students resulted in the creation of only 231 models.

### 103.4.1 First Iteration (Years 1 and 2)

In Year 1, a BIM knowledge benchmark was established using a start-of-term survey and an evaluation survey was conducted at the end of term to both quantify learning outcomes and inform toolkit refinement and use in future years. 14 questions were asked on this quiz, covering both professional practice and technical aspects. Results showed improvement on all but one question (which had 98% correct responses initially), with four showing statistically significant differences (95% confidence). The most helpful element was from the students' perspective were the data-driven design project (33%), followed by the tutorials for GBS (26%) and quantity take-offs (16%), respectively. When asked which element was most valuable and why, representative student comments are: "*The video tutorials we received for project 1* (were the most valuable)*, simply because I continue to find myself using them for other projects, especially the Revit design ones.*" and "*For the individual project, we had tutorials, 3 of them were very important for the project to do energy analysis, but also the other tutorials were really good too. I never knew that BIM could give all the light, energy, analysis, in a very short amount of time*."

Starting in Year 2, the iteration savings were analyzed statistically alongside error rates and the frequency of design insights arising from this work. On average, students were able to achieve a 26% reduction (interquartile range (IQR):15–34%) in the building performance using GBS defaults for 12/7 occupancy. Of these models, 94% provided expected results, while 25 (5.9%) provided simulation results inconsistent with the expected building performance. An investigation into these models classified these issues as excessively high underground losses likely due to incorrect ground plane definition (16),

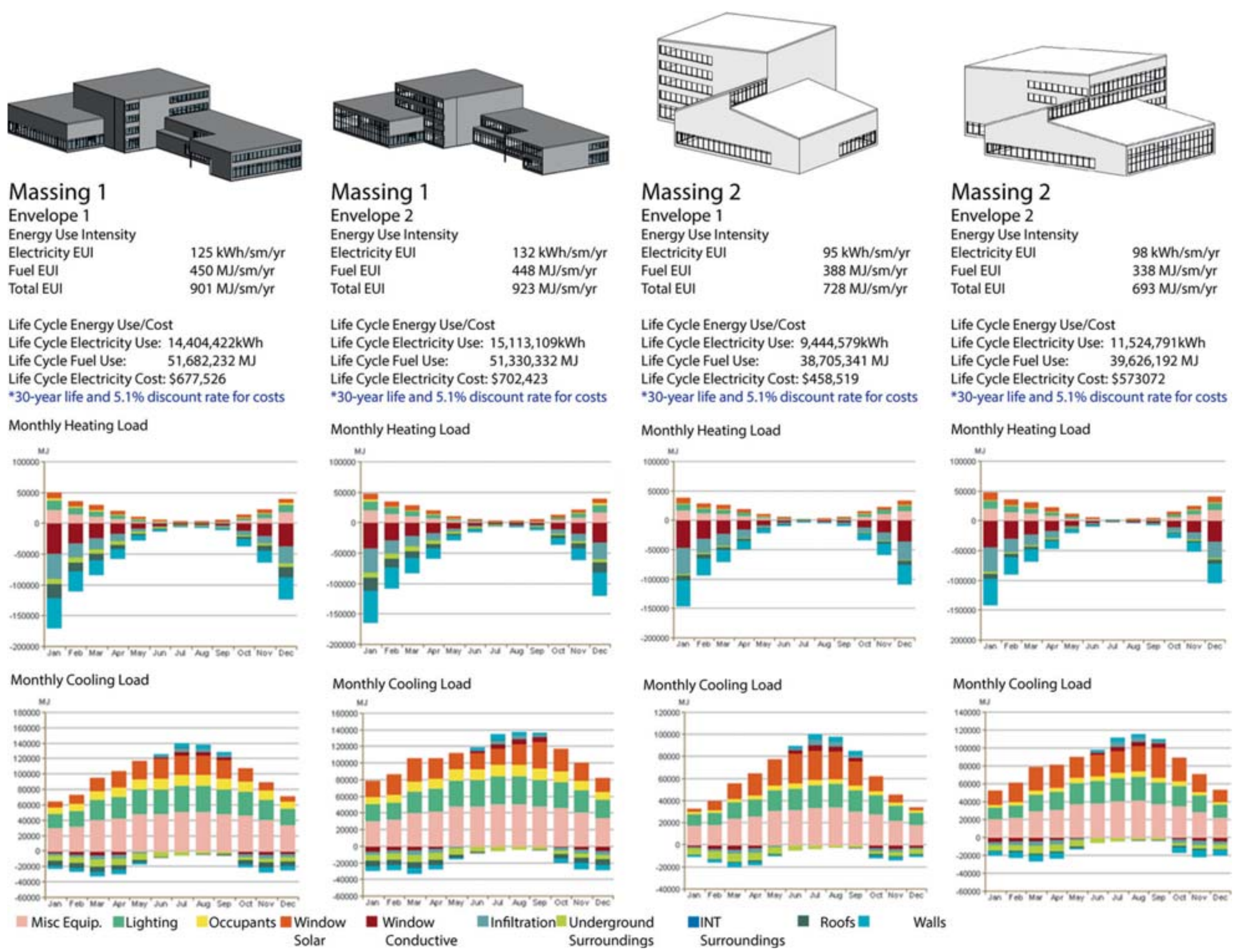


**Fig. 103.2** Factorial investigation—case study #2 (used with permission)

zero window solar or conduction gains due to incorrect window family definitions (5), highly variable occupant densities due to inconsistent energy settings (2), and extremely high roof losses due to inconsistent material assignments (2).

Three student investigations have been selected to demonstrate student engagement. The first student tested variations in the WWR as well as overall building compactness. Describing the first investigation, they noted: "*This exploration showed how slight adjustments to the components of a facade could produce great savings on a project. It also showed the ability to more easily make comfortable spaces, putting less strain on mechanical systems to make up for the heat exchange*." Investigating this in conjunction with a more compact form, they noted that as-predicted, this was the most efficient massing. This student continued to use their model to guide design beyond this course and through to the end of the design project the following term.

A second student project (Fig. 103.2) investigates the impact of a tighter envelope with the same overall floor area, along with dramatically reduced glazing for each, and shows the student's response to the building performance simulation at each iteration. They concluded that "… *although amount of glazing plays an important role in determining the energy consumption of a building, the mass form is also a large determining factor in its performance. A more condensed mass will reduce energy loads significantly, and appears to be more effective at doing so than glazing reconfigurations*."

In the third case study, the student was clearly proactive in using GBS as a data-driven design tool. Figure 103.3 shows the massing development in response to the results and includes the student's narrative on how they were used to shape the final design.

This example clearly illustrates the stepwise iteration of design with constant feedback offered to designers through the use of GBS for early-stage building performance simulation. These case studies are representative of the student experiences as a whole; 96% of students noted the daylight-heating/cooling load trade-off of high amounts of glazing and were able to improve building performance through adjusting both the window-wall ratio (96%) and/or specific glazing orientation (44%). In addition, 53% of students used this exercise to quantify the energy savings associated with increasing the compactness of the built form, and were able to use this insight to further refine their schematic design.

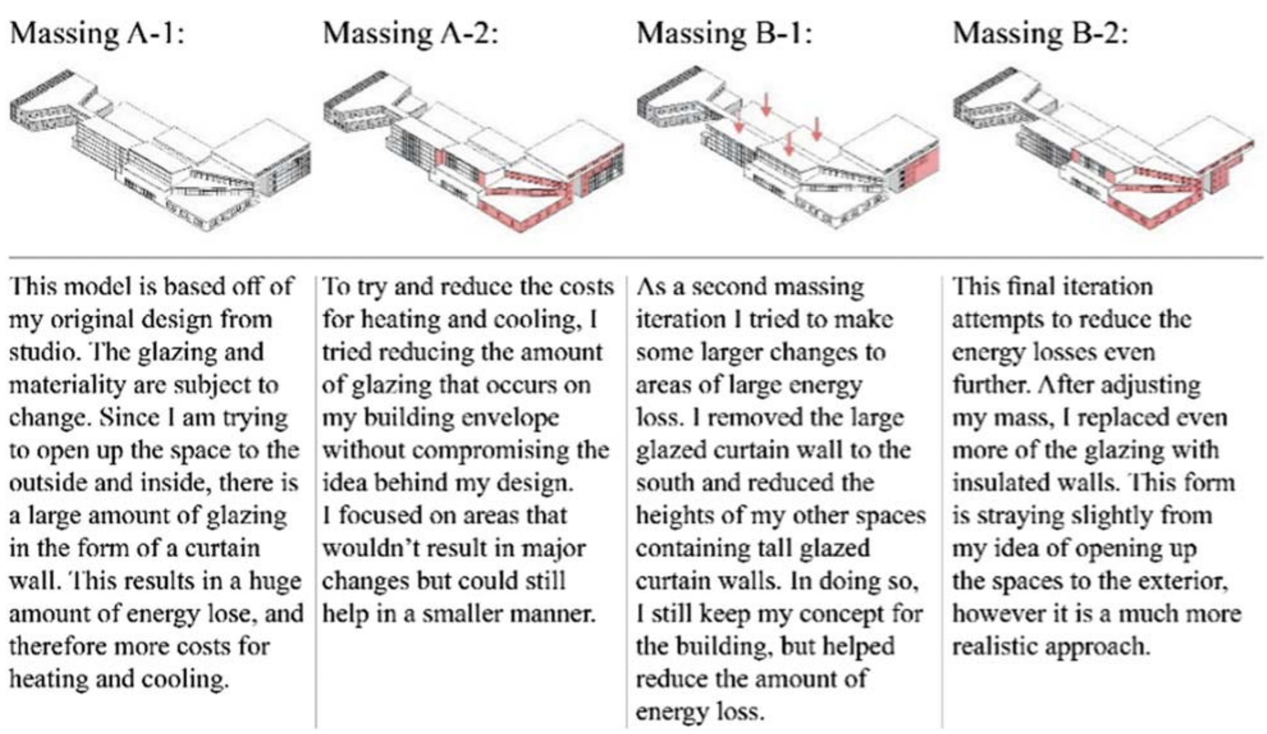


**Fig. 103.3** Factorial investigation—case study #3 (used with permission)

## 103.5 Second Iteration (Year 3)

In the third year, the data-driven design project was refined to guide students through a process similar to that illustrated in Fig. 103.3. This refined project was completed in pairs to provide students with peer-learning and teaching opportunities. Through their massing study, students generated a total of 238 models, a selection of which are illustrated in Fig. 103.1. In the individual portion of the project, 75% of students achieved EUI savings on their first design iteration. On average, individual students were able to achieve a 14% reduction (IQR: 5–18%) in building performance using GBS defaults for 12/7 office occupancy. Of the models developed, 89% provided reasonable results, based on evaluation of EUI, end-use breakdowns, and fuel use ratios. Because the final design optimization was based on cost, rather than just energy, only 27% of the final proposed massings resulted in an improved EUI, though 76% decreased their lifecycle costs. On average, the lifecycle cost reduction achieved was 5% (IQR: 1–16%).

Three student investigations have been selected to demonstrate student engagement with the refined project in contrast to the previous iteration. In the first, the students noted that the greatest benefits occurred when the building compactness was increased, the east-west axis was elongated to permit significant glazing on the south façade, and minimize glazing to the north. Applying these strategies to refine the initial massings resulted in approximately 12% life cycle cost savings compared to all previous iterations. In the second case study, one student started with a central glass atrium feature, but determined that this was a significant source of solar gains during the cooling season and winter losses. This was removed in their second iteration, resulting in a 13% energy (EUI) savings. Their partner similarly noted the effect of high glazing percentages on the southeast and southwest facades, and reduced the window wall ratio to achieve 12.5% energy savings. The final design was determined after multiple glazing iterations and combined the desired architectural features of both approaches.

In the third case study, the student maintained the overall form of the massing, and manipulated the window to wall ratio to assess the difference in breakdown of the electrical loads. Figure 103.4 demonstrates this exploration in the massings. From this analysis, the student was able to identify and understand the correlation between electrical lighting loads and mechanical loads in regards to the percentage of glazing. This understanding was able to be applied to the student's final model massing model that showed a 6% decrease in the building's total EUI from the previously most-efficient massing. The logic that brought the students to this final design is expressed in their own words as-follows: "*… The massing was further developed to increase its efficiency by ensuring that the window to wall ratio is within the ideal range … The curtain wall area and the number of windows was decreased to avoid excessive heat loss during the winter seasons (…) floor area was also decreased by combining programs to create a more compact building to lessen energy usage. (…) Better materials were*

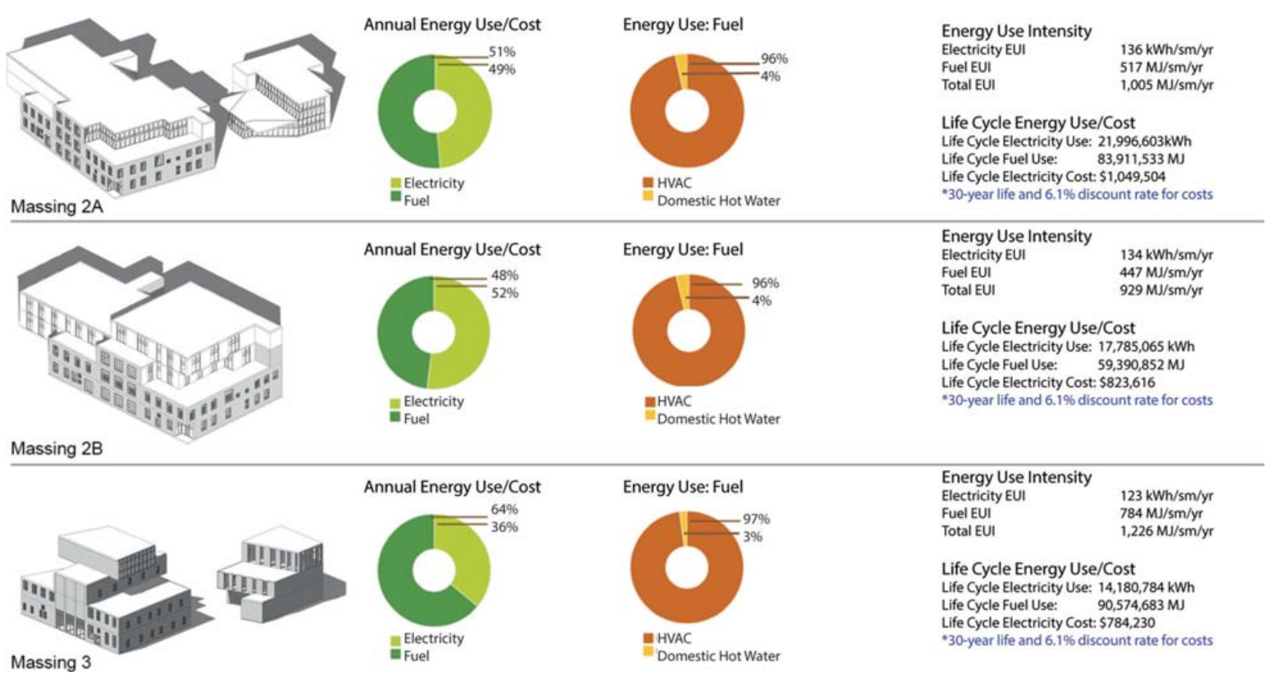


**Fig. 103.4** Year 3 example [used with permission of students (names withheld)]

*invested to the exterior cladding to increase efficiency for the long run. This investment contributed to the reduction of energy use in the building … wind is mostly coming from West Southwest direction; the windows allocated west of the building were decreased to minimize wind infiltration. Certain volumes were also oriented in an East-West direction to allow an even distribution of natural light thus increasing efficiency throughout the building.*"

Once again, the majority (76%) of students noted the daylight-heating/cooling load trade-off and were able to improve building performance through adjusting the window-wall ratio (95%) and/or increasing envelope R-Values (41%). In addition, 69% of students used this exercise to quantify the energy savings associated with increasing the compactness of the built form, and were able to use this insight to further refine their schematic design, in addition to the finalized form.

## 103.6 Discussion

It is apparent from student work that in the first iteration of the project, students consistently achieved Levels 3 (Apply) and 4 (Analyze) of Bloom's taxonomy as applied to BIM [7], with some progressing into Levels 5 (Synthesize) and 6 (Evaluate). When the project was restructured to specifically guide students to use the BIM-bases analysis as a design tool, students intrinsically synthesized and evaluated their results to generate new and improved design iterations, thus consistently engaging them at higher levels. While a minority of students (<10% overall) had modelling issues, the tutorials provided adequate support to resolve issues. A very small number of students (<5 per year) sought support from the professor or teaching assistant to resolve model issues. Student feedback obtained through surveys and course evaluations demonstrated that this project is effective not only to provide students with increased BIM capabilities, but also encouraged them to synthesize a broad range of data generated through simulation to refine and develop their designs.

The learning outcomes of the project were significant. Beyond demonstrating an increased degree of comfort using BIM software and specific BIM uses, this project guided students to engage with the broader curriculum. For example, many expressed surprise at discovering the heating and cooling penalty associated with glazing far outweighs daylighting savings due to Toronto's extreme climate (+31 °C summer/−22 °C winter design conditions). Students engaged with previous building science course material to address this issue as they worked to refine their design. Because this formed part of a project economics course, the students also gained insight on the relative cost of construction (25%) versus operation (75%) and the necessity of energy-efficient design.

## 103.7 Conclusions

The results of this study demonstrate how an experiential approach to BIM focused on iterative design-analysis-synthesis cycles permit students—even at an undergraduate level—to engage in a sophisticated manner with BIM. As demonstrated in the selected examples and statistical analysis presented, students consistently demonstrated an increased understanding of building physics as well as project economics through their engagement with this project, effectively using BIM to undertake simple analysis and evaluate this analysis to make informed decisions to refine their designs. While the incremental refinements demonstrated by the students were modest, on the order of 10–15%, they demonstrated the use of BIM for analysis, synthesis, and evaluation, thus beginning to achieve the ambitious recommended by Sacks and Pikas [5]. Based on the success of this project, the use of GBS for design analysis and refinement have been regularly integrated into the design student course in the winter term, providing students with additional opportunity to engage with simulation to evaluate design alternatives and achieve improved building performance.

The key student learning outcomes were: (1) a better understanding of how particular design decisions—particularly the impact of glazing and overhangs—affected building performance, and (2) significantly increased confidence with BIM as an interactive design evaluation, rather than simply design authoring, tool. As noted, some students had poor modeling skills, resulting in erroneous results; the majority of those students were further unable to determine that their results were incorrect. A one week BIM bootcamp for 2nd year students has been developed to help address the former issue while the latter is unsurprising as energy simulation is a specialized skill taught primarily in 4th year or graduate courses. To address this issue, a document highlighting the key GBS outputs and the pattern of expected results was provided to help students interpret these results.

While the approaches presented have been tested over multiple years, the single-program context limits generalization. However, this approach aligns well with recognized best practice and pedagogical recommendations. Future research to test this approach in other contexts would be valuable to better gauge the results; the corresponding author would be pleased to actively support such work. An additional line of inquiry is the potential application of parametric design tools to enable rapid refinement and testing. This was tested as part of a competition entry [12] to achieve a net-zero building design. Finally, it would be valuable to track how increasing BIM execution (software) knowledge obtained prior to university will change student engagement with the curriculum. Given the focus on the *impact* and *appropriate use* of BIM, this increase in skill level is unlikely to dramatically change the content delivery, though it will ease the software learning curve for these students.

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