Education
Teaching Building Performance Simulations to students with a diverse background by using a Control Method

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Abstract
Performing advanced and reliable Building Performance Simulations (BPS) in order to study, for example, the energy use of future buildings is an important ability to gain as a future energy specialist. Learning and understanding BPS software and results may be arduous, notably for groups with disparate knowledge. Frustration may arise among students, making learning even more difficult. In this paper, we use questionnaires to evaluate the introduction of a so-called “control method” in the first BPS teaching module of a Master Programme attended by students with diverse backgrounds. The control method verifies – or controls - the results of a basic energy simulation of a traditional shoebox model with those obtained via an Excel sheet based on building code. Through a smoother and guided introduction of BPS to novices, the method aims to increase the level of confidence in BPS tools and more independence in the work. The questionnaires’ answers suggest that the method fulfills its goals to a reasonable extent.

Introduction
One fundamental ability for energy specialists is the competence in Building Performance Simulations (BPS). Teaching BPS and critically analysing the results may be challenging, especially in courses with students of diverse backgrounds (Tojo and Kiss, 2015).

Lund University provides a two-year Master Programme in Energy-efficient and Environmental Building Design, yearly attended by about 25 students. They have background in engineering and architecture, from different countries. BPS is introduced early in the programme. The adopted software are widespread among Swedish and international practitioners, and they include: a 3D modelling interface, a visual programming environment, and the actual energy simulation engine. The aim is to generate a tight link between education and practice, which is in line with IBPSA's view (Clarke, 2015) and the expectations of students themselves (Göçek and Dervishi, 2015).

BPS tools are introduced by using collaborative learning (Cohen, 1994) in groups of three-four students. Literature on group cognition seems to support learning in small groups, particularly for computer technology (Lou, Abrami and D’Apollonia, 2001), while diversity in the group is both an opportunity and a barrier. For example, Curşeu and Pluut (2013) have clearly demonstrated that gender and nationality diversity have potential to increase the collective knowledge of the group, but diversity in the team’s expertise negatively affects the quality of teamwork.

Based on anecdotal observations, we argue that also diversity in previous knowledge is a barrier to group development. In the past years, we observed that teams with different areas of expertise tended to share their workload based on individual strengths, which led to an unsought shift from collaborative learning to cooperative learning (Dillenbourg et al., 1995). Individual strengths can be software skills (i.e. how to practically handle the software) or theoretical skills (i.e. how to set-up the input and scrutinize the results of a BPS). If the groups tend to use cooperative learning, the Master programme objectives cannot be reached, as the student will tend to simply reinforce the existing individual strengths.

We also argue that the lack of trust in newly introduced software enhances cooperative learning. Namely, if the student faces difficulties in understanding functioning, input or output of one of the software, then the student will contribute to the group report only in the areas or software where she/he has already competences.

Therefore, cooperative learning may be reduced by enhancing trust in software. This is supposed to also boost student’s self-confidence and reduce a sense of frustration. In order to do so, we introduced a so-called ‘control method’.

The control method verifies – or controls - the results of a basic energy simulation of a traditional shoebox model performed with a BPS tool with those obtained via an Excel sheet based on building code.

The control method is thought for introducing BPS to classes with significantly different educational background and where time in class to teach BPS is limited. The pedagogical purpose is to improve trust and understanding of the newly introduced software, hence prompting the student to use BPS independently during the individual study time.

The control method does not aim to teach BPS faster or at very advanced level, but it simply tries to bring the entire class to a level of knowledge to which each student feels capable to run and interpret a simple BPS in an independent way.

This paper reports the evaluation of the control method by exploring students’ satisfaction, understanding of
software, and reduction of cooperative learning. To achieve this, two classes were compared, before and after the introduction of the method. We surveyed these students via anonymous online questionnaires with mainly open-ended questions.

Need for a customized teaching method

In our programme, we teach BPS using Archsim and EnergyPlus (E+) via the Grasshopper (GH) interface (Solemma LLC, 2019). In this course, the GH environment is chosen because the students will work extensively with this environment in the following courses and a gradual exposure to GH was expected to give the best learning experience for students. One difficulty is that, in this course, three different type of tools are introduced for the first time: (i) a 3D CAD modelling software (Rhinoceros 3D), (ii) a visual programming language (GH), and (iii) an energy simulation software (E+). On top of mastering these three different tools, students should also understand relations between building parameters and its energy performance.

Students in the programme have different prior knowledge; some are new to energy simulations, some never modelled in 3D, most of them are completely new to visual programming language, and few of them have experience with all the tools but they may have previously used other software (e.g. Dynamo instead of GH).

In summary, the students face the following challenges:

- They have to learn three different tools at the same time. We noticed that the steepest learning curve has been the introduction of GH and gaining an understanding of energy simulations.
- They have to understand the relationship between the energy performance of a building and the geometry and characteristics of the building. Students should have prior knowledge about building physics, but it may have been taught in a different way and maybe never applied to a project.

Helping the students throughout these two challenges is a difficult task for the involved teachers. We investigated existing pedagogical papers on the topic before conceiving a method ex-novo.

For example, Reinhart et al. (2012) introduced a game-based method to improve students’ understanding of different design solutions. The game proposes a range of design choices that, combined, offer about 400 000 solutions with different energy use intensity (EUI) and costs; students group achieving the lowest EUI and acceptable costs are awarded with extra credits in their examination. The method is extremely interesting, but it focuses on how to inform design, while we needed a method that, at the same time, was developing basic BPS skills.

Zweifel (2017) presented an interesting competition-based method to introduce novices to BPS. In this method, the trainer provides a full-modelled building in IDA-ICE. A number of building parameters in the provided model are not optimized; the students are required to identify and optimize such parameters in a two-step process. As the first step, the students define and optimise areas of intervention (e.g. building envelope). As second step, the students are free to choose any combination of measures leading to energy performance optimization. This second step is proposed as a competition. As the author mention, a potential risk is that students use several measures together in step two, which may create some difficulties in understanding the impact of each measure. The method proposed by Zweifel (2017) seems to be very effective for learning the impact of a number of building parameters, but the students are provided with a complex and fully functional model from the beginning. One of the scope of our course, instead, is to introduce the student to the modelling part in parallel to the simulation part.

Rabenseifer (2015) highlighted three obstacles in learning BPS for novices: (i) complexity of quality software, (ii) time for modelling, and (iii) existence of many different standards to describe identical building physics issues. The author illustrated a method based on a simple generic simulation model controlled via external interface aiming at overcoming such obstacles. Our control method is, to some extent, similar to what Rabenseifer (2015) proposed, since it provides a ready-made model to start with, and it reduces the degrees of freedom in the model in order for the students to deal more easily with complex software. Differently from Rabenseifer (2015), the control method does not use a simple interface and it is based on the existing interfaces of the adopted tools (Rhinoceros 3D and Grasshopper); on the contrary, it compares the results with these from a very basic and familiar tool, like Excel.

Beausoleil-Morrison and Hopfe (2015) formalized a pedagogical framework to teach BPS based on the Experiential Learning Theory (ELT) by Kolb (2014). The framework is based on a continuous cycle in which the student recursively face theoretical learning, application of BPS, analysis of BPS results, and reflections linking learning experience to theory. The framework was applied successfully to students with no previous experience on BPS, which were able to handle two BPS tools in just three weeks of training (Beausoleil-Morrison, 2019).

One issue highlighted by Beausoleil-Morrison (2019) is that the ELT-based framework does not assure that students could make reliable predictions. The issue of making reliable predictions is commonly highlighted in literature (Beausoleil-Morrison and Hopfe, 2015; Berkeley, Haves and Kolderup, 2015) and most of BPS trainers have probably experienced that in their careers. Therefore, Beausoleil-Morrison (2019) further developed the ELT-based framework and extended it to a so-called BPS learning spiral. In the generalization of this model, several of the continuous cycle “theoretical learning > application of BPS > analysis of BPS results > and reflections linking learning experience to theory” are interconnected; together, they built a learning spiral aiming at a full understanding of BPS, from underlying theory to the actual handling of software. For the specific case, Beausoleil-Morrison (2019) identified and
implemented 15 cycles in the spiral: one for the introduction to BPS, five to handle “indoor environment” related aspects, six for “exterior environment”, and three for the “building envelope”. A final cycle, a “culminating trial” integrates all the learnings together (Beausoleil-Morrison, 2019, p. 312). By providing specific examples from teaching experience, the author demonstrated that the method allows students to make predictions, that are more reliable, and they gain confidence and understanding in the simulations. The full implementation of this method would require an entire semester, but the method is modular to some extent. For shorter courses – as for our case – a trainer may simply use less cycles and leave the remaining cycles for follow up sessions.

Although this method would fit the purpose of this work, it could not be tested since the control method was designed and implemented before this publication appeared in literature.

**Methodology**

BPS tools are introduced during the course ‘Energy use and thermal comfort in buildings’ (7.5 ECTS). The course includes a theoretical introduction to topics which are later scrutinized in the Master programme (basics of thermodynamics, thermal comfort, air quality, heat balances, heating and cooling strategies, moisture safety, thermal bridges, thermal performance of windows and frames), and a practical part, where BPS are introduced for the first time in the Master programme.

The course content is introduced as in Figure 1. After the theoretical part, the lecturer provides an Excel sheet for calculating the annual energy intensity of a simple shoebox, which is based on the Swedish Building Code BBR (Boverket, 2018). The static calculations consider transmissions losses through the building envelope, ventilation and infiltration losses, the thermal mass, and a template value to consider the internal loads and solar gains.

![Figure 1: Overall course structure](image)

Then, students get some theoretical lectures on BPS and start working with the modelling in Rhinoceros 3D, and with the BPS part in Archsim/E+ in GH environment. In previous years, as assignment, the students were required to model a shoebox identical to the one calculated in Excel and try to match the resulting annual energy use intensity by forcing the dynamic simulation to be “static”, for example by creating a weather file with constant outdoor temperature. Because of the students’ experience and the large number of settings and inputs in the BPS, the difference in results generated ambiguity; namely, the student was not sure if the difference was linked to physical factors, some inputs that were overlooked, or her/his own errors.

In 2018, the control method was introduced in the course structure.

**The control method**

The control method goes through different steps, where the complexity of the energy calculation and simulation is steadily increased. The control method is looking at the same simple shoebox, initially without windows, and then with a window (Figure 2). The output are the annual energy use intensity and the energy peak load.

![Figure 2: the shoebox model used in the course](image)

The steps of the control method are: 1) room with no windows, no internal loads, no ventilation, no infiltration, no solar gains and a constant ambient temperature, 2) add infiltration, 3) add intentional ventilation, 4) add heat exchanger, 5) add window to the model, and 6) add internal loads. The final step is to add irradiation and a varying ambient temperature, but in this case, Excel is not able to calculate that. In Table 1, the differences for the annual energy use intensity between the different methods are shown.

**Table 1. Example of difference in results for the annual energy use intensity (/kWh/m²y).**

<table>
<thead>
<tr>
<th></th>
<th>Excel</th>
<th>Archsim/E+</th>
<th>Diff</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>= windowless</td>
<td>12.59</td>
<td>12.82</td>
</tr>
<tr>
<td></td>
<td>=</td>
<td>+ infiltration</td>
<td>13.74</td>
</tr>
<tr>
<td></td>
<td>=</td>
<td>+ ventilation</td>
<td>22.14</td>
</tr>
<tr>
<td></td>
<td>=</td>
<td>+ heat exchanger</td>
<td>15.84</td>
</tr>
<tr>
<td></td>
<td>=</td>
<td>+ window</td>
<td>17.04</td>
</tr>
<tr>
<td></td>
<td>=</td>
<td>+ internal loads</td>
<td>14.04</td>
</tr>
</tbody>
</table>

Each simulation step is run with the teacher. This has two important advantages:

1. If the student gets a different result, she/he is immediately aware of some errors at that step in her/his simulation; hence, the student can check in detail where the error was made.

To support students in that, we produced video tutorials on Vimeo explaining how to redo the control method at home.
2. On the contrary, if results match, the student knows that the difference in results does depend on underlying equations and approximations and not on her/his own mistake; hence, the student may autonomously scrutinize the theoretical reasons of such difference.

To support the students in that, the teachers relied mostly on the documentation of Archsim and the E+ and incited students to perform further research.

It was considered relevant to show students that dynamic simulation programs will give slightly different results than handmade, static calculations (considering the same conditions) because of the nature of both methods. In both methods, assumptions and simplifications are made to approach complex physical real-world situations, resulting in different outcomes with different accuracy.

In a pedagogical perspective, the control method follows the framework of the Structure of Observed Learning Outcome (SOLO) taxonomy proposed by Biggs and Collis (1982). The control method intervenes at a unistructural level of understanding, and it guides the student towards a relational level (Figure 3), i.e.: understanding why and how different parameters of the energy simulation affects each other. From that point, the student has confidence and ability to produce autonomously new building designs, to propose solutions to improve building efficiency, and to predict the simulation outcomes. In other words, the student is capable to reach independently an extended abstract level of competence (Figure 3).

Figure 3: the SOLO taxonomy (Biggs and Collis, 1982) applied to the here presented control method

In respect to the learning spiral proposed by Beausoleil-Morrison (2019), the control method follows a linear theoretical framework. The fundamental prestructural knowledge is progressively enriched with relational capacities, in a single “block”. The learning spiral, instead, utilizes several “blocks” to build knowledge and reach the extended abstract of knowledge.

Beausoleil-Morrison (2019) suggests that “We need to teach important theoretical concepts, and I argue [...] that this is best accomplished by allowing students to explore and experiment with BPS tools in a guided manner” (Beausoleil-Morrison, 2019, p. 310). Despite the differences in theoretical frameworks, this is, after all, the ground from which both the learning spiral and the here presented control method were conceived.

Evaluation of the control method

The evaluation follows a between-groups study design. Two anonymous questionnaires were submitted to the classes attending the ‘Energy use and thermal comfort in buildings’ course in 2017 (before the introduction of the control method) and in 2018 (after). The questionnaires were:

- the standardized CEQ questionnaire (Ramsden, 1991). This is a standard course evaluation method for the majority of courses held at Swedish universities. The CEQ evaluation forms provide an overall evaluation of the course were BPS are introduced. The CEQ questionnaire is automatically submitted to students when the course ends.
- a custom-made online questionnaire with open ended questions addressing specifically teaching and learning of BPS within the course (Table 2). The custom made questionnaire was handed in to both classes at the end of the 2018 course. This means that the 2017 class answered one year later, which is a limitation of the survey.

Because of the between-groups design, the CEQ questionnaire was mainly used to identify biases linked to different appreciation of the overall course, namely a class largely unsatisfied with the course may provide partial evaluation even for the BPS part. The custom-made online questionnaire, instead, first identifies the groups’ differences by addressing students’ previous knowledge in the field of BPS, by means of closed-ended questions (Table 2). Secondly, and most importantly, it explores students’ satisfaction, understanding of software, and reduction of cooperative learning in regards to the BPS part only. Within this overarching goal, the questionnaire aims at identifying strength, weaknesses, and room for improvement for the control method. Provided also that the statistical population in the analysis is relatively small, a survey with open-ended questions was judged a more suitable tactic of enquiry (Robson, 2011).

In order to keep evaluations as objective as possible, none of the students were aware that a new method for introducing BPS was used in the 2018 edition of the course. For the same reason, the custom-made questionnaire does not address the method itself, rather it asks general feedback on teaching and learning, assuming that positive feedback are triggered by an effective teaching method (Table 2).

The subsequent analysis of qualitative data adopted a thematic coding approach (Robson, 2011, p. 467) and, in general, the analysis was conducted by following best practice.
Results
First, based on the custom-made questionnaire, the students’ background is reported. Then, results of the two questionnaires are discussed.

Students’ background and previous knowledge
Seven students of the 2017 class (34% response rate) and 17 students of the 2018 class (81% response rate) answered to the questionnaire. Statistical significance tests are not reported due to the small effect size.

The background of the two groups differs only in terms of students’ countries of provenience, the control method group being formed by a majority of students from outside Europe. Roughly, 70% architects and 30% engineers form both groups (Figure 4). A 2018 student declared a background in “other”, specified owing a bachelor in “architecture, sustainability” and was hence included in the architects group.

Previous knowledge of 3D CAD software is much more common among students with background in architecture (88%) than engineering (56%), independently from provenience and year of the course. The majority of engineers had only experience of 2D CAD. However, most of the students having previous 2D or 3D CAD knowledge commented that this was superficial (e.g. “Very brief sketches in CAD. Very basic knowledge”).

Figure 4: Background information of the students. Inner doughnut shows 2017 students (previous teaching method); outer doughnut shows 2018 students (control method)

Independently from groups and students’ background, previous knowledge in energy simulations and visual programming is limited. In this case, engineers are more prone to be familiar with energy simulations (44%) than architects (12%), while 12% of engineers and 25% of the architects had some kind of experience with visual programming. Interestingly, on visual programming, one students claiming experience, commented as follow:

“To be honest, my answer here should only account as half a yes, since the Software I used was LEGO Mindstorms. However, it was a great basic experience, as it was a fun time to make a robot do something according to your script […]”

We claim that the comment has the same tacit pedagogical grounds of the BPS learning method by playing proposed by Reinhart et al. (2012), and it deserves consideration for future studies.

CEQ questionnaire
The CEQ questionnaires were handed in by 16 students in 2017 (76% response rate) and 15 students in 2018 (71% response rate). The CEQ evaluation of the course was different from 2017 to 2018. In the CEQ questionnaires, the general evaluation of the course, is provided on a scale going from -100 (very bad) and +100 (very good), with 0 being neutrality. The general evaluation consists of the following elements: 1) good teaching (in 2017, the CEQ score for this element was +31, in 2018 the number was +37), 2) Clear Goals and standards (2017: +15, 2018: +39), 3) Appropriate assessment (2017: +28, 2018: +22), 4) Appropriate workload (2017: +18, 2018: +25) and 5) generic skills (2017: +21, 2018: +47). This shows that in general, the 2018 students evaluated the course much better than the 2017 students did.

Students were also allowed to give free-text answers. In that section, we looked for software-related answers. In 2017, students answered amongst others that they had a Good experience with Excel sheet, students wanted more time to understand “Grasshopper” (which could mean GH or BPS connected to GH), students complaining about the amount of different software that had to be learned.

In 2018, students experienced it as positive to learn multiple programs, students experience the comparison between Excel and Archshim/E+ “interesting”, but students also stated that they needed more time.

The CEQ clearly showed that the whole course was evaluated more positively, but it was less specific about the BPS part.

Custom-made questionnaire
The totality of students from 2017 recalled difficulties in learning the logic behind GH. The comments were generally negative and they completely ignored the modelling and simulation parts, as if the entire course would have been based on GH:

- “[…] I had super hard time understanding why we connected where […]”
- “[…] the base script that was provided was working and we could get a result. However, at that point I had great difficulties with understanding what each single part of the script did […]”

This suggests that the visual programming part was absorbing all the students’ energy, and the BPS learning was not really a concern. One student confirmed that quite clearly:

- “[…] even if we were highly motivated, we run out of time, and I did not consider the results to be used in the assignment”.

When evaluating what they liked and disliked most in the course, the students’ had contradictory feelings. On the
one hand, they recognized the usefulness of parametric BPS and the power of GH in that field; on the other hand, learning difficulties raised a sense of frustration.

- “[…] I really liked the fact that we used grasshopper”
- “[…] Like: learning new useful things which will be huge asset on market”
- “I would say, that we were introduced to the right software for the scope of the masters […]”
- “[GH] plugins have been very useful to me later but I remember that my beginnings were difficult and I had to look for help in different tutorials available on the internet, which I do not think is wrong either”.

According to the students, improvements in the way in which BPS should be introduced (last question in Table 2), are still almost entirely concerning GH.

- “More lectures focusing on basic functions, more explanations of components.”
- “Individual assignments, using GH tutorials to get a better understanding of the software.”
- “[…] we should focus more on the initial handling of Grasshopper.”

Finally, on cooperative learning, some comments seem to confirm the worry that students’ split work based on their expertise:

- “[…] In the end of the day I have to admit, that for the assignment I was not working with E+ […], we divided the simulations for the assignments into three parts, one each […].”
- “Not everybody participated in learning the software. This is now a “problem” in the public building course (the following course, an), there are only 3 out of 7 groups using the Grasshopper interface to make energy simulations”.
- “I highly recommend individual assignments, where students have to use E+ […] themselves and individual, so everybody is forced to spend some time in the very beginning”.

After introducing the control method in 2018, the students’ evaluation was different. The students were generally more positive about the way in which BPS are taught and most importantly, students provided feedback – both positive and negative - on all the three tools that were introduced (Rhinoceros 3D for modelling, GH, and Archsim/E+ for energy simulations). For example:

- On the modelling, “The modelling in Rhino was a bit tricky since I was only introduced to 2D modelling.”
- On GH, “It was difficult to write a script independently.”
- On the energy simulation, “[…] you guys did a great job and try your best to teach us the programs and give us the theoretical knowledge in thermal physics.”

The Grasshopper environment seems to be less hostile to the 2018 students, most probably because the control method allows more systematic guidance on how the GH environment works and how to use GH, combined with Archsim (“Because we did the scripts all together in the class and it was a short script, it was easy to follow and understand.”).

Students felt less lost (“It was glad to see that the simulation exercise started from a very basic level.”) and they had time to dig into the results, rather than only focusing on making things working (“[I liked] The fact that I got the time to go by myself into the program. Most likely it was thanks to the assignment since we need to compare the program, which was really nice.”, but also “The idea to be able to simulate an environment is in itself exciting. Seeing results change by varying different design parameters is also exciting.”).

The students found that the three tools are powerful, but they could recognize a steep learning curve in order to master them properly:

- “I like the complexity of the software and it seems you can do pretty much anything with it. On the other hand, the complexity also makes the software very time consuming to master which I know will be a struggle in the future.”
- “[I find the simulations very useful, once understanding better the software […]]”

Thus, the control method students do not perceive the BPS learning as an insuperable obstacle, and they seem to feel less frustration in comparison to the other group.

Although the control method attempts to meet the needs of all the class independently from the background knowledge, some students still found the method either too complex or too easy. For example:

- an engineer, with experience in 2D CAD: “The big amount of parameters in the simulations made it harder to control what was being changed and led to some wrong results”;
- another engineer, with experience in 2D CAD: “I would propose from the beginning simpler exercises to get to know the software.”;
- a third engineer, with experience in energy simulation: “It would be better if we could learn much more details and basics about the simulation programme not that only settings for some tabs”.

One student suggested that a risk of the control method is that students tend not to leave from their comfort zone: “[…] we were introduced so many things and there are different ways to do one thing, in order to be on the safe side, we didn’t try other methods but kept with the given script”.

The control method seems to favour collaborative learning in respect to cooperative learning. In fact, differently from the 2017 class, one comment was explicitly mentioning “[I liked] teamwork”, while only one student out of 17 commented on teammates who shared work based on their expertise:

- “[…] if you are not the one doing the simulations and doing another part of the project you don’t get to learn and the other members of the group don’t share what they have done”.

This is in sharp contrast with the 2017 class, where three out of seven students reported the issue.
Conclusion

This paper has shown the results of an intervention in an energy course with the goal to increase students’ individual learning of building performance simulation software. A control method was introduced, where students systematically compared the energy balance of a simple shoebox with Excel and by simulating it with Archsim/E+. The introduction of the control method was evaluated via a standard course questionnaire and a custom-made questionnaire for the BPS part. In the standard course evaluation, students evaluated the whole course more positively for the course after introducing the control method. The open comments showed that the control method students were more aware of the potential of the software that were introduced to them, rather than commenting their lack of understanding GH. They were also more confident with the newly introduced software, and some comments suggest that they may be keener on trying additional exercises on their spare time.

Probably in consequence of increased confidence, free comments on group dynamics indicates that the control method may also support collaborative learning.

In conclusion, the control method seems to offer a smooth way to introduce BPS in classes with diverse background knowledge. Although the comments make difficult to judge whether the control method was actually beneficial to understanding and interpreting results of BPS, the fact the students had desire and allowed time to dig into results is certainly a positive sign in this direction.

The student mentioning programming games as good learning occasion for visual programming in BPS suggested ideas for follow-up work. For example, future courses may merge - in some ways - the pedagogical principles of “learning by playing” with the need for a smooth and systematic introduction to BPS as done by the control method.

Acknowledgement

The authors wish to express their gratitude to the students responding to the questionnaires.

References


Table 2: Content of the custom made questionnaire.

<table>
<thead>
<tr>
<th>Question</th>
<th>Options and other info</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. I come from (one choice)</td>
<td>‘Europe’/‘Outside Europe’/‘I prefer not to answer’</td>
</tr>
<tr>
<td>2. Previous education (one choice)</td>
<td>‘Engineering’/‘Architecture’/‘Other’</td>
</tr>
<tr>
<td>3. Independently from your previous selection, please specify the type of education</td>
<td>Open-ended</td>
</tr>
<tr>
<td>4. Did you ever use CAD software before joining our Master course? (one choice)</td>
<td>(‘Yes’/‘Yes, but only 2D’/‘No’)</td>
</tr>
<tr>
<td>5. I would like to add more about my previous experience with CAD software</td>
<td>Open-ended</td>
</tr>
<tr>
<td>6. Did you ever run energy simulation before joining our Master course? (one choice)</td>
<td>(‘Yes’/‘No’)</td>
</tr>
<tr>
<td>7. I would like to add more about my previous experience with energy simulations</td>
<td>Open-ended</td>
</tr>
<tr>
<td>8. Did you have any previous experience with visual programming languages (e.g. Grasshopper or similar)? (one choice)</td>
<td>(‘Yes, Grasshopper’/‘Yes, but not Grasshopper’/‘No’)</td>
</tr>
<tr>
<td>9. I would like to add more about my previous experience with visual programming languages</td>
<td>Open-ended</td>
</tr>
<tr>
<td>10. Please add all the relevant 3D modelling, energy simulation and visual programming languages that you may have used in the past and that are not included in our list. (multiple choice)</td>
<td>(‘Rhino 3D’/‘AutoCAD’/‘SketchUp’/‘3ds Max’/‘IDA-ICE’/‘EnergyPlus’/‘IES-VF’/‘Design Builder’/‘Revit’/‘Grasshopper’/‘Autodesk Dynamo’)</td>
</tr>
<tr>
<td>11. Add other software and comments</td>
<td>Open-ended</td>
</tr>
</tbody>
</table>

Now a difficult exercise… Please try to recall your feelings when you were attending the “AEBF10 Energy use and thermal comfort in buildings”. For what possible, try not being biased by your current knowledge in simulation software.

<table>
<thead>
<tr>
<th>Question</th>
<th>Options and other info</th>
</tr>
</thead>
<tbody>
<tr>
<td>12. At that time, which difficulties did you face for the simulations part?</td>
<td>Open-ended</td>
</tr>
<tr>
<td>13. What did you like the most and the least about the simulations part in that course?</td>
<td>Open-ended</td>
</tr>
<tr>
<td>14. Today you are several steps ahead with energy simulations. Considering your current knowledge, do you think that simulations could have been introduced differently in that course?</td>
<td>Open-ended, submitted to the 2017 class only</td>
</tr>
</tbody>
</table>
Use of eQuest in the teaching of design and analysis of HVAC systems: lessons from Building Engineering courses

Radu Zmeureanu
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Abstract
This paper presents the author’s experience from courses that focused on the design and analysis of a complex HVAC system of a school building in compliance with National Energy Code of Canada for Buildings (NECB). The courses are designed to achieve the following teaching objectives: (i) exploration and application of NECB for the preliminary design, (ii) learning and usage of the eQuest energy analysis program, (iii) estimation of the whole building energy performance, along with the indices of performance of HVAC equipment, and (iv) learning from mistakes in the input data and HVAC system description. The students’ results presented a large dispersion around the average values due to errors and misinterpretations. If only the annual whole building energy performance is analyzed, some input errors are not discovered. Other results directly extracted or calculated from the simulation results should be compared with codes requirements and indices from publications and consulting firms.

Introduction
The review of proceedings of the Building Simulation (BS) conference over the past 20 years revealed that only nine papers highlighted in the title the words of education, teaching, or students; three papers at BS 2017 (San Francisco), five papers at BS 2015 (Hyderabad), and one paper at BS 2011 (Sydney). In all 10 BS conferences, there were only two dedicated sessions: (i) Education at BS 2017, and (ii) Teaching modelling simulation at BS 2015.

Charles and Thomas (2009) developed an introductory course for a population of both undergraduate architecture and engineering students with the scope of achieving a balance between: (i) an insight gained through Building Performance Simulation (BPS), (ii) an insight gained through basic physics calculations, and (iii) an insight gained from measuring physical phenomena. Students were exposed to tools such as TRNSYS, CONTAM, Design Advisor, THERM, and WUFI-ORNL.

Reinhart et al. (2011) applied a game-based learning approach for teaching BPS to architectural students. A class of 47 architecture students competed for the lowest Energy Use Intensity (EUI) of an office building in Boston. The students, divided into ten groups, selected between eleven building massings, eight orientations, building envelope configurations and electric lighting and control systems. The design baseline values were selected according to ASHRAE 90.1-2007. Other ten students with better knowledge carried out simulations using preconfigured DesignBuilder/EnergyPlus models. The EUIs of the final designs were 22% to 31% below the baseline model.

Beausoleil-Morrison and Hopfe (2015) concluded, from a detailed analysis of current situation, that the teaching of BPS should be done through a complete and continuous learning cycle, composed of four stages: (i) Application of BPS, (ii) Scrutinizing results, (iii) Diagnostic investigation, and (iv) Studying theory. They presented the experience from teaching a graduate-level course on BPS with 21 students. They were asked to predict the annual space heating and cooling loads, by using ESP-r and/or EnergyPlus programs, of one of the basic low-mass test cases defined in ASHRAE Standard 140 (ANSI/ASHRAE 2007). The students’ results were compared with predictions from eight combinations of BPS tools and experienced users, presented in Standard 140. Through the analysis of results and diagnosis of errors, students were able to better understand the models and simulation methods.

Kumaraswamy and de Wilde (2015) discussed the education pathway on BPS followed by students at the undergraduate Architectural Technology program at Plymouth University (UK). Students registered in three modules in sequence: (i) ENBS117 that introduced students to theoretical aspects of building physics and HVAC systems; (ii) TECN201 that introduced students to a series of software such as IES, THERM, and SAP; and (iii) ATE202 where students used the software.

Rabenseifer (2015) used generic models (developed from models available in Physibel, TESS, and TRNSYS) controlled via external user-friendly interface using Excel Workbook. The generic models were designed for a particular type of building, building component or equipment. He concluded that the generic models represent a way to overcome the obstacles, which keep architects and designers from using BPS.

Strobe et al. (2015) presented the use of building information modelling (BIM) coupled with two models for the estimation of residential buildings heating demand; first model was based on the official calculation method in Flanders, and the second was a multi-zone model based on ISO 13790. The approach was used in a student exercise with 11 master students in architecture.

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and engineering plus four exchange students. Every student used a different building type and topology. They used the passive house guidelines to estimate the energy use of baseline design, and then they explored the impact of several design alternatives. The authors concluded that students became aware about the impact of design choices.

Hopfe et al. (2017) presented the findings of a survey conducted at different architecture schools at universities in Australia, India, the US and the UK about teaching BPS.

Zweifel, G. (2017) presented the teaching of building simulation to students in a bachelor program, by using one core module (Modelling and Simulation 1), plus other elective modules. The focus of the core module is on the strength of building simulation as a means of integrated design. The module is composed of three parts: (i) the development of a mathematical-physical model of a problem; (ii) the development of a simple two-zone model, using IDA Indoor Climate and Energy (an equation based thermal simulation program); a sensitivity study and optimization were also included; and (iii) the introduction to computational fluid dynamics, or lighting and daylighting simulation. The scope of optimization exercise, carried out on a five-zone building model, was to minimize the overall operation primary energy use, while keeping the comfort conditions in an acceptable range.

The International Journal of Building Performance Simulation published a few papers related to this topic. For instance, Schmid (2008) explored the benefits of teaching building simulation to architectural students, knowing that most of them will not become simulation experts. The author’s thesis was that building simulation has pedagogic relevance for architectural students, as they will be able to apply physical principles in the design process, and will become aware about the consequences of the design choices. The paper presented the results of case studies carried out between 2005 and 2008. He thought that students would acquire a comprehensive view of their decisions by using a professional simulation tool, rather than using simplified tools such as spreadsheets for estimating the building cooling loads.

Reinhart et al. (2012) expanded on an earlier paper about the use of game-based learning approach.

Beausoleil-Morrison’s thesis (2018) was that a solid understanding of the fundamentals of BPS is critical for the good representation of physical processes in buildings and HVAC systems. He listed a few approaches used for teaching BPS. He expanded on the Experiential Learning Theory, applied in a previous paper by Beausoleil-Morrison and Hopfe (2015), by including the BPS learning spiral, where the completion of a cycle of simulation of one topic should lead into the subsequent topic. He used this approach for a series of distinct heat or mass transfer processes. In the final step of integration of learnings, students predicted the thermal performance of a research house located on the Carleton University campus. Students compared their predictions with measurements, followed by the simulation autopsy to diagnose and understand causes of disagreement.

Bernier et al. (2016) presented, at the IBPSA-Canada conference, the structure of a graduate level course on building energy modeling and simulation with the scope of teaching fundamentals (governing equations, assumptions, and solution methods). The course was composed of 11 modules covered over 40 hours of lectures. Students solved manually the governing equations, for some applications, before using TRNSYS. In the building heat transfer module, students were exposed to three estimation methods: steady state, lumped-capacitance, and heat balance. In the module of HVAC equipment modeling, students were exposed to first principles models (e.g., heat transfer in a pipe subjected to a constant heat transfer rate), grey-box models (e.g., a heat pump model), and black box models (e.g., DOE-2 model for chillers). Other modules covered climatic data, lighting and daylighting, fenestration, occupants, calibration, infiltration/ventilation, thermal storage, and optimization. Students were exposed to programs such as TRNSYS, EES, WINDOW, ExcalibBEM, and SIMEB (interface to DOE-2.2), CONTAM, GenOpt, and BeOpt.

**Description of courses**

The undergraduate Building Engineering program at Concordia University in Montreal, Canada received continuous accreditation since 1982 from the Canadian Engineering Accreditation Board. For more than 30 years, it was the only Building Engineering program offered by Canadian universities. Recently, the program started at Université de Sherbrooke (Quebec) and Waterloo University (Ontario). Table 1 presents examples of core and elective courses. The department offers also graduate programs at the Master’s and Ph.D. levels.

<table>
<thead>
<tr>
<th>Table 1: Example of undergraduate courses.</th>
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<tbody>
<tr>
<td><strong>Building Engineering Core</strong></td>
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<tr>
<td>BLDG 365 Building Science</td>
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<tr>
<td>BLDG 366 Acoustics and Lighting</td>
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<tr>
<td>BLDG 371 Building Service Systems</td>
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<tr>
<td>BLDG 463 Building Envelope Design</td>
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<tr>
<td>BLDG 471 HVAC System Design</td>
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<tr>
<td>BLDG 476 Thermal Analysis of Buildings</td>
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<tr>
<td>BLDG 490 Capstone Building Engineering Design Project</td>
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</table>

**Option A — Building Energy and Environment**

| BLDG 465 Fire and Smoke Control in Buildings |
| BLDG 472 Building Energy Conservation Technologies |
| BLDG 475 Indoor Air Quality |
| BLDG 477 Control Systems in Buildings |
| BLDG 479 Commission of HVAC systems in buildings |
| BLDG 483 Integrated Solar Systems: Design and Operation |
| BLDG 484 Building Diagnostics and Rehabilitation of Building Envelope |
The course outline of BLDG 472 and BLDG 6781 (a graduate course) has six chapters as follows:


Chapter 3 – Building energy-related standards. National Energy Code of Canada for Buildings (NECB, 2015); Regulation respecting energy conservation in new buildings, E-1.1, r.1, Quebec; ASHRAE 90.1.


Chapter 5 – HVAC systems with high performance. Case studies.

Chapter 6 – Introduction to building commissioning, retro-commissioning and ongoing commissioning of existing buildings. Energy signature and weather normalization techniques.

For increasing the students’ experiential learning, the course work included three assignments that counted for 60% of the final grade, in addition to final examination for 40%.

After two lectures about different methods for the estimation of space cooling/heating loads and energy demand (e.g., bin, CLTD, heat balance), students were exposed to the Radiant Time Series (RTS) method. This newer method is suitable for the estimation of peak cooling load for design purposes. In addition, it gives a quick estimation of how the conductive heat gains, for instance through walls, are separated into the convective component of the space cooling load, and the radiative component that takes into account the thermal storage and later release. For the assignment no.1, students wrote the code in Matlab or Excel for the RTS method. Students received the following information:

1. The room has only one exterior wall facing South of 4 m x 4 m, without windows.
2. The outdoor air infiltration and internal gains from people, lights, and equipment are neglected.
3. Thermostat set point is 22.0 ºC. Inside surface of exterior wall: \( h_o = 17 \text{ W/m}^2; \alpha = 0.87 \).
4. Outside surface of exterior wall: \( h_{\text{convection}} = 4 \text{ W/m}^2; h_{\text{radiation}} = 3 \text{ W/m}^2 \).
5. Inside surface of exterior wall: \( h_{\text{convection}} = 4 \text{ W/m}^2; h_{\text{radiation}} = 3 \text{ W/m}^2 \).
6. Weather data for summer design day.
7. Conduction Time Factors (Table 16, ASHRAE, 2017) and Radiant Time Series (Table 19, ASHRAE, 2017).

They applied the RTS method for the estimation of the space cooling load of this room over 24 hours, and compared the results obtained from two different walls (ASHRAE wall #1 and wall #2) (Figure 1).

The goal of the assignment no.2 was the estimation of annual energy performance of a school building that complies with the National Energy Code of Canada for Buildings (NECB, 2015) and Regulation respecting energy conservation in new building (Quebec, 2018). ANSI/ASHRAE/IES Standard 90.1 (2016) was used for additional requirements, when needed.

The assignment no.3 was a continuation of the second assignment with the goal of estimation of changes of the energy performance of base case model (assignment no.2) due to energy conservation measures (ECMs).

The class population was composed of 19 undergraduate students in the fourth year of the Building Engineering program, and 18 graduate students with different first degrees (e.g., mechanical, civil, architecture) registered for M.A.Sc (thesis option), M.Eng (courses option) and Ph.D. programs.

To compensate for the difference of one credit compared with the U/G course, the graduate students completed additional work. In the assignment no.2, they calculated the life cycle cost of energy use for the building operation, using the economic indicators from Bank of Canada and Hydro Quebec, and building economic duration of 30 years. In the assignment no.3, they estimated the impact of changes of the building envelope on the environmental impact, expressed by Global Warming Potential index in ton-eqCO\(_2\), using the Athena Impact Estimator software (Athena, 2018).

Assignment no.2

The assignment had the following teaching objectives:

1. Exploration, learning and application of the requirements of National Energy Code of Canada for Buildings (NECB, 2015), and Regulation respecting energy conservation in new building (Quebec, 2018), for the preliminary design of a school building and HVAC system.
2. Drawing of the schematic flowchart of the HVAC system, and explanation of the system operation. Selection of design and operation variables in compliance with the codes/standards.
3. Understanding, learning and usage of a detailed building energy analysis program (eQuest, 2018) for the estimation of energy performance of a school building with a complex HVAC system.

4. Understanding of relationship between the: (i) space cooling/heating loads, (ii) secondary HVAC system cooling/system loads, and (iii) primary equipment energy use.

5. Estimation of the whole building energy performance, along with the indices of performance of HVAC equipment.

6. Learning from mistakes and errors in the input data and HVAC system description.

7. Raising students’ confidence in their ability to estimate the energy performance of a building by using a detailed energy analysis program (eQuest).

The case study school building in Montreal has the footprint 40 m x 70 m with five floors above ground, with the large facade facing south (Figure 2). The complexity of the building follows the complexity of reference building as defined in NECB (2015).

Figure 3 presents the monthly end-use electric demand of the school building as an example of results obtained by one student, as displayed by the eQuest program in the summary output. Figure 3: Example of monthly end-use electric demand of the school building from eQuest program.

To verify the simulation results, students were asked to review the simulation input and output files. They looked for errors, and compared the simulation results with the codes/standards prescriptions and design indices. If required, they needed to execute a few iterations to reach that compliance with the codes. They compared the predicted annual energy consumption with data from existing buildings of similar type and climate, energy price, codes and operation context.

Each student was asked to submit a report of no more than 12 pages including a table of design data according to codes/standards; schematic diagram of HVAC system; analysis of results; conclusions; and references. The author requested from each student the input file (.INP) and simulation output file (.SIM) for verification.

Results of assignment no.2 and discussion

The author compiled two classes of results from the simulation output files:

1. Indicators that are usually reported for the assessment of annual whole building energy performance, and for the model calibration:
   (i) Monthly and annual site energy use, in kWh/(m²·yr) (from BEPU report),
   (ii) Monthly and annual energy cost, in $/(m²·yr) (from ES-E report),
   (iii) Monthly and annual peak electric demand, in W/m² (from PS-E report), and
   (iv) Monthly and annual electric load factor (ELF).

2. Indicators that provide additional information about the model performance, directly extracted or calculated from the eQuest outputs. However, students do not frequently extract these results from the eQuest simulation file for further analysis. Some indicators used in this assignment are as follows:
(i) Total space cooling and heating loads (from LS-D report);
(ii) Total HVAC system cooling and heating loads (from SS-D report);
(iii) Total electric system load (from SS-D report);
(iv) U-value of walls, windows and overall U-value of envelope (from LV-E report);
(v) Design supply fan flow rate, in L/s/m², and fan power demand, in W/L/s (from SV-A report);
(vi) Specific cooling capacity, in m² floor area/kW of cooling (from SS-D),
(vii) Power demand of pumps for chilled and condenser water, in W/kW of cooling (from PV-A and SS-D reports), and
(viii) Contribution of major end-uses (lights, appliances, cooling, heating, fans and pumps) on the annual energy use (from PS-B report).

The compilation of results from all students required first the verification of data quality.

(i) Three students used wrong input data for walls, which led to U-value of 3.25 or 13.05 W/(m²·K) compared to the NECB (2015) value of 0.247 W/(m²·K) prescribed for Montreal that is in zone 6 with 4300 Celsius heating degree-days;
(ii) Two students misinterpreted the NECB (2015) description of the reference system no.6 that is recommended for schools. They selected the multi-zone system option in eQuest when they should have selected the variable volume (VAV) system option. The author noticed that a few students have not recognized the jargon used in tool interfaces.
(iii) In a few cases, the structure of electricity rate of Hydro Quebec was not correctly input, which led to annual energy cost of about 75 $/(m²·yr) compared with the average of about 20 $/(m²·yr) obtained by all other students.

The author presumed, upon the detailed analysis of all input and output files, that not all students had the patience to perform all iterations as suggested for improving the quality of simulations. As a result, some errors noticed in the final submission might explain the variation of results among students.

The summary of main results from the eQuest simulations, extracted from the .SIM reports of all 37 students, are presented in Table 2, and compared with the corresponding benchmarks.

### Table 2: Summary of main results from all 37 students.

<table>
<thead>
<tr>
<th>Predicted index of performance</th>
<th>Mean ± standard deviation</th>
<th>Benchmark</th>
</tr>
</thead>
<tbody>
<tr>
<td>Whole building annual energy use [kWh/(m²·yr)]</td>
<td>150.00 ± 55.2</td>
<td>275 (Issa et al., 2011)</td>
</tr>
<tr>
<td>Whole building annual electricity cost [$/(m²·yr)]</td>
<td>20.5 ± 11.5</td>
<td></td>
</tr>
<tr>
<td>U-value of windows [W/(m²·K)]</td>
<td>2.53 ± 0.65</td>
<td>&lt; 2.2 (NECB, 2015)</td>
</tr>
<tr>
<td>U-value of exterior walls [W/(m²·K)]</td>
<td>0.24 ± 0.06</td>
<td>&lt; 0.24 (NECB, 2015)</td>
</tr>
<tr>
<td>Total supply airflow rate [L/(s·m²)]</td>
<td>4.85 ± 1.17</td>
<td>&lt; 3.8–5.0</td>
</tr>
<tr>
<td>Power demand for motors of combined supply and return VAV fans [W/(L/s of supply air)]</td>
<td>1.92 ± 0.23</td>
<td>&lt; 2.65 NECB (2015)</td>
</tr>
<tr>
<td>Specific chiller capacity [m²/kW]</td>
<td>12.27 ± 3.0</td>
<td>&gt; 9.3-11.9</td>
</tr>
<tr>
<td>Power demand for motors of all the pumps in the hydronic system [W/kW of cooling load]</td>
<td>15.77 ± 2.84</td>
<td>&lt; 14 [NECB-2105]</td>
</tr>
</tbody>
</table>

**Figure 4: Annual energy cost versus annual energy consumption.**

3. Total predicted supply airflow rate was higher than the recommended range of 4.03-9.58 L/(s·m²) (ASHRAE 1987). However, the predictions are in agreement with the current practice of about 3.8–5 L/(s·m²) for new buildings with improved lighting systems and heat recovery from exhaust air.

4. Predicted specific chiller capacity was much higher than the recommended range of 3.97-6.34 m²/kW (ASHRAE 1987). However, the predictions are closer to...
the current practice of about 9.3-11.9 m²/kW in the case of new buildings.

5. Most predictions of the combined power demand, required by the motors of all the pumps in the hydronic system, exceeded the maximum allowed by NECB (2015).

6. All predictions of the power input to pumps of condenser water loop exceeded the maximum allowed by NECB (2015).

7. NECB (2015) prescribes the minimum performance of HVAC equipment. For instance, the minimum COP of a packaged water centrifugal chiller, water-cooled is given in terms of the chiller capacity in kW. In most cases, students used either the eQuest default value of COP, or the minimum value of COP=3.98 from Quebec (2018). They should have selected the value of COP in terms of cooling capacity (e.g., COP=5.236).

The author compiled and presented in the classroom the results of all students, and discussed the errors and misunderstandings noticed in the reports and input files. In this assignment, all students used a building of given dimensions, and physical properties and VAV system in compliance with building energy-related codes. However, the estimations of annual whole building energy use were scattered around the average value obtained by 37 students, with the Coefficient of Variance of the Root Mean Square Error (CV-RMSE) of 39%. For the annual energy cost the CV-RMSE was 56%.

The average value of different indicators was almost equal from U/G and graduate students, with a larger dispersion of results from graduate students. The author concluded that the predictions of annual whole building energy use and cost should not be the only outputs of interest. The assessment of simulation quality should include other indices of performance at the system or equipment level. Those indices should be compared with code/standard requirements or design specifications.

The model calibration of an existing building with many unknown or uncertain values of design and operation variables is challenging. Hence, the variation of predictions made by several users for an existing building would be even larger than of the results presented in this paper.

**Assignment no.3**

Students investigated the impact of two separate ECMs applied to the base case building (assignment no.2):

ECM#1 uses the daylighting control, and two different values of the window-to wall ratio: (a) WWR= 0 and (b) WWR=1; the base case model WWR = 0.4; and ECM#2 uses the natural gas as the energy source for heating needs, and electricity for all other energy needs. For each ECM, students predicted the change of annual whole building energy use, annual peak electric demand, annual energy cost, and annual Electric Load Factor.

### Results of assignment no.3 and discussion

The decrease of annual whole building energy use and cost due to the energy conservation measure ECM#1(a), ECM#1(b), and ECM#2 is presented in Table 3.

**Table 3: Decrease of the whole building energy use and cost due to ECMs.**

<table>
<thead>
<tr>
<th>ECM#1(a)</th>
<th>ECM#1(b)</th>
<th>ECM#2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>WWR= 0</td>
<td>WWR=1</td>
</tr>
<tr>
<td>Annual building energy use [%]</td>
<td>10.7 ± 11.4</td>
<td>-(-11 ± 18.4)</td>
</tr>
<tr>
<td>Annual energy cost [%]</td>
<td>14.5 ± 8.0</td>
<td>-(-9.8 ± 16.2)</td>
</tr>
</tbody>
</table>

In the case of changes to the building envelope, the change of annual energy cost followed the trend of change of annual energy use.

In the case of changing the energy source for heating from electricity to natural gas (ECM#2), the annual energy use increased because of lower thermal efficiency of boiler of 0.83 (NECB, 2015) compared with electric heating, and the additional power input to pumps of the hot water loop. However the annual energy cost decreased because of lower price of natural gas ($3.55/GJ or $0.0128/kWh) compared with about $0.07/kWh of electricity (including the price of energy use and peak demand).

The large variation of students’ predictions of annual energy use for ECM#2 was due two causes:

(i) Some students selected the natural-gas boiler thermal efficiency of 0.8 (default value in eQuest) instead of 0.83 (NECB, 2015).

(ii) Some students connected the natural gas-fired boiler only with the heating coil of AHU, or only to the heating coil and the re-heating coils of VAV boxes. When the baseboard heaters were not connected to the hot water loop, they received warnings of insufficient heating capacity in zones. They simply disregarded those warnings.

**Conclusion**

The scope of work requested from students registered in these two courses was much larger than the scope of other core or elective courses that they completed in previous terms. Those courses focused on: (i) the fundamental concepts and methods of assessment of energy flows in buildings, and (ii) the key elements of design of HVAC systems.

The author asked students to apply the codes requirements for the preliminary design of a school building and a complex VAV system, and to estimate the energy-related performance at the building, system and equipment level, by using eQuest, a detailed energy analysis application.

The learning curve was abrupt. The author’ comparison of all students’ results proved that the annual whole
building energy use and cost should not be the only results of interest from such a detailed simulation. If only the whole building energy performance is analysed, many weaknesses and errors are not discovered. Other results directly extracted or calculated from the output file should be compared with codes requirements, indices from reference publications, and indices derived by consulting firms from their practice.

The author considers that the time available for the completion of assignments no.2 and no.3 was sufficient for achieving the teaching objectives. The program used in these assignments, eQuest, is free of charge and most students installed on their own laptops. In addition, the program was installed in the computer laboratories of the faculty.

Each student developed his/her own building model with eQuest; this was an individual not a group assignment. The diversity of values selected by students for inputs (as observed by the author in all students’ input files), and the differences of results led the author to the conclusion that they really submitted an individual work, although it is possible that in the computer laboratory they communicated and explored together the issues faced during the development of eQuest file.

The complexity of prescriptions and performance path model (NECB-2015) made impractical the development of the “true eQuest model,” as students are not limited to one single value for some inputs. For instance, students are allowed to select any reasonable value of thermal resistance of exterior wall that is greater than the minimum required by eQuest, or a chiller with greater COP than the minimum required by NECB (2015).

In the case of assignments no.2 and no.3, the building dimensions were given to students, and the physical properties and HVAC system details were supposed to comply with the code. Even though the conditions were controlled, the results from all students presented a large dispersion due to errors and misinterpretations.

One can expect that in the case of modeling of an existing building, with many unknown or uncertain values of design and operation variables, the variation of predictions made by several users would be even larger than of the results presented in this paper.

Acknowledgement
The author acknowledge the work of students registered in these two courses who have contributed with their results to this paper.

References


Integrating Building Physics and Performance Simulation in Architectural Curricula: A Collaborative Effort

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Abstract
This paper presents an effort toward integrating building physics and building performance simulation in architectural curricula. The main objective of this effort, which is undertaken within the framework of a project supported by the European Union (IMPAQT) is to initiate a paradigm shift toward a more integrative, people-centred, and technologically agile professional profile of young architects. The present contribution focuses on those curriculum features related to building technology and performance assessment. The building technology track is described in detail, along with its relationship to the curriculum's other thematic tracks. Specifically, we explain the structure and content of the building simulation course and its strategic position within the building performance track.

Introduction
Motivation
This paper reports on efforts toward improving architectural education in the framework of the project IMPAQT (“Integrative Multidisciplinary People-centred Architectural Qualification & Training”) supported within the ERASMUS+ Programme (EACEA, 2018; IMPAQT, 2018) of the European Union. The main objective of this project is to promote a paradigm shift toward a more integrative, multidisciplinary, people-centred, and technologically agile professional profile of young architects. Thus, specific attention is paid to integrate social, urban, human, and technological aspects in a number of courses within a new architectural curriculum.

As such, material related to building physics or building performance simulation is already included in most architectural curricula. However, the preparatory work (including a gap analysis) in the initial stage of the IMPAQT project points to a number of needs and challenges in this area. Efforts were made to address these challenges in the course of the project. Toward this end, engineering disciplines and human sciences, aided by information and communication technologies, were deployed in a context-sensitive manner to encounter the challenges associated with sustainable human settlements.

The main focus of the present paper concerns the sequence of the components of the building technology track within the proposed curriculum. This building technology track is explained in detail, along with its relationship to the curriculum's other thematic tracks. Specifically, we discuss the intellectual underpinnings of the structure and content of the building simulation course projected to acquire a special strategic position within the building performance track (Berger, 2018). The integration of thermal building performance simulation should enable architecture students to approach design, amongst other things, as an iterative process to balance energy and carbon reduction targets with indoor environmental quality objectives.

Background
The three-year project IMPAQT started in October 2017. Within this project two main objectives are pursued: On the one hand, the project focuses on the development of a five-year undergraduate architectural engineering program. On the other hand, life-long learning modules in three subject areas (including building ecology and building physics, human requirements and contemporary city) are designed for a continuing education program. A group of four European and six Egyptian academic and non-academic partners contribute to these tasks with various levels of involvement according to their fields of specialization (including architecture and urban design, structural and construction systems, building physics and building ecology, and human behaviour). This collaborative effort enriches the project work by complementing the curricula with different thematic strength (Berger, 2018).

Structure
The present work first gives a summary representation of the aforementioned gap analysis. Subsequently, we focus on the development of the architectural curricula. Moreover, the sequence of the components of the building technology track is explained in detail, along with its relationship to the curriculum's other thematic tracks. Specifically, the integration of thermal building performance simulation within the curriculum is discussed.
Challenges in architectural education

Prior to the development of the curriculum, a gap analysis of needs and shortcomings in architecture education was performed. This gap analysis explored and analysed views and opinions from both practitioners and academics of the current architecture education. In order to obtain a comprehensive gap analysis, different instruments (including an online questionnaire and interviews of academics and practitioners) were developed and designed within the project IMPAQFT team (Shehayeb et al., 2018a). Over a period of three months, about 110 students and faculty of multiple schools of different countries participated in the online questionnaire and about 30 practitioners and academics agreed to participate in an interview. Table 1 shows a partial result of this gap analysis. It includes a selection of questions posed regarding potential shortcomings in existing educational programs in architecture together with respective responses by students and faculty members obtained via the aforementioned online questionnaire. The results suggest that about 50% of the respondents see a major problem in the lack of awareness of advances in building technology, material science, and construction methods. Other expressed shortcomings relate to the lack of integration of design-support tools (such as environmental simulation or parametric design tools), inadequate learning environments and tools, as well as poor integration of theoretical courses in design studios. About 51% of the respondents identify the gap between theoretical knowledge and their application in design studios as a crucial problem. As such, they underline the importance of technology integration in design studies.

Further key shortcomings mentioned are insufficient information concerning the job market for architecture graduates as well as lack of clarity regarding the practical relevance of the academic studies for the real world challenges (estimated by 58% of the respondents as a major problem). In this context, a number of respondents propose to further emphasize the link between theory and real practice, for instance via field visits to ongoing project sites, participation in related working meetings and workshops, as well as interactions with practitioners in architecture, building construction, and aligned fields. In general, some respondents suggest, schools should put more emphasis on the kinds of professional profiles for their graduates that are practice-oriented and embody technical competence. Furthermore, many respondents rate BIM (Building Information Modelling) knowledge and a connection to the real-world activity domain as important features they would introduce or change in current architecture education.

Another main problem is the students’ wanting knowledge of essential building codes and standards in a number of countries. Thus, an improved integration of codes related to architecture and urbanism in the architecture education is necessary.

Table 1: Selected gap analysis questions and responses: major problem (black), neutral (grey), no problem (white) (derived based on information by Shehayeb et al. 2018a).

<table>
<thead>
<tr>
<th>Selected questions</th>
<th>Responses</th>
</tr>
</thead>
<tbody>
<tr>
<td>Q1 Lack of technological awareness</td>
<td>50% 27% 21%</td>
</tr>
<tr>
<td>Q2 Theory-application divide</td>
<td>52% 24% 24%</td>
</tr>
<tr>
<td>Q3 Lack of design-support tools</td>
<td>31% 28% 21%</td>
</tr>
<tr>
<td>Q4 Inadequate learning environment / tools</td>
<td>50% 23% 23%</td>
</tr>
<tr>
<td>Q5 Lack of course integration</td>
<td>49% 22% 29%</td>
</tr>
<tr>
<td>Q6 Ignorance regarding job perspectives</td>
<td>58% 13% 24%</td>
</tr>
<tr>
<td>Q7 Studies vs. real-world market</td>
<td>58% 27% 15%</td>
</tr>
</tbody>
</table>

The gap analysis both confirmed and sharpened a number of pre-existing concerns about existing architectural education paradigms, thus motivating the project team toward concerted efforts to address some of these needs and shortcomings in the course of the present curriculum development.

The general structure of the proposed curriculum

The developed curriculum encompasses a five-year undergraduate program in architectural engineering that comprises 280 ECTS (i.e., 160 credit hours). Conceptually, the curriculum development was guided by the intention to ensure a multidisciplinary approach in the architecture education. In this context, Figure 1 illustrates a schematic concept of the curricular proposal and its five main thematic fields (including human sciences, history/ theory, urban planning, design and technology).

The concrete structure of the overall curriculum is captured in Table 2. Note that a preparatory first year provides general courses to acquire basic knowledge in social, urban, and technological subjects. Based upon this foundation, design studios, and theoretical modules are assigned to successive semesters of the studies. The last year of the program mainly focuses on the graduation project, which is conceived as a two-term design studio.
Table 2: Structure of the overall curriculum (derived based on program description of the Nile University by Shehayeb et al. 2018b).

<table>
<thead>
<tr>
<th>Semester</th>
<th>Design Studio 1</th>
<th>People-Centered Theory</th>
<th>Urban</th>
<th>History of Architecture</th>
<th>Building Technology</th>
<th>Structure &amp; Construction</th>
<th>Visual</th>
<th>Language &amp; Electives</th>
</tr>
</thead>
<tbody>
<tr>
<td>Year I</td>
<td>Basic for Design Drawing / Modelling</td>
<td>Ethics</td>
<td>Critical Thinking</td>
<td>Selected Topics in Humanities: Environmental Psychology</td>
<td>Probability &amp; Statistics</td>
<td>History of Architecture and Urban Form I</td>
<td>Computer &amp; Information Skills</td>
<td>Language I</td>
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<tr>
<td></td>
<td></td>
<td>Contemporary City</td>
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<td>Language II</td>
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<tr>
<td></td>
<td></td>
<td>Critical Thinking</td>
<td></td>
<td></td>
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<td></td>
<td>Language III</td>
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<tr>
<td></td>
<td></td>
<td>Design Thinking</td>
<td></td>
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<td>Writing Skills</td>
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<td>Mapping Preferences</td>
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<td>Colour and Art</td>
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<td>Architecture Photography</td>
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<td></td>
<td>Design Studio 2: Public Realm Street Design</td>
<td></td>
<td>Dwelling and Neighbourhood Design</td>
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<td></td>
<td>Design Studio 3: Dwelling &amp; Neighbourhood design</td>
<td>Building Types Places for People</td>
<td>Theory of Architecture and Urban Form I</td>
<td>Building physics II</td>
<td>Construction II</td>
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<td>Sustainable Heritage Conservation</td>
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<td></td>
<td>Landscape architecture and planning</td>
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<td>Internship</td>
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<tr>
<td></td>
<td>Design Studio 6: Multi-Function Adaptive Re-use Urban Regeneration</td>
<td></td>
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<td></td>
<td>Structure III</td>
<td>Building Information Modeling</td>
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<td>Sustainable Development</td>
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<td></td>
<td>Building Ecology</td>
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<td></td>
<td></td>
<td>Urban Planning 2</td>
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<td></td>
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<td></td>
<td>Informal Areas</td>
</tr>
</tbody>
</table>

Building technology track

Table 3 illustrates the general structure of the building technology track within the proposed curriculum. In the first preparatory year, basic science courses in probability, statistics, and physics are included. Building on this foundation, the mandatory courses "Building Physics I – The thermal environment", "Building Physics II – The visual and acoustical environment", and "Building Systems Integration" follow. The course "Building Physics I – The thermal environment" provides an introduction to the fundamentals of the thermal aspects of building performance. Within the course "Building Physics II – The visual and acoustical environment", scientific foundations of building acoustics, room acoustics, daylighting, and illuminating engineering are discussed. An introduction to the fundamentals of
buildings’ technical systems (including HVAC systems, fire safety, water and wastewater infrastructure, electrical installations, transportation systems as well as building controls and automation) is given in the course "Building Systems Integration". Thereafter, the course "Spatial and Urban Dynamics", which has a strong focus on urban environments' spatial and physical dynamics, is integrated. The building simulation course "Building Performance Computing" is situated in the fourth year. In the last year of studies, a number of electives provide possibilities to specialize in different thematic fields while pursuing the graduation project. For instance, the elective course "Building Ecology" provides an introduction to the description and evaluation of ecological performance of building components, systems, and structures.

Table 3: The general structure of the building technology track within the proposed new architecture curriculum.

<table>
<thead>
<tr>
<th>SEMESTER 1</th>
<th>Probability &amp; Statistics</th>
</tr>
</thead>
<tbody>
<tr>
<td>SEMESTER 2</td>
<td>Natural Sciences</td>
</tr>
<tr>
<td></td>
<td>Physics Fundamentals</td>
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<td>SEMESTER 3</td>
<td>Building Physics I</td>
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<tr>
<td></td>
<td>The thermal environment</td>
</tr>
<tr>
<td>SEMESTER 4</td>
<td>Building Physics II</td>
</tr>
<tr>
<td></td>
<td>The visual and acoustical environment</td>
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<tr>
<td>SEMESTER 5</td>
<td>Building Systems</td>
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<td></td>
<td>Integration</td>
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<tr>
<td>SEMESTER 6</td>
<td>Spatial and Urban Dynamics</td>
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<td>(Urban)</td>
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<td>SEMESTER 7</td>
<td>Building Performance</td>
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<td>Computing</td>
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<td>SEMESTER 8</td>
<td>Building Ecology</td>
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<td></td>
<td>(Elective)</td>
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<tr>
<td>SEMESTER 9</td>
<td>Graduation Project</td>
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</table>

The performance simulation integration

Most stakeholders in the building design and delivery process agree that architectural design is not just about formal appearance or basic functional solutions. Rather, the professional community and building users alike appreciate the importance of buildings' performance and the quality and robustness of services they provide (Bleil de Souza and Knight, 2007). Likewise, there appears to exist a consensus in the professional community that the integrity and accountability of the design process can benefit from the deployment of computational design support tools in general and building performance simulation tools in particular.

Hence, the building performance simulation course has a special strategic position within the building technology track. Labelled "Building Performance Computing", this course gives an introduction to computational methods and applications for building performance assessment in advanced semesters. The course introduces thermal and visual modelling and design fundamentals of building performance simulation. In addition, case studies and assignments on the application of simulation in building design and operation are processed.

The design of this course is informed by our previous findings regarding the theory and practice of building performance simulation (Mahdavi, 2011; Mahdavi et al., 2003) as well as in teaching performance simulation within the framework of the graduate program "Building Science and Technology" at TU Vienna (BST, 2019). A key aspect of these experiences, shared by a large number of colleagues teaching simulation in other universities, is as follows: Proper understanding and competent use of building performance simulation tools necessitates a prior solid understanding of the foundations of building physics, building construction, and knowledge-based design principles. It is also important to nurture an intuitive sense of the involved physical phenomena in building behaviour, together with an overall order-of-magnitude feeling for the values of commonly computed building performance indicators.

These insights explain in part the placement of the simulation course within the technology module of the curriculum. In our experience, the communicated preceding knowledge on physical processes and technical issues enables the students to reliably validate and properly interpret simulation results obtained. Hence, the implications of the design decisions (specifically, the choice of design options) on buildings' future thermal and visual performance (including its consequences for occupants' health, comfort, and satisfaction) can be systematically assessed and evaluated. This approach is believed to entail the potential to unlock the power of performance simulation as a tool to support an iterative approach to design process.

Within the developed curriculum, different approaches are used to integrate building performance simulation application in the overarching design methodology. Figure 2 provides a schematic depiction of the underlying conceptual approach. On the one hand, more “traditional”
and frequently "single-domain" simulation engines such as EnergyPlus (EnergyPlus, 2018) and Radiance (Radiance, 2018) are adopted. These tools are seen as direct computational derivatives of first-principle physics-based models in building science, involving, for example, numeric heat and mass transfer. The associated scientific foundations are covered, as mentioned earlier, in the prior courses of the technology track. Thus, students are expected to be equipped with basic knowledge required for the proper understanding and interpretation of detailed thermal and visual performance analysis.

On the other hand, and in parallel, the complementary option of parametric modelling tools applications (with assorted disciplinary plug-ins) is pursued. There has been an increasing – and mostly promising – trend toward the deployment of parametric and generative tools both in architectural schools and in architectural practice. Parametric modelling tools and 3D modelling software such as Rhino (Rhino, 2018) and Revit (Revit, 2019), augmented with versatile technically oriented plug-ins such as Ladybug (Ladybug, 2018), Honeybee (Honeybee, 2018), etc. can support generative performance-based parametric design workflows. As such, they can offer a relatively simple usability level for connecting basic design models (building geometry and construction information) with analysis tool pertaining to domains such as energy and daylighting. Moreover, the overall increase of the digital literacy in the population of young students allows for the widespread use of programming tools and platforms such as platforms for visual scripting, for example, Grasshopper for Rhino (Grasshopper, 2018).

The above assertions have been validated, in part, by a recent study concerning the usability of building performance simulation environments within the design process (Bazafkan et al., 2019). The study identified, amongst other things, certain strengths associated with tools such as Ladybug (Ladybug, 2018) and Honeybee (Honeybee, 2018). The latter tools benefit from an easy-to-use interoperability with geometry models generated in Rhino (Rhino, 2018). Moreover, the tools offer intuitive opportunities for the comparison and evaluation of different design alternatives: Users can obtain information regarding the impact of each design decision while working on the model. The design process (i.e., testing and documenting model manipulations) can also benefit from the tools' various visualisation possibilities. This two-fold approach facilitates, in our experience, a mode of simulation tool integration in the design development that has the potential to be both robust and intuitive. The students are thus encouraged to deploy analytical means already during the design development as such means reveal the different implications of design variations on buildings' performance.

**Ongoing implementation**

The realization of the proposed curriculum in the target university is a work in progress. Nonetheless, a brief mention of certain related issues may be of general interest to the academic communities keen on integrating building performance simulation in respective curricula.

For instance, in the course of discussions with instructors of the foundational courses in mathematics and physics, the topical foci and depth of instruction was discussed, so as to address the later requirements for thorough understanding of the relevant energy and mass transfer processes simulated by computational tools. These topical foci (for instance, differential equations and their numeric solution methods) are not always covered in typical basic level science courses of most architecture and engineering schools.

A second important issue pertaining to the integration of technical courses in general and performance computing in particular concerns the relationship to design studios. In multiple discussions with the future instructors of these studies, cross references to technical topics (so-called vertical integration) was addressed.

The consensus emerging from these discussions highlights the significance of a kind of collaborative instructional spirit amongst the faculty: Whereas such a spirit cannot be formally mandated in all settings, efforts toward coordination of content, methods, and tools should be encouraged whenever possible. One concrete outcome of these discussions was the decision to explore the degree to which "light-weight" (e.g., web-based) computational tools could both support partial specific design tasks in the context of the design studios and prepare the students for the later dealings with more extensive, comprehensive, and challenging simulation environments.
Concluding remarks
The present work reported on the ongoing efforts aiming at the realization of an integrated approach to innovative architectural undergraduate education. Based on a comprehensive research and a gap analysis of needs and shortcomings in architecture education, potential for improvement were identified. In order to address this potential, a new architectural engineering program is being developed by a number of experts in their fields of specialization within the framework of the project IMPAQT. We focused, in the present contribution, on describing the building technology track within the proposed undergraduate curriculum. Specifically, we outlined the underlying intellectual background as well as implementation specifics regarding the integration of (thermal and visual) building performance simulation in the curriculum in general and in conjunction with design teaching in particular.

Future steps within the project IMPAQT will involve the full implementation of the undergraduate architectural program at the School of Engineering at Nile University in Egypt. Moreover, the project will focus on a close feedback loop that informs both the technology track evolution as well as the design studio sequence toward a systematic outcome-based educational strategy.

Acknowledgement
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References
Abstract
At The University of Adelaide building performance simulation (BPS) has been taught to architecture students, both at the undergraduate and postgraduate levels, for the last 20 years. BPS is taught in an environmental technology course that links to an architectural design course or studio. The main reason for introducing BPS this way, rather than as an independent course separated from the design studio, is to demonstrate to students the important role BPS plays in a design process.

This paper focuses on the experience in learning and teaching BPS at the postgraduate level to assist students in designing mixed-use multi-storey buildings. The paper discusses the structure of the course, the learning/teaching methods, an example of student projects, as well as evaluation by students. Student evaluation includes quantitative evaluation based on Likert Scale and qualitative comments. Lessons learned from this experience will be summarized.

Introduction
It is well understood that architects, as well as other professionals responsible for the design, delivery, and operation of buildings, play significant roles in minimizing the adverse impacts of buildings on the environment and health of the occupants. In the last 20 years, BPS has been taught in an architecture program at The University of Adelaide in South Australia, and since 6 years ago, BPS has been taught as part of a compulsory course in both the undergraduate and postgraduate programs in architecture. Teaching BPS in an architecture program is not new; it aligns with previous studies suggesting that in order to foster the use of BPS in architectural practices, BPS needs to be integrated with design studio teaching (e.g. Charles and Thomas, 2010). However, not all architecture schools teach BPS as part of a compulsory subject even though a previous international survey conducted in the US, UK, Australia and India recommended that BPS be taught as a compulsory subject in tertiary education of architecture (Soebarto et al, 2015). The follow-up survey of the latter study showed that only 50% of the respondents (or 30 architecture programs) indicated that BPS was taught as a compulsory subject (Hopfè et al, 2017).

In many architecture programs, BPS is often used to understand and analyse the impact of design decisions on the building energy use. Reinhart et al (2012), for example, introduced BPS as a “game” activity with a goal to reduce the simulated Energy Use Intensity (EUI) of an office building. In their approach, a team of ‘simulation experts’ conducted the simulations while the students were not asked to carry out the simulation themselves. The researchers argued this was not only to save time, but also due to the fact that, in practice architects did not typically conduct simulation. Students made the design decisions and then placed their ‘orders’ to the simulation experts to carry out the simulation.

Quite the opposite of the above approach, at The University of Adelaide the focus is on directly exposing students to BPS so that they themselves will be able to explore design strategies and simultaneously see the impact of their decisions on the building performance. Rather than solely focusing on reducing the EUI, the emphasis is on achieving thermally comfortable spaces without the use of heating and cooling – in a ‘free-running’ mode – as much as possible. In other words, while reducing energy use is an inevitable goal, the main focus is on analysing indoor thermal comfort. Reducing lighting energy through incorporating daylighting as well as ensuring that daylight can reach relevant indoor spaces as much as possible is also emphasised. Both issues of achieving a certain level of thermal and visual comfort as well as reducing energy use are indeed critical in the context of assessing the overall environmental performance of a building.

Until 2018, the IES VE for Architects program (Integrated Environmental Solutions 2011-2019) was used due to its graphical interface, found to be adequate for architecture students, and its claimed capability to import models done in CAD packages such as SketchUp and Revit. Students used the program to explore the impact of building shape, volume and orientation; envelope materials; opening size, location, position and operation; external and internal shading strategies, as well as building operational schedules, on indoor thermal comfort, energy use, and internal daylight. They used reference values, such as ASHRAE adaptive thermal comfort model in ASHRAE 55 (2013) and energy use target relevant to the location to judge their design decisions. In addition, environmental performance assessment tools, such as LEED, BREEAM and Green Star were introduced, and students were to conduct partial assessments of their design using one of these assessment tools, particularly to rate the indoor environmental quality and energy use.
This paper will discuss the program and course structures as well as the course delivery and show case a student work as an example. It will also discuss student evaluation of using BPS and of the learning experience in general, as well as the learning outcomes. Both the advantages and problems in using BPS during a design process will be particularly highlighted.

**Program and course structures**

**Program structure**

In this school of architecture, BPS is first introduced in the second year of the 3-year undergraduate level. Students first use BPS to analyse the indoor environmental performance of an existing, small building (usually residential). They then use BPS to investigate the impact of making design changes on the indoor thermal comfort. Only when indoor thermal comfort, with boundaries specified by the adaptive thermal comfort model according to ASHRAE 55 (ASHRAE, 2013) cannot be achieved for more than 90% of the time by implementing “passive” design strategies, can students propose using some kind of heating and cooling in the building. The design changes to be explored include window shading and glazing, envelope materials, insulation, thermal mass, and natural ventilation. However, since the building is existing, no change of the building orientation can be proposed although as an exercise, students can make changes on the building orientation, to explore the relationship between building location, orientation and indoor comfort. If heating or cooling is applied, the total heating and cooling energy use must not exceed the maximum allowable amount, as determined by the relevant energy efficiency provision of the building code.

In the postgraduate program, BPS is re-introduced in an architectural technologies course for the second year of the Master of Architecture program. The course accounts for 25% of the semester load, and is taken in conjunction with an architecture design studio. The studio focuses on designing multi-storey mixed-use buildings in an urban context. Typically, the building will have retail spaces on the ground and lower levels, office spaces on the levels above them, and residential spaces (apartments and/or hotels) on the upper floors. Typically, there are around 80 students enrolled in this course.

While the issues addressed in the design studio range from planning, feasibility study, site analysis, historical and cultural contexts, as well as project costs, much emphasis is placed on minimizing the environmental impact of the design, making the use of BPS in the design process very relevant. It is acknowledged that, as argued by Reinhart et al. (2012), it is unlikely that in practice an architect of a building of this size will be able to perform BPS during the design process. However, exposing students at this level in their architecture education to BPS allows them to be confident yet critical about their own design decisions rather than simply speculating (that their design “will work”). This premise aligns with an argument by Rauen (2001), even though their focus was on clinical educations, that *simulation teaches critical thinking.*

**Course structure**

As this paper focuses on BPS in the postgraduate program, the course structure discussed here is of this program only.

This is a 12-week course, with one hour of lecture and two hours of tutorial or computer workshops per week. Due to space and time constraints, BPS is only taught for 4 weeks, during weeks 8 to 11. It is worth pointing out that prior to 2018, BPS was taught earlier in the semester during weeks 4 to 7; however, this structure proved to be challenging. While the idea of introducing BPS early was so that students could explore their design strategies as early as possible during the design process, we found that they used BPS superficially (i.e. to simply receive marks or grades for their work). This was because during those earlier weeks, they still had not had any concrete design that they could test or explore with BPS as they were still in the planning and feasibility study stages. After they had completed the assignment of using BPS to explore design ideas and changes in this architectural technologies course, we found that many students ignored the results and their final design in the studio had no relationship with the simulations they had done earlier. Based on this earlier experience, since 2017, BPS has been introduced during later weeks in the semester after students have progressed their design into the design development stage. This may not be an ideal approach; however, this timing proves to produce much better outcomes.

The course is basically divided into three stages. During the first stage (weeks 1-4), while students are in the planning and concept stage in their design studio course, they are exposed to topics such as “green” design, zero energy and zero carbon (multi-storey) buildings. Their first assignment is to examine and graphically analyse case study buildings from around the world, claimed to be “green”, “sustainable” and/or zero energy/carbon. During the lecture sessions, various environmental design strategies and technologies, applicable for multi-storey mixed used buildings, are explored.

During the second stage (weeks 5-7), most students will have developed their design concept into a more concrete preliminary design. Thus, during these three weeks students have to develop their environmental design strategies, based on the lessons they have learned during the first four weeks of the course. They develop and explore, conceptually, relevant strategies, so that the spaces in the building will potentially be thermally comfortable without the use, or with minimal use, of heating and cooling, and receive sufficient amount of daylight. These form the second assignment. Note that while the focus during this stage is on “passive design” strategies applicable to such buildings, active heating and cooling systems are also explored during lectures, and so are issues around indoor air quality and material finishes.

Finally, BPS is introduced in week 8 and further design explorations using BPS are conducted during the subsequent weeks. It is important to mention that, as this is a postgraduate program course, it is assumed that...
students will have had sufficient knowledge about building physics, which is necessary in understanding the fundamentals behind BPS, as we teach building physics in the undergraduate program. Thus, unlike in the undergraduate level, where building physics are explored for 6 weeks prior to teaching BPS, in this course there is no in-depth building physics lectures prior to teaching BPS. However, students are referred back to the building physics notes provided in the undergraduate program, which include topics around climate and weather, thermal comfort, heat transfers through building envelope, heat loss/gain calculations and energy use in buildings.

The final assignment is a demonstration on how students have used BPS to improve the indoor thermal and daylight performance of the building they design in the studio. Students are to present the initial design and any design changes that they have explored to improve the building design. In case of using heating and cooling to improve thermal comfort in the building, they also need to present the predicted energy use of the initial design and that of design changes. In addition, they also present the potential energy and indoor environmental quality scores that they could obtain from an environmental rating system, such as Green Star.

The basic structure of the course is presented in Figure 1.

<table>
<thead>
<tr>
<th>WEEK</th>
<th>LECTURE</th>
<th>TUTORIAL/WORKSHOP</th>
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</thead>
<tbody>
<tr>
<td>Week 1</td>
<td>1 March Overview: Green, Sustainable, Zero Buildings</td>
<td>Discussion – Assignment 1</td>
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<tr>
<td>Week 2</td>
<td>8 March Case Study</td>
<td>Site visit (tbc)</td>
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<tr>
<td>Week 3</td>
<td>15 March Design strategies, sitting, zoning, form, materials</td>
<td>Discussion of assignment 1</td>
</tr>
<tr>
<td>Week 4</td>
<td>22 March ‘Passive heating’, cooling, ventilation</td>
<td>Presentation of assignment 1</td>
</tr>
<tr>
<td>Week 5</td>
<td>29 March Active heating and cooling</td>
<td>Consultation</td>
</tr>
<tr>
<td>Week 6</td>
<td>19 Apr Case Study</td>
<td>Discussion of assignment 2</td>
</tr>
<tr>
<td>Week 7</td>
<td>26 Apr Indoor Air Quality, finishes</td>
<td>Presentation of assignment 2</td>
</tr>
<tr>
<td>Week 8</td>
<td>3 May Introduction to Building Performance Simulation</td>
<td>Simulation workshop 1</td>
</tr>
<tr>
<td>Week 9</td>
<td>10 May Lighting and daylighting</td>
<td>Simulation workshop 2</td>
</tr>
<tr>
<td>Week 10</td>
<td>17 May Water and Waste On-site energy generation</td>
<td>Simulation workshop 3</td>
</tr>
<tr>
<td>Week 11</td>
<td>24 May Environmental assessment</td>
<td>Simulation workshop 4</td>
</tr>
<tr>
<td>Week 12</td>
<td>31 May Summary</td>
<td>Presentation of Assignment 3</td>
</tr>
</tbody>
</table>

**Figure 1: Course structure.**

**Learning/teaching methods**

An experienced BPS user and researcher teaches the BPS software in a computer lab setting. Two tutors are also present to support students who require one-on-one occasional help. While various on-line tutorial materials and videos exist, the instructor/teacher has also created workshop materials and videos specifically tailored for the course.

The structure of the BPS teaching is as follows:

- Introduction to BPS and the BPS software
- Workshop 1: building geometry and shading
- Workshop 2: materials, use profiles, window opening and simulation
- Workshop 3: heating and cooling, daylighting and simulation
- Workshop 4: natural ventilation and demonstration of CFD
- Help sessions to individual students to model and simulate their own building

During Workshop 1, the instructor/teacher leads students to create a geometrical model of the building using the BPS software. Students also explore the various features of the software. Due to limited time, usually by the end of the first workshop most students are unable to complete the entire model of the building. Therefore, at the end of the session, a complete model, usually of 4-storey hypothetical office building, located in the same site as the one used in the design studio, will be provided to students so that they can explore the program in their own time after the workshop. Figure 2 shows the basic model that was used in 2018.

**Figure 2: Basic building model used in 2018 to introduce BPS.**

In the second and third workshops, students continue to use the same model to explore the topics, as mentioned above. When a topic is presented and discussed, for example on how to model building materials, the impact of using another material is tested immediately by asking students to run the simulation and compare the initial indoor operative temperatures during a peak period in summer or winter, to those of the changed design. This way students will be able to immediately see the impact of building design, no matter how simple the design alteration is, on the building performance.

Due to limited time available to teach BPS, during the third week, students need to start modelling their own building design. Students who use Revit or SketchUp to model their building usually prefer to use the importing capability of the BPS software and import their Revit or SketchUp model into the BPS program. Unfortunately, many students find this process time-consuming and not
More often than not, converting a Revit or SketchUp model into the BPS program results in a building model with missing walls or windows, which means the model cannot be simulated. Such problem is not unusual and often occurs during the importing process from a building information model (BIM) or CAD model into a BPS model. Hyun, Marjanovic-Halburd, Raslan (2015) have summarised that this problem is due to different approaches in modelling the building zones in BIM and BPS programs, differences in the data format of the two programs, and different information required.

To save time and avoid the above problems, most students directly model the building in the BPS software. The challenge, however, is on modelling a complex building, particularly one with curved walls or roof or other complex shapes. When this is the case, as the intention of the exercise is to first and foremost improve the thermal and daylight performance of certain spaces rather than looking at the whole building energy use, they will be advised to only model parts of the building that are relevant to be explored. If modelling curved walls or roof proves to be too time consuming, students will be advised to model the curved walls or roof into segments of straight surfaces, as the simulation results of such simplification will not be significantly different.

After the fourth workshop, students have the opportunity to show to the tutors the initial design and alterations as well as the simulation results during one-on-one tutorials. The course instructor and tutors also check the simulation inputs to ensure that they simulate the buildings correctly. Students are then present their completed work in the final week of the semester.

Example
Below is an example of student work. The brief was to design a multi-storey mixed-use building in Adelaide CBD (34.9 °SL, 138.6 °EL), consisting of retail spaces on the ground floor, medical offices and clinics on the next three floors, and serviced apartment units in the tower part of the building. The student presented his environmental design concepts, ideas and approaches, such as the building massing, shape and orientation, and ideas for shading and natural ventilation for the apartment units. Although the first goal was to design spaces that would be thermally comfortable without the use, or with minimal use, of heating and cooling, realistically for a building of this size and height, he also had to explore the use of a centralised heating/cooling system. See Figures 3-5.

In this city, commercial and apartment buildings contributed to around 48% of the total CO2 emission (Government of South Australia, 2015) and most of this was due to the use of air-conditioning and lighting. Therefore, in the third stage of the course, students used a BPS tool (IES) to test the performance of the building they designed in their design studio and attempted to minimize the dependent upon air-conditioning and electric lighting in order to reduce energy use and greenhouse gas emissions from the building.

In this example, the student explored the following design parameters, focusing on the fourth level of the building (Figure 6) as well as one of the apartment levels:

1. Glazing type
2. Application of double skin
3. Change of wall materials

While a building such as this would normally use (centralized) heating and cooling systems, the student first tested the impact of design alterations only on the indoor temperatures without the use of heating and cooling. This was based on the assumption that if relatively comfortable indoor temperatures, as recommended by the adaptive
model in ASHRAE 55, could be achieved for most of the time without heating and cooling, the building would use little heating and cooling energy, thus minimizing CO2 emissions.

**Stage 1 – Glazing assessment**

As the windows contributed most of the heat gains and losses in the building, the student explored the impact of using different types of glazing: single, double, double low-e with argon infill, and triple low-e with argon infill, on the indoor temperatures when no heating and cooling were in operation. The exploration only focused on two months: February, when the highest summer temperatures usually occurred in this place, and July, when the lowest winter temperatures occurred. Note that in these explorations, all windows were assumed to be closed.

The results showed that there was little difference between using double and triple glazing with argon infill (Figures 7 and 8). However, considering that the use of triple glazing in this region was uncommon and very expensive, the student decided to use double-glazing with argon infill for the next explorations.

**Stage 2 – Application of double skin**

In the second stage, the student tested the impact of adding another layer to the external wall, or creating a double skin façade (Figure 9) as a way to shade the windows – to reduce solar heat gain and excessive sunlight. However, before testing this, the student predicted the indoor temperatures in February if the windows were fixed/closed and if they were operable.
The results (Figure 10) showed that the indoor temperatures without cooling would only be within the acceptable range if the windows were operable. Opening the windows when the outdoor temperatures were below 30 °C and above 18 °C would result in relatively comfortable indoor temperatures in the summer compared to when all the windows were closed/fixed. However, there would be times during hot summer days when the indoor temperatures still exceeded 35 °C as the outdoor temperatures reached almost 45 °C.

Following this test, an outer layer constructed of 200 mm glass-reinforced concrete skin was applied. The percentage of openness of the skin was 80%, 80% and 30% for the east, north and west façade, respectively. Applying this outer skin lowered the indoor temperatures in the summer to a more desirable level when the windows were open at the right time. During winter, the indoor temperatures were also kept at a reasonable range as long as the windows were closed (Figure 11).

Stage 3 – Change of wall materials

In the final exploration, the student changed the materials of the external and internal walls focusing on one of the apartment levels. The initial external wall materials were either 200 mm precast concrete with plasterboard lining for the west façade (U = 1.742 W/m2.K) or insulated fibre cement sheeting on steel frames with plasterboard internal lining (U = 0.447 W/m2.K) for all other facades. The initial internal walls were plasterboards on double-steel studs with double insulation (U = 0.345 W/m2.K). The external wall materials on the west façade were then changed to 110 mm precast concrete with 80 mm insulation and rainscreen external cladding and plasterboard internal lining (U = 0.9 W/m2.K) while for the other external walls the same construction was used but with thicker insulation (U = 0.413 W/m2.K). For the internal walls, the same construction was applied but with increased insulation (total U = 0.314 W/m2.K).

With the improved wall materials (plus operable windows) the indoor temperatures during summer as well as winter months improved: cooler in summer and warmer in winter, as shown in Figure 12. Note that in both Figures 11 and 12, the dotted lines indicate the temperatures of the base case.

**Figure 11:** Predicted indoor temperatures with additional outer skin in a summer month (top) and winter month (bottom).

**Figure 12:** Predicted indoor temperatures with improved wall materials in a summer month (top) and winter month (bottom).

**Student Evaluation of Learning & Teaching**

The above work is only one example of the kind of explorations that architecture students usually do in this course by using BPS software. Explorations by other students included investigating the impacts of adding an atrium on daylight penetration, illumination and brightness levels; the impacts of green roof on indoor temperatures and cooling energy; and the impact on whole-building energy use from changing various design parameters, e.g. window area, adding external shading, and changing thermostat setting.

At the end of the semester, students evaluated their learning experience in the course (not just about the use
of BPS) through a formal student evaluation of learning and teaching conducted on-line. The evaluation was anonymous and on a 7-point Likert scale. Students also provided comments in the open-ended sections of the evaluation to indicate the positive and negative experience in the course.

Table 1 summarises the mean scores and medians of student evaluations from 55 students (maximum point of each evaluation category was 7). As can be seen in the table, students valued the use of digital activities and resources (i.e. the use of BPS). Most students indeed found BPS to be a very useful tool in understanding the impacts of design decisions on the environmental performance of the building, as shown in some of the open-ended comments, such as:

“Great practical knowledge that relates directly to the architecture industry”

“The practical knowledge allows not only insight into how designs are meeting issues such as climate change, environmental issues and clever ways of saving energy with the use of assisted systems.”

“[The best aspect of the course is] learning new software and engaging with innovation”

<table>
<thead>
<tr>
<th>Evaluation</th>
<th>Mean</th>
<th>Median</th>
</tr>
</thead>
<tbody>
<tr>
<td>Satisfied with quality of the course</td>
<td>5.9</td>
<td>6</td>
</tr>
<tr>
<td>Helps build understanding of key concepts</td>
<td>5.7</td>
<td>6</td>
</tr>
<tr>
<td>Intellectually stimulating</td>
<td>6.3</td>
<td>6</td>
</tr>
<tr>
<td>Includes digital activities and resources that help me learn</td>
<td>6.3</td>
<td>6</td>
</tr>
<tr>
<td>Receives useful feedback</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td>Assessment tasks help me learn</td>
<td>5</td>
<td>6</td>
</tr>
<tr>
<td>Helps to develop thinking skills (problem solving &amp; critical analysis)</td>
<td>5.9</td>
<td>6</td>
</tr>
</tbody>
</table>

Initially, we anticipated that inter-operability (for example, between this BPS software and CAD packages such as Revit, Rhino or SketchUp) would be the main issue that students would raise. While some commented that it was not easy to import a building model created in any of those CAD packages, this turned out to be not a major issue. Some students were able to convert their Revit models into the building model readable by this BPS software, though with difficulties. For the majority, they found that it was relatively much faster to model the building directly in the BPS software instead of spending time trying to redo the building model in Revit in order to make the model file readable by the BPS software. Since we provided students with templates for occupancy schedules, temperature settings, HVAC use profiles and any other relevant parameters that they could use for the base case building, based on applicable standards and common building practices, all the students needed to do after modelling the building was to place the building in the right location and apply the given templates. Thus most of their time was spent on (1) modelling the building geometry, then (2) applying the design changes, as well as (3) understanding and interpreting the results.

Nevertheless, the main criticism about the course, and indeed about the BPS-related activities, was the user-friendliness of the software itself, and the fact that, for some technical reasons, the software crashed too frequently. It appeared that the software worked perfectly on individual computers, but presented numerous problems when executed from the main server of the computer lab. Students’ comments include:

“Modelling software is very one dimensional and difficult to use.”

Students who used the BPS software in the computer lab (instead of using it on their own personal computer) stated:

“The state of the … program at the Architecture School in its current state is awful. Constant crashing, awkward user interface, etc make it a battle to work with.”

“The vital program in which the course is based around is completely broken.”

“I found the workshops hard to keep up with due to the amount of crashing of the program and by the time I had rebooted it, I was well behind where the tutor was up to.”

While the technical issues the students experienced had nothing to do with the software capabilities, the fact that these technical problems (i.e. program crashes) occurred too frequently did affect students’ willingness to learn and use the BPS software, despite the fact that they saw the benefits of using it. Parallel to this was the user-interface of the software, which, for many, was perceived as too difficult to use due to a less clear structure.

**Discussion and Conclusion**

Even though in practice very few architects would perform BPS during the design process and the majority would leave performing BPS to the environmental consultants, our students were able to see and understand the benefits of using BPS during a design process. Unfortunately, the user-friendliness of the user-interface of the BPS program, as well as the technical issue relating to running the software from the server, was the main hindrance. The user-friendliness issues mainly relate to the structure of the user-interface, and for some students, it had to do with the modelling capabilities of the software. As part of their education, architecture students need to explore many design possibilities, including non-simple geometry, while most BPS researchers or engineers and BPS software developers tend to model, or create BPS software to model, simpler and more straightforward building geometry.

So, while students see the power of BPS and the role it plays in a design process, the current limitations of the
user interface and modelling capability of the BPS program continue to be a major issue and may affect their willingness to use it in their future career. This evaluation echoes the findings by Attia et al. (2012) and Hopfe et al. (2017) and continue to be the challenge that needs to be overcome if we want BPS to be part of architectural design processes.

One might argue that it is unnecessary for architects to perform, and thus for architecture students to learn, BPS. In practice, most architecture offices, particularly the large scale architecture firms, would either have BPS specialists within the firm (who do not necessarily have an architecture background) or outsource the task to a specialist outside the firm. This paper, however, argues that, considering that architecture students understand the role BPS plays in the design process, and so do architects in practice (Soebarto et al., 2015), if the BPS software has a clearer structure and is able to model complex building geometry, it is not impossible for architects to use BPS in practice. Architects or building designers only want to explore the impact of location-related aspects (such as building orientation, external structures), building design, envelope materials, and internal usage, on the building performance, and not detailed environmental control systems, thus it is still critical to have a BPS tool that can support the need for design explorations.

With the increasing demand by clients to have ‘zero energy’ or ‘zero carbon’ building, architects do need to perform BPS without having to rely too much on the specialist during the design process. Detailed simulation, such as for the building services systems, can then be performed during the later stages by the engineers and/or building services simulation specialists.

In summary, this paper has highlighted that architecture students do appreciate and understand the value of using BPS in a design process. As architecture students (and architects in general) like to “push the boundary” through their design, it is important that the user-interface of the BPS software has a clear structure and sufficient modelling capabilities. This will allow these building designers to explore the impact of various aspects of building design on the building performance without sacrificing the complexity of the design they would like to explore.

Acknowledgement

The author wishes to acknowledge the work by James Frow, which has been used as an example presented in this paper.

References


Learning Performance-driven Design. Students Approach Integrating Urban Form Studies and Building Performance Analysis

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Tallinn University of Technology, Tallinn, Estonia

Abstract

Solar radiation is a crucial factor for the design of healthy dwellings, efficient buildings and sustainable cities. Urban form has a significant influence on solar energy received by buildings. Architects and designers are increasingly requested to take into account environmental performance of buildings since the very early stages of the design process. Architecture schools struggle to educate students consider building and urban performance as design principle and provide them the skills to perform simulations and analysis. The present study introduces methods and outcome of a course taught by the author integrating form studies and performance-driven design.

Introduction

Contemporary cities are inhabited by more than half of total world population, account for the consumption of more than two third of the entire energy produced and is responsible of three quarters of total carbon emission, and their population is foreseen to increase steadily (United Nations, 2018; IPPC, 2013). Urban form together with transportation, economic and geographical characteristics account for 37% of urban energy use (Creutzig et al., 2013). Comfort of building interiors, pedestrian comfort and buildings energy use depend significantly on urban form (Ratti et al., 2005). Studies show that energy savings up to 50% are possible through integrated urban design based on environmental simulations and performance analysis (Kanters et al., 2014). Solar energy together with daylight can guarantee in large quantity the energy needed for heating, cooling, electric lighting and hot water (Vartholomaios, 2015). Urban density and building morphology have a significant impact on the solar energy received by building facades and pedestrian areas thus improving the use of environmental simulations during schematic design phase can increase buildings’ sustainability (Chatzipoulka et al., 2016). Architects and planners are urged to improve the performance of buildings and urban environments for occupants’ comfort and energy efficiency. Solar radiation is one of the most significant factors for the design of sustainable cities. Recently developed methods can help designers to include solar access as building form driver during the early stages of design process (De Luca, 2017a).

Following the awareness of the necessity of an improved sustainability, environmental integration and energy efficiency of buildings and urban environments, the use of computer simulations is spreading in the architecture schools worldwide. However, environmental and energy simulations still tend to be not utilized in early stages of the design process, when they would be more effective, thus decreasing their potentialities in driving design decisions (Samuelson et al., 2012). A second issue in the utilization of computer simulations is that also architects more attentive to the environmental and sustainable aspects either lack the necessary skills to perform and integrate in the design process the different simulations or do not fully know how to interpret correctly the results provided by building performance specialists (Reinhart et al., 2012). Evidence show that providing simple models, preparation lessons and simulation tips during daylight simulation classes, improve student results and confidence in applying the procedures on future projects (Ibarra and Reinhart, 2009). It is therefore very important that architects could learn during their studies how to prepare properly models, carry-on basic environmental simulations, interpret the results and use the evidence obtained for design decisions.

In architecture schools the teaching of environmental and energy performance analysis of buildings and urban environments through computer simulation is assigned to specific building systems courses often not directly related with architecture studio courses (Charles and Thomas, 2009). Integrating building physics and environmental design principles within studio courses enhance students learning and consciousness of sustainability issues through role-play exercise and team working (Westrup and Planander, 2013). The shared convinacement of the importance of sustainable design and the large utilization in schools nowadays of performance analysis do not match with the actual skills of architecture graduates. Studies show that students can learn to perform simulations efficiently and can use the results to improve their design (Reinhart et al., 2015).

The present study introduces methods and outcome of the course Performance-driven Planning and Design taught by the author to 3rd year architecture students at Tallinn University of Technology during Fall 2017. The students had the opportunity to integrate architectural form studies and building performance simulations. The expected learning outcome were the increased awareness of students of the importance of building performance as one of the principles guiding architectural design decisions and the ability to perform parametric studies for solar access and solar radiation analysis.
Methods

The aim of the course Performance-driven Planning and Design was twofold. Firstly, make the students aware of the importance to consider building performance analysis as one of the guiding principles of architectural design, and make them experiment evidence-based design integrating architectural form studies with performance-driven form finding. Secondly, teach the students the basics of solar energy, to perform solar related simulations, and to integrate the analysis in the early stages of the design process to drive design decisions.

The three main aspects of the presented methods are form studies of building cluster patterns, modeling and simulation, students work evaluation.

Form studies

The innovative aspect of the course is the integration of architectural and urban form studies with performance-driven design. At the beginning of the course the students form seven groups, six composed of two members, one with three members, evenly matched on the basis of students’ skills in the use of CAD. Consequently, the author selects same quantity of building cluster patterns and study areas in the city of Tallinn, Estonia (Figure 1). The patterns are representative of widespread typologies used in new residential developments in Tallinn, and of architectural form layouts used in contemporary design (Ching, 2007; Neufert et al., 2012). The building typologies used as cluster patterns are Point, Line, L-shape, Tree, Box, Court and Open block (Figure 1).

The selected study areas are located in high-density urban environments such as city centre and residential areas characterized by panel housing blocks. During a discussion that involved the students about characteristics of the different pattern morphologies and urban environments, the author assigned to each group one building cluster pattern and one urban area.

Consequently, the students perform form studies applying architectural and urban design principles learnt in design studios and develop different 2-dimensional diagrams. During a major review they select the most architecturally sound layout to use it for parametric design variations and performance analysis (e.g. the group of the Line building cluster pattern selects a parallel building layout).

3D Modeling

After having worked with sketches and drawings, the first students approach on the software is modeling the assigned urban area. At the beginning of the course, students learn the basic principles and tools of 3D modeling with the software Rhinoceros (McNeel, 2019a). The online Estonian Geoportal is the source of information about urban morphology and building heights through GIS imagery. Students learn to model buildings surrounding the plot as simple “shoeboxes” using polysurfaces. Polylines define the plots they will use as boundary of the building cluster. Consequently, the author shows to students how to reference the urban model in the parametric design software.

Parametric modeling

The students perform parametric modeling of building clusters, solar design and solar radiation analysis using the software Grasshopper for Rhinoceros (McNeel, 2019b). Differently than the 3D modeling section, the author presents to students more in detail methods and tools of algorithmic design, of which all of them are novice.

The students use the layout selected for the assigned building cluster pattern to realize three variations through parametric modeling. The author shows them how to model building footprints using rectangular closed polylines based on a 3m module. The sizes requested for the depth of the linear buildings are 12m, 15m and 18m, whereas the square elements must have sides of 18m and 36m. Additionally, parametric models have to take into account a minimum distance of 8m as required by fire safety regulations.

The parametric model performs variations of position, distance and orientation of the elements of the building cluster. This way the students experiment potentialities of parametric design for form finding. The author presents to students workflows to generate surfaces from building footprint contours, to subdivide them using square cells 3m in size and to extrude them by 3m, the typical residential floor-to-floor height, generating cubic polyhedra of ground floor. Students learn how to generate vertical array of polyhedra and the corresponding buildings mass composed of cubic cells with different maximum eight for the different urban areas.
Solar envelope generation

Rights of light is the first performance required to the building cluster. The scope is to teach the students to consider the impact of a proposed design on the surroundings and to present the rights of light requirement of the Estonian standard “Daylight in dwellings and offices” (Estonian Centre for Standardization, 2015). Though not following exactly the prescription of the standard, inasmuch too complex for the scope of the course, the author presents the method to generate a solar envelope (SE) for the assigned plot (Knowles, 1981).

Together with methods of algorithmic design, the author presents tools for solar design to students. Each group generates the sun path for the city of Tallinn (Lat. 59°26'N Lon. 24°45'E) using the environmental design plug-in DIVA4 (Solemma, 2016). Consequently, students have to select the 5 hourly sun positions from 10am to 2pm for June 21st to guarantee a consistent volume of the SE for design purposes (Figure 2).

The simplified method to generate solar envelopes as taught to students is composed of the following steps: selection of the façade most affected by the new buildings; generation of vector lines from the façade baseline in the opposite direction of the 5 sun vectors; creation of planar surfaces using pair of lines of the same hour; surfaces vertical extrusion; subtraction of the resulting 5 volumes from the volume extruded on the plot.

Solar radiation simulations

The third part of the course introduces students to environmental principles and factors influencing building and urban design and presents methods and tools for simulation with special regard to solar radiation, which students will use in their design.

Prior to performing simulations, students have to modify cluster building masses to be contained into the generated solar envelope. The method presented to students is based on workflows, developed by recent research work, to generate solar envelopes for high-rise buildings and to assess building clusters buildable area and solar access in dense urban environments (De Luca, 2017b; 2017c).

The author presents to students the workflow through a specific algorithm to test inclusion of cluster building cells into the solar envelope and to eliminate the cells outside the solar envelope. Consequently, the algorithm joins the remaining cells and generates the external envelope of the buildings composed of vertical and horizontal surfaces 3x by 3m in size (Figure 3).

The core section of the course introduces students to solar radiation analysis using the simulation software Radiance (Ward, 1994) through the Grasshopper plug-in DIVA4. The main required data and steps presented to students for building envelope solar radiation simulation are:

- Weather data
- Objects and materials
- Simulation grid
- Raytrace quality setting

Solar radiation simulation takes into account Tallinn weather data using epw file (EnergyPlusWeather). The author shows to students the location on the computer lab server of the file and how import data in the parametric model. Simulation period is the entire year. Students receive detailed information about the procedure to assign material reflectance value (R) to ground, surrounding and cluster buildings using a specific component and to set simulation grid parameters. Suggested values are R 20% for ground and R 35% for the surrounding and cluster buildings, and 3m for the grid, which corresponds to the façade cell size. The plug-in DIVA4 permits an easy set-up of Radiance parameters through selection of raytrace quality settings (Lowest, Low, Medium, and High). The author presents principles of backward raytracing to students and emphasizes the importance of using accurate...
settings. Nevertheless, for the scope and time limit of the course it is suggested to use quality Low, corresponding to Radiance parameters -aa .15 -ab 2 -ad 1024 -ar 256 -as 128, for work in progress analysis and at least Medium, corresponding to Radiance parameters -aa .1 -ab 4 -ad 1024 -ar 256 -as 256, for the final work.

The author presents to students the output of simulations, total solar energy (SE) (kWh) and solar energy density (SED) (kWh/m²). Since SE and SED are conflicting (larger number of buildings increase SE but decrease SED because buildings overshadow each other), students’ task is to select the best trade-off variation among the three.

During a specific lesson, the author shows to students the procedure to iterate the three variation simulations using one parametric model (Figure 3), and how to export results in Excel for evaluation and presentation. Additionally, in the course is taught Daylight Factor analysis which was planned to be a performance to be included by students in their studies, but discarded for the complexity of evaluating cluster variations using two different simulations and for course time limits.

### Evaluation criteria

The course results are evaluated in three ways. The first evaluation is based on a checklist of possible errors (Table 1). 3D and parametric modeling, solar design and simulation modeling errors are analysed following methods of existing studies (Ibarra and Reinhart, 2009). The most significant modeling and simulation input are selected for different modules. For each input possible errors done by the students are listed for a maximum of 7 as the number of work groups. The quantity of errors is the sum of the interim review and final presentation, though few of the issues were still present in the final works. Same errors are marked only once.

The second evaluation method compares the results of the student simulations, using their final models, with new simulations performed by the author on new models of the urban areas and related students’ selected best variation of building clusters. The third evaluation is performed through a questionnaire about the course provided by the author to the students. Queries and students assessments are presented in section Results.

### Table 1: List of modeling and simulation input, possible errors used for evaluation and quantity of errors.

<table>
<thead>
<tr>
<th>Module</th>
<th>Modeling and simulation input</th>
<th>Possible errors</th>
<th>Errors</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>3D modeling</strong></td>
<td>Setting of correct model units</td>
<td>Not meters</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Import of GIS map</td>
<td>Urban area map not in scale</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>Modeling of surrounding buildings</td>
<td>Few buildings modeled</td>
<td>6</td>
</tr>
<tr>
<td><strong>Parametric modeling</strong></td>
<td>Parametric model of building cluster footprint variations</td>
<td>Closer than 8m or overlapping</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>Subdivision of cluster building footprints</td>
<td>Partially outside the plot</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Polyhedra of cluster buildings mass</td>
<td>Not square cells</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Cells size not 3m</td>
<td>3</td>
</tr>
<tr>
<td><strong>Solar envelope</strong></td>
<td>Sun path</td>
<td>Not correct input of Lat. and Lon.</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Solar envelope</td>
<td>Wrong façade baseline selection</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Wrong extruded volumes for SE subtraction</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Unsuccessful subtraction operation</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Fixed maximum height</td>
<td>6</td>
</tr>
<tr>
<td><strong>Solar radiation</strong></td>
<td>Cluster buildings mass</td>
<td>Outside the solar envelope</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Cluster buildings cells</td>
<td>Polyhedra instead than envelope planar cells</td>
<td>-</td>
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<td></td>
<td>Solar radiation model</td>
<td>Missing weather data</td>
<td>-</td>
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<td></td>
<td></td>
<td>Surrounding buildings not included</td>
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<tr>
<td></td>
<td></td>
<td>Ground plane not modeled</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Cluster buildings not included</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Wrong surr. building materials reflectance</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td></td>
<td>No material reflectance for ground plane</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Simulation grid wrong size or offset</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Wrong raytrace quality settings</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Wrong output selection (only SE or SED)</td>
<td>5</td>
</tr>
<tr>
<td><strong>Iteration</strong></td>
<td>Iteration</td>
<td>Unsuccessful simulations iteration</td>
<td>6</td>
</tr>
<tr>
<td><strong>Variation selection</strong></td>
<td>Best trade-off variation</td>
<td>Unsuccessful trade-off variation selection</td>
<td>5</td>
</tr>
</tbody>
</table>
Results

The present section presents results for the evaluation criteria. Modeling and simulation errors are discussed for the main workflow modules (Table 1). Solar radiation analysis results of student works are compared with new simulations performed by the author and questionnaire assessments are presented.

Modeling and simulation errors

Results of modeling and simulation errors show that the most critical module of the workflow is the one related to solar radiation simulations. It is important to notice that between the interim review and the final presentation the quantity of errors of student group works decreased significantly. Nevertheless, all the groups repeated few errors mostly in the module Solar radiation simulations also for the final models, despite that the author explained thoroughly to students the importance of specific modeling steps.

The most common errors for the 3D modeling module are the inaccurate scaling of urban area map, though in most cases by a small deviation, and the small quantity of buildings modeled around the plot. These are typical errors of novices, which at the beginning of the design process do not understand the importance of a proper modeling accuracy and its relation with the simulations to perform.

The module Parametric modeling is the one with the least total number of errors due to several hands-on lessons tutored by the author. The largest number of errors done in the parametric modeling workflow concern the precision of the variations of the building cluster footprints.

Also for the module solar envelope generation few errors are marked, though they concern not crucial modeling steps. Different days and hours have been used by the groups, though the author request was to generate a solar envelope for June 21st for the hours from 10am to 2pm, and fixed maximum height has been used, the same of the cluster buildings, though it hasn’t been required.

The most critical errors of the module Solar radiation simulations concern the modeling of the ground plane, the inclusion of cluster buildings in the simulation as elements blocking solar radiation on each other and assignment of correct material properties, and raytrace quality settings. Almost all the groups repeated the most common mistakes for the interim as well as the final models. The reason is that they permit anyway to perform simulations though the results are less reliable. Hence, the students did not perceive these modeling steps as critical although the author stressed their importance.

Almost all the groups failed in optimizing the parametric design workflow. Students modeled three times the portion of algorithm to perform solar radiation simulations for the three design variations instead of using the same algorithm with the addition of an iteration component. Finally, most of the groups selected as best variation the one receiving the largest value of SE instead of the one with the best trade-off between SE and SED.

Comparison of solar radiation analysis results

To evaluate students’ solar radiation simulations the author modeled the urban environments and building clusters, performed new simulations and compared SE results (Figure 4). The student models used are those with the best performance trade-off, though the majority of the groups for the final presentation selected as best variation the one with the largest total solar energy. To perform new simulations the author used the group models after having amended the errors present in their final works. The errors are presented in Table 2.

<table>
<thead>
<tr>
<th>Groups</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ground not mod. / w/o mat.</td>
<td>●</td>
<td>●</td>
<td>●</td>
<td>●</td>
<td>●</td>
<td>●</td>
<td></td>
</tr>
<tr>
<td>Cluster build. not included</td>
<td>●</td>
<td>●</td>
<td>●</td>
<td>●</td>
<td>●</td>
<td>●</td>
<td></td>
</tr>
<tr>
<td>Surr. buildings wrong mat.</td>
<td>●</td>
<td>●</td>
<td>●</td>
<td>●</td>
<td>●</td>
<td>●</td>
<td></td>
</tr>
<tr>
<td>Raytrace quality</td>
<td>●</td>
<td>●</td>
<td>●</td>
<td>●</td>
<td>●</td>
<td>●</td>
<td></td>
</tr>
</tbody>
</table>

Five groups either didn’t model or didn’t assign any material reflectance to ground planes (objects without material assigned are not included in simulations by DIVA4). Five groups included in the simulation the cluster buildings only as elements receiving solar radiation and not also as shading elements. Four groups assigned a wrong material or reflectance to surrounding elements.

Figure 4. Total solar energy results comparison between students and new simulation results.
buildings. All the groups except one used Low quality setting for raytrace calculations. The author amended the models using the settings requested during the course, i.e. use of ground plane with opaque material reflectance 20%, cluster building included in the simulation as shading objects with the same surrounding buildings opaque material reflectance of 35% and raytrace quality Medium. During the course the author recommended to students to use Medium quality setting for final models, though it doesn’t guarantee very accurate solar radiation analysis (Radiance main parameters -aa .1 -ab 4 -ad 1024 -ar 256 -as 256), due to short available time to perform simulations.

Results show that most of the student simulation results (groups 1-3, 6 and 7) overestimate total solar energy mostly because their models didn’t include cluster buildings as shading elements. The large differences of performance, which range between +18.3% of group 7 to +95.1% of group 6, are due to different quantity, size and morphology of building clusters.

Group 4 students included in their final model the ground plane, the cluster and surrounding buildings with correct assignment of materials reflectance. The small increase of total solar energy in the new simulation is due to a more accurate calculation obtained using the Medium raytrace quality setting.

The small decrease of total solar energy for the new simulation with group 5 model is due to the combined results using Medium raytrace quality that increase performance and modeling the ground plane with low reflectance value of 20% which reduces solar radiation on lower building floors.

**Questionnaire outcome**

For the third evaluation of the course, the author delivered a questionnaire to the students (Table 3). Each student evaluated with a score from 1 to 5 the level of difficulty and the confidence in developing the work for the different steps of every module. The questionnaire, submitted by the students together with their final works, presents more detailed steps than the list of modeling and simulation input of Table 1. The sum of the unweighted scores of each step is 15, as the number of students. For the assessment, the final difficulty score of each step is obtained through summation of the weighted scores, where the weight is the number of level of difficulty that is multiplied by the score of the level.

The lowest final scores of level of difficulty among the different modeling and simulation steps are related to the course module 3D modeling. The reason is that most of the students already had CAD drafting and 3D modeling skills of varying level with different software. Also the last module Variation selection presents low level of difficulty final scores due to prior basic knowledge of the students in using Excel to design charts.

The main modules of the course, Parametric modeling, Sun path generation, Solar envelope generation and Solar radiation simulation present similar level of difficulty final scores. The highest scores assigned by students are related to the Parametric modeling module. The highest score is related to the step Building cluster footprint parametric variations. The lowest difficulty scores assigned by students among the main course modules are related to Solar radiation simulation. The lowest scores are related to steps Selection of simulation grid, Selection of buildings and ground, and Selection of weather file.

### Table 3. Questionnaire scores and weighted sums.

<table>
<thead>
<tr>
<th>Level of difficulty</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>Σ</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>3D modeling</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Urban area map import</td>
<td>11</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td></td>
<td>24</td>
</tr>
<tr>
<td>Urban area map scaling</td>
<td>8</td>
<td>3</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>29</td>
</tr>
<tr>
<td>Buildings footprint drafting from area map</td>
<td>8</td>
<td>5</td>
<td>2</td>
<td></td>
<td></td>
<td>24</td>
</tr>
<tr>
<td>Modeling of surrounding buildings</td>
<td>5</td>
<td>7</td>
<td>1</td>
<td>2</td>
<td></td>
<td>30</td>
</tr>
<tr>
<td><strong>Parametric modeling</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Building cluster footprint parametric variations</td>
<td>3</td>
<td>7</td>
<td>4</td>
<td>1</td>
<td></td>
<td>48</td>
</tr>
<tr>
<td>Subdivision of cluster building footprints</td>
<td>2</td>
<td>5</td>
<td>6</td>
<td>2</td>
<td></td>
<td>38</td>
</tr>
<tr>
<td>Array of cells for building mass</td>
<td>1</td>
<td>5</td>
<td>7</td>
<td>1</td>
<td>1</td>
<td>41</td>
</tr>
<tr>
<td>Culling of the cells outside the SE</td>
<td>1</td>
<td>4</td>
<td>6</td>
<td>3</td>
<td>1</td>
<td>44</td>
</tr>
<tr>
<td>Union of remaining cells for building envelope gen.</td>
<td>7</td>
<td>5</td>
<td>2</td>
<td>1</td>
<td></td>
<td>42</td>
</tr>
<tr>
<td><strong>Sun path generation</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Input and output of sun path component</td>
<td>1</td>
<td>5</td>
<td>7</td>
<td>2</td>
<td></td>
<td>40</td>
</tr>
<tr>
<td>Input of latitude and longitude</td>
<td>4</td>
<td>9</td>
<td>1</td>
<td>1</td>
<td></td>
<td>29</td>
</tr>
<tr>
<td>Input of month, day and hours</td>
<td>6</td>
<td>6</td>
<td>3</td>
<td></td>
<td></td>
<td>27</td>
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<tr>
<td>Sun vectors output</td>
<td>4</td>
<td>7</td>
<td>4</td>
<td></td>
<td></td>
<td>45</td>
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<tr>
<td><strong>Solar envelope generation</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Façade baseline selection</td>
<td>2</td>
<td>3</td>
<td>6</td>
<td>4</td>
<td></td>
<td>42</td>
</tr>
<tr>
<td>Vector lines generation from façade baseline</td>
<td>2</td>
<td>5</td>
<td>8</td>
<td></td>
<td></td>
<td>36</td>
</tr>
<tr>
<td>Loft surface generation from vector lines in pairs</td>
<td>1</td>
<td>5</td>
<td>7</td>
<td>2</td>
<td></td>
<td>40</td>
</tr>
<tr>
<td>Volumes generation</td>
<td>1</td>
<td>5</td>
<td>4</td>
<td>3</td>
<td>2</td>
<td>45</td>
</tr>
<tr>
<td>Subtraction of volumes from extruded plot</td>
<td>1</td>
<td>6</td>
<td>2</td>
<td>6</td>
<td></td>
<td>43</td>
</tr>
<tr>
<td><strong>Solar radiation simulation</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Selection of simulation grid</td>
<td>3</td>
<td>10</td>
<td>2</td>
<td></td>
<td></td>
<td>29</td>
</tr>
<tr>
<td>Selection of buildings and ground</td>
<td>6</td>
<td>6</td>
<td>3</td>
<td></td>
<td></td>
<td>27</td>
</tr>
<tr>
<td>Assignment of materials reflectance values</td>
<td>1</td>
<td>5</td>
<td>6</td>
<td>2</td>
<td>1</td>
<td>42</td>
</tr>
<tr>
<td>Selection of weather file</td>
<td>6</td>
<td>5</td>
<td>3</td>
<td>1</td>
<td></td>
<td>29</td>
</tr>
<tr>
<td>Selection of raytrace quality settings</td>
<td>2</td>
<td>5</td>
<td>5</td>
<td>1</td>
<td>2</td>
<td>41</td>
</tr>
<tr>
<td>Simulation output selection</td>
<td>1</td>
<td>7</td>
<td>5</td>
<td>2</td>
<td></td>
<td>38</td>
</tr>
<tr>
<td>Simulations iteration</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td></td>
<td></td>
<td>45</td>
</tr>
<tr>
<td><strong>Variation selection</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Saving of solar radiation simulation results</td>
<td>4</td>
<td>3</td>
<td>7</td>
<td>1</td>
<td></td>
<td>35</td>
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<tr>
<td>Comparison of performance results</td>
<td>5</td>
<td>7</td>
<td>3</td>
<td></td>
<td></td>
<td>28</td>
</tr>
<tr>
<td>Building cluster selection</td>
<td>2</td>
<td>10</td>
<td>2</td>
<td>1</td>
<td></td>
<td>32</td>
</tr>
</tbody>
</table>
Discussion
This section discusses results related to students modeling and simulation errors and their assessment of level of difficulty for different course modules and steps. The outcome is twofold. On one side the questionnaire confirms outcome of modeling and simulation error analysis, on the other presents differing outcome that permit to evaluate further students learning needs.

Students answers confirm that the 3D modeling module is not difficult, indeed they didn’t make any crucial error for the different steps. Similarly, students assessed solar radiation simulation iteration step as one of the most difficult. Indeed, almost all the student groups did not perform any iteration, but copied the same algorithm two times to perform the required simulations of the three variations of building clusters.

Unexpectedly the Parametric modeling has been evaluated by students with high difficulty scores whereas few errors have been marked for this module. Conversely, the module Solar radiation simulation does not present the highest difficulty score but is the one related to errors the students repeated in the interim review and in the final models. The author presented thoroughly to students both modules during the course lectures.

The author argues that the opposite outcome is due to different modeling methodologies. Parametric modeling requires one to build detailed algorithms using specific components for each function and to be in control of all the component connections and of the input and output methods. Simulations using environmental design tools integrated in parametric modeling software are performed using complex components. These present many inputs with default settings and hidden options, which are easily overlooked by novices. This way students lose control of the simulation process and consider acceptable output with significant errors.

Similarly, the students assessed as not difficult also the module Variation selection whereas most of them did not select appropriately the most performative cluster variation. The author will put more attention in the future to let students correctly select the best trade-off for maximum total solar energy and solar energy density.

Learning outcome
In relation to the expected outcome, the course succeeded in making the students aware of the importance to integrate urban form studies with environmental performance analysis to drive design decisions and to improve building quality, comfort and efficiency.

Students have been successfully active during the course. At additional queries of the questionnaire all the students responded positively saying they will try to use the learned methods and skills in future design studio projects and in their professional activity.

The course has been partially successful for the expected outcome related to the students learning of the process and tools for solar design and performance-driven design. Students learned appropriately 3D modeling of urban environments, parametric modeling of building cluster variations and solar envelope generation to guarantee rights of light on neighbouring facades. Students encountered difficulties in learning solar radiation simulation and iteration, performance comparison and optimal building cluster selection.

Results show that students learn more efficiently when the process of modeling is divided in small steps characterized by single functions. Students realized successfully parametric models using workflows based on multiple components. The learning performance of students related to input, output and accuracy of simulation results are smaller because different functions are incorporated into a single step. This is the case of the components used for simulations integrated into parametric design software.

Using the research outcome the author will develop further the successful aspects of the presented course and will address the critical aspects through the useful insights obtained. The lesson learned by the author is that in future courses the different input and options for simulations will have to be more explicit in the parametric model and the importance and effects of the different simulation options will have to be explained more in detail.

Additionally, through design and simulations the students learned the potentialities of integrating two different approaches: (1) the deductive one that moves from the general to the specific; and (2) the inductive one that moves from the specific to the general. The first, typical of speculative and artistic thinking, permitted students to generate buildings layout through architectural principles. The latter, typical of scientific thinking, permitted them to finalize their design using evidence, objective data and analysis. This way students learned the method of selection to deduce optimal design. The author believes that the ability to prove the quality of their design through objective data and indisputable results it is a crucial skill for contemporary students and future architects.

Conclusion
The present paper presents and discusses methods and outcome of the course Performance-driven Planning and Design held by the author during Fall 2017 at Tallinn University of Technology (TalTech).

The students had the possibility to merge in one single process architectural design principles and performance-driven design methodologies. The performance used in the design were those related to solar access and solar energy. Students developed building cluster layouts using architectural design principles, layout variations through parametric design and selected the most performative configuration for rights of light and solar radiation.

Results related to students modeling and simulation errors, comparison of solar radiation analysis performed by student groups and new analysis performed by the author and questionnaire outcome present useful insights to improve future courses syllabi.

Lessons learned in the presented course can be relevant also for professional designers. Suggestions and recommendations are the following:
• Use building simulations from the very early stages of the design process, when they are more effective.
• Build accurate 3D models of urban environment and project buildings.
• Spend adequate time to study the simulation input options and their effects on the output and results.
• Perform simulations with different input options for sensitivity analysis of inputs to optimize results reliability and computation time.
• Chose the final design option with the best trade-off of the different performance and not the one with best result for one single performance.

In conclusion, the method based on integrating qualitative aspects of architectural and urban design and quantitative aspects of building performance gave the students the opportunity to experiment evidence-based design processes to drive design decisions. The course succeeded as well in increasing the students awareness of the importance of environmentally conscious design.

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References


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Abstract
Given the substantial energy and carbon footprint of buildings worldwide, building simulation technology continually strives to facilitate high-performance designs, yet many simulation tools inform building construction only after major design decisions have been made. Alternatively, early design simulation tools help design teams embed energy and environmental performance into the core design. This paper presents an EnergyPlus-based early design decision-making framework for building simulation that when furnished with basic inputs generates design options that can be filtered by energy performance, carbon footprint, and cost criteria. The framework is used to inform the design of hypothetical eight-story office buildings in Washington D.C. and Phoenix, AZ, USA. This framework aims to assist architects in developing and refining high-performance preliminary designs based on their project and budgetary constraints.

Introduction
With the reality of climate change, cities and municipalities across the globe are attempting to reduce their carbon footprints. In the past year, Copenhagen, London, Montreal, New York City, Paris, Stockholm, Sydney, Tokyo, Tshwane, and ten other cities pledged to ensure all buildings in their cities will meet net-zero carbon standards by 2050 (C40, 2018).

Much research has been dedicated to improving building energy simulation tools and technology to aid in the design of high-performance buildings. However, the vast majority of this research has focused on tools and models that suggest improvements to highly resolved designs. One study found that of the 400 building energy simulation tools listed on the U.S. Department of Energy’s website in 2013, less than 8% of them had the potential to inform the pre-design phases (Batueva and Mahdavi, 2014). This conventional design process can miss opportunities to significantly improve energy performance and reduce cost through simple design modifications. Alternatively, tools intended to aid architects and design teams during pre-design and schematic design stages can lead to high-performance designs through a more integrated process (Hygh, DeCarolis, Hill, and Ranji Ranjithan, 2012; Østergård, Jensen, and Maagaard, 2016).

Most building performance simulation software can only evaluate refined designs, are difficult to modify quickly if the design changes, and are not user-friendly for architects (Attia, Gratia, De Herde, and Hensen, 2012; Østergård et al., 2016). Thus, simulation software intended for the early design phases must have different qualities than typical building simulation software. A recent review of building simulation software asserts that early stage design simulation software should be proactive, intelligent, capable of accommodating rapid design changes, and holistic (Østergård et al., 2016). Proactive software is especially crucial since it provides multiple design options instead of evaluating an existing design. A survey of architects and engineers found that architects prioritize intelligence, or the ability to support decision-making throughout the design phases, in simulation software over usability, accuracy, and interoperability (Attia, Hensen, Beltrán, and Herde, 2012). Since architects usually make critical design decisions such as building massing, orientation, and structure that greatly impact the energy and carbon footprint, early design simulation software should ideally cater to architects. Overall, these criteria suggest that a successful early design software should be proactive, intelligent, rapidly adaptable, and architect-friendly.

Some building simulation tools in recent years address this gap in early design simulation software. Attia et al. proposed an early design simulation tool that helps designers select interventions that meet thermal comfort and energy performance goals in hot climates (Attia, Gratia, et al., 2012). Ochoa et al. similarly proposed a pre-design tool for intelligent façade design that takes into account aesthetic design requirements like view direction and open or closed office configurations that would impact the façade (Ochoa and Capeluto, 2009). Østergård et al. presented a simulation methodology to help design teams select designs optimized for energy efficiency, thermal comfort, and daylighting in the early phases (Østergård, Jensen, and Maagaard, 2017). Although each of these studies presents proactive, intelligent, and flexible approaches that give designers multiple options, they focus on energy performance, and in the case of Østergård et al., still require an experienced modeler to run simulations.

Embodied energy and carbon in buildings receives even less attention from early design building simulation research. One notable study by Eleftheriadis et al. presents an approach to optimize the structure and various building components for lifecycle carbon emissions and costs. The results showed over a 50% reduction in carbon footprint and a 10% reduction in lifecycle costs between
optimized examples, demonstrating the environmental and economic value of models that focus on lifecycle carbon emissions (Eleftheriadis, Schwartz, Raslan, Duffour, and Mumovic, 2018). Given the increasing number of cities targeting carbon neutrality, many design teams will need to consider the full carbon footprint of buildings, not just operational energy use. This approach has a few drawbacks, including that it first focuses on optimizing the structure and then on improving energy performance. It also requires a predetermined massing and structural material, making it more applicable to schematic design than pre-design phases.

The papers discussed thus far describe several intelligent and proactive methodologies for addressing building energy performance and comfort, or in the case of Eleftheriadis et al., carbon footprint and cost. However, none provide an integrated, flexible approach for exploring the optimal energy, carbon, and cost performance concurrently throughout the pre-design and schematic phases of a building project.

This paper presents a proactive, holistic early design decision-making framework that assesses design options based on energy performance, embodied carbon, and cost, allowing architects and design teams to quickly identify basic designs optimized for their specific environmental goals, programming needs, and budget. The framework is implemented in Rhino/Grasshopper, a popular CAD platform (Robert McNeel & Associates, 2019). It utilizes the EnergyPlus-based simulation engine Archsim (Dogan, 2018) paired with a “shoeboxer” algorithm (Dogan and Reinhart, 2017) to rapidly run energy simulations, and an “autozoner” algorithm (Dogan, Reinhart, and Michalatos, 2016) that allows users to opt for automatically generated ASHRAE 90.1 thermal zoning. These tools enable both brute-force exploration of the parametric design space in several hours or rapid trialling of design options in seconds. The use of the Rhino/Grasshopper platform also allows architects to easily import or model custom building geometry and input it into the simulation. Reinhart et al. used a similar Rhino/Grasshopper set-up as a teaching tool to help architecture students analyse energy models and improve performance (Reinhart, Dogan, Ibarra, and Samuelson, 2012).

Since every design project has unique goals and constraints, this framework does not inherently prioritize one assessment criteria over the other, but instead empowers the design team to select options that fit their goals and constraints. Importantly, the framework is flexible enough for use in pre-design into schematic design phases, assisting architects with key decisions at multiple stages. In essence, this framework is intended to supplement an architects’ intuition during early design, fulfilling an underserved function among building performance simulation software.

**Methods**

This version of the framework applies only to office buildings ranging from one to twenty stories, with several options for shell constructions and structural systems based on typical constructions in the U.S. as well as “green” and mass timber options that have lower carbon footprints and better environmental performance. The framework’s structure can be easily expanded in the future to include other building typologies since it simply requires inputting the relevant cost, carbon, and thermal data into the existing templates. The framework is intended to work throughout the pre-design (programming and analysis phase) and into the schematic design phase of projects. It can be used before massing and other aspects are resolved and then updated with details like the envelope, structure, and orientation as the project progresses.

**Data Collection & Organization**

To provide estimates for the building’s carbon footprint, energy usage, and cost over time, data was collected from multiple sources, including RSMeans Online, a building cost estimation database (Gordian, 2018), and the Inventory of Carbon and Energy database (ICE), which provides general estimates of the cradle-to-gate embodied carbon and energy per mass of material for common construction materials in the U.K. and globally (Jones and Hammond, 2011).

The data, organized by Uniformat Level 1 categories of the substructure, shell, interiors, services, and equipment & furnishings, was inputted into building and zone templates, from which embodied carbon and cost for multiple combinations of wall constructions, roof, structure, glazing, and services can be calculated. Figure 1 shows the overall flow of inputs and data to produce simulation results. Data categories like interiors, substructure, and equipment & furnishings were set to a default “green” or low-environmental impact construction.

![Figure 1: Flowchart of inputs and data for simulation.](image)

The framework expanded the EnergyPlus-based engine Archsim’s libraries to include embodied carbon and cost data for materials and assemblies. Cost data originated from RSMeans for the national U.S. average in 2018. RSMeans’s square foot estimator, which provides cost estimate breakdowns for standard and “green” office building constructions in the U.S., generated most of the cost data. Assumptions included an open shop construction, architectural fees of 8% and contractor fees of 25% of the construction cost. Additional data for
special constructions, such as mass timber and triple pane windows, supplemented the square foot estimations.

Structural system data originated from both RSMeans’ square foot estimator and assembly data. Starting with user-specified structure of either concrete, steel framing, or timber framing, the framework uses RSMeans’ standard structural elements, configurations, and loads for the material type and range of building stories (1 story, 2-4 stories, 5-10 stories, and 11-20 stories) to estimate the cost and volume of structural materials per m² of floor area. This combined with ICE data provided an estimated carbon footprint of the structure. The structural system was assumed to be independent of the exterior envelope.

**Simulation**

At the beginning of a project, a brute-force batch run of simulations is conducted for each possible combination of major building components to provide initial estimates using the Grasshopper plugin Colibri (Thornton Tomasetti, n.d.). The results can be outputted to Design Explorer (Thornton Tomasetti, 2017) to generate an interactive parallel access plot for each iteration, which allow users to easily explore and visualize the best initial design options. This first run is computationally expensive since the simulation workload increases exponentially with every building component option considered. However, this method provides the team with a comprehensive understanding of the parametric design space.

As the design progresses, users can set more inputs and customize geometry. Users can either run a smaller set of combinations using Colibri or simulate single designs, both of which can be computed quickly.

**User Workflow**

At the beginning of a project, the user inputs at minimum the project’s estimated size in square meters, number of stories, and location (either selected from sim EPW files or loaded by the user). From these inputs, the simulation assumes floor plates with an equal area per floor, oriented due south and a story height of 3.66 meters (12 feet) for 1-10 stories or 3.05 meters (10 feet) for 11-20 stories. The framework then simulates all combinations of the variable building parameters, including exterior wall, roof R-value, glazing, structure, window-to-wall ratios, shading, and floorplate shape. The results are compiled in Design Explorer's interactive parallel-axis plot, which allows the user to highlight, sort, or cull results based on the variable inputs or outputs of estimated energy use intensity (EUI), embodied carbon of the materials, operational carbon emissions, construction cost, and operational cost.

As the project progresses, design teams can further manipulate and refine the model to match design details or test alternative options, including specifying HVAC and lighting options. Users can interact directly with the Rhino/Grasshopper interface to either model or import custom building massings and manipulate non-geometric inputs on the Grasshopper canvas. Each of the variable parameters can be narrowed to a smaller range of options or made static, reducing the final field of possible designs.

**Case Study: Eight-story Office Building**

To demonstrate how this framework might assist design decisions, a hypothetical eight-story, 1,600 m² office building was considered for a case study exercise. The building was modelled in two of the major climate zones in the US: Washington D.C., USA (a mixed humid climate) and Phoenix AZ, USA (a hot dry climate). In the first phase, batch runs were conducted to show the full parametric design space of these buildings in both climates. Static parameters included the floor area, number of stories, story height, general construction (which was set to “green”). HVAC (which was set to a COP of 3 for heating and cooling, similar to minimum energy code requirements) and artificial lighting (which was set to LEDs and daylight dimming) were static because they do not depend on geometric parameters yet have significant impacts on EUI. Daylight dimming was turned on so that geometric parameters could be assessed for their impact on daylighting. The full HVAC and lighting options were reintroduced in later phases.

Variable parameters included exterior wall construction (Brick and CMU, precast concrete, or plywood structurally insulated panels (SIPs), each with varying R-values), structural system (steel, concrete, or timber), roof R-value, glazing type (double pane with a 0.8 SHGC and 2.7 U-value – “Type 1”, double pane with a 0.4 SHGC and a 1.5 U-value – “Type 2”, double pane with a 0.6 SHGC and a 1.5 U-value – “Type 3”, or triple pane with a 0.8 SHGC and a 0.8 U-value – “Type 4”), window-to-wall ratios (WWRs) of either 30% or 70% for the south, east and west, and north facades, exterior shading (none, static, or dynamic), and the floorplate shape (either east-west rectangle, square, or north-south rectangle – Figure 2). Including all the options available in the framework produced over 1.6 million possible design iterations. To reduce the number of iterations and run time, only the extreme options of each parameter were included (e.g. only the lowest and highest R-values for exterior walls and roofs were selected). These ranges were roughly based on standard constructions dictated by RSMeans and energy code and advanced green constructions. Once the design resolved further, more middle ground options were reintroduced.

**Figure 2: Floorplate shapes used in initial simulations.**

The initial runs for Washington D.C. and Phoenix each simulated 10,368 combinations of the above variables. The results were compiled and imported into Design Explorer for analysis.

Based on the results from the initial runs for Phoenix Washington D.C., the building designs were narrowed to
a few parameters. Four custom massing designs, taking cues from the more successful floorplate shapes for each climate, were inputted into the framework (Figure 3). The simulations were run again, this time with only 256 combinations per massing design. Results were compared in Design Explorer.

**Figure 3: Four custom massings modelled in Phase 2 for the Phoenix and Washington D.C. climates.**

**Results**

The case study of a typical eight-story office building served to demonstrate how the framework can aid decision-making throughout the design process, uncover design options that might not otherwise be considered, and help designers balance energy, embodied carbon, and cost considerations across climates.

**Phase 1: Pre-design Simulation for Phoenix**

Phase 1 simulated 10,368 combinations of basic building components and configurations. The results displayed by the parallel-axis plot shown in Figure 4 are initially convoluted due to the amount of data. Assuming that a design team might be interested in lowering EUI, the results were culled to include only design options below 61 kWh/m²/yr. Selecting different inputs highlights (through colors) their influence on EUI and other outputs. Type 2 glazing (low SHGC) outperforms other options and the east and west WWR causes a notable decrease in EUI at 30% (Figure 5). 30% north and south WWRs slightly outperform 70% WWRs. Steel and concrete structures outperform timber in terms of EUI, likely due to thermal mass. The east-west rectangular floorplate results in a slightly higher EUI than the north-south rectangular or square floorplates. Static and dynamic shading options result in slightly lower EUIs than no shading. Wall construction and roof R-value have negligible effects.

Alternatively, a design team might consider the lowest embodied carbon options. Excluding design options above 260 metric tons of CO2eq shows that only options with a timber structure achieve this low of an initial carbon footprint after construction (Figure 6). However, if a team is truly interested in the building’s total carbon footprint, they would also need to examine operational carbon emissions (tons CO2eq/yr), which is completely dependent on the energy performance. Figure 7 shows only options below both 260 tons CO2eq in embodied carbon and 130 tons CO2eq/yr in operational carbon (the threshold for doubling the carbon footprint after two years of operation).

Most design teams are also likely looking to lower cost. Figure 8 shows options under $5,400,000 in construction cost. Brick and precast concrete wall constructions, high WWRs, and timber structure options are eliminated.

**Phase 2: Refined Design for Phoenix**

Based on insights from Phase 1, a design team might decide on several parameters and refine the geometry. The results from Phase 1 suggest certain imperatives for an environmentally-conscious design. Type 2 glazing outperformed other options and is cheaper. A 30% WWR for east and west façades also performed well. A timber structure significantly lowers embodied carbon. Using SIPs over brick or concrete walls can lower construction cost without compromising energy performance or carbon footprint. The roof R-value can be set to 20 because it has little effect and is the minimum required by code. Since the north-south rectangle and square floorplates performed better, this can guide bespoke massings. HVAC and lighting options can be introduced since the passive design parameters have been narrowed.

Thus, variable parameters for Phase 2 included four R-values for the SIPs walls from 13 to 33, shallow or deep static shading, WWRs of 30% and 40% for north and south facades, LEDs or LEDs with daylight dimming, and code-compliant HVAC efficiency or HVAC with a COP of 5 and heat recovery. These parameters were applied to two custom massings loosely based on the best-performing floorplates and WWRs (Figure 3).

From the results, daylight dimming and high-efficiency HVAC systems have significant impacts on EUI. The massing have mixed results (Figure 9) but they affect the impact of shading. The deep static shade has a small advantage over other options only when combined with stacked square floorplate, likely because the I-shape self-shades. The south and north WWRs have mixed results, and higher R-value wall options correspond to small decreases in EUI.

**Phase 1: Pre-design Simulation for Washington D.C.**

In direct contrast to the Phoenix results, Type 4 glazing (triple pane) and Type 3 glazing (double pane with a high SHGC) outperform other options in the Washington D.C. climate (Figure 10). Additionally, a 70% southern WWR slightly lowers EUI instead of a 30% WWR. Steel and concrete structures also significantly outperform timber in terms of EUI, more so than in either Phoenix. The north-south rectangle floorplate performs best by a tiny margin compared with the square and by a larger margin compared to the east-west rectangle. Like Phoenix, a 30% northern WWR slightly lowers EUI, and a 30% WWR on east and west facades vastly lowers EUI. Wall constructions, roof R-values, and shading have relatively little effect on EUI.

**Phase 2: Refined Design for Washington D.C.**

In contrast to the Phoenix scenario, Washington D.C.’s results in Phase 1 indicated that a concrete structure could be a better option over timber due to its substantial impact on EUI in this climate. Additionally, shading is eliminated, and new variable parameters include 60-70% southern WWRs, 30-40% northern WWRs, and either Type 3 or Type 4 glazing. Two custom massings (Figure 2) prioritize a north-south rectangular floorplate and...
southern exposure. Other parameters like HVAC, lighting, the SIPs wall construction, and a static east-west WWR of 30% match the Phoenix settings.

Again, the efficient HVAC and daylight dimming options dominate the results. Massing also has a distinct impact, with the convex floorplate outperforming the stacked rectangle due to lower heating and lighting (Figure 11). This also affects glazing, with Type 4 slightly outperforming Type 3 on the stacked (Figure 12) but showing no distinct advantage on the convex massing. Wall R-values again have a subtle influence on EUI, and a smaller north WWR performs better. Southern WWR and roof R-values had mixed results.

Figure 4: Parallel axis plot of results from initial simulations for the Phoenix climate.

Figure 5: Effects of glazing and east-west WWR on EUI in Phoenix. Type 2 (red) distinctly outperforms Types 1 and 4 (which are eliminated) and Type 3 (blue). A 30% east-west WWR outperforms 70% (eliminated).

Figure 6: Effect of structure on embodied carbon. Timber (red) has significantly lower embodied carbon.

Figure 7: Low embodied and operational carbon options for Phoenix. Lowering both embodied and operational carbon eliminates several glazing options, high south and east-west WWRs and concrete and steel structure options.
Figure 8: Lowest cost options for Phoenix. Only SIPs for wall construction and steel or concrete structure options remain.

Figure 9: Lowest EUI results from Phase 2 for Phoenix. Only efficient HVAC and daylight dimming options remain, while the floorplate shapes have mixed impact on EUI.

Figure 10: Lowest EUI results for the Washington D.C. climate. Notably, a 70% southern WWR performs better, and Type 1 and 2 glazing as well as timber structure options are eliminated.

Figure 11: Lowest EUI results from Phase 2 for Washington D.C. The convex floorplate (blue) outperforms a stacked rectangle. Again, only efficient HVAC and daylight dimming options remain.

Figure 12: Lowest EUI results from Phase 2 for Washington D.C. for the stacked rectangle floorplate. Type 4 glazing (blue) outperforms Type 3 (red) only for this floorplate, but the results are mixed for the convex floorplate (not shown).
Discussion

Data Gathering

This framework required the collection and assembly of many datasets around material thermal properties, embodied carbon, and construction and assembly costs, making it possible to simultaneously assess EUI, carbon footprint, and costs. This unique combination of data not only gives design teams a comprehensive look at their designs but reveals synergies between these typically isolated performance metrics. Like any simulation framework or tool, the accuracy is dependent on this data and assumptions. Publishing this database could make this framework more widely accessible and accurate.

The Simulation Process

The eight-story office building case study demonstrated how initial simulations can reveal the extents of the parametric design space for nascent designs and display key relationships for the design team. Notably, the interactive parallel-axis plot allows users to manipulate the results and define which performance metrics are most important to the project. If a design team is particularly concerned with energy performance, the results show that glazing WWRs and floorplate shape affect EUI differently depending on the climate. If the team is concerned about embodied carbon, timber becomes the best structural option. Lowering the cost reveals that a SIPs wall construction may be a better option than brick. Phase 2 simulations revealed both how HVAC efficiency and daylight dimming as well as geometric parameters have clear impacts on EUI, demonstrating the importance of early design simulations.

This combined mode of assessment also reveals some trade-offs between energy, carbon, and cost performance. For instance, embodied carbon pales in comparison to operational carbon after a few years for most design options. However, if operational energy is lowered, then embodied carbon has a larger impact on the building’s lifecycle carbon footprint. Therefore, a design team aiming to build a low-carbon building must consider lowering energy use as a top priority before investing in low-carbon building materials.

The Phase 1 simulations for the two climates reinforced both the adaptability and effectiveness of the framework. The same parameters were considered for both Phoenix’s and Washington D.C.’s climates, yet the framework revealed different optimal combinations for each climate. Low SHGC glazing performed better in the hotter climate of Phoenix but worse in Washington D.C. A high southern WWR was best in Washington D.C. but worse in Phoenix. Phase 2 with the Phoenix and Washington D.C. climates displayed how this framework can accommodate more resolved designs that appear in later pre-design and schematic design phases. Custom massing designs were modelled in Rhino and inputted directly into the Grasshopper script for simulation, demonstrating the ease of use for architects. Notably, the results display a closer relationship between building performance and geometry, with the “I-Shape” massing reducing the need for shading or better glazing to improve performance and the “Convex” massing distinctly outperforming a stacked massing. This provides actionable information for a design team. Once the field of parameters were narrowed, the framework revealed these subtler relationships.

Phase 2 simulations also displayed how this approach could work with rapidly changing designs. Considering that the simulation run times are close to instantaneous, a design team could potentially trial many more massing design variants in a feasible amount of time.

Potential Improvements

Although this first iteration demonstrated the breadth of the proposed framework, several improvements could make later iterations more robust and intelligent. First, some of the options could be expanded, like options to define open versus closed offices with different zones. Secondly, a sensitivity analysis of the parameters could help designers better navigate the results of Phase 1. Design Explorer’s parallel axis plot presents results succinctly, but the sheer number of options makes it difficult to easily draw conclusions for the next steps of the design. Including a baseline option that meets minimum code requirements could also provide design teams with a standard to compare iterations against.

The framework could also account for climate change impacts. A climate-morphing feature, like the CCWorldWeatherGen tool (Jentsch, James, Bourikas, and Bahaj, 2013), could help design teams consider the resilience and long-term effectiveness of design options in changing climate.

Limitations of Embodied Carbon and Cost Estimates

The current method for estimating embodied carbon in this version of the framework has some limitations. The calculation technique for the structure is less accurate for buildings with unusual massings that might require extra structure such as cantilevers or supports. In future iterations, a physics engine such as Karamba3D (Karamba3D, 2018) will likely be used to automatically generate structural configurations for a given building massing and structural material to produce more accurate carbon and cost estimations.

Embodied carbon estimates do not include items like interior partitions or substructure, which were excluded from this first iteration of the framework because they were considered relatively constant across all building types. Total embodied carbon is likely underestimated by the framework and thus should only be used for relative comparisons between design variants simulated through this framework. Future iterations will aim to refine the carbon estimation process.

Mass timber constructions in the simulation may be relatively inaccurate in terms of cost and carbon. Timber costs vary widely by region. Additionally, the ICE database does not account for the stored carbon in mass timber construction, which although subject to debate, could be substantial enough to offset embodied carbon from harvest and processing (Hafner and Schäfer, 2018). Further data could resolve these issues but also increase...
the complexity of the framework. Thus, simplicity was prioritized over accuracy of mass timber estimates. This framework uses standard plug loads and occupancy schedules for offices as described in the SIA Merkblatt 2024 standard (2006), but occupant behavior can vary and heavily impact EUI. In the early design phase, detailed information on occupant behavior and use of the building is often unknown. Hence such variability seemed unnecessary to account for in an early design framework but should be considered in later design stages.

The framework also relies on national construction cost averages for the U.S. in 2018, but material and labor costs do vary based on the time period and location.

**Conclusion**

In this first iteration, this proposed decision-making framework has demonstrated its potential to address building simulation in the underserved but critical early design stages. By simulating energy performance, carbon footprint, and cost concurrently throughout the early stages of a design process, this framework highlights options and relationships that design teams may otherwise overlook. Its proactive, intelligent, and adaptable format make it ideal for use by architects during the rapid design development at the beginning of projects.

Given the sizable influence of early design decisions on the energy performance, carbon footprint, and cost of buildings, the proposed decision-making framework will enable design teams to develop optimal designs early on, saving time and money while producing higher performance buildings. This framework aims to strengthen architects’ abilities to meet stringent demands on building performance and address the climate crisis.

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**References**


From Tangibility to Complexity: Integrating Analog Analysis Techniques and Building Performance Simulation in Architectural Design Process

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Abstract
The paper presents a pedagogical approach to teach building’s environmental performance by using tangible architectural analysis techniques combined with complex computer simulations. The aim was to enhance the learning process for simulation-illiterate architectural students. Through interpreting and translating information from one mode of analysis to another, students prioritized what may have affected energy flow, therefore, they could strategize how to assess the given system, helping them to design high-performance buildings.

Introduction
Recent studies on teaching building performance simulation, henceforward interchangeably called BPS, in the US, UK, Australia, and India laid out some important aspects (Hopfe, 2016; Hopfe, Soebarto, Crawley, & Rawal, 2017). They showed that a large portion (87%) of the architects were desired to incorporate BPS in practice, even if most of them (74%) did not currently use it. This was a meaningful message for the industry as a whole in that architects are the ones that typically have the earliest access to the project development when the most potential is poised to be harvested. On the other hand, the study showed two interesting aspects of BPS in higher education: 1) BPS was taught mostly to postgraduate students (50%) significantly more than to undergraduate students (12%), even if undergraduate programs were recognized more suitable, and 2) interpreting the simulation results were more challenging than learning the simulation tools. These aspects were particularly revealing in that data literacy, being recognized as a soft skill, is a more critical skill than simulation tools themselves, confirming our own observations in both design studios and seminar courses for the past 5 years.

The approaches to teach BPS to architecture students are diverse, yet they can be divided by a simple question: whether the performance assessment is outside of the design process or part of it. Considering the most typical practices, it is understandable the prior approach can be found more often, being outside design studio courses. Hence, the pedagogical focus has been on data interpretation and a general understanding of building performance (Reinhart, Dogan, Ibarra, & Samuelson, 2012). In this approach, grouping with engineering students became an evident method to enhance how architects’ practices in studio settings (Charles & Thomas, 2010). On the other hand, the performance assessment can be regarded as a part of architects’ design practice so that BPS is taught as a design tool. With this approach, architectural students learn BPS in design studios, quantitatively assessing building performance, integrated with qualitative design explorations (Kim, Phillips, & Braham, 2013; Morbitzer, Strachan, Webster, Spires, & Cafferty, 2001). It is an open discussion, which approach may be the more suitable, yet it certainly shows how diverse the role of BPS can be in architectural education systems, resembling the various types of practice models.

Defining the role of BPS may have been started in architectural education. National Architectural Accrediting Board (NAAB), one of the most influential institutions since it grants and accredits professional degrees in the US, addressed the needs of assessment tools by describing environmental analyses in one of the student performance criteria in “Environmental Systems” (NAAB, 2015). It would not be unrealistic that the assessment tools would refer to BPS and other numerically-oriented methods. On another side, the American Society of Heating, Refrigeration, and Air-Conditioning Engineers (ASHRAE) have laid out the standards and methodologies to conduct building performance simulation throughout the design processes. Relevant to the architect’s interest, it included conceptual design modeling, design refinement, and design integration and optimization (ASHRAE, 2018). This set of standards shall be helpful to establish and solidify the role of BPS in professional practices. What NAAB and ASHRAE laid out can be significant precursors in architectural education toward a sustainable environment and perhaps move educators forward to find a more suitable and effective pedagogical framework for their needs.

In this context, the investigation presented in this paper introduces a pedagogical approach for undergraduate students with architecture majors who were previously not educated with BPS. Notable is we adopted analog analysis techniques in architectural design, including physical model making and diagramming, for tangibility and familiarity to the students. This is aligned with an existing approach in that tangible mediums may promote learning effectiveness for engineering education (Stone & Mcadams, 2000). The analog analysis techniques were considered a bridging mechanism to learn how to model and assess the environmental performance of buildings with computer simulations.
Materials and Methods
The pedagogical methodology in the paper was investigated by the instructors’ observation and student surveys of a class in two semesters. As a background, the class has been evolved over the past 10 consecutive semesters by the same instructors. The two most recent semesters in fall 2018 and spring 2019 were focused on their major change with the newly-introduced analog analysis techniques that students were already familiar with through their prior courses. After introducing the course, the author will elaborate on the findings relevant to the subjects.

The overall process began upon students’ selection on a building from a provided list, each of which contains exterior shading elements in the envelope system. The envelope system was analyzed in a sequence with 4 modes of analyses: solar tracing diagram on section drawings, physical model making for daylight, computer simulation for daylight, and computer simulation for thermal performance (Fig. 1). Solar tracing diagrams were done solely relying on the student’s intuition, approximating what would happen at the building’s geographic information. Climate analysis was conducted in advance with the weather data to inform seasonal solar locations. Climate analysis also helped to set up the light source for photographing of the physical model, which led to visual analyses for daylight.

The results from the analog analysis techniques were compared to the result of computer simulations. The point of the comparison was to observe how the shifting among different analysis modes would have helped students to learn the inherence assumptions in all engaged analysis techniques. At the same time, students were expected to gain a critical understanding of the role of building design components so that they can further apply them to another climatic condition.

- Demography: 35 undergraduate architecture students in a U.S. college, 2:3 gender ratio of female to male, a balanced mix of juniors and seniors, in 9 groups
- Buildings of interest: Siemens HQ in Masdar City UAE, New York Times Building in New York USA, IAC headquarters building in New York USA, Jockey Club Innovation Tower in Hong Kong China
- Simulation tools: DIVA-for-Rhino 4 for daylight, DesignBuilder/EnergyPlus 5.5 for thermal, and Climate Consultant 5.0 for climate analysis.

Simulating Unit System
A small portion of the building was modeled in isolation for analytic simplicity, establishing a unit system that was composed of the envelope and its adjacent indoor space in one structural column bay of a building. An example unit system was shown in Figure 2. This isolated approach was adopted in almost all analysis modes, except for the very last one with the whole building, being situated at an urban site. It was assumed that in the last part of the semester, students had gained confidence and technical skills in running computer simulation, understanding the subject design, and the correlation between the design and its performance.

While switching to another mode of analysis in the sequence, more information was added for increasing complexity and the more required input. Following the solar tracing diagram and physical daylight analysis, the information on building materials was added in the daylighting simulation. For thermal performance, other types of information were added such as occupancy, construction systems, HVAC system, lighting control.

![Figure 1: Overall Workflow.](image1)

![Figure 2: Unit System in Section of the New York Times Building.](image2)
Establishing the Base Cases

Two base cases were established as a point of comparison to understand the certain building components and their role in environmental performance. The first base case was in the unit system. Students identified the shading components, which then were hypothetically eliminated and became the base case in Figure 3. This process occurred earliest in the semester, using solar tracing diagrams that later in the process informed computer modeling of daylight and thermal analyses. Notable was that the base case was modeled as a single zone for both daylight and thermal simulation, same as the “Shoebox” model as often used in building simulation practices.

The second base case was in the whole building system that was provided to students at the end of the semester. All team was given with the same building so that the change that each team had made on envelope could be compared to the change of other teams. As shown in Figure 4, an urban context was situated as a design constraint that the student had to respond with the envelope system they studied. The key characteristics of the building are below and in Table 1. For both the unit- and whole-system, the same set of aforementioned simulation tools were used to maintain the capabilities and assumptions.

- 4 story residential row house
- Located at Brooklyn New York (US)
- 20 feet wide and 50 feet deep
- Shared walls on the long sides
- Annual Source EUI: 86.31 kBtu/ft²
- Construction Cost: USD 671,174

Table 1: U-values and Window-to-wall Ratio (WDW)

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<td>6.121</td>
<td>2.857</td>
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Physical Model Construction and Visual Analysis

A physical model was constructed by each team for the unit system of envelope design as shown in Figure 5. The base information came from the prepared solar tracing diagrams. Students were asked to consider envelope, interior, and structure, together which constitutes a unit system as a whole. Envelope components, in particular, must have included glazing, mullions, substrates, and shading elements that control heat and light. The model scale was 1”=1’ (=1/12), which was determined for its suitability to study the penetrations of diffuse and direct daylight (Bodart, Deneyer, De Herde, & Wouters, 2007).

Upon the completion of a physical model, students were asked to conduct a visual analysis for daylighting. Students chose a light source that they positioned and angled to emulate solar location at the solstices and equinoxes of the building location. The task was to evaluate how the natural light, being modified by the envelope system, may positively or negatively contribute to the light requirement of the space, considering the building use and the seasons. Comparing back to the solar tracing diagram was another task, rectifying it if needed.
Computer Simulation

The unit system of envelope design was further assessed with computer simulations. The goal was to validate the visual analysis of its physical model while expanding the evaluation criteria. The identical geometry was digitally constructed and more information was added such as construction materials as shown. The evaluation criteria for daylight simulation included glare and light level, adopting Daylight Glare Probability (DGP) and Daylight Autonomy (DA) as shown in Figures 6 and 8. For glare evaluation, a set of workstations was provided and situated near a window, which guided students to focus on the influence of the envelope.

The evaluation criteria for thermal simulation included energy use intensity (EUI), heat balance as well as thermal comfort with indoor temperature and humidity. These criteria were applied to both the unit envelope and the whole building system. Notable was that during the geometry modeling for daylight simulation, students were able to identify the missing components in the physical model and added them in for their potential role in daylight performance.

Architectural Design Optimization

In the last process, students were given a task to optimize the envelope design. The goal was to improve the environmental performance of the base case building while applying the envelope that they studied. Due to the given location, Brooklyn, New York, which was in the heating-dominant climate, students immediately identified the obvious, such as the shading components in the envelope may not positively contribute to the overall energy use, even if it may be beneficial for daylighting and for reducing the cooling load. At the same time, the surrounding buildings may cast shadows, limiting solar exposure to the building, adding another challenge for heating seasons. Therefore, more realistically, minimizing the negative impact was the performance goal of the optimization, while keeping the design integrity.

For the simulation literacy level at this point, having passed the three quarters in the semester, students became somewhat familiar with the tools in that they can independently model with the available resources from the tool developers. Hence, students held responsibilities to implement a simulation strategy on how to assess the performance of the optimized building with regards to effectiveness and computational efficiency in mind. Since they were very familiar with the subject design systems and had already simulated in an isolated domain, assigning the modeling responsibility was considered reasonable.

In the process of optimization, it was very interesting that students had to propose a very significant change in the envelope system design. Responding to the drastically different climate of the site, a team that analyzed on the Siemens Building in a Desert Climate changed its open external shading system in the envelope (Fig. 8) to a closed double-skin envelope system, of which cavity shall work as a thermal buffer for the heating dominant location in New York (Fig. 7). They also proposed to add thermal mass walls inside the cavity to minimize temperature extremes and to make use of stored heat for night time. Some teams showed modest changes, by responding to solar exposure in the microclimate. A team that worked on the NYT building that was already in New York adjusted the spacing of the external shading system to correspond to the varying sun exposure by height. This demonstrated their understanding of the surrounding buildings as constraints before they proposed and simulate their final proposal.

Results & Discussion

Shifting Analyses and Inventing Simulation Methods

During the shift to another mode of analysis, students identified and prioritized the crucial elements in the subject design. This process was crucial for students to investigate capabilities and limitations in each analysis
mode, leading to invent their own assessment methods for the design specificities. Particularly for computer simulations, the student-invented methods were tested for the effectiveness prior to adding more details. One of the common discussions was whether to use internal functions of a simulation tool or to construct elements for a physics-based assessment, especially regarding shading components.

For the physical model of the IAC building as an example, a fritting pattern on the envelope was made by sanding a clear plastic sheet to emulate diffusion of light. In part, students recognized the difficulty to model a large set of micro-scale elements: a numerous circular disk in 1/12-inch diameter in the scaled model. Hence, they explored and discovered the material and technique that could make a similar light effect. This discovery informed how they approached in computer simulations, using translucency for daylight simulation and visual transmittance for thermal simulation. Another group of students, modeling the NYT building, discovered a limitation of the simulation tool. At a certain size, shading elements were not accounted for in DesignBuilder, even if they were visualized properly with shadows. Hence, students decided to switch to one of the internal functions that would emulate the shading effect. Window louvers were adopted and angled to emulate the shading effect of the circular cross-sectional tubes that would work in both winter and summer. These simplified modeling methods would have generated the most accurate solution, but they were reasonable to approximate the heat balance from solar exposure, allowing them to explore various design options.

**Students’ Recognition of Analog Analysis**

After completing physical and computer simulation of a unit system, students were asked to identify the advantages and disadvantages of using physical model making and its analysis. Below were the responses.

- Advantages: quick assessment once it was modeled; limited types of assessment; once established quick and easy to change the solar angle for different seasons; more realistic and aesthetical ambiance due to scale, physical, and 3-dimensional nature.
- Disadvantages: imprecision in light projection from the source; inaccurate solar ray tracing; hard to create material diversity; inaccurate characteristics of the material for daylighting due to the typical material choices; takes longer time in model making.

It was notable that they recognized solar tracing would not be reliable due to the light source and its diverging angle in the photographing. They valued more computer simulation for it was relatively easy to change materials and its potential parametric study.

Another set of questions focused on whether students recognized the role of the analog analysis techniques and their effectiveness in performance assessment and learning of computer simulation.

- Physical modeling and its analysis were useful to strategize how to model in a computer simulation.

54% of students indicated it was very useful and 25% of students useful, 20% indicated neutral, and no students said it was useless.

- Solar tracing diagram was chosen as the most preferable analysis. 42% of students indicated as most preferable, yet physical modeling and computer simulation was in 25% and 23%, respectively.
- Solar tracing diagram was helpful to assess building performance. 29% indicated it was very useful and 58% useful. 11% indicated neutral, and no students indicate it was useless.
- Interpreting computer simulation results became less challenging with physical modeling and solar tracing diagram. 49% indicated that they were “very helpful” and 38% indicated “helpful”. 12% indicated neutral and no student indicated “not helpful”.

**Daylight Analysis to Thermal Analysis**

Students were asked in surveys what types of information they would acquire from daylight analysis for being useful in thermal simulation. This question was asked after they completed both analyses to see if they may have been able to approximate it with analog techniques, especially solar tracing section diagrams with their knowledge on the local climate. Below were the three main answers. Understanding the first and second answer, it would not be too far of a stretch that the analysis may further influence their design decision to control the heat gain.

1. Indoor solar exposure and its heat gain
2. Heat storage with building materials
3. Seasonal temperature variation

**Building Performance Simulation in Design Studio**

Another set of questions were asked for the general usability of BPS in the design process. The first question was whether adopting building performance simulation could be beneficial in design studios. These questions asked twice at the beginning and the end of the course work. As a result, 36% of students strongly agreed and 37% agreed at the beginning, showing the level of the initial interest of students. However, 82% of students strongly agreed and 18% agreed in the end, showing the stark increase in their interest. Notable was there was 27% did not agree at the beginning all turned positively. Potentially, they have come from a lack of prior knowledge and experience.

- 100% of students thought that adopting building performance simulation could be beneficial in design studios.

The second question was on students’ own opinions of what features in a BPS were important. Responding to this multiple-choice question, more students chose the knowledge base for decision making (80%) over tool usability (40%) or interoperability with their familiar design tools (13%). This was particularly interesting that they have consistently complained to the instructor about the difficulty and complexity of computer simulation throughout the semester, till the end, yet they thought the capabilities BPS was more important than what could facilitate modeling tasks.
The third question was what types of computational analyses were important to assess the carbon footprint of a building, out of climate analysis, thermal simulation and daylight simulation. This was a multiple-choice question asked at the beginning and end of the semester. There were increases in thermal and daylight simulation by 19% and 23% respectively. All students, in the end, thought the thermal simulation was important. On the other hand, there was a decrease in climate analysis by 14%, not very significant, but it may suggest students had recognized the gap between climate assessment and building performance assessment with it.

**Collaboration Challenges in Thermal Simulation**

At the beginning of the thermal simulation process, the instructor observed that students identified it was particularly challenging for collaboration as a group. The challenge was inherent in that a thermal zone has to be defined in relation to all other ones. Hence, students recognized thermal simulation as a single-person task, leading to appoint a lead student for modeling, for which others had to wait and take other subsequent tasks, such as visualizing and interpreting the results. The author believed it was not uncommon for any analysis task that may engage in complex tasks. However, it may be very helpful that the thermal simulation tool would have been developed to allow distributing the workloads in modeling given it was found the most time-consuming.

Later in the process, the design optimization with the whole building system, using thermal simulation became less challenging and every student in a group was able to work independently to analyze a new solution that each student came up with. This observation showed the presented approach worked appropriately even if it seemed very challenging at the beginning of the thermal simulation.

**Conclusion**

The proposed pedagogical approach was in line with a trend in architectural education for the past 10 years in the US and internationally. It aimed to enhance the learning experience of students who had a diverse educational background. Analog techniques were adopted for its tangibility and familiarity in the architectural design practices. The study showed that the analog techniques helped to build up students’ intuition to approximate the building performance, especially by switching back and forth from computational analyses. The proposed approach uncovered the necessary challenges in how to teach performance simulations for design studios, considering the counter-intuitive results and time constraints.

Another aspect of the approach was to incorporate what was typically taught in studio teaching: design exploration. After going through the learning cycle from simple diagramming to complex simulation, the major building component of interest, the envelope system design, was further exploited and optimized for another building. In this process, the value of diagramming was reinstated for its readiness and flexibility for the expanded scope with the performance approximation.
The proposed approach increased the overall learning effectiveness through the combined use of the tangible medium and the persistent intuition refinement. The conducted survey showed that the confidence of students was significantly improved in the result interpretation and intuitive approximation for daylight. More students recognized the connection between design and performance, while most students identified the more need to use performance simulation. It was important to note that the students' approximation showed noticeable discrepancies from their thermal simulation results. As a remedy, students and the instructor examined the relationship between the input and output of the simulation and identified what would have caused them. The main causes were identified to warrant further developments in the approach: 1) complexity in the whole building analysis and its simulation and 2) whole year weather data that disproportionally affected heating and cooling load, 3) inhomogeneous thermal conditions in the building.

As future work, it seemed logical to expand the application of the combined analysis method to other design areas than the building envelope, for its demonstrated effectiveness in student learning. This may include building morphology studies and site analyses, for which physical models and solar tracing diagrams were among the common exercises in university teaching and professional practices. Yet, considering the time constraint in 15 weeks a semester, it would be better to have them in another course in the sequence.

References


Measuring the Effectiveness of Simulation-Based Education (SBE) in the Performance-Based Design Studio

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Abstract
Simulation based-education (SBE) is becoming increasingly widespread among architectural design studios worldwide. SBE supports students with an innovative and effective learning environment. Its overall objective is to allow students an experimental environment for design testing, and to enhance the transition of the skills learnt to real life professional practice. The effectiveness of SBE is related to a variety of factors that may be either student or faculty driven, tools and technology driven, curriculum driven (i.e. related to the time of offering or mode of application) or a hybrid of all. To measure the effectiveness in a core course offered half way in the architectural program, a study was conducted to identify the studio learning challenges and accordingly the proper metrics that can be identified to construct future performance indicators for instructors that can quantify the effectiveness of the teaching methods used. Several questionnaires, focus groups sessions, and evidence-based analysis of student work came together to form the research design. The findings validated earlier assumptions in similar previous studies, and recommended the use of a common structure for effective measurement of learning outcomes and teaching methods, with recommendations for future consideration.

Introduction
Building Performance Simulation (BPS) is being used more and more during the development of design proposals for architectural design students in undergraduate programs. Due to the shift in the technological and pedagogical approaches, in addition to the market demands, teaching architectural design for students -typically half way in the architecture program- is a process of great complexity, with a set of tools designed for professionals only. Today, integrating sustainability into the architectural design education is more of a market demand and an indicator of success for programs seeking quick placement of their graduates in the job market.

While the job market continues to demand specific capabilities for entry-level architectural graduates, students are required to show evidence of knowledge concerning building energy performance; accordingly, a sound and comprehensive undergraduate training is required. BPS tools are not a product of charts and tools only, but continue to emerge as an evolving tool for design thinking process. Previous studies have discussed new approaches to help with design problem solving (Casakin & Goldschmidt, 1999), hence improving the complexity of the design solutions through projects that maintain the core of the architecture education. Using BPS tools during the design thinking process gives the design great potential; on the other hand, it does have its challenges and a varied range of limitations (De Wilde, 2017). Several studies have addressed the topic of using BPS tools in the design studio and their suitability for innovation and visualisation. Previous studies offered simulation courses which were based on a method of knowledge transfer than as a dedicated design tool, and the integration of simulation in the architecture curriculum and the challenges facing it (Delbin, 2007). Other studies such as (De Wilde et al., 2002) discussed offering simulation training at the proper time and during early stages of design, and asserted the value it adds to the program. Since designers are solution-led, not problem-led (Cross, 2006), it was recommended to have foundation classes using BPS in order to integrate and comprehend the assessment in the design process and to produce relevant design solutions (Pedrini and Szokotay, 2005). In order to evaluate the solutions, the output of the simulation and its proper interpretation must be well understood at the different stages of design. A study addressed the significance of BPS on the form and design (Naboni, 2013), where daylight can be one of the design drivers, (Ibara and Reinhart, 2013) focused on this aspect of the tools. Of the earlier works published about the topic, a study discussed using unconventional teaching methods, where learning by playing through gaming is used (Reinhart et. al, 2012), the game based approach was the most favourable among students (DeBaillie, 2012 and Tarabieh et al., 2013).However, it did not specifically mention the additional value in comparison to the conventional learning approaches. To advance the teaching method, curriculum restructuring was addressed to give the student the maximum potential to integrate with SBE (Satish, 2014) and the introduction of simulation in the classroom through instruction to both engineering and architectural students (Charles and Thomas, 2009). The issue of the introduction of SBE in architecture education, where it is a continuous cycle of learning and application, was addressed by (Morris and Hopfe, 2015). It was addressed not only at the early stages of design, where BPS is the main design-guiding tool (Timothy, 2013), but on the full stage as well. Several
studies on the integration of BPS and its limitations documented the students’ utilization of the tools and its implementation during the design development phase, (Biggs, 1996 and Cotrell, 2013) in addition to the limitation of tools and the need for a generation of tools with more friendly interfaces (Soebarto, 2005). Recent studies addressed the possible educational barriers when teaching SBE to students (Hopf et al., 2017), along with detailed documentation of teaching resources and course structure (Strand et al., 2016). In addition, it touched upon the barrier of the “why” rather than the “how” to use the tools among students (Göçer and Dervishi, 2015 and Al-Matameh and Fethi, 2017). Lastly, a study addressed the curriculum development in light of integrating BPS tools during design process, to maximize the potential of the tool and to fill the gap between the theory and practice with highlighted potential of applying BPS (Beausoleil-Morrison, 2019) and additional challenges to the learning method (Hernandez Neto, 2018).

Based on the previous studies, a number of questions shaped the boundary of the discussion as follows:

- Is the adoption of Simulation Based Education (SBE) enough to support the students with an experimental environment for design testing and to improve the transition of the skills learnt to real life professional practice?
- How should the faculty approach the integration of a design dimension within a one-semester undergraduate design studio on BPS?
- How and when should we implement the integration of BPS in undergraduate architecture design education?

**Methodology**

The study addressed the integration of Building Performance Simulation within higher education environment - specifically the architectural education environment - to promote Simulation Based Education (SBE). Through a survey-questionnaire, a design studio taught by the instructor was mapped in tool use and student reflections; the chronology of the tools used throughout several years of offering were documented as well. Three surveys were distributed to the students, faculty and alumni of the program. These surveys were compiled, analysed, and used for re-programming the course learning outcomes and student assessment. Thirty students from Design Studio Two (Year 2 in the Program) who passed a prerequisite course in Environmental Controls (Theory) were selected for the study. They participated in a questionnaire-based survey to measure the students’ willingness to learn and experiment with the SBE course.

The objective of this study was identifying the challenges and limitations of SBE in architectural education and design process, reaching out to the student community and using the experiences gained in previous studies to structure the survey questions. This is because the effectiveness of SBE is related to a variety of factors that may be student or faculty driven, tools and technology driven, and or curriculum driven (i.e. related to the time of offering or mode of application) or a hybrid of all factors.

**Course structure**

The test course focused on using simulations to comprehend the impact of the design on thermal performance, indoor comfort, and energy use. The instructor taught the same class throughout 12 semester offerings (7 years) with different tools wand an almost identical student profile, monitoring the impact of simulation tools on their learning process and professional life of the students.

The length of the course was typically fixed to sixteen weeks, inclusive of final exams with lectures, studio work and tutorial sessions. The lectures addressed the basics and fundamentals of building performance simulation and address with detail-selected tools and programs. The students were required to work on a set of assignments to utilize the tools for initial practice and then apply the learned skills on their studio project while using the tools for development.

**Survey Questionnaire**

The research investigation was based on a survey-questionnaire; some questions were multiple choice, and others were short answers along with statement rating. The respondents were able to add additional information and share their experience and feedback to assist with the future development of SBE. The main objective of the research was to analyze the role and value of simulation tools in a performance-based design studio. Specifically, the study revolved around the use of simulation tools in the design studio among the undergraduate early design courses, graduation design courses and graduates in practice. All the students were directed to learning by doing methodology to individually interact with the tool’s functionality using their own design projects at different levels of design development and experiment with the different capabilities of the tools. Due to the students’ level and background in building physics and building systems along with their general technical ability to work with the tools, it was understood that not all of them were able to conduct a full simulation exercise. Since the students had varied backgrounds along with their technical abilities, not all of them possessed the skills to conduct a full simulation and to understand the output clearly.

Thirty undergraduate students who passed the main course introducing the tool concepts were selected for the present study. They participated in a detailed questionnaire-based survey to measure the student acceptance of the simulation for design development and to get written student feedback to advance the development and integration of SBE within the curriculum in the future. It is also worth noting that all students surveyed were required to take one environmental controls course which touched on issues of fundamentals and theory; the following term they were required to take a core studio with a theme of sustainability in architectural design. Much of the tools
learned took place during the latter course. The questionnaire was structured into four sections: background knowledge, application, course outcomes and future considerations.

Section One - Background knowledge: assesses the background of the student in relation to using simulation tools, the duration of exposure to the topic of simulation along with skills. The purpose is to understand the attitude towards the topic of simulation, delving into the learning methodology to measure the level of willingness to learn along with the tools used and to map out the students’ skills and familiarity with simulation tools, background knowledge and training.

Section Two - Application: Focused on the application of simulation along with other areas to observe the students’ level of expertise and to know whether they were able to relate the information given with other coursework or not.

Section Three - Course Outcomes: reflects the course outcomes of the design studio and the exposure to BPS tools, looking at the student’s comprehension of simulation during the design process and the complexity of the tools, and to identify its characteristics and what makes it “Student Friendly”. Focus group sessions were conducted and helped to identify the proper metrics and associated KPIs for instructors to quantify the effectiveness of the teaching methods used.

Section Four - Future Considerations: assesses the area of development and future considerations proposing virtual reality as one of the alternatives for future simulation education. The survey focused on the notion of how to integrate SBE within the current curriculum through the assessment of the student response to the limitations and challenges of the tools, thus the target is to:

(a) Observe if SBE provides the students with an innovative and effective learning environment, encouraging the students to develop their designs creatively, allowing experimentation of design alternatives to reach creative architecture solutions, and facilitating the transition of the students to real life professional practice.

(b) Identify the main factors that ensure the effectiveness of SBE are relevant to Student driven factors, faculty driven factors, tools and technology driven factors (i.e. generation of tools with more friendly interfaces), and curriculum driven factors (i.e. Related to the time of offering or mode of application).

(c) Develop a set of metrics that can shape future key performance indicators to ultimately help to quantify the effectiveness of the SBE teaching methods used, addressing the tool popularity during a conventional studio setting (i.e. lectures within class applications) or an unconventional studio setting (i.e. learning by playing through gaming).

(d) Assess if the current offering of Building Performance Simulation Education is adequate to support the required project design quality requested by the Architecture Curriculum and Real Life Professional Practice, evaluating the effectiveness of simulation tools in the design process and final product.

Results

More than half of the respondents were not familiar with SBE or BPS tools before taking the course (90%). The majority (60%) had between 0 to 12 months of experience to learn BPS. The duration factors played into the willingness of the students and their capacity to comprehend and apply the basic principles of BPS. The majority (63.3%) of the respondents received their first BPS education during a design studio, while 36.6% received their education in hands-on training and 20% during a mandatory training session as an application part of a course (Figure 1). The main teaching method was face-to-face teaching, which included lectures and supervised in-class-assignments. The survey aimed to identify the appealing factors that attract students to BPS tools, in order to integrate the attractive element in the educational process in an effort to introduce SBE as a continuous learning cycle.

![Figure 1: Teaching methods used – multiple selections were possible](image1)

The majority of the tools used in studio were REVIT (with Autodesk Insight 360), Climate Consultant, and Ecotect. Sketch-Up (with add-in of Skelion) and Autodesk Vasari were also widely used (Figure 2). A few respondents commented on their preferred tool: they depended on a user-friendly interface, while allowing the chance to explore the impact of the architectural decisions during the design process.

![Figure 2: Software programs most commonly used among students - multiple selections were possible](image2)

Application
The survey findings indicate that through experiential learning, a deeper understanding and integration of SBE in the design studio is possible, as indicated by the general interest of the students in the topic. This definitely supports the call for a continuous learning cycle of BPS in continuous and successive design studios. The areas of BPS-taught modules that were of interest to the students are shown in Figure 3. From the respondents, it is apparent that the more friendly and graphical the visualization of the tools are, the higher the interaction of the students with the tool. Eighty four percent of the students utilized REVIT primarily as both a drafting and analysis tool specifically for Daylighting Analysis; eighty percent used it for shading and shadow analysis, and seventy three percent integrated energy simulation in their process of design development.

Figure 3 shows the different applications used and the tendency of the students to deviate the analysis towards the graphical attractiveness of the output charts rather than the purpose of the analysis.

The research team identified that time plays a role in the comprehension process and the ability to apply the assessment results on the design. In order to understand the impact, we asked if SBE tools were offered at an adequate stage during design, sixty percent of the respondents replied that they weren’t, while forty percent replied that their BPS education was at an adequate stage.

The majority of the respondents (66.7%) applied their SBE education during the schematic stage of the design, while ten percent applied it during development stage and 23.3% applied it during conceptual phase. On the other hand, it was observed that despite the design limitations during the conceptual phase due to the simulation results, the final designs were more responsible, functional and justifiable. This attested that a need for an integrated BPS exposure was best at a much earlier design stage. Forty seven percent of the respondents reported that they understood the assessment, but were unable to apply it on their design, due to comprehension and data interoperation obstacles.

To identify the challenges arising from technology change, we asked the respondents if SBE tools validated or discouraged their design, seventy percent reported that it validated the design, but on the other hand, only sixty percent were able to apply the assessment results on their designs. The correlation between the time of application and level of satisfaction and comprehension of the BPS principles were identified. Those who were able to comprehend the concepts altered their designs to a degree that did not affect the original concept of their building design. Figure 4 demonstrates the most common sources of discouragement during assessment.

There were misconceptions identified among the students on the difference between “running a successful simulation” and “interpretation of the output data”. Students faced many challenges in the interpretation of the output data, 56.7% reported that it conflicted with the design, while fifty percent reported that it requires advanced knowledge and forty percent of the respondents reported that it was due to the tool complexity. This question allowed for three main research observations: the main target user of the SBE tools, the impact of SBE tools on creativity in design and the difficulties with data interpretations.

Observation 1: the tools were not made for educational purposes, but for professional ones. 83.3% of the respondents confirmed their awareness that the tools utilized are for professional use, 93.3% reported that they would use a more simplified version of the tools utilized. 56.7% reported that REVIT (most preferred tool among students) was not properly utilized. When asked to provide their insights, the respondents reported that it was used as conceptual tool without putting into too much consideration for how projects would be accurately built. The most common response was on the need for a balanced teaching method between traditional and performance-based driven studio objectives and to support the transition of the studio to be a more interactive hands-on environment.

Observation 2: SBE tools conflict with the design process in the typical design studio. For the questions on limiting of creativity, surprisingly, only 20% reported ‘Yes’, while 40% reported ‘No’ and 40% ‘Maybe’. This may indicate confusion or misunderstanding of the role of SBE tools during the design process. 80% of the respondents confirmed that running simulation of the design proposals signifies “the end” of the design process. This indicates some of the misconceptions, which was not comprehended earlier explaining simulation as a ‘process’ not as an ‘end result’.

Course Outcomes
The students need to be able to grasp the importance of their design decisions by being able to investigate the impact of such decisions on their designs in different
performance criteria, moreover, be able to make links between the values (numerical) required for the simulation and the architectural solutions. Accordingly, the research team wanted to measure the awareness of the respondents on the importance of SBE tools, so we asked if the BPS tools played an integral role in advancing the design. 86.7% of the respondents confirmed the importance of BPS tools during their design process, but the respondents did comment on how they would like to have SBE as part of their design and studio culture, because they only use BPS tools when asked to. In an attempt to focus the “why” not the “how”, we asked the respondents if they were able to grasp the effectiveness of the assignments to identify how and where was simulation easy enough for the students to comprehend, where it was serving the student not the process of simulation itself. 40% of the respondents acknowledged the importance of the daylighting assignment, while 43% agree with the efficiency of the tool. On the other hand, Energy simulation on REVIT was the least utilized tool with 9%, reflecting back on how the input data and the interface play an important factor in the comprehension process. Figure 5 shows the respondents’ perceptions towards different BPS tools.

**Figure 5: Effectiveness of the BPS Modules among Students**

**Design Studio Future Development**

Figure 6, demonstrates the different teaching methods in question. The shift in the studio teaching towards a more unconventional teaching method, where a conventional approach (i.e. lectures with in class applications) and an unconventional approach (i.e. learning by playing through gaming). The majority of the respondents (96.7) were leaning towards a more unconventional learning method.

**Figure 6: Preferred Learning Methodologies to promote SBE - multiple selections were possible**

The respondents have acknowledged the importance of BPS tools and the potential of having an SBE mindset, but if offered in a less formal method during the early design studios. They recommended that SBE to be introduced early in every design studio to allow time for analysis and optimization. 74% reported that they would consider BPS as a conceptual design-guidance tool upon the re-structuring of the simulation offering methods. The respondents have expressed their willingness to learn, but also that they needed less formal teaching methods, especially during early design stages where they can apply what they learned, rather than have to practice with the tool alone.

**Discussion**

To evaluate the utilization of environmental simulation tools and their integration in the typical undergraduate education and its effectiveness, the research team was able to identify, using the surveys, a group of metrics and indicators for goal assessment and measurement of the learning outcomes. These indicators are:

- Appropriateness/Suitability of the learning environment
- Student intent to use BPS as a design guide
- User friendly interface and impact on usability
- Data volume required for simulation and ease of interpretation
- Ability to provide a flexible/unconventional continuous learning approach
- Complexity of the tool and ease of comprehension

**Future Suggestions**

**BPS to be a Continuous Cycle of SBE**

The research team was aware that students were not utilizing the full potential of the tool because they were not exposed to the full Building Information Modeling (BIM) functionality of the commonly used tool. While REVIT is the most used among students, it remains complex and not fully comprehended both for those who seek results or assessment. The students suggested using a simplified tool because they wished to integrate BPS results and optimize their designs. It was discussed that the current education offering is not adequate to support the real life professional practice; as a result, a gap between the real job market (practice) and the educational platform (learning and research) exists. Accordingly, with these findings, it was suggested to continuously survey the program graduates to measure the validity of these findings. Furthermore, it was suggested to monitor the students’ comprehension through continuous improvement of design, and to encourage the development of alternative solutions to maintain the quality of a design, develop new and innovative ideas and consistent use of BPS throughout all phases of design process to maintain the desired continuous learning cycle. It was mentioned that BPS would be more desirable if the students were able to get accustomed to utilizing the tools during design studio in earlier stages -from Year 1, for example- in order to learn a solid foundation on the fundamental knowledge and skill set needed to conduct a successful performance based studio-utilizing BPS.

Accordingly, BPS should:

- Be the design decision driver.
- Be the main structure of the design problem.
- Improve the decision making process, making it easier to comprehend the impact of any architectural decision.
- Make students more aware of the implications of their architectural decisions on the performance.

**More of a Program Culture rather than a Dedicated Studio**

SBE supports students in an innovative and effective learning environment; its overall objective is to allow the students an experimental environment for design testing and to enhance the transition of the skills learnt to real life professional practice. Looking more into the impact of SBE on the courses that follow, it was decided to question the impact of the prerequisite courses and to apply building performance simulation and the need to expand the curriculum to include more courses relevant to building physics in lieu of just introducing the fundamentals only, where it expands beyond one semester. BPS should be more of a culture rather than a studio, and should start to be more ubiquitous throughout the rest of the coursework so that it becomes more of an integral part that interacts with the design process rather than being an option. The overall initiative is to have BPS as a coherent element in the design process. Suggestions were made to enhance the educational process and exposure mechanism to BPS tools to the students through the integration of information in the earlier years of the program. One suggestion was to link the design projects with practice allowing actual clients to be part of the studio jury as well as design professionals.

**A Continuous Process of Course Development**

Utilizing the outcomes of the focus groups and the survey questionnaires, the structured development of the course over the span of seven years, with the implementation of the student feedback and the simulation tools used at every mapped out stage. The course ran through fourteen offerings, where there was the challenge of learning different tools to expose the student to a variety of simulations to be integrated in the design. The tools changed over the span of the course development due to the fast-pace changes in the technology platforms used to support SBE. Using energy simulation in student design projects is becoming a robust task as generations of tools, like REVIT, are starting to be associated with a more friendly interface and the analysis mainly performed in the cloud; however, a consistent issue persists on the quality of input data used and the coherence of the output data.

The amount of time spent between teaching theory, application and analysis needs further thinking to address the method of comprehension and development of BPS concepts among the students.

**Recommendation for a Student Based Simulation Tool**

The study indicates that the current tools on the market are created for the sole purpose of commercial/professional use, and therefore are too complex for the typical student to comprehend. The choice of tool depends on its accuracy, flexibility (interoperability with other applications and the ease of use to develop architectural models), duration of analysis and ease of data interpretation, geometry inputs (ease to simulate complex designs), and the user interface. As a result, a tool that offers design exploration coupled with simplified level of analysis is needed to assess the impact of the architectural decisions. The tools could develop simplified metrics and indicators for the students to be able to comprehend the complex notion of the numerical data input/output as they work towards a common goal or objective.

Due to the wide variation among the different tools that support BPS environment, students are not able to get accustomed to the process of using BPS during the design process if they get exposed to different tools during a short duration. As a result, the students do get to use the programs and comprehend the impacts on the design, but the question is if they understand the concept of BPS. Moreover, not all students take the results to the application process, which means that they do not perceive BPS as an integrated design development tool. Architectural programs could seek to develop the issues of design development through the integration of BPS tools with the design thinking process.

To ensure that the students are more involved and engaged with the application of simulation, the guidelines for what the tool be characterized by are to be highly graphical, does not require complex numerical input that would produce a clear model with expert knowledge to navigate through. Students need to have a solid background knowledge in building physics and systems design before using simulation tools or risk having difficulties in the comprehension of data due to lack of proper skills and knowledge base. It is also recommended to have a co-instructor in the course with strong background in building systems to act as a Mechanical/Electrical/Plumbing (MEP) advisor to help the students in the proper interpretation of the output data and accordingly for the suggested design changes.

The current limitations were acknowledged as the lack of emphasis of the importance of SBE, along with the need to develop a software that is user friendly to the students, where they can comprehend the simulation results through a simpler and less complex simulation tool. This would increase the student willingness to experiment. Other limitations include time-consuming nature of the professional and complex tools, where the students do not know whether to focus on the design or the skill to manage the tool. Finally, there is a need for horizontal and vertical coordination between different courses that can take SBE into consideration as one of the main objectives of the program as a whole.

**Conclusion**
This research utilizes an actual course as the case study; a sample of thirty students responded to a structured survey questionnaire along with focus group discussions and one-on-one discussions. We understand the study is local so the course in question and the data should not be generalize the wider community of BPS users. However, we believe that the current tools shared across many programs worldwide and available for students are still complex and may cause a learning problem as it requires specific skill and preparation for the quality of data input/output explanation. The study is comprised of the total number of the students involved in one of the course offerings. Acknowledging this bias, future scaling of this research for the software development stage should engage a larger audience to properly report and generalize the research study outputs. The research aimed to address misconceptions on the timing of conducting a simulation in the course, along with the purpose and ability of output data interpretation. The objective of developing the curricula should continue to revolve around teaching the students to be producers of architectural design rather than producers of simulation models; however, the performance-based aspect of these designs cannot be assessed except with simulation tools. Lastly, the study outcomes help as guidelines to develop an adaptive course curriculum that can allow for a balanced approach between creativity and performative teaching environments.

In conclusion, we strongly suggest a closer look at the available tools for students and how we prepare these students for the professional market, particularly as it relates to the understanding of the performance gaps in the understanding of the generated output and whether it is understood well at the different levels. As the rate of students willing to integrate BPS tools in their design process has increased and shows potential, the risk of misinterpretation of results still remains. Additionally, at some point the nature of data produced—which is not fully coherent yet-is trusted because it is commercialized as a validated tool. We are seeking to educate BPS users rather than producers. The study vouches for a student oriented tool, to produce a generation of aspiring architects with experience in interdisciplinary studio work involving BPS, where they have received support with data interoperability and prior knowledge in principles of simulation. Should the students understand uncertainty and data challenges, the algorithm “engine” of the tool used? Is SBE a proper method of learning for undergraduate design studio? Are we moving in the direction of restriction of BPS tools and allowing it for the advanced level analysis only “graduation project level” and professional use, thus, prohibiting the use of it for the remainder of the undergraduate education? The previous questions require further investigation and research to better equip students with means of good interpretation of data, design user friendly and easy to comprehend tools, and establish a good understanding of the tool in lieu of the common use of completing the requirements with coloured charts that fill the analysis gap.

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