Pedagogical insights of using urban and building performance simulation in a problem-based learning context

Christiane Berger[1*], *Luis Santos*[1], and *Runa T. Hellwig*[1]

[1]Department of Architecture, Design and Media Technology, Human Building Interaction, Aalborg University, Aalborg, Denmark

Abstract. Integrating building performance simulation (BPS) in design workflows for the built environment is becoming increasingly common as it holds the potential to assist designers in making informed decisions regarding efficiency, sustainability, and overall environmental quality. Consequently, BPS has been integrated into the curriculum of several architecture and engineering programs. The paper specifically focuses on the pedagogical potential of using BPS in a project-based and problem-based learning (PBL) environment and discusses existing related pedagogical strategies. To this end, this work examines the benefits and challenges of using BPS in teaching along two case studies. Finally, the paper outlines pedagogical strategies to overcome typical shortcomings of using BPS in project-based learning and PBL environments and critically discusses pedagogical insights of using simulation in architecture and architectural engineering programs.

1 Introduction

With the proliferation of urban and building performance simulation (BPS) and several front ends to different BPS tools, adopting BPS is becoming increasingly common in all design stages. Integrating BPS in design workflows for the built environment promises to enhance efficiency, sustainability, and overall environmental quality. It also holds the potential to assist designers in making informed decisions, considering challenges posed by climate change, e.g., extreme weather events in design workflows, and steering design processes of structures that are simultaneously functional, environmentally responsible, and cost-effective. Consequently, BPS has been integrated into the curriculum of different architecture and architectural engineering programs.

Despite the potential benefits of using BPS in design and a learning environment, there are some challenges. For example, using BPS allows designers and students to assess different environmental performance aspects of several design variants quickly. However, it could also lead to misinterpretation driven by a fascination with what Sherry Turkle coined as "pretty pictures" in the book "Simulation and its discontents" [1] or hampering the ability

* Corresponding author: chbe@create.aau.dk

to correlate the prediction of an environmental indicator and its correspondent phenomenological experience.

This paper discusses and reflects on the benefits and challenges of using simulation as a teaching tool. It will start by providing some background on the subject to outline different pedagogical strategies and give examples for integrating simulation in architecture and architectural engineering classes (e.g., gamification). Then, the authors discuss the benefits and challenges of using BPS in specific case studies, which address outdoor comfort and carbon flows in a project-based and problem-based learning (PBL) environment. To that end, the paper also briefly introduces and discusses PBL and its aims in a design-oriented program.

Finally, the paper outlines pedagogical strategies to address typical limitations and shortcomings of using BPS in a PBL environment. It also, discusses how to create an environment for students to develop a critical mindset towards simulation, particularly in the definition of feasible design criteria and performance goals.

2 Background

2.1 Project-based and problem-based learning

Savery [2] describes the problem-based learning (PBL) pedagogical model as an *"approach that empowers learners to conduct research, integrate theory and practice, and apply knowledge and skills to develop a viable solution to a defined problem."* Project-based learning is a related form of active learning in a group-based setting that can be linked to problem-based learning [2, 3]. Thereby, *students' "learning activities are organized around achieving a shared goal (project)"* [2]. In contrast to project-based learning, *"problem-based* [learning] *approaches structure students' activities more by asking them to solve specific (open-ended) problems rather than relying on students to come up with their own problems in the course of completing a project"* [4].

A recent review discusses different problem-based learning teaching practices at different universities, including McMaster University in Ontario, Canada, and Maastricht University in the Netherlands as well as Roskilde and Aalborg University in Denmark. Thereby, key elements of the pedagogical model as well as the role of teachers in the educational process are discussed and compared in such review [5]. For more details about the nuances of different PBL modalities or related pedagogies the authors refer the reader to the work of Servant-Miklos [5].

The literature often presents the pedagogical approach of PBL as stimulating students' motivation and group creativity [6]. Furthermore, PBL's active and collaborative learning approach can potentially enhance design and engineering students' technical and professional skills, including teamwork and communication skills [7]. This paper focuses explicitly on the pedagogical potential of integrating BPS in a learning environment geared towards PBL.

2.2 Examples of applying simulation in the architecture and architectural engineering teaching context

As alluded to before, integrating BPS in different stages of design provides the possibility to support and steer the design process of environmentally friendly and cost-effective buildings and urban structures. Given these possibilities, BPS has been integrated into the curriculum of several architecture and architectural engineering programs. Previous research has reported on different teaching formats and related benefits and challenges of using simulation

in teaching. The following discusses a selection of prior research considerations regarding this matter.

Reinhart et al. [8] present a gamification teaching approach that introduces students to building energy simulation and its integration into their design process using a game-based format. The authors report that the teaching method is efficient as it enhances students' engagement and interest in the topic. However, it also indicates that a more systematic theoretical framework is needed to use BPS efficiently as a design decision tool.

To showcase how BPS is being taught at several architecture programs at different universities, Hopfe et al. [9] conducted an international effort to present the outcome of a survey conducted in Australia, India, the US, and the UK. The paper specifically discusses the difficulties and barriers of using BPS and gives recommendations on the integration of BPS in architectural curricula. One issue often pointed out is the need for more knowledge of the basic principles of simulation among students [9, 10]. Likewise, Berger and Mahdavi [11] emphasize that an *"a priori solid understanding of the foundations of building physics, building construction, and knowledge-based design principles"* is crucial for competently using building performance simulation tools.

Freudenberg et al. [12] present the integration of BPS in architecture education at TU Dresden, Germany, in two teaching formats: i) a course accompanying a design studio, and ii) a seminar in an advanced semester. Both formats focus on introducing BPS to support design decisions related to daylight, overheating, and renewable energies. Likewise, the architecture education at Karlsruhe Institute of Technology (KIT), Germany, integrates different BPS tools at both undergraduate and graduate levels. The aim is to assist students in evaluating their design decisions regarding daylight, indoor environment, and energy requirements [13]. The architecture curriculum at the University of Kassel, Germany, addresses topics related to energy-efficient and sustainable buildings in lectures and seminars on both undergraduate and graduate levels [14]. The teaching includes dynamic building energy simulation tools for detailed hourly analysis and spreadsheets for energy requirement calculations.

Another research effort specifically discussed the integration of BPS in the early design phases of an architectural design [15]. The authors conducted a survey to examine the potential and barriers to existing BPS integration in architecture curricula and related teaching experiences. The survey was carried out between 2019 and 2020 and included replies from 18 lecturers from both architecture and civil engineering programs. The questionnaire addressed BPS teaching in topics related to ease of use, accuracy, integration of intelligent design knowledge, affordability and accessibility, compatibility and interoperability, and visual representation of simulation input and output. The authors emphasize that deploying BPS in building design and providing an iterative bidirectional feedback loop can benefit students' inspiration and inform their design decisions already in the early design stages.

Teli et al. [16] report on teaching experiences in architecture and building engineering education regarding the topic of thermal comfort. In terms of holistically integrating adaptive principles in the design, the authors consider that *"simulations can support iteration of design decisions: simulating the effects of adaptive behaviours, e.g. operable windows, exterior blinds, ceiling fans, etc. on occupant comfort and building performance"* [16].

3 Method

The paper discusses two case studies of BPS implementation in undergraduate architecture education at Aalborg University. Both case studies focus on teaching activities that introduce BPS in a PBL learning environment, which is the general teaching approach at this university. In the programme, every semester, students get involved in at least one large project and

typically also two small projects in course modules. The following outlines the learning goals, pedagogical strategies, and the assessment of both case studies regarding workflow, students' evaluations, and instructors' considerations.

3.1 Case study 1

This case study examines a course on sustainability assessment based on the Danish sustainability rating system (DGNB), including Life-Cycle Assessment (LCA) and Life-Cycle Cost (LCC). The course takes place on the 5th bachelor's semester of Architecture and Design at Aalborg University.

The course focuses on an urban cross-section consisting of the interface of an outdoor space and building façade. The simulation-related part of the course consists of assessing the DGNB outdoor comfort indicator in an urban courtyard by estimating equivalent temperatures in terms of the Universal Thermal Climate Index (UTCI) and conducting a simplified estimation of Global Warming Potential (GWP) of the retrofit of one of the façades that face the urban courtyard. The LCA and LCC methodologies supports the façade retrofit design workflow. The students use a predefined Ladybug/Honeybee template script to estimate UTCI, whereas they used a template spreadsheet for LCA and LCC studies. The course content is defined in the module description. The course takes place prior to an urban design focused main semester project module. In addition, the course reported in case study 1 takes place before the course reported on in case study 2. The two case studies partially overlap regarding outdoor comfort.

The instructors framed the learning goals of this course within Bloom's taxonomy [17] as follows:

1. Knowledge/Remember:
    - Analysing the perceived temperature phenomena
    - Understand LCA and LCC methodology, including phases and indicators
2. Comprehension/Understanding:
    - Interplay of microclimate factors in outdoor comfort
    - Impact of building form, orientation, vegetation, and other factors in thermal comfort of outdoor spaces
    - Types of building materials and associated embodied carbon (measured in GWP) as main indicator for environmental impact
    - Impact of industrial processes and transportation on the embodied carbon footprint in building materials and related cost
3. Application/Applying
    - Define adequate design criteria and parameters for a given problem
    - Use simulation software to predict phenomena
    - Use simulation data to inform a design process

The pedagogical strategy of this case study focuses on a group-based working and learning approach within a PBL environment. Thus, students work in pairs, and each group is responsible for developing strategies to improve outdoor comfort and minimize GWP and cost while developing attractive architectural and urban design solutions. The instructors segment the exercise into three phases – outdoor comfort, LCA, and LCC – and introduced the topic and the relevant tools before the start of each phase. The introduction of each topic focuses on the relevant parameters related to the design task, and the instructors introduced the tools via tutorials followed by small in-class exercises. In sum, the strategy aimed to introduce the students to a complex multi-criteria design task for the first time. Students should be able to articulate different design criteria and parameters and understand the impact of design changes to inform their design process.

3.2 Case study 2

Case study 2 concerns a workshop also within the 5th bachelor's semester of Architecture and Design at Aalborg University that provides students with an introduction to outdoor comfort assessment during the early design stage of their main project design. The learning goals of this workshop are also mapped along the cognitive learning goals based on Bloom's taxonomy [17] as follows:

1. Knowledge/Remember:
    - Analysing phenomena
    - Identification of evaluation parameters relevant for a given problem of the design project
2. Comprehension/Understanding
    - Dimension of outdoor comfort
    - Impact of building form, orientation, vegetation, etc. on outdoor spaces
3. Application/Applying
    - Define adequate design criteria and parameters for a given problem
    - Use simulation software to predict phenomena
    - Use simulation data to inform a design process

The pedagogical strategy of this case study focuses on a group-based working and learning approach within a PBL environment. Thereby, students formed groups of five to six people, each focusing on an individually defined problem. The integration of BPS specifically aims to assess outdoor comfort parameters during the early design stage of their project design. The workshop introduced students to a simulation tool in a web-based environment suited for early design stages, Autodesk Forma [18]. Before deploying the BPS tool, the instructor provided a brief recap of theoretical understanding and basic principles underlying the simulation framework, a discussion about parameters related to outdoor comfort, and a step-by-step case study example. This format aims to expand and activate already existing knowledge of the students as well as encourage them to evaluate how specific parameters impact their design decisions.

3.3 Assessment

To assess the case study approaches in a structured manner, we evaluated along three main categories:

1. Workflow
2. Students' evaluation
3. Instructors' observations

The first assessment category concerns the workflow of the integration of BPS in each specific course setting based on instructor's evaluation. Such evaluation examines the following aspects:

- Learning curve
- Modelling effort
- Data interpretation and visualisation

The second assessment category concerns the feedback received by students. The students' evaluation consisted of a quantitative and qualitative survey that included 19 questions covering topics related to course content, knowledge transfer, and overall assessment. The quantitative part of the student evaluation consists of a set of Likert statements. For each Likert statement, the students needed to specify their level of agreement or disagreement using the following 5-point scale: strongly disagree, disagree, okay, agree, strongly agree.

Regarding course content, the survey asked students if they found the learning goals were clear, the course topics relevant, and whether the integration of the course topics in design tasks was visible and clear by assessing the following statement:

The learning goals/objectives of the course were clear and noticeable.

Related to knowledge transfer, the survey focused on whether the support material, such as templates, supporting slides, tutorials (video-based or written), and workshop sessions, supported the understanding of the course topics and their application in design tasks. The questionnaire had the following Likert statements related to knowledge transfer:

Transfer of Knowledge A: The relation and integration of the simulation tool to the project was visible and clear.

Transfer of Knowledge B: The exercises are relevant for learning about using/applying the simulation tool.

Concerning overall evaluation, students provided quantitative and qualitative feedback on their learning experience by i) scoring if they had a playful and enjoyable experience attending the course, and ii) reporting positive aspects as well as topics that could be improved. The questionnaire had the following Likert statement related to overall evaluation:

The provided materials support me in my project work.

This paper summarizes the qualitative answers in the result section, as they provide a better insight in students' perception of their learning experience.

The third assessment category consists of reflections conducted by the instructors based on their observations during teaching and examination. This reflection focuses on the perceived learning progress, both on the core concepts of the course and the use of the tools.

4 Results

4.1 Case study 1

The following section presents the results regarding case study 1 along the three assessment categories outlined above.

4.1.1 Workflow

For calculating outdoor comfort, this course used an environmental simulation package (Ladybug/Honeybee) in a visual programming language (VPL) (Grasshopper) environment. Fig. 1 illustrates such a workflow. The instructors assumed that using VPL would provide more liberty in setting up bespoke analysis and post-processing simulation data by querying and visualising it. Nevertheless, this liberty would come at the cost of a steep learning curve. To smooth the learning effort in students not accustomed to VPL environments, the instructors needed to prepare well-documented template scripts and extensive tutorials either in written or video format. This provided the typical learning scaffolding encouraged by the PBL constructivist pedagogy. Although this structured approach smoothed the workflow, it did not avoid some difficulties experienced by the students in adapting to the simulation environment. In the LCA and LCC part of the course, students needed to use, manipulate,

and extend a calculation spreadsheet. Because the students were more familiar with the spreadsheet program (Excel), they reported fewer difficulties initially.

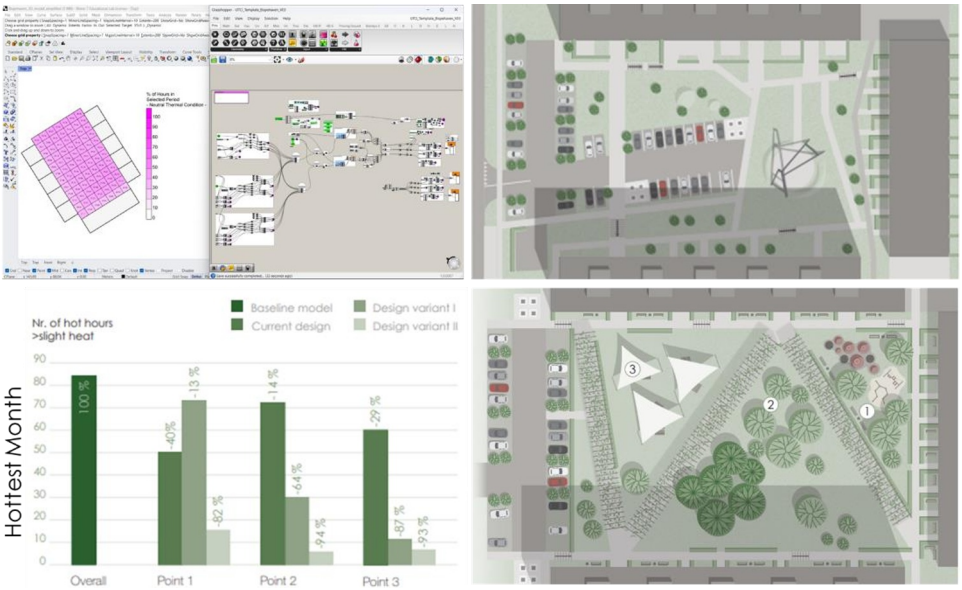

Fig. 1. Insight to case study 1 simulation-based design workflow regarding outdoor comfort. Top left: Simulation environment in VPL. Top-right: current site condition. Bottom left: heat stress performance comparison of 3 design variants. Bottom right: simulation environment in VPL.

Provided the structured templates, the modelling effort was minimal. It mainly consisted of modelling geometry for outdoor comfort analysis and partially extending the calculations of the LCA and LCC templates. However, when the students wanted to assess the outdoor comfort of a design alternative that could not be natively modelled in the simulation environment, the instructor assisted them in developing assumptions and alternative modelling methods.

Finally, the outdoor comfort analysis template automatically produced some useful visualisations, while the LCA and LCC did not. The students were responsible for manipulating, extending, and generating data visualisations. The instructors anticipated some difficulties with this and provided examples of how data could be visualised and post-processed. Nevertheless, a significant part of the students presented some challenges in making consistent comparisons or presenting data in a clear and effective way.

4.1.2 Student's evaluation

Fig. 2 shows a subset of the evaluation done by 26 students. The majority of the students (88.5%) felt that the course project helped them to use and apply the simulation tool (Transfer of Knowledge A). Likewise, most students (77%) either strongly agreed or agreed that the tools and knowledge the course provided are sufficient and support them in project work or related tasks (Transfer of Knowledge B). Understanding the course's learning goals could have been clearer for the students, as only 69.2% admitted that they not fully grasped the purpose of the course. The articulation of different topics needed to tackle the multi-criteria design problem of this course might have contributed to the perceived ambiguity of the course goals. Moreover, the overall curriculum places the first introduction to LCA and LCC in an urban design-focused semester which might not be intuitive to students as well as instructors.

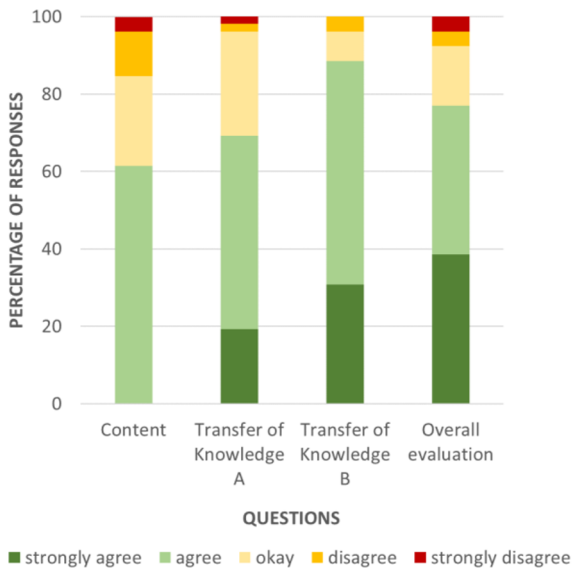

Fig. 2. Subset evaluation of case study 1 related to the use of simulation tools in the course.

Regarding the qualitative feedback of the students, overall, the students reported that tutorials (in the format of template files, videos, and step-by-step guides) have been beneficial. Most of the students mentioned when they mastered the workflow, using simulation in their design process was playful and enjoyable. The leading cause for this reaction was that the simulation enabled them to test and compare different design alternatives. The students who decided to tackle challenging modelling tasks that fall outside of the modelling capabilities of the provided simulation ecosystem experienced some initial struggles. However, after circumventing the tools' limitations, using reasonable assumptions and rules-of-thumb, they felt satisfied and happy with their accomplishment.

When the instructors did not provide tutorials for a specific task, students specifically asked and requested them. The multiplicity of tools, which follow the diversity of the course topics, was the less praised aspect, indicating that students would have preferred to stay within the same tool ecosystem.

4.1.3 Instructors' observations

Well-documented tutorials and templates were essential, particularly in tasks supported by simulation front ends in a VPL environment. By following up on tutorials and examples, students' difficulty using simulation in a VPL environment was lower than expected. Moreover, following tutorials before classes allowed more space for insightful discussion during supervision. When students felt comfortable using digital simulation, they could generate and evaluate several design alternatives. Although this structured approach smoothed the workflow, it did not avoid some difficulties experienced by the students in adapting to the simulation environment. On the one hand, such challenges might induce frustration and cause demotivation; on the other hand, such difficulties can be desirable when students overcome them, as they provide a positive feeling of accomplishment and fuel motivation.

Providing too many structured or easy-to-use simulation workflows also comes with the cost of limiting the opportunities to acquire a better insight into the relationship between inputs and design parameters in the simulated phenomena or system. In that regard, because

the instructors asked the students to extend and build up part of the LCA and LCC calculations, they better understood connecting inputs and design parameters in GWP and cost estimations.

The instructors also observed that although the students can use the simulation tools, it is not clear that they fully understand the conceptual framework of the simulation and the dynamics of the simulated phenomena or system. This observation indicates a disconnection between the perception of the phenomena or system being simulated and simulation output. Eventually, this disconnection explains the tendency of several students to subvert a design task to a mere optimization game, where the focus is to minimize or maximize a performance indicator at all costs without considering other implications (e.g., architectural, and spatial quality).

There were a couple of exceptions to the lack of overall understanding of the dynamics being simulated. Exceptional students were able to detect the limitations of the tools (e.g., the simulation of annual wind flow patterns limitation in Ladybug/Honeybee), generate plausible assumptions, and manipulate the use of the simulation tools to circumvent such limitations.

Finally, given that the template scripts and spreadsheets had limited data visualisation capabilities, students needed help interpreting some results. Even when the data visualisations were automatically generated, the instructors observed that some students struggled to interpret the meaning of false-colour-mapped results. For example, it was common to associate the red or blue colour with thermal sensation in a heatmap, while the colour value referred to a percentage of time a specific thermal condition would be experienced at a particular location. The usage of inconsistent scales in comparison tasks was also common. Nevertheless, the difficulty in visualising and querying data is more related to data visualisation illiteracy than to the use of specific tools to produce graphs or filter data. Addressing such illiteracy was outside the scope of this course.

4.2 Case study 2

The following presents case study 2 results along the three assessment categories outlined in the methods section.

4.2.1 Workflow

The learning progress seems to be smoother than in case study 1 due to the perceived intuitive use of the tool. The modelling effort appears to be small due to the interoperability between different 3D modelling tools and the web-based simulation environment. Regarding data interpretation and visualisation, students occasionally report incorrect comparisons using mismatching value scales. As in case study 1, there also seems to be a tendency to associate a meaning with a specific colour without checking the respective value scale. Also, occasionally, students did not clearly formulate the initial simulation goals or framing questions. As such, it often resulted in imprecise or unclear data visualisation. Fig. 3 illustrates an exemplary workflow of case study 2.

4.2.2 Students' evaluation

Fig. 4 shows a subset of the evaluation done by 46 students. The majority of students (87%) could clearly see how the BPS tool could be linked to their project work and related tasks. Students specifically mentioned that the step-by-step case study example was very helpful in understanding both how to work with the tool and how to link simulation to their project tasks. Some students expressed that they would like to have a video tutorial in addition to the

step-by-step instruction so that recap at a later stage is easily possible. Furthermore, several students expressed preference towards extending the timeframe for the workshop. Overall, the students mentioned that they find the tool intuitive to use. They like working with it because it is interoperable with other CAD tools, which makes iterative testing of different design options accessible.

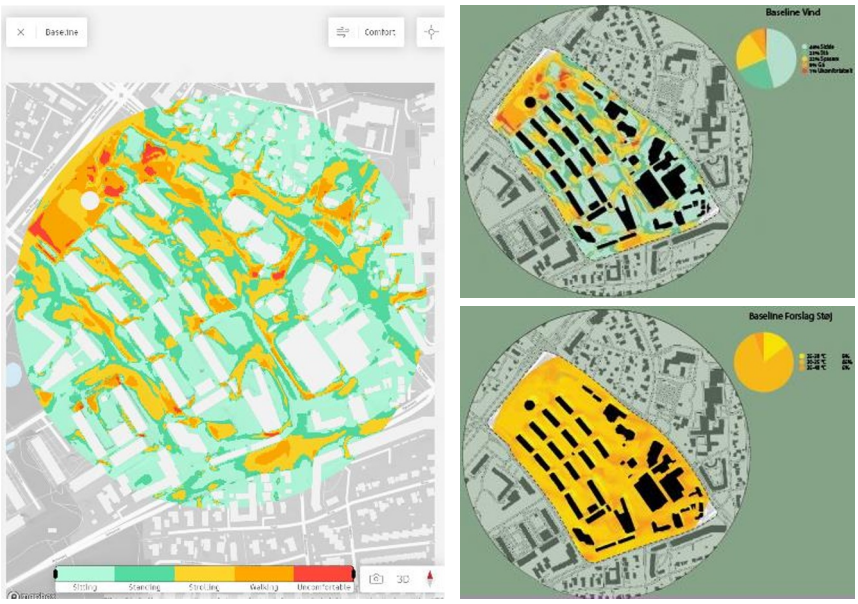

Fig. 3. Insight into part of the simulation workflow of case study 2 regarding urban wind flow patterns (left) and exemplary work by students showing iterations regarding wind and microclimate under selected conditions (right).

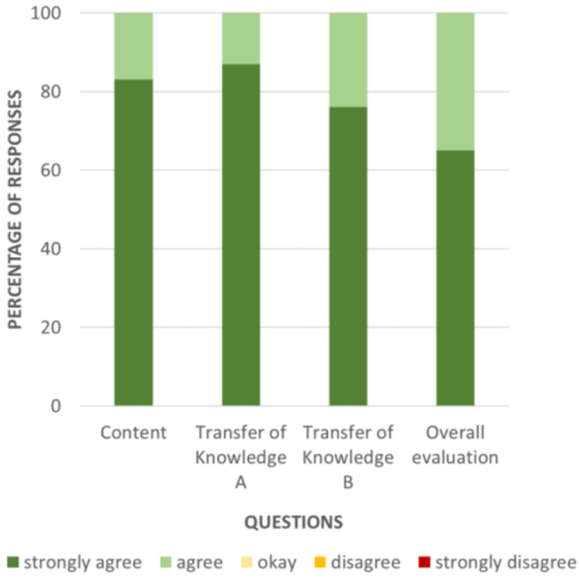

Fig. 4. Subset evaluation of case study 2 related to the use of simulation tools in the course.

4.2.3 Instructors' observations

Overall, similarly to case study 1, most of the students could generate and evaluate several design instances. Also, the students were motivated to work with the tool as they perceived the tools' interaction as intuitive.

It appeared that few students did not have a full and clear understanding of the conceptual framework underlying the tool and of the fundamental knowledge related to building physics principles regarding the outdoor environment. Hence, it seems necessary to dedicate more time to recapping basic principles before the BPS integration.

Alike case study 1, there is the risk that students limit the simulation task to a mere optimisation. Moreover, there was some difficulty with understanding and interpreting the simulation results. It seems necessary to raise awareness of this issue to better understand the comparison of simulation results and avoid misinterpretations. For example, providing a framework for analysis beforehand could guide the students regarding this issue.

As the tool has limited capabilities in adjusting input parameters or data post-processing, its deployment on an advanced simulation level is restricted. However, the tool's intuitive interface, the interoperability options with other tools, the native visual representation capability, and the tool usage in the early design stage are beneficial as they allow an accessible iteration loop.

5 Discussion and conclusion

The following discusses the benefits and challenges of using BPS in a PBL environment. Thereby, we differ between pedagogical-related and workflow-related aspects.

Regarding pedagogical-related elements, we can outline key observations relating to both benefits and challenges. The beneficial aspects of using BPS are summarized as follows:

- BPS allows students to evaluate several design instances and correspondent parameters.
- Overall, it appears that the group-oriented setting of the PBL environment in the reported two cases allowed peer-learning and fostered students' motivation. This circumstance enabled students to learn to deploy the tool, partially understand the phenomena underlying the simulation, and realize the impact of design decisions on relevant performance indicators.
- Some students found the use of the tool extremely playful and enjoyable and were extremely motivated and enthusiastic about using simulation in the design process.
- As soon as students overcame the challenge of mastering a BPS tool, they often perceived a feeling of achievement, which boosts their motivation even further.

The following summarizes the pedagogical-related challenges:

- The playfulness of teaching with BPS might lead to some narrow-mindedness in the students as they might perceive the task as more tool-centred rather than phenomena-centred. Specifically, when the format of gamification is used, the design process is strongly oriented towards performance optimisation.
- The authors could observe that there is occasionally a mistaken sensation of expertise when students master a BPS tool.
- Peer learning has several beneficial aspects. However, there is the risk of propagation of misleading views and approaches.
- The absence of guidelines or examples of assessement quality of simulation results inhibits the development of a critical mindset in the students towards simulation use in design. Consequently, students tend to develop a culture of unquestioningly trusting simulation results and not associating simulation output with phenomenologic experiences. The lack of critical insight into simulation use also

contributes to a shallow or even misleading understanding of the phenomena or system being simulated and, therefore, difficulty defining design criteria and performance goals in design processes.

Regarding workflow-related aspects, key beneficial observations address the following points:

- Workflows based on interfaces that use visual scripting or spreadsheets indicate a better understanding of required input parameters and respective phenomena modelling.
- Workflows based on interfaces that use visual scripting or spreadsheets are typically open-ended, meaning the user can post-process the data in numerous formats.
- Workflows supported by an intuitive graphical user interface (GUI), such as Autodesk Forma [18] facilitate the usage of simulation in the design process.
- Additionally, workflows supported by an intuitive GUI, allow to quickly inform the design even at its early stages.

The following outlines the workflow-related challenges that emerge from this study:

- Workflows based on interfaces that use visual scripting or spreadsheets require data post-processing a priori knowledge.
- Workflows based on interfaces that use visual scripting or spreadsheets have a steeper learning curve. They do not scale well with increased complexity and demand effort to master the tool. The complexity increase might lead to students spending most of their time just trying to run a simulation, which could subsequently result in demotivation.
- Workflows based on an intuitive GUI, such as the simulation framework discussed in case study 2, come at the cost of limited input control and options for post-processing data.

Considering the key observations of using BPS in teaching listed above; the authors conclude that the role of the instructor is critical given several aspects. First, best practices in using the tool need to be provided. Second, the relation between simulation results and phenomenological experiences needs to be promoted in teaching practices. Further, peer-learning needs to be moderated in order to avoid the propagation of misleading views. Additionally, when integrating BPS in teaching, careful consideration and differentiation of using BPS at early or advanced design stages is essential.

Finally, it has to be noted that the scope of this paper is limited to two case studies and its conclusions cannot be generalized to other classes that use BPS even in a PBL context.

The authors thank the 5th bachelor semester students in Architecture and Design at Aalborg University whose work samples are presented in this paper and for all that participated in the course evaluation surveys.

Christiane Berger: writing – original draft, collect and post processing data from case study 2, methodology, and formal analysis.

Luis Santos : writing – review and editing, collect and post processing data from case study 1, methodology, and formal analysis.

Runa T. Hellwig: writing – review and editing, supervision, and resources.

References

1. S. Turkle, Simulation and its discontents (The MIT Press, 2022)
2. J. R. Savery, Overview of problem-based learning: Definitions and distinctions, Interdiscip. J. Probl.-Based Learn., **1**(1), 5-15 (2006) https://doi.org/10.7771/1541-5015.1002
3. M. Savin-Baden, Using Problem-based learning: new constellations for the 21st century, J. Excell. Coll. Teach., **25**, 197-219 (2014)
4. M. Alcock, M. Fisher, A. Zmuda, The quest for learning - How to maximize student engagement, (Bloomington: Solution Tree, 2017)
5. V. Servant-Miklos, Problem-oriented project work and problem-based learning: "Mind the gap!", Interdiscip. J. Probl.-Based Learn., **14**(1) (2020) https://doi.org/10.14434/ijpbl.v14i1.28596
6. C. Zhou, A. Kolmos, J. D. Nielsen, A problem and project-based learning (PBL) approach to motivate group creativity in engineering education, International J. Eng. Education, **28**(1), 3 (2012)
7. N. Fang, Improving engineering students' technical and professional skills through project-based active and collaborative learning, International J. Eng. Education, vol. **28**(1), 26-36 (2012).
8. C. F. Reinhart, T. Dogan, D. Ibarra, H. W. Samuelson, Learning by playing – teaching energy simulation as a game, J. Build. Perform. Simul., **5**(6), 359–368 (2012) https://doi.org/10.1080/19401493.2011.619668
9. S. Delbin, V. G. Da Silva, D. C. C. K. Kowaltowski, L. C. Labaki, Implementing building energy simulation into the design process: a teaching experience in Brazil, in Proceedings of PLEA 2006, 755-760, September (2006)
10. C. Hopfe, V. Soebarto, D. Crawley, R. Rawal, Understanding the differences of integrating building performance simulation in the architectural education system, in Building Simulation 2017, 15, 1249-1256 (2017) https://doi.org/10.26868/25222708.2017.319
11. C. Berger, A. Mahdavi, Integrating building physics and performance simulation in architectural curricula - A collaborative effort, in Building Simulation 2019, **16**, 1595-1600 (2019) https://doi.org/10.26868/25222708.2019.210117
12. P. Freudenberg, D. Weiss, B. Funcke, Gebäudesimulation und bim in der architektenausbildung an der TU Dresden – Serie: gebäudesimulation und berechnungstools in der lehre, Bauphysik, **44**(6), 344–350 (2022) https://doi.org/10.1002/bapi.202200028
13. A. Wagner, I. M. Rodriguez, L. Alanis, P. Mann, R. Rissetto, Rechnerbasierte planungswerkzeuge an der professur building science & technology am Karlsruher Institut für Technologie (KIT) – Serie: Gebäudesimulation und berechnungstools in der lehre, Bauphysik, **45**(4), 220–224 (2023) https://doi.org/10.1002/bapi.202300009
14. A. Maas, M. Vukadinovic, S. Klauß, Einsatz von softwaretools am fg bauphysik der universität kassel mit exemplarischen aufgaben – Serie: Gebäudesimulation und berechnungstools in der lehre, Bauphysik, **44**(4), 230–233 (2022) https://doi.org/10.1002/bapi.202200020

15. I. K. Rizaoglu, K. Voss, building performance simulation to stimulate architectural early design, in Proceedings of PLEA Conference 2020, 1525-1530, September 1-3 (2020) https://doi.org/10.17979/spudc.9788497497947
16. D. Teli, R.T. Hellwig, M. Schweiker, J.-H. Choi, M.C.J. Lee, R. Mora, R. Rawal, Z. Wang, F. Al-Atrash, Teaching the concept of adaptive thermal comfort in building design education, in Proceedings 16th Indoor Air 2020, ABS-0556 (2020)
17. B. Bloom, M. Englehart, E. Furst, W. Hill, D. Krathwohl, Taxonomy of educational objectives: The classification of educational goals. Handbook I: Cognitive domain (Longman, New York, 1956)
18. Autodesk, Autodesk Forma, Online (2023) https://www.autodesk.com/company/autodesk-platform/aec