Building Performance Simulation in Design Education: Design-Integrated versus additive Use

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Abstract

In the light of an extensive literature research and the *Building Performance Simulation (BPS) in teaching* survey, conducted among German universities, it is deduced that using BPS as a part of design process rather than an evaluation tool for existing designs is a prominent way to teach BPS, particularly in architectural education. New methods are needed to adopt BPS not only as a performance evaluator, but also as a design stimulator during design exploration. This paper shares teaching experiences gained through architectural design courses by comparing the *additive* and the *design-integrated uses* of BPS.

Introduction

Utilizing design and BPS tools in tandem can be an important pillar for supporting efficiency, variety and flexibility of the design process. Most architects meet BPS during their education, and the experiences gained throughout play a significant role in terms of adoption of BPS tools in their future works. However, BPS is often an additive in design education rather than an inherent part, therefore new methods are needed to provide design-integrated use experiences.

In an earlier paper (Kalpkirmaz-Rizaoglu, et al., 2020) authors shared an extensive literature review regarding pros and cons of early integration of BPS in architectural design, as well as the results of the BPS in Teaching survey, which aimed to find out how BPS is taught especially in high education in Germany. It is conducted by the participation of 18 lecturers from 13 different universities, who have been using BPS tools for teaching in architecture and civil engineering education. Most mentioned reason for choosing a specific BPS tool in teaching was ease-of-use. Another highlight from the survey was that CAD tools rated as most used design and documentation tools by 72% of the respondents, while Building Information Modeling (BIM) was the least preferred with 8%. Another important finding of the survey is that 76% of the courses are independent courses and 12% are part of a design studio, while the remaining 12% are a separate course, but support the design course.

The literature review over the topic corresponds with the survey results and emphasize the ease-of-use. While some claims that BPS is not very common in undergraduate level courses due to the students' lack of knowledge on building physics (Soebarto, 2005; Fernandez-Antolin, et al., 2020) Some others claim that available BPS tools are too advanced for beginners (Delbin, et al., 2006). One author (Augenbroe, 2011) says that: "*In many cases simulation only needs to be adequate for comparative analysis of design variants.*". Others (Hensen, et al., 2011) signify that although design parameters have to be considered in an integrated manner, different design stages focus on different parameters. A gradual interaction with BPS promotes confidence among students and allows them to move independently to more specific tools at later stages (Fernandez-Antolin, et al., 2020). In early design, BPS is used for detecting and ranking the key parameters and gaining an insight for a possible future performance of a building (Hopfe, et al., 2005). Further, it is important to gain an awareness regarding consequences of decisions and a critical understanding of limitations inherent in BPS tools (Beausoleil-Morrison, et al., 2016).

A need of a stronger link between design and BPS tools was another most mentioned issue in the literature. Regarding the early design phase, it is found out that 3D CAD modeling environments are more prevalent than BIM environments (Soebarto, et al., 2015). Due to required high level of detail and complexity of BIM, architects are more likely start their design works in CAD. Also, according to the result of one international survey, CAD tools were the most used design and documentation tools by architects with 80%, while BIM tools with less than 30%. (Hopfe, et al., 2017). Also, it is stated (Attia, et al., 2011; Fernandez-Antolin, et al., 2020) that architecture students generally tend to prefer the BPS tools providing visual representation instead of numeric representation.

Regarding the interdisciplinary approach, another study (Fernandez-Antolin, et al., 2020) states that: "*Energy simulation and architectural design have traditionally been considered as separate elements in the design process.*". The aforementioned international survey reveals that the percentage of the mentioned courses that BPS is taught as a part of design studio was only 8% (Hopfe, et al., 2017).

In response, this paper presents methods, which are developed and tested through design courses in an architecture master program, for integrating BPS in architectural design workflows.

Experiences gained through Architecture Master Courses

Studio - *Sustainable Building and Building Performance (S.NB)* is a 2-semester-long master design course as part 1 and part 2 with a total of 12 credits. And the part 2 is directly addressing BPS.

In this paper, the experiences gained at part 2 through two separate winter semesters are shared. Not to be repetitive, S.NB-2 in winter semester (WS) 2020/2021 is called *Studio A*, and S.NB-2 in WS 2021/2022 is called *Studio B*.

Introduction to courses

Structure of the master program supports students with two preceding courses as a base for the studio. Although these are not prerequisite for the studio, students are advised and guided in that order. One of them (NB.1) is about improving the energy performance to an annually net energy positive building, while maintaining architectural quality, via well-known residential case-studies from the classical-modern style. The other one (NB.2) is about simplified indoor climate simulations and real site measurements by comparison of confidence intervals. Therefore, it can be said that students come to the studio with a certain level of BPS knowledge and a skill of critical thinking. Further, BPS can accompany the integrated design course (E5) and the master thesis (MA) based on the content and student's preference. The courses in master program that BPS is addressed can be seen in Figure 1.

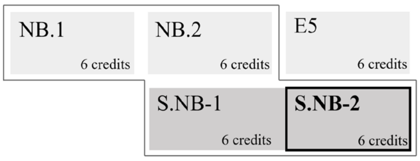

Figure 1: The courses that BPS is addressed.

In Studio A, students investigated performance of their designs, which they created in S.NB-1, by using BPS tools integrated to design tools. Differently, in Studio B, students started from scratch for a new design. In Studio B, the same design and BPS tools were used, as well as other design and simulation technics; i.e. parametrization, optimization.

Main performance tasks of the both courses were the same: climate and site integration, solar energy utilization, daylight availability and achieving indoor thermal comfort while minimizing active heating and cooling.

A design upgrade for an overall performance was requested as a final work of Studio A, and only a design proposal for Studio B. Final submission and the study structure, i.e. individual and group works, were decided considering the semester duration, the work load and the level of collaborations between students.

While Studio A phases were structured based on performance tasks, Studio B phases by the methods applied. Moreover, in Studio B, students are grouped for locations with different climate patterns and started their investigations considering both present and future climate scenarios of assigned locations for the same design task.

Methods

Speaking of the teaching methods, student-centered approach was adopted. Both students and the lecturers played an active role throughout workshops and supervision. Students' learning has been continuously measured via comprehension questions and assignments. Booklets and exhibition posters were aimed as final outputs to highlight the key topics and have a clear picture of intended learning outcomes. To balance the theory and the hands-on-sessions, lectures were held only to give theoretical information, when needed. Instead of long lectures, case-studies were used as warm-up sessions before the main tasks. Case-studies served to refresh the students' knowledge and introduce them new BPS tool and simplified approaches of the course. Also, discussions on default settings of simulations, as well as simplified methods were made throughout these sessions. It is thought to be useful for students to be cognizant of the pros and cons, and be able to decide when and how to use that default and /or simplified approaches.

Based-on the experiences gained in Studio A, more time was invested in workshops in Studio B, in order to promote learning-by-doing (Fig. 2).

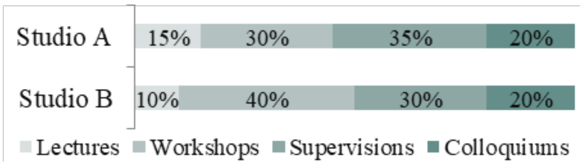

Figure 2: Time percentage spent for activities of each studio throughout a 14 week-long semester

In the context of this paper, while *additive-use* refers to using BPS only for performance evaluation for advanced or completed designs, mostly via BPS tools not integrated to architectural design ecosystem, *design-integrated use* refers to adopting BPS in design process as earliest as possible, not only for performance evaluation, but also as informer and stimulator, and utilizing BPS tools that is integrated with design tools. In this regard, for the students evaluated already existing designs, although they used a BPS tool, which is available in their design ecosystem, Studio A can be considered as *semi-additive*. On the other hand, the Studio B students started using BPS tool during their early form investigations, therefore Studio B was *design-integrated*. Examples of solar energy utilization investigations by using solar radiation analysis from Studio A and B can be seen in Figure 3. While in

Studio A, only slight revisions were possible for the fractions of existing building; in Studio B, massing studies were accompanied by solar radiation analysis.

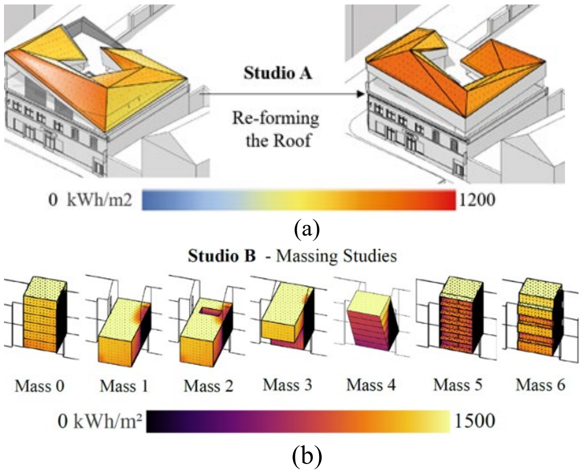

Figure 3: Solar radiation examples from the Studios. (a) existing roof design upgrade from Studio A and (b) massing studies from Studio B.

While the Studio A students were asked to consider all geometric and non-geometric properties of the existing designs for first BPSs, the Studio B students started their investigations by considering only geometric properties, and other required simulation inputs were provided by custom templates for a start. It is observed that the Studio A students had difficulties to comprehend BPS inputs for they had to cope with all inputs at once. The amount of simulation inputs was likely to be overwhelming. For early design phase focuses on investigation of possible form alternatives, rather than the optical and thermo-physical properties of a design, including BPS in this phase seems to be advantageous in attracting the attention of students and enabling an easy get-in BPS.

In both studios, step-by-step approach, i.e. one parameter at-a-time, was adopted. This was useful for students to see the individual effect of each parameter on a performance task. Later, combinations of selected parameters were also tested. It was possible to encourage the Studio B students to try more extreme variations, especially regarding geometric parameters, to enable them to see the effect of a specific parameter clearly. Investigating the limit values of geometric properties was also likely to bring new design ideas in process. This was not the case in Studio A, due to the already decided forms; only small revisions were possible. Moreover, the students were likely to be reluctant to apply even these small revisions, for they were already highly coalesced with their designs.

Tools in architects' ecosystem

ClimateStudio (CS) [V.1.6.8] (Solemma, 2019), which is a BPS plugin with educational free license for Rhinoceros3D CAD software [V.6] (McNeel, 2010), was used in both studios. CS was preferred, for it is integrated in the design tool, as well as built on the validated simulation engines EnergyPlus and Radiance. CS uses Rhinoceros3D's interface and also provides additional visually rich graphical user interface (GUI) for simulation inputs and results. CS is also available in Grasshopper (CS for Rhino), which is a graphical algorithm editor in Rhinoceros, and enables coupling number of tools; in the context of the studios, for modeling, parametrization, simulation and optimization. Model-based optimization tool Opossum (Wortmann, 2017) [V.2.2.4], which is a – free plugin for Grasshopper, was used for multi objective optimization (MOO). This machine learning-related optimization strategy was selected, because it is appropriate for time-intensive performance simulations. While parametric modeling allows fast and flexible generation of design alternatives, model-based optimization supports finding well-performing variants, based on defined performance goals. In Studio A, only *CS for Rhino* was used; in Studio B, both *CS for Rhino* and *CS for GH* were used. For the Studio B students developed their models parametrically from scratch, it was possible to extend the investigations from Rhino to GH environment. Moreover, working in GH environment enabled using the optimization solver in workflows of Studio B (see Fig. 4).

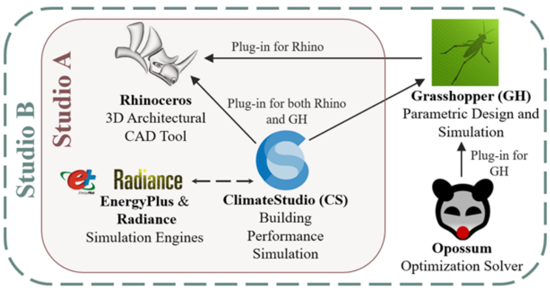

Figure 4: Tools and Workflows of the Studios

Previous knowledge of the tools was not a prerequisite for the studios. Most of the students were already familiar with Rhino, but not with the GH, CS and Opossum. Therefore, required training was provided via case-studies and workshops.

Simplifications of BPS for teaching

In early design investigations, less complex and less time-intensive design integrated methods and tools of BPS have a significant potential to be adopted by larger number of architects, because early design seeks detection and quick evaluation of possible design alternatives in relatively short time and with relatively less input (Kalpkirmaz-Rizaoglu, et al., 2020). In addition, considering beginners, adopting simplified methods integrated to design workflows seems to be promising way to enable easy and attractive start. Besides developing knowledge of building physics and BPS skills, one of the important aims of teaching BPS might be to show students how important their role is as future architects for the indoor comfort and the sustainability of the built environment, as well as how important a leverage can be using BPS tools.

Simplifications applied in the studios can be grouped as technical and theoretical. Theory related simplification only applied in Studio B. Regarding the technical simplifications, in both studios, custom templates were prepared. After first run of simulations, students were assisted to figure out the most significant parameters in the context of their designs, and detailed inputs were introduced in the later steps. Also, in Studio B, a range of types for each construction element were prepared, and students were enabled to test different types by simply selecting them via dropdown menus. For example, instead of asking students to find the most appropriate specific heat capacity of an exterior wall for a design condition, a range of walls, i.e. light, medium and heavy, are provided to simplify the early investigations. Custom schedules for occupancy, lighting and equipment and ventilation by residential and non-residential options were also provided. During parametric design and simulation, students started with example workflows, which are tailored for the studio by lecturers. In the further steps, students were asked to adapt these workflows to their works.

Active solar energy utilization

First simplification regarding the theory applied for active solar energy utilization. Differently from Studio A, solar radiation analyses are integrated to massing studies in studio B. Students searched the most promising forms in terms of maximizing suitable surfaces for active solar energy utilization. Additionally, instead of directly getting in detailed photovoltaic (PV) calculations, students were asked to run annual solar radiation simulation and shadow analysis for detecting the building surfaces with high potential for PV installation with provided specifications; e.g. panel dimensions, panel and inverter efficiency. Later, students were asked to calculate a *solar production to energy load* by using an energy use intensity of a case study. This task aimed to give an insight about the potential of renewables by simply comparing potential of energy generation and load.

Daylight availability

The massing studies were also coupled by daylight availability analyses to draw the students' attention to the possible relations between the form and daylight performance. Metrics, which are spatial daylight autonomy (sDA) and useful daylight illuminance (UDI), selected for daylight analysis. This preference was quite useful to show the students high level of daylight availability does not necessarily leads to high level of visual comfort.

Thermal comfort

Another simplification was applied for thermal comfort. The inspiration was gained from *Building 2226* - low-tech of Baumslager & Eberle in Lustenau, Austria - which was the case study of the first phase of Studio B. It is noticed that the thermal comfort concept of the building, which is defined in a range of temperatures was easy to comprehend for students. Therefore, similar approach was adopted for the Studio. Percentage of *heating*, *cooling* and *neutral hours* were used as an indicator of thermal comfort performance. Hours equal to and between 20°C and 26 °C of operative temperature (Top) were considered as "neutral hours", which refers to the capacity of a building to run without active heating and cooling. *Neutral hours* is more of a simplified approach to give students an insight about thermal comfort rather than a definitive method of a building's cooling and heating demand.

Integration of intelligent methods

In Studio B, parametrization and optimization methods were adopted after a certain level of knowledge was assured to make the investigation more attractive and less time consuming, as well as the investigation space larger. In the second phase of Studio B students were introduced parametric modeling and simulation. In this phase, performance investigations were made manually. Combinations of geometric and non-geometric parameters are tested separately for each performance task to detect the key parameters and their optimum variations. An example parametric investigation for daylight availability can be seen below (Fig. 5).

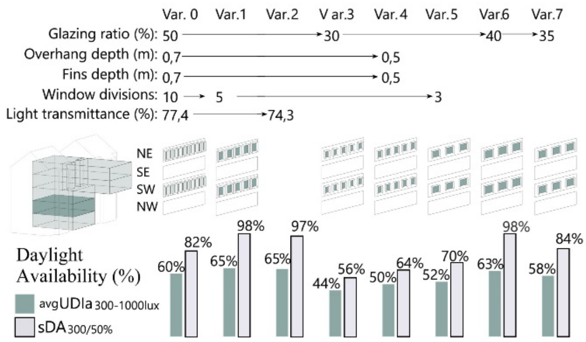

Figure 5: Parametric investigations in Studio B.

In the phase 3, students were requested to come up with specific problems for their designs. They defined the parameters to further investigate the designs for the selected performance goals, and they were ready to get in optimization (Fig. 6). After an introduction lecture and a workshop about the optimization theory and the tool, students were supported to create their own parametric geometries and optimization workflows connected to simulation workflows.

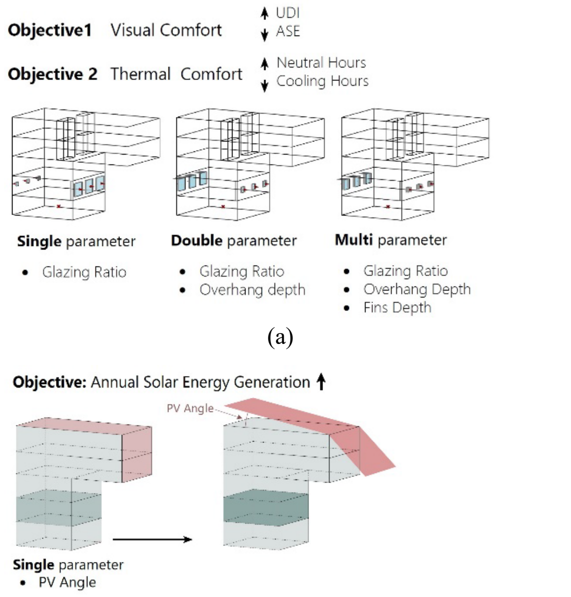

Figure 6: Example optimization sketches in Studio B: Façade (a) and PV angle (b) optimizations.

Evaluation surveys – capturing students' views

Anonymous studio evaluation surveys were conducted to capture the students' views about the studio experiences by the end of each course. Each survey had 8 respondents. A rating range is given between 0 (low) and 4 (high) points, and the results are presented as weighted arithmetic means.

It is asked that how useful did they find the studio activities. While the mean in Studio A was 2,3; in Studio B it was 3,25. Detailed ratings for studio activities can be seen in Figure 7.

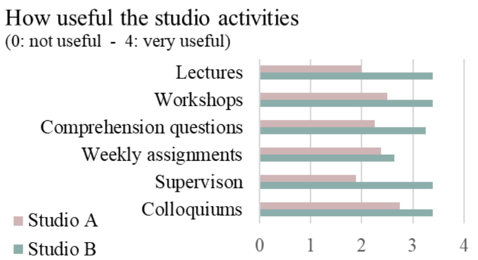

Figure 7: Rating for the studio activities.

Both studios selected *thermal comfort* as the most difficult topic. The most prominent reason given by students was that although they could directly use their 3D model for other simulations, for thermal comfort they had to create a thermal zone model, and this was difficult. When students are requested to compare their expectation to the simulation results, vast majority pointed out that *the whole investigation showed them something new, but not much different than their expectations*. Possible reasons for this result might be that students had already a good level of knowledge or / and results were likely predictable for the design cases.

Several questions were asked about the BPS tool CS (Fig. 8). Both studios students found the tool easy-to-get-in (2,8) and the simulation time acceptable (2,6). While the Studio A students were likely to be neutral about the ease-of-use, Studio B students agreed that it was easy to use. The difference can be interpreted based on the amount of inputs to be defined at once in each studio. It is asked if they have found the integration of BPS and design tools attractive. The Studio A students almost fully agreed (3,5) and the Studio B students almost agreed (2,88). The lower rating of Studio B might be resulted from extending the CS workflows from Rhino to GH, which has less user-friendly GUI, as well as lack of previous knowledge of GH.

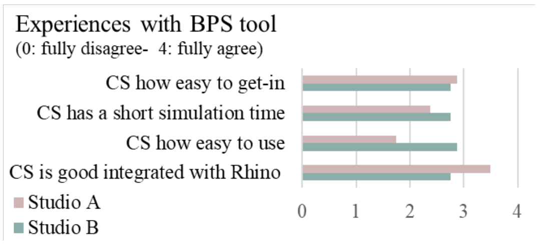

Figure 8: Feedback for the BPS tool.

The students were asked *the level of improvement regarding their skills and self-confidence for using a BPS Tool by the completion of the studio*. While the Studio A students answered the question between medium and high (2,5), Studio B students indicated a level as very high (3,88).

Only half of the Studio A students and all studio B students, except for one, indicated that they plan to use BPS in their future studies. Reasons for not considering the use of BPS were feeling mentally limited during design, overwhelming amount of simulation inputs, time intensive simulation process and not having concrete plans for the master thesis yet.

Main findings

Adoption of BPS tools within design ecosystem at the earliest stage possible, structuring a course by gradually increasing level, starting by more geometry related inputs, appropriate simplifications for a design phase, hands-on-session, intensive supervision and utilization of intelligent technics were found as the highlights of the research in terms of integrating BPS in a design process. When the learning objectives of the courses were reviewed at the end, it is seen that outcomes highly achieved the goals of the studios. On the other hand, especially in Studio B, although students were quite satisfied with the course in general, when they were asked their opinions about possible revisions, the common request was decreasing the workload. This might be due to the high number of performance tasks, and the tools they had to learn and apply in one semester.

One limitation of applying BPS in early design was the uncertainties regarding the simulation inputs. Yet, for it was an early phase, custom templates and pre-defined workflows were helpful as plausible solutions.

After students were introduced to BPS with simplified workflows, they were more likely to move towards detailed investigations in further steps. Theoretical simplifications were helpful for students to gain insight into performance at the early steps, as long as they were accompanied by critical thinking. For instance, regarding the *thermal comfort simplification*, it was important to consider the risk of the accumulation of *cooling* or *heating hours* just behind the boundaries of limit temperatures that define *the neutral hours;* and to check the operative temperature curve graphics.

Including the parametric design and simulation techniques increased the flexibility, and encouraged the students to test more design variables, for it was much easier to change the design geometry and other simulation inputs. But for some, geometry related predefined parametric workflows appeared as a limitation for design aesthetics. By the integration of optimization solver, the performance investigation process was extremely sped up. On the other hand, it is seen that before using optimization techniques, students need to go through manual investigations to recognize key parameters and optimization goals.

Acknowledging the necessity of simplifications for early learners and/or early design phase, it is important to guide students to understand pros and cons of these simplifications through critical thinking, for them to be able to decide when to use these simplifications and when to turn to more advanced methods and tools.

Conclusion

This paper presented an example for integrating BPS within the design course by sharing the pros and cons of the developed simplification methods. Outcome of the study shows that interdisciplinary and simplified methods supported by intelligent design and simulation techniques within architects' design ecosystem have a high potential to achieve integration of BPS in architectural education.

A future international survey with broader population is planned, as well as collaborations with other chairs in order to structure new courses, in which design, BPS and computational techniques are smoothly integrated, providing a comfortable and adequate learning process; e.g. two-semester-long courses.

Acknowledgement

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References

Attia, S., De Herde, A. 2011. Early design simulation tools for net zero energy buildings: A comparison of ten tools, 12th IBPSA Conf. Proc. Build. Simu.

Augenbroe, G. 2011. The role of the simulation in performance-based building / Building simulation for design and operation, ed. Hensen, J., Lamberts, R. London, Spon.

Beausoleil-Morrison, I., Hopfe C. 2016 Developing and testing a new course for teaching the fundamentals of building performance simulation, eSIM 2016, Hamilton.

Delbin S. [et al.] 2006. Implementing building energy simulation into the design process: A teaching experience in Brazil, 23rd Int. PLEA Conf. Pro. Geneva.

Fernandez-Antolin, M.M. [et al.] 2020. The Relationship between the use of building performance simulation tools by recent graduate architects and the deficiencies in architectural education, Energies, Vol. 13. - p. 1134.

Hensen J., Lamberts, R. 2011. Building performance simulation for design and operation. London, Spon.

Hopfe, C. [et al.] 2005. Exploration of using building performance simulation tools for conceptual building design, IBPSA-NVL Conf. Pro. Delft.

Hopfe Christina J. [et al.] 2017.Understanding the differences of integrating building performance simulation in the architectural education system, 15th IBPSA Conf. Pro., p. 1249

Kalpkirmaz-Rizaoglu, I., Voss, K. 2020. Building performance simulation to stimulate architectural early design, 35th PLEA Conf. Pro.Coruña, p. 1525.

McNeel R., [et al.] 2010. Rhino3D Version 6.0. Seattle : Robert McNeel & amp Associates, WA.

Soebarto, V. [et al.] 2015. Capturing the views of architects about building performance simulation to be used during design processes, 14th Int. IBPSA Conf. Pro.

Soebarto, V. 2005. Teaching an energy simulation program in an architecture school: Lessons learned, 9th Int. IBPSA Conf. Pro. Montréal p. 1147.

Solemma. 2019. ClimateStudio. [https://www.solemma.com/climatestudio]

Wortmann, T. 2017. Opossum: Introducing and evaluating a model-based optimization tool for Grasshopper.