Abstract
The development of BPS tools for practice is often based on assumptions or wrong interpretations of what architects need, think, and do when they design buildings. This paper reports on the use of co-creation workshops between researchers and building design practitioners to enable simulation-based support for a design activity called “Organising 2D layout”. The result was the first version of a useful tool where architects easily can get a visualisation of the overheating risk and useful daylight illuminance directly in their 2D layout sketches in RhinoCeros. More generally, the paper illustrates that a co-creation process seems to be a key to the successful implementation of BPS in design practice.

Key Innovations
- Enabling the use of BPS in the design activity “Organising 2D layout”.
- Highly automated simulation procedure.
- Evidence that co-creation is a key to better integration of BPS in design practice.

Practical Implications
Building designers can now – with a few additional inputs to their 2D layout sketches – get a simulation-based assessment of overheating risk and useful daylight illuminance in multi-story residential apartment buildings.

Introduction
Designing buildings that provide thermal comfort, good indoor air quality, and good daylight conditions while fulfilling legislative requirements for energy performance is a critical task for building designers that need to be integrated into the decision-making process of the early design stage. The use of integrated thermal and daylight simulation tools for virtual performance evaluation of design proposals is ideal for this. The literature review in the paper by Purup and Petersen (2020a) identified and discussed many research-based efforts that seek to enhance the efficient use of such tools in the early design stage. They found that the predominant research approach is to propose workflows or procedures for integrating the tools in design practice. However, the uptake of these proposals in design practice seems to be rare. A reason could be that the research methods are chosen by researchers often are decoupled from design practice and proposals, therefore, are based on assumptions of, or they interpret wrong, what architects need, think, and do when they design – a concern also raised by Bleil de Souza (2011). Furthermore, several researchers have identified various types of barriers for the uptake of BPS tools in design practice, e.g. Attia et al. (2009), Kanters et al. (2014), and Petersen et al. (2014), such as ‘Tools are too complex’, ‘Tools are too expensive’, ‘Tools are not integrated into drawing software’, ‘Tools take too much time’ and ‘Tools not integrated into workflow’. As also highlighted by Clarke and Hensen (2015), there seems to be a need for a research-based effort that investigates how to integrate the BPS tools into the actual design practice.

In another paper, Purup and Petersen (2020a) consequently proposed a research framework to pursue the notion that tools must be conformed to fit common design practices in the early design stage – not vice versa. The research framework is based on existing and well-known research methodologies and approaches and is as such an attempt to help researchers to structure, conduct, and document practice-oriented research activities in a systematic manner. -

Building performance simulation supporting typical design activities: The case of ‘Organising 2D layout’
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In another paper, Purup and Petersen (2020b) reported on the use of the aforementioned framework to investigate the research question: How can tools for indoor climate and energy performance simulation be conformed to fit architectural design practice? The authors analysed data from semi-structured interviews with practicing architects and found that the design process is different from project to project, i.e. difficult to generalise. Instead, it seems that the design process can be regarded as a project-specific or personalized sequence of generalizable design activities; a total of 31 unique design activities were identified from the interview data.

Previous studies have investigated how combined daylight and thermal simulation tools can be applied to support identified design activities. Petersen and Purup (2019) investigated to support the design activity called “Reference picture” where building designers look for pictures of already realised building designs – usually on the internet – as inspiration to their own design. They made a prototype of a façade design database with parametric models connected to combined daylight and thermal simulation tools and presented it to practicing architects who indicated that they would benefit from having access to such a database in the early design stage. Purup et al. (2020) investigated how to support a design activity called “Volume massing” in which the building

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designer manipulates the outer boundaries of new building(s) relative to the landscape/urban setting. They proposed a prototype, and an initial test indicated that it had the potential to support the design activity. The approach has various similarities to the work of Dogan and Reinhart (2013).

This paper reports on an effort to enable simulation-based support for the design activity where the building designer is manipulating the 2D layout of the building inside of an already defined outer building boundary. The design activity is called “Organising 2D layout” according to Purup and Petersen (2020b). The effort focused on providing simulation-based decision support in terms of overheating risk and annual daylight performance in multi-story residential apartment buildings.

Method

The effort was intended to be a product of a co-creation process where a group of building designers from practice joined forces with BPS researchers to come up with a solution that enables fast and reliable simulations of the consequence on energy performance and thermal indoor climate when conducting the design activity “Organising 2D layout” in a CAD tool. However, the COVID-19 situation meant that the initial co-creation setup had to be scaled down to a minimum. Instead of a group, only one architect participated in the co-creation. This particular architect was a lead architect in a studio that used “Organising 2D layout” as the main design activity when designing multi-story residential apartment buildings.

First, the researchers prototyped an interface where building designers could manipulate geometric design variables of 2D layouts, and (with a few additional user-defined inputs) simulate thermal and daylight performance using the tools ICEbear (Purup and Petersen, 2017; Petersen et al. 2018) for thermal performance and DIVA (2020) for daylight. ICEbear is a tool that expands the hourly thermal simulation method described in ISO 13790 (2008) to include performance assessment of various typical heating and cooling strategies. The method has been demonstrated to be expediently precise when compared to the outcome of more sophisticated algorithms (Jokisalo and Kurnitski, 2007; Liu et al. 2011; Michalak, 2014). Furthermore, ICEbear has an advanced model for natural ventilation (Purup and Petersen, 2016). The prototype also proposed a way of visualising the simulation results to the building designer within the interface. The researchers then invited the lead architect for a co-creation workshop. Here, the architect was first asked to tell about the current design workflow in the studio with special emphasis on their “Organising 2D layout” design activities. This was considered to be a ‘warm-up’ exercise for the next part of the interview where the researchers presented the tool prototype and asked the architect to make comments. The whole co-creation workshop was audio-recorded and notes were made to log data for how to further develop the tool. Next, the researchers analysed the comments provided by the architect and made changes to the tool accordingly. The revised tool was presented to the architect at a second co-creation workshop where yet another round of comments was recorded and used for developing the first version of the final product. Finally, discussion and conclusions on the whole effort are made.

Results

Prototype

The researchers used the Human UI (2020) plug-in to Grasshopper to prototype an interface to a Grasshopper model where building designers could manipulate geometric design variables of 2D layouts and window geometries of rooms in an apartment (Figure 2, top). Pushing the bottom “Run the simulation” send geometry data to ICEbear where a thermal simulation was conducted using a user-selected predefined template with all the information needed for a thermal simulation (envelope U-values, window energy data, HVAC system settings, etc.). The use of templates means that the user does not have to set up everything from scratch which often is a time-consuming process in combined daylight and thermal simulation, and it is noted that user can create their own templates, or easily access and modify the predefined template if desired. The same geometry data and a predefined light transmittance for the glazings were sent to DIVA for daylight performance simulation. The simulation output was displayed in the layout plan (Figure 2, bottom). Here, the simulation data was presented as the Useful Daylight Illuminance (UDI) in the center of the room and the overheating risk was evaluated according to the guidelines in the Danish building code (maximum 100 hours above 27 °C and maximum 25 hours above 28 °C throughout the year). Furthermore, a more detailed data visualisation including energy performance was created using the Conduit (2020) plugin for Grasshopper (Figure 3).

![Figure 1: Input interface, first prototype.](image-url)
First co-creation workshop

In the following semi-structured interview of the lead architect, it was already suspected during the initial narratives about their current design workflow of “Organising 2D layout” design activities that the prototype was in line with aspects deemed important by the lead architect but that was also fundamentally flawed on other aspects. This became even clearer in the subsequent discussion of the prototype.

The lead architect found the principle of minimal input needed for simulation and the presentation of output showing whether building code requirements were fulfilled appealing – actually essential to the practical uptake of such tools. However, the lead architect found the prototyped slider-based interface for manipulating the geometric design variables of 2D layouts and windows to be in direct conflict with the current workflow of the studio; here, the architects are used to just make and manipulate simple 2D geometries in a Computer-Aided Design (CAD) program – in this case, Rhinoceros. The lead designer, therefore, suggested that a simulation tool should be able to use this geometry directly with no (or very little) additional effort from the architects.

Furthermore, the lead designer explained that the workflow of this design activity does not start by manipulating the geometry of rooms in an apartment but by manipulating whole apartments on a whole-building level. Consequently, the suggestion was to visualise performance simulation output at the apartment level with a simple colouring scheme and then provide more detailed information when zooming in on the single rooms of the apartments.

Regarding the simulation output, the lead designer found the detailed data in Figure 3 to be unnecessarily detailed for this stage of the building design process. Any simulation result should first be presented in a very simple manner – basically just indicating whether performance requirements are fulfilled or not. Detailed simulation results should only be provided visually if actively chosen. Furthermore, the lead designer preferred to view and access all simulation output visualisations in the Rhinoceros Viewport also to enable easy vector format export.

Finally, the lead designer proposed a tool functionality that somehow was able to automatically propose window size and geometry needed to fulfil requirements to avoid excessive time spent on manually ‘guessing’ these.

Second prototype

Based on the feedback from the first co-creation workshop, the researchers scrapped almost everything from the first prototype and created the second prototype; its principle is shown in Figure 4. This prototype was able to read the “raw” geometry drawn in Rhinoceros (Figure 4, top), and with additional inputs about the room and building height, outer wall depth, desired glass-to-facade ratio and placement in the facade, choice of systems template for ICEbear, and settings for DIVA (Figure 4, middle), it was able to automatically simulate the thermal performance of the apartments as one thermal zone, and the thermal and daylight performance of the individual rooms of the apartment. The simulation output was displayed by colouring the apartments/rooms red if requirements are not fulfilled or green if requirements are fulfilled. A text further detailing the simulation output is printed on every apartment/room.
Second co-creation workshop

The new prototype was presented to the lead architect at the second co-creation meeting. The feedback was positive. The designer liked that the prototype automated simulations for the entire apartment layout and rooms using only a few additional user inputs. The simple simulation result overview on apartment level using red/green to indicate whether performance requirements are fulfilled, the simple text providing details, and the option to analyse performance on room level were also appreciated. Overall, the lead architect found the second prototype very interesting, and could easily imagine the tool being used in their current architectural practice.

![Figure 4: Prototype 2. Top: Geometric input from Rhinoceros. Middle: Additional input needed for simulations. Bottom: Simulation output visualisation.](image)

The first version of the final product

This section describes the first version of the final product coming out of the co-creation workshops. Figure 5 illustrates the additional steps in the workflow of the “Organising 2D layout” design activity.

![Figure 5: The steps of the proposed “Organising 2D layout” workflow](image)

The geometric input from Rhinoceros must be 1) a single curve defining the outer boundary of the apartment block, 2) curves defining the outer boundary of the apartments, and 3) curves defining the outer boundary of all rooms. A Grasshopper script then automatically detects the external facades of the apartments and the rooms with an external façade (“Room selector” in Figure 5). Additional inputs are provided by the user as per Figure 4 (middle). The user-defined glass % of the façade is added to each apartment (“Apartment” in Figure 5); only simulation of overheating risk is simulated in the apartments. At room level, windows are assumed to have a floor-to-ceiling height placed center in the façade for both daylight and overheating calculations (“Room” in Figure 5).

The geometries are sent to ICEbear and DIVA for performance simulation (“Simulation” in figure 5) before results are illustrated in the layouts (“Results” in Figure 5). Figure 6 shows the simulation output visualisation on the 2D layouts for a floor in four different apartment buildings. The drawings in column 2 show whether the apartment as a single thermal zone fulfills the overheating criterion in the Danish building code (green=yes, red=no). Columns 3 and 4 show fulfillment of the overheating criterion and the custom UDI criterion, respectfully. For UDI, green is “within criterion”, Dark grey is “excessive time with too little daylight” and Light grey is “excessive time with too much daylight (glare)”. The detailed simulation output can be illustrated with text as shown in Figure 6 (bottom). The simulation time for the apartment floor in Figure 6 (top) was 6 minutes (11 apartments and 23 rooms), Figure 6 (middle) 7 minutes (15 apartments and 26 rooms), and 9 minutes (20 apartments and 40 rooms), respectively, and for Figure 6 (bottom) 23 minutes (26 apartments and 54 rooms) on a MacBook Pro A1398 2.8 GHz Core i7 16 GB ram (from mid-2014) running virtualized Windows 10. Differences in simulation time were – besides the number of simulations – especially affected by the degree of building self-shadowing and shadows from opposite buildings.

![Figure 6: Simulation output visualisation on the 2D layouts for a floor in four different apartment buildings.](image)
Figure 6: Simulation output visualisation for a floor in four different apartment buildings.

Discussion
The first version of the final product was the result of co-creation workshops involving only one building designer from practice. This is a potential limitation of the usability of the product; future validation studies should investigate whether other building designers also find the product useful.

There are some practical limitations to the current product. For example, it is currently not possible to customise the form and placement of windows in the facades, and an apartment/room cannot have more than three facades of different orientations which could be an issue for penthouse apartments or unusual façade geometries.

Another future work is to develop a tool functionality that automatically proposes window size and geometry needed to fulfil requirements to avoid excessive time spent on manually ‘guessing’ these as suggested by the building design practitioner.

Conclusion
The paper presents the current status of a product that can provide support for the common design activity "Organising 2D layout" when designing multi-story residential apartment buildings. The product was developed for Rhinoceros in a co-creation process between building performance simulation researchers and a practicing lead architect. Using the product, building designers can – with a few additional inputs to their 2D layout sketches – get a simulation of the overheating risk at apartment level, and overheating risk and useful daylight illuminance on room level. The simulation outputs are visualised directly in the Rhino model. The practicing lead building designer who participated in the co-creation expressed a desire to adopt the product in the current workflow of the design studio. The more general conclusion of the effort is that it seems possible that BPS tools can be integrated into the design activity “Organising 2D layout” in such a way that the designer finds it neither intrusive nor disruptive but rather informative and constructive. It seems that the co-creation process was key to this success, and is thus recommended that BPS researchers adopt this approach when developing BPS tools for design practice.

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References


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