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Assessing integrated workflows for multidomain simulations in the design process through a student design competition

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ABSTRACT

Building performance can be evaluated using a wide range of performance measures. To design buildings that benefit both the occupant and environment, multiple angles may be taken, based on the objectives for envelope performance, daylight performance, energy demand and generation, and occupant comfort and well-being. The challenge of considering multiple domains within the design process is evaluated in this work by means of a teaching experiment in design education, in which engineering and architecture students collaborated to participate in a student design competition. This work presents the workflows of the students for integrating multidomain considerations across the design process. The integration of a multitude of performance measures and the communication between students is analysed from students' perspectives, with questionnaires administered at the end of the design process. Findings indicate that while students faced challenges such as interoperability issues, steep learning curves, and communication gaps, they also benefited from the understanding of design-performance tradeoffs and synergies. The results are interpreted within the broader context of literature on the challenges arising from integrating multidomain simulations and facilitating trans-disciplinary communication in design workflows.

1. Introduction

The global challenge of climate change and the need for rapid decarbonization have made building performance evaluations an increasingly recognized feature in the conception of sustainable, energy-efficient architecture. The global population growth [1] adds to the environmental stress in urban areas, which are expected to increase from 56 percent in 2021 to 68 per cent in 2050 [2]. To design buildings that benefit the city, the environment, and the occupant, multiple aspects can be considered based on a wide array of performance measures, including energy performance, daylighting, and occupant comfort and well-being. When designing for climate change, integrating these building performance simulation (BPS) considerations have been shown to be vital [3]. Furthermore, de Wilde [4] emphasizes that performance analysis must encompass a wide spectrum of interrelated metrics - spanning technical,

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environmental, and human-centric aspects - each influencing the building lifecycle. His work also underscores the need for robust frameworks for quantifying performance measures, particularly in early design phases, to guide evidence-based decision making.

1.1. Potentials of multidomain performance simulations in design

A number of reviews give an overview on the application of multidisciplinary performance simulations to drive urban design [5–7]. The position paper on multi-domain simulation workflows by Bleil de Souza et al. [8] underscores the challenges of working within disciplinary silos and the critical need for integrated tools and workflows that allow practitioners to address complex, interconnected problems effectively. It emphasizes the potential for simulation to inform sustainable urban design by bridging diverse knowledge domains, fostering evidence-based solutions for challenges spanning energy, comfort, and environmental impact. Aligning with this perspective, Naboni et al. [3] demonstrated a workflow for considering and visualizing multiple performance measures, including urban energy use and production, daylighting, outdoor thermal comfort and daylighting for present and future climate scenarios. Their approach highlights the potential of evidence-based urban design to address these multifaceted challenges. Prior studies have also combined energy consumption and thermal comfort evaluations to illustrate improvements achievable through refurbishment measures on historical buildings using green walls [9]. Via simulations, an overall theoretical reduction of electricity consumption by 17,8 % and a reduction of real gas consumption by 28 % were determined, while thermal comfort indices improved significantly. Yet others were able to show the benefit of multi-domain simulations in increasing the efficiency of energy systems of urban infrastructures by exploiting synergies across different domains including gas, electricity, heat, waste, water, and wastewater [10]. Through cross-domain considerations, unused electrical potential of 179 kWh from renewables were eliminated and the import of conventional gas was reduced by 11 kWh. Focusing on trade-offs between performance criteria, prior research has demonstrated the performative differences of energy load and spatial daylight autonomy for different building design and density scenarios in urban design [11]. As a final example of prior work, researchers have explored the trade-off between urban density and energy balance and optimized building typologies for zero-energy neighborhoods [12]. Courtyard typologies specifically stood out in terms of maintaining a high floor area ratio while achieving low energy demand in climates with cold winters and hot summer. To summarize, a plethora of studies have demonstrated 1) the potential of simulations to give guidance towards performance improvements 2) the potential to exploit synergetic effects when integrating multiple domains or objectives, and 3) the challenges and approaches to finding compromises and trade-offs between different performance measures.

1.2. Challenges to the integration of BPS in practice

The early design stages can be especially impactful when designing for energy efficient buildings [13]. The integration of simulations in the design process may however be accompanied by challenges and difficulties, particularly in practice. In a study on the introduction of BPS in an architectural practice, Hobbs et al. [14] identified several obstacles, including the complexity of creating simulation models, an increased risk of liability for the practice, and a perceived increase in workload. In expert interviews [15], commonly mentioned challenges to applying building performance optimization in practice included a lack of appreciation for such techniques in the architecture, engineering, and construction (AEC) industry, the requirements for high expertise, a low trust in the results, long computation time, missing information for simulation input, interoperability issues and lack of user friendly environments for post processing and visualization. In another survey on daylighting design practice [16], respondents who did not use computer simulations cited reasons such as clients not paying for simulations, not knowing how to get started with simulations or the required training period. Participants were also asked which challenges they mostly encountered when considering daylighting in projects. Responses included time constraints during planning, budget constraints, designers' objections for aesthetic reasons, concerns about heat loss through large windows and a lack of knowledge on strategies that really work. Challenges to the integration of energy performance simulation in the design process were identified on a technological level, domain knowledge integration level, and design decision support system level by Lin and Gerber [17]. In their literature review, they highlighted interoperability issues, tools being ill-suited for early design stage support and complex geometrical exploration as technological limitations. They also identified challenges in domain knowledge integration, including the lack of expertise on performance simulation among designers and the late involvement of domain experts in the design process. Finally, simulation tools failing to provide informative context to early stage design decision making were noted as limitations of simulation tools as design decision support systems. Negendahl [18] further pointed out that a key challenge, particularly in the early design stages, was the inability to accommodate to a rapid changing design process. This included their limitations in providing valid feedback and being flexible enough for design changes.

1.3. BPS in design education

Future generations of architects and engineers need to be able to engage with these challenges. In an effort to teach students BPS basics, a combination of sessions including simulation and optimization exercises were proposed, in which a group of building services engineering students learned the impact of simulation settings and design variables (mostly related to building control [19]). The aim of the programme was not to train simulation experts, but to grow the competency of students as discussion partners for simulation experts. Similar focus was apparent in the approach of [20], where architecture students learned to grow their skills on reading energy simulations results in game-like exercises. Both studies additionally showed the value of simulations in improving simulated building performance. Another study focused on teaching BPS fundamentals and preparing students to apply BPS and BPS results effectively in practice [21]. Their approach was described with four learning models: *study theory*, *simulation exercise*, *autopsy* and *reflect and connect*.

Autopsy referred to comparing, contrasting, and collectively analysing results, including the analysis of input files and collective diagnosing of issues. *Reflect and connect* referred to reflecting on the simulation results, re-analysing results with different inputs, and connecting studied theory with experience from the *simulation* and *autopsy* exercises. A similar focus on training simulation experts was laid out in the study of [22], who presented their module programme and practical assignment for teaching students BPS fundamentals to understand the underlying principles of commercial simulation tools and apply them for problem solving. Thus, studies so far were designed for architecture or engineering students and focused on teaching the following aspects: the value of BPS to improve building performance, the basics of BPS so that students may understand simulation results and become good discussion partners for experts, and/or the fundamentals of BPS so that students may apply BPS effectively. Still, there is a lack of knowledge regarding the processes involved in interdisciplinary exchange through simulation. The reported studies also limited the number of simulation domains in terms of energy, thermal, or CFD simulations. Therefore, the objective of this study was to monitor a group of students from architecture and engineering through their first attempts in multi-domain building performance simulations to collaborate on a given design task for a group of buildings.

2. Methodology

2.1. Module design

This work assesses the challenges of considering multiple domains within the design process by means of a teaching experiment, in which MSc. students with different majors in Engineering (e.g. civil, environmental, business or sustainable energy supply) collaborated with MSc. Architecture students to participate in the REHVA Healthy Homes Design Competition 2022 [23]. The design brief required the design of a residential complex in a suburban, semi-industrial area with suboptimal outdoor air quality and noise pollution from the surrounding industry, highways, and busy waterways (Fig. 1). 10 % of the net floor area was to be designated as communal areas. The design of public hybrid spaces was encouraged, and 33 % of the site was to be dedicated to general and public use. At an urban scale, the challenge was to revitalize suburban areas and find creative solutions to promote healthy living and sustainable buildings in such heavily constrained surroundings.

To facilitate informed decision-making, we structured the collaboration such that the architecture students were responsible for the design work and conducted thermal simulations using Sim-Vicus, while the engineering students performed annual energy demand and daylighting simulations in Revit using plugins such as Revit Lighting, Revit Solar, Revit Linear, and Energy Optimization for Revit. Acting as consultants, the engineering students provided feedback on design choices and, together with the architecture students,

Fig. 1. Google maps satellite view of the site and plot of land for the design competitions.

explored possible variations based on the simulation results. The full list of software used, and simulations undertaken is given within the results section as part of the workflow specifications provided by the students. The course duration extended over a period of 4 months from mid-October (12.10.2021) to mid-February (submission date 15.02.2022 for the design studio and 01.03.2022 for the competition). The simulations were to be used to inform design decisions as shown in Fig. 2. Interim results were presented and discussed in three colloquia including the final design crits. In these colloquia, students presented their status followed by critique of the teaching staff and invited experts. As shown in Fig. 2, simulations were run in the form of a sensitivity analysis, whereby 2 to 3 variations of a parameter were to be implemented and tested for improvement or detrimental effect on different design objectives for daylighting and energy. The specified workflow was in the form of a sequential search, whereby better performing designs could be used in the next design phase and tested with different parameter variations (as opposed to simulating all combinations). The simulation results were intended not as absolute values but as indicators, prompting students to observe the trends in increases or decreases in performance resulting from modifications in design parameters. An integrated design approach was emphasized, and students were required to establish data exchange requirements and workflows between the architectural design and building performance simulation programs during the initial month of the module. Additionally, it was a module aim to prioritise constant communication between disciplines from the early design stage onward, so that design decisions at each step could be continuously informed by both the expertise of the team members and the simulation results.

2.2. Survey structure

The design work was done in groups of two architecture students collaborating with two engineering students, with the exception of one group, where only one engineering student formed a group with 2 architecture students. An online questionnaire was administered at the end of the course to assess the workflows of the students for integrating multi-domain considerations across the design process. The online questionnaire administered to the engineering students is presented in the Appendix. The questionnaire for the architecture students was analogous, with certain questions adapted to address the architectural counterpart. All 15 students of the Engineering program and 6 out of 16 students in the Architecture program participated. Two separate surveys were created for the two majors and publicized via Google Forms. Participation in the survey was anonymous, voluntary and independent of later grading.

The survey consisted of four parts (Fig. 3). The first part covered general questions related to the performed simulations and data exchange. In the second and third part, the same questions were repeated - once referring to the initial phase from October to the end of December, and once to the final phase from January to the beginning of March. The fourth part recorded a final evaluation of the overall process and the lessons learned. The questions for the engineering and architecture students varied in parts to account for their respective fields. This is highlighted where appropriate with the letter (E) or (A) for engineering and architecture students within the figure headings respectively. Where survey questions were structured as multiple-choice questions, a text field was added for the option ‘other’. The results from the analysis of survey Part I (see Fig. 3) will be presented first. This will be followed by the analysis of survey Parts II and III, which are combined to enable a comparison between the first and second halves of the design studio. Finally, results from survey Part IV will be presented alongside examples from the coursework to illustrate and contextualize the findings.

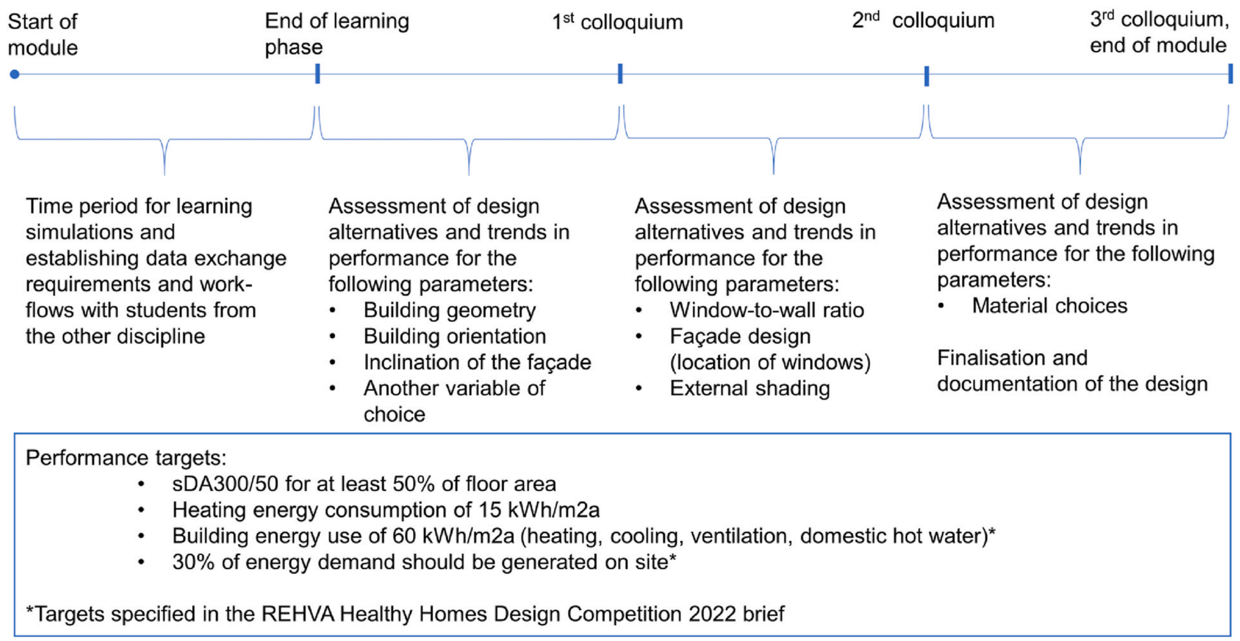

Fig. 2. Integrated simulation workflow.

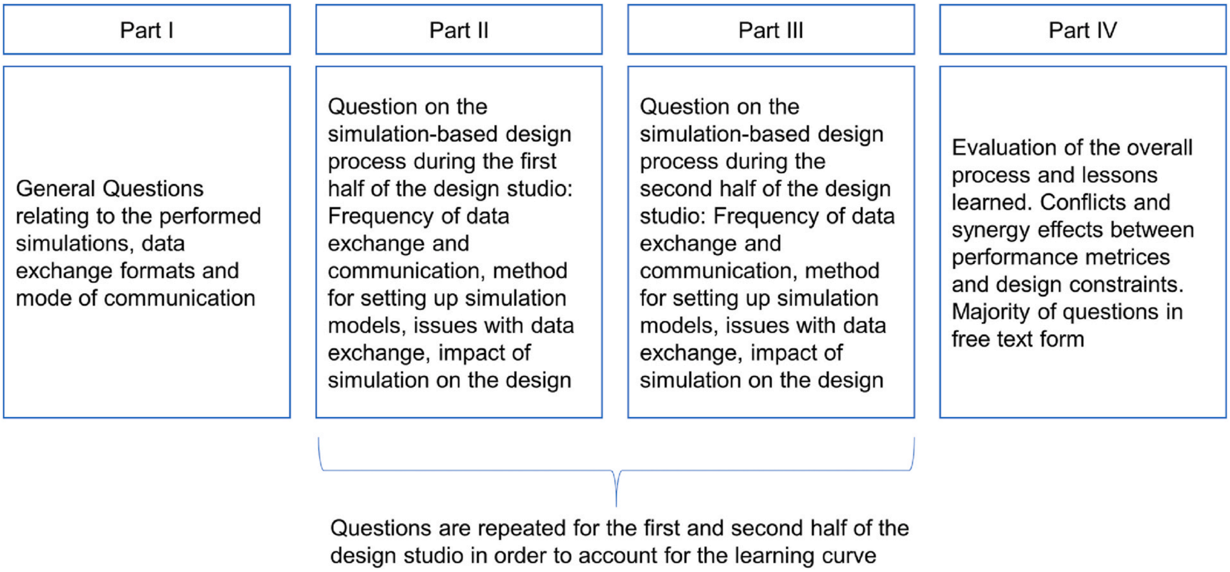

Fig. 3. Overview of survey sections and respective questions.

3. Results

3.1. General questions relating to the performed simulations, data exchange and communication

This section summarizes and evaluates the survey questions relating to the performed simulations, data exchange and communication. The architectural design by the architecture students was mainly done in ArchiCAD and/or Revit (Fig. 4). Only one group used AutoCAD for the design. The simulation tools used by the engineering and architecture students are shown in Fig. 4. Most of the engineering students performed the simulations with Revit plugins: Revit LINEAR (for heating and cooling load calculations and dimensioning of HVAC systems), Revit Solar (for solar radiation analysis and investigation of the PV potential), Revit Lighting (for daylight simulations) and Energy Optimization for Revit (for energy performance simulations). With the exception of LINEAR, these tools were also used by architecture students. However, the majority of respondents among the architecture students used SIM-VICUS (for thermal comfort simulations) as suggested by the course assignment.

Simulations were run across several disciplines to assist in design decision making. The simulations performed by the architecture and engineering student groups are displayed in Fig. 5. The majority of the engineering students performed energy simulations, followed by daylight simulations and the analysis of the PV potential. Most of the architecture students performed thermal simulations, followed by daylight simulations. Typically, there is a significant learning curve for mastering the software and performing the simulations. To better assess the additional effort required to learn to use the software, the engineering students were asked about their Revit skills (Fig. 5). Most engineering students had no prior experience using Revit. To the same extent, most of the architecture

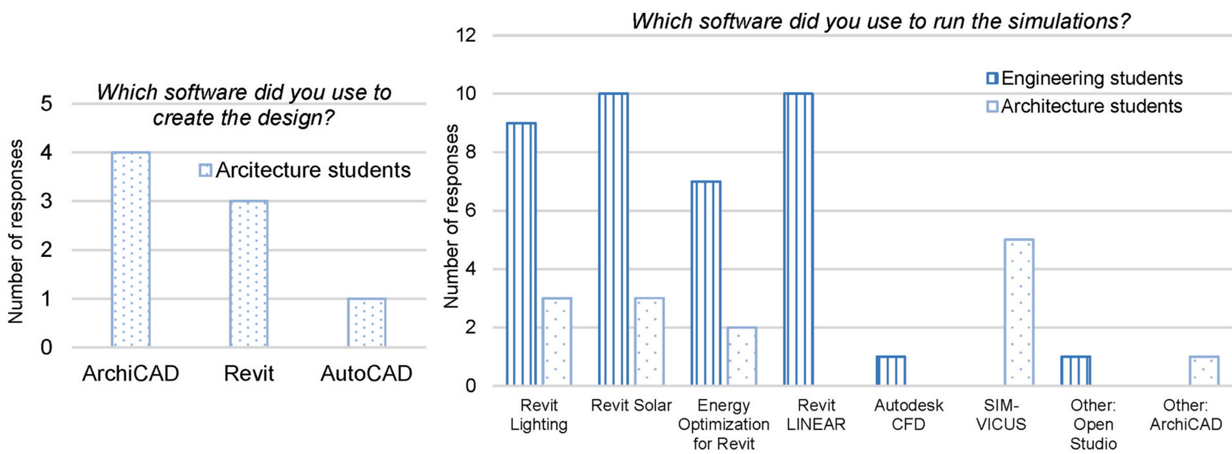

Fig. 4. Architecture software used (to the left) and simulations performed by the students (to the right).

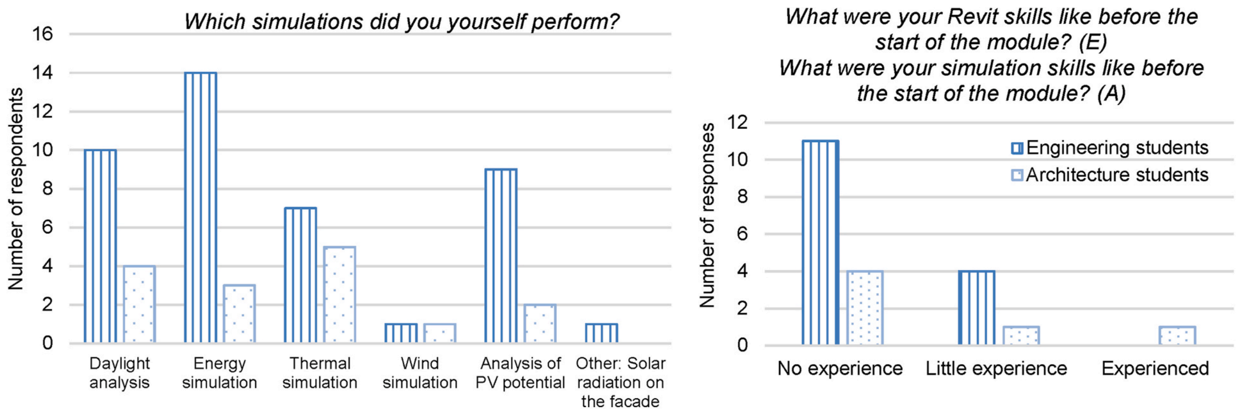

Fig. 5. Performed simulations (to the left) and prior experience (to the right).

students indicated they had no prior experience with simulations (Fig. 5). Only a few students on both sides considered themselves as having little experience or being experienced.

To assist with information management, data exchange and documentation, projects were set up for all architecture and engineering students in Autodesk Construction Cloud, a project management platform and common data environment formerly known as BIM 360 [24]. As shown in Fig. 6, the majority of students made use of this, but also opted for other cloud-based platforms, especially Sciebo, a platform for universities in the state of North-Rhine-Westphalia freely available to all students at RWTH Aachen University. As for the data exchange formats, most of the engineering students appear to have received IFC files to import the architectural model into Revit. However, DWG files and native Revit files were also exchanged. Native ArchiCAD files, which architecture students used heavily, were not exchanged.

All students participated in the module during the second winter of the Covid pandemic (Oct. 2021 to March 2022), when partial restrictions were still in place to minimize physical contact. Although a majority of design reviews were held in person, students chose their mode of interacting with each other freely. Most engineering students and all architecture students used WhatsApp for communications. Additionally, engineering and architecture students alike relied on Zoom, followed by in-person meetings.

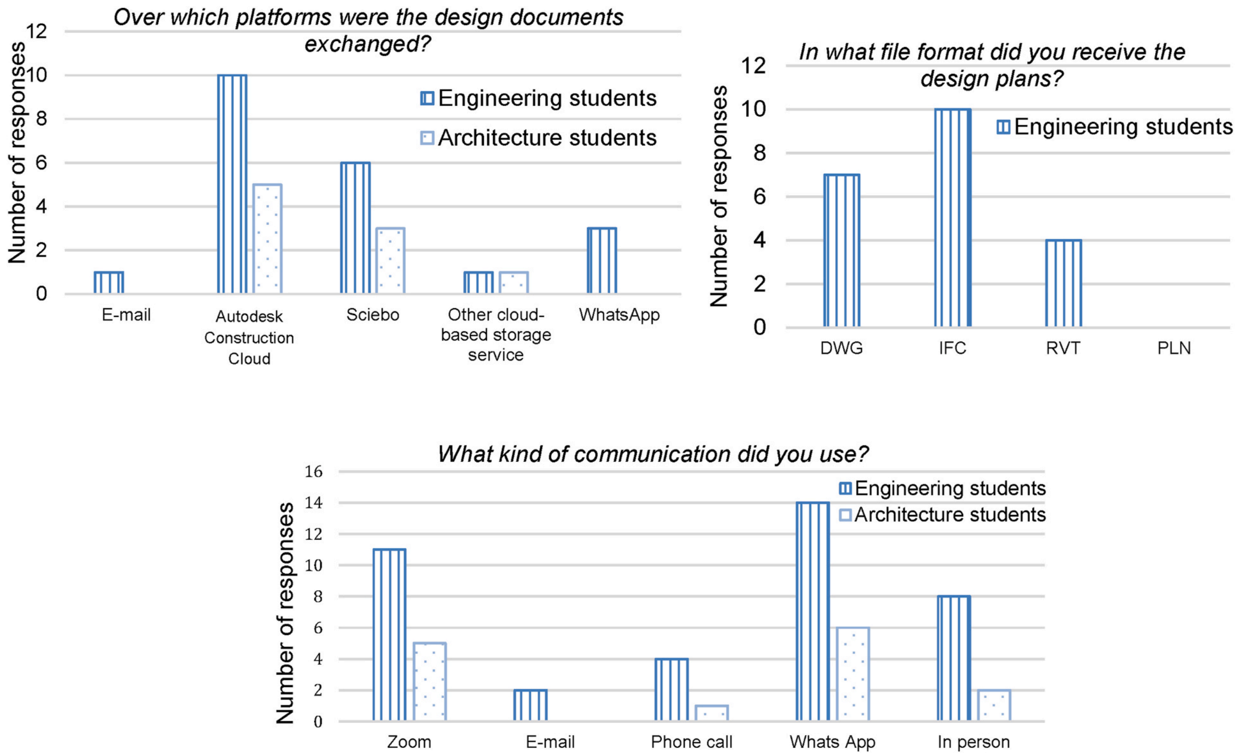

Fig. 6. Platforms used for data exchange (to the left), file exchange formats (to the right), and method of communication (to the bottom).

To run the simulations, students had to export the architectural model (mostly in ArchiCAD) and import it to another program to set up the model for simulations (mostly in Revit or SIM-VICUS). By doing so, students were faced with interoperability issues between architectural and simulation software. All student groups were therefore asked about their process for setting up and running simulations within a different environment. The majority of engineering students indicated that they had to remodel the architectural design within the simulation environment in order to perform the simulations (Fig. 7). Three of the engineering student respondents indicated they were able to use the architectural model, but had to edit it in order to set up the simulation model. Only one engineering student respondent was able to directly use the architectural model within the simulation environment. As for the architecture students, two respondents said they had to remodel the architectural design within the simulation environment, while one student reported to having partially edited the architectural model, and yet another student reported that they were able to use the architectural model directly to run simulations.

3.2. Comparison of the first (Oct–Dec) and second (Jan–Mar) half of the design studio

The second and third sections of the survey were composed of questions aimed at evaluating the design process in two periods running from October to December (referred to as the first half of the design studio) and January to March (referred to as the second half of the design studio). This was done to account for the learning curve that the students were faced with, not only to learn the required software skills, but also to establish their workflows. In the following, attitudes and approaches during the first and second period of the design studio are compared.

Both the engineering and architecture students consulted each other for the design, and the frequency varied in the two periods (Fig. 8). During the first half of the design studio, engineering and architecture students reported having communicated either once per week (the majority of engineering students and half of the architecture students), or irregularly, less than once per week. Overall, the frequency increased during the second half of the design studio, with a few respondents from both student groups now indicating that they had consulted each other two to three times per week. Two engineering students also reported having had exchanges more than thrice per week. However, the increased communication during the second half of the design studio was not reported by all students, as some engineering students still reported having consulted each other irregularly, less than once per week.

Next to the frequency of communication with each other, all students were also asked about the frequency with which models were exchanged (Fig. 9). Here, the majority of engineering students and half of architecture students reported irregular model exchanges up to once per month during the first half of the design studio, while several others reported providing/receiving the architecture model two to three times per month. Only two students from the architecture group reported providing their models to engineering students three to five times per month during the first half of the design studio. The frequency of model exchanges once again increased during the second half of the design studio, as reported by all student groups. Although several engineering students still reported receiving the architectural model irregularly, less than once per month, the majority of engineering students reported receiving them once per month, and one student reported receiving them two to three times per month. These reports differed from those given by architecture students, the majority of whom (three students) indicated they had exchanged the model two to three times per month, with one student even reporting having exchanged the model more than three times per month.

Architecture software companies often define guidelines for modelling workflows when considering exports to specific formats such as IFC, or imports for specific purposes such as energy performance modelling (e.g. see Ref. [25]). This may require additional time and effort when modelling the architectural design. Similarly, remodelling, editing or setting up a model for simulations requires time and effort. The time all students reported to have spent on this part of modelling is shown in Fig. 9. Most of the engineering students reported spending between three to five (5 students) or more than 5 h (5 students) for setting up one simulation model during the first half of the design studio. During the second half of the design studio, the number of students reporting spending more than 5 h

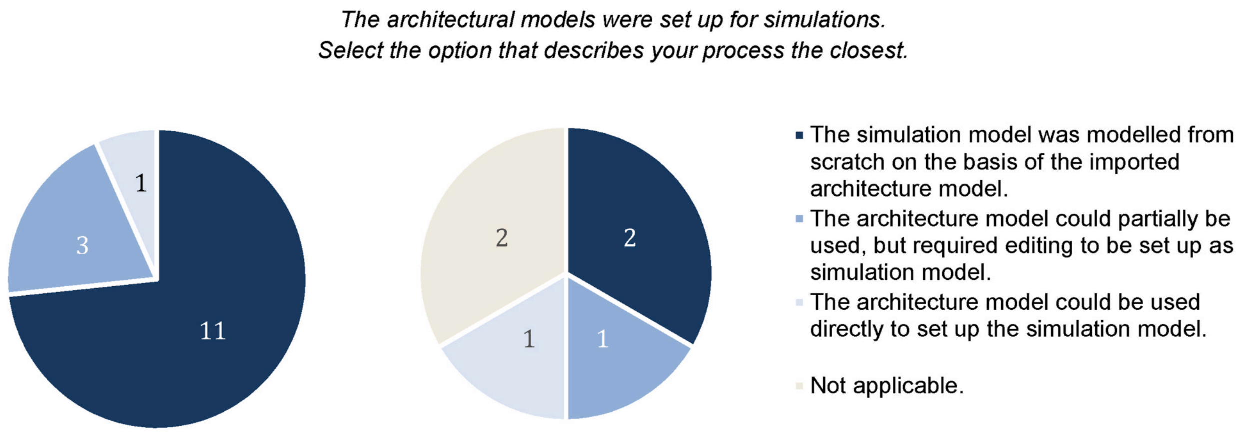

Fig. 7. Architectural model to simulation model workflow adopted by the engineering students (to the left) and the architecture students (to the right).

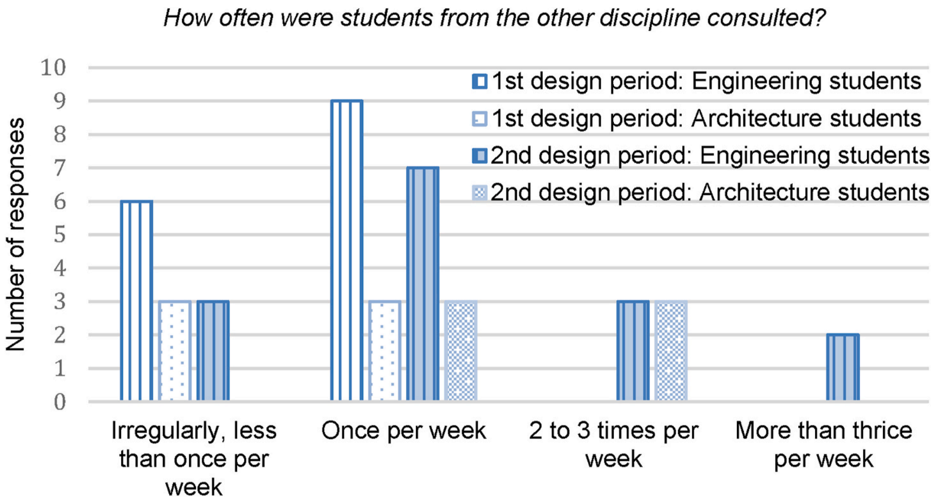

Fig. 8. Frequency of communication.

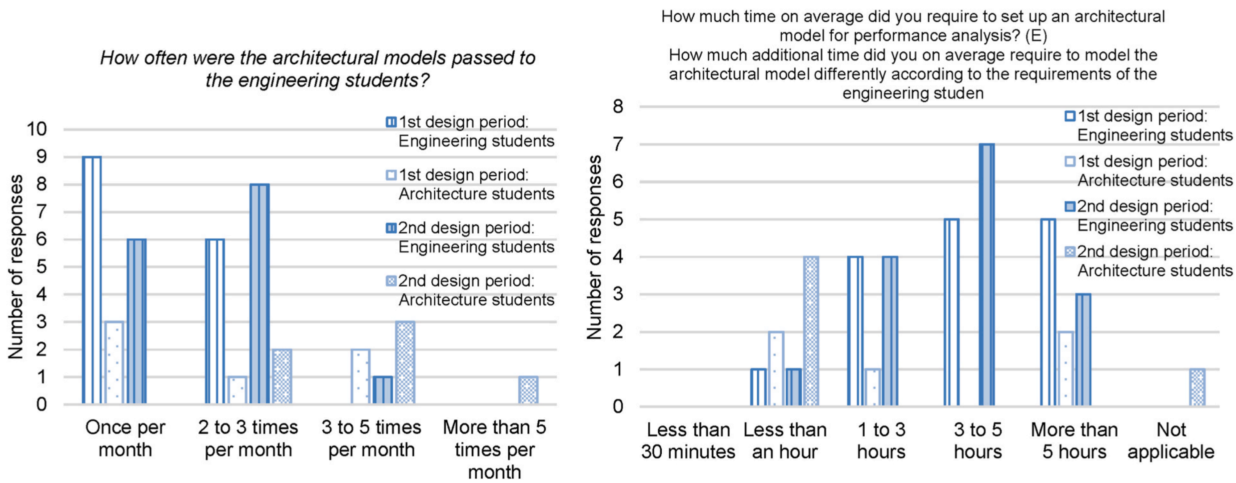

Fig. 9. Frequency of data exchange (to the left) and time spent on processing the model for simulations (to the right).

on one simulation model decreased. Responses from architecture students were mixed for the first half of the design studio, as some students reported spending less than an hour on one simulation, while others spent more than 5 h for modelling the architectural design according to requirements of the engineering students. During the second half of the design studio, this changed drastically, as the majority of architecture students indicated spending less than an hour on this part of the assignment.

All students were asked about the topics most frequently discussed during both periods (Fig. 10). For the first half of the design studio, the two most frequent topics of conversation were *issues with data exchange* and *issues with simulations* for engineering and architecture students alike (Fig. 10). Regarding *design options and design decisions*, most of the engineering students (seven students) stated that they had discussed them occasionally, while most of the architecture students (three students) chose the answer option 'rarely'. During the second half of the design studio, the most frequently discussed topics among all students were the simulation results. *Design options and design decisions* were also discussed more frequently compared to the first half of the design studio. All students also report fewer problems with data exchange, which had been the most frequently discussed topic during the first half of the design studio. Responses to the frequency of discussions about *issues with simulations* varied. Although some engineering and architecture students reported that the topic was still discussed 'often' and 'very often' during the second half of the design studio, overall, the reported frequency of the topic decreased compared to the first half of the design studio.

How often did discussions involve the following topics?

As noted, the students indicated facing issues with data exchange and simulations. In order to identify the exact content of the issues, the engineering students were asked about the most common mistakes that occurred while a) working with IFC files received from the architecture students, b) working with DWG or RVT (native Revit format) files received from the architecture students, and c) modelling, editing, and setting up the simulation model in Revit. For the second half of the design studio, students were asked to name

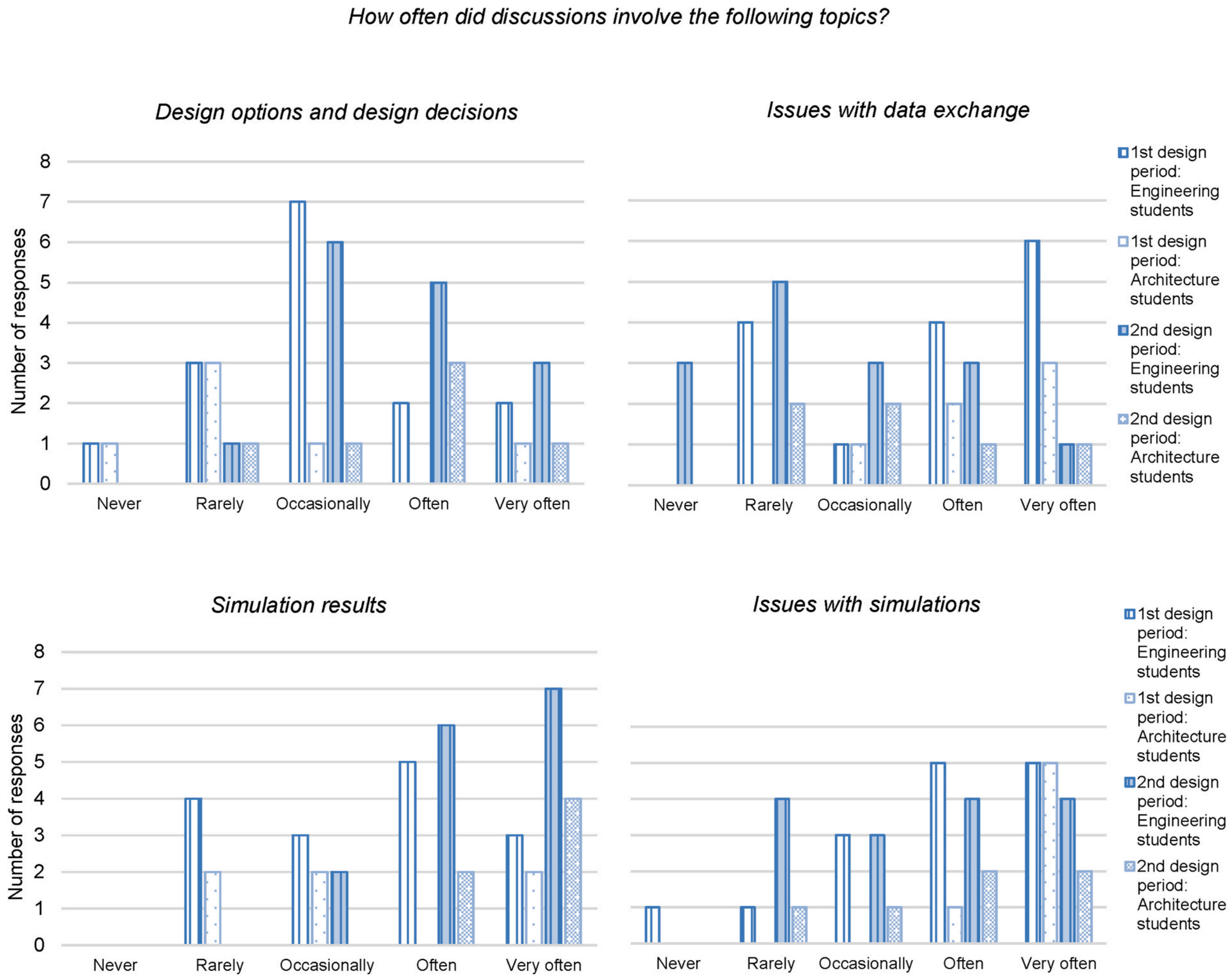

Fig. 10. Frequency of discussed topics during the first and second half of the design studio.

only the additional errors not mentioned in the first half of the design studio. Responses indicating that the question was not applicable to the workflow are excluded from the summary.

The following common errors were reported on a) working with IFC files. The number of mentions is noted in brackets, for the first and second half of the design studio, respectively.

- building components were missing (2, 2)
- rooms/zones were missing (1, 0)
- material properties could not be read (2, 1)
- imported file was not properly read in Revit (2, 0)
- imported models were exploded in the Revit environment (1, 1)
- walls were imported as curved surfaces, and energy performance simulations could therefore not be run on the model (1, 0)

In summary, the majority of errors reported by students stemmed from the incorrect modelling of IFC objects in the native software and the incorrect export or import of IFC models. Objects need to be assigned appropriate semantic definitions in order for IFC exports and imports to work. This is because objects can be purely a geometry, a building component or attributes. If the descriptors are not assigned while modelling in the native format, the information is lost during data exchange. While some generic building components may have corresponding IFC containers (e.g. generic walls may be exported as IFC-walls), other building components may require specific user action to export them. Similarly, with a wrong version of IFC specified (e.g. IFC4 or IFC2x3), or depending on export settings, the modelled objects may be incorrectly converted to IFC format. As for the import, some tools contain automatic error detection and correction for IFC import, such as the plugins for Revit. Two students reported that the problem could be resolved after installing the IFC-plugin IFC 2021 [26] in Revit. Thus, the majority of errors stemmed from manual mistakes and a lack of skills with IFC elements. The workflows could therefore be improved upon by all students: on the side of the architecture students in terms of modelling IFC objects, and the side of the engineering students, in terms of explicitly specifying required elements (e.g. ifc rooms) as well as in terms of model post-processing skills.

The following common errors were reported for b) working with DWG and RVT files during the first half of the design studio:

- building components were missing (1, 0)
- ground level was not defined (1, 0)
- rooms/zones were missing (1, 0)
- space boundaries could not be read/the building model was not an enclosed space, presumably due to gaps or overlaps between floor, wall, and ceilings (1, 0)
- imported models were exploded in the Revit environment (1, 0)

No additional errors were reported for the second half of the design studio. Similar to the errors with IFC formats, building component information went missing during export and import. When using DWG, this may be due to information loss when exporting to a non-native format, and interoperability issues between software, whereby not all modelled information can be read in a different environment. Overall, fewer errors were reported for DWG formats. This may be because a majority of student worked with IFC (Fig. 6) or because DWG files were often imported as reference models or plans to build the Revit model rather than being used for setting up the simulation model directly.

The following common errors were reported for c) modelling, editing, and setting up the simulation model in Revit. The number of errors mentioned are noted in brackets, for the first and second design half of the design studio, respectively.

- Drawing errors: the upper limit of walls was modelled incorrectly (1, 0), ceilings were forgotten (3, 0), interior walls were forgotten (1, 1), incorrect level allocation of ceilings (2, 0), mix-up of rooms/zones (0, 1),
- issues with modelling/simulating the inclined façade (3, 1)
- issues defining blinds (1, 1)
- some building components were not compatible with the simulation, e.g. material properties were read incorrectly, such that glass façades were treated as walls (1, 0)
- issues assigning appropriate ventilation zones across multiple storeys (1, 0)
- difficulty finding and assigning the intended materials from the Revit library (1, 0)
- difficulty defining rooms and MEP-rooms (1, 0)
- wrong settings for the simulations (1, 0)

The majority of reported errors may be attributed to a lack of skills in Revit as well as manual errors resulting from having to remodel the architectural design. The named difficulties in modelling hint at the learning curve for students. As for the drawing errors, being able to use the architectural model in Revit on the condition of working IFC or DWG export/imports may have saved time and effort. The steep learning curve will have strained the progress in employing workflows to more seamlessly integrate simulations into the design process. A couple of errors were related to a lack of skills and experience with the simulation plug-ins. These include applying appropriate settings for simulations, and modelling components so that they can be properly read by the simulation engine (i.

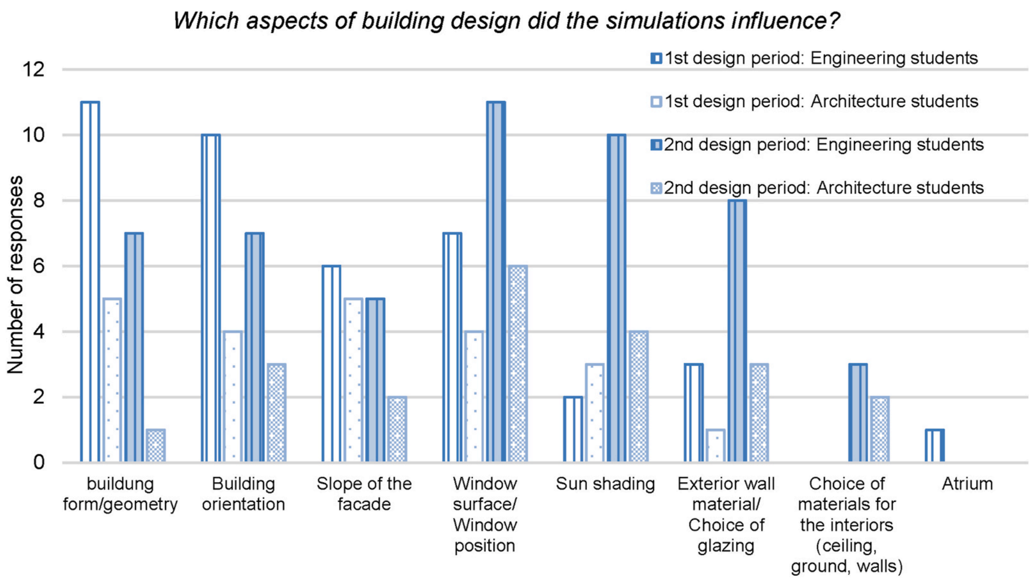

Fig. 11. Aspects of building design, that were influenced by simulations.

e. blinds, material properties and curved or inclined surfaces). Despite the challenges, students were able to run simulations on variations of the architectural building design.

All students were asked about which aspects of the design the simulation had an impact on (Fig. 11). The responses are largely in line with the setup of the module assignment, with investigations focusing on geometry, orientation and façade shape in the first half of the design studio, and on window surface area and positioning on the façade, shading design and material choices during the second half of the design studio. All students were also asked to rate the perceived influence of simulations on the design outcome on a scale of 1 (“not at all”) to 5 (“greatly”). While responses varied (Fig. 12), most responses from the engineering students indicate that the simulation results had less influence on the design outcome in the first half of the design studio, and most responses from the architecture students suggested a neutral to high influence during the first half of the design studio. During the second half of the design studio, the perceived influence of simulations on the design outcome increased for both engineering and architecture students. Most responses from the engineering students were spread between indicating a neutral or high influence on the design outcome, while the majority of architecture students indicated that the design outcome was greatly influenced by simulations. There is a notable discrepancy in responses between the two student groups, whereby the perceived influence on the design outcome was greater for the architecture students. The finding that not all engineering students felt that the simulations had an impact on the design may allude to challenges in communication on both ends. Regarding who was responsible for the design changes, perspectives varied between the engineering and architecture students during the first half of the design studio. While many engineering students considered themselves responsible for the design variations and changes, the architecture students too reported themselves to be the ones making the design changes. In the second half of the design studio, both engineering and architecture students indicated that the design changes were undertaken by the architecture students.

Finally, architecture students were asked if they had difficulties incorporating the simulation results into the design (Fig. 12). Interestingly, most responses from the architecture students indicated difficulties. The reported difficulty increased from the first to the second half of the design studio. The following reasons were given by the architecture students in free text form and are paraphrased with the number of mentions added in brackets:

- miscommunication (1)
- difficulties interpreting results (1)
- the results could only be used to validate design decisions, not to inform them, as simulation results were always handed over too late (2)
- inconsistency in the interpretation of simulation results between the initial and later design phase, assumed to be because of the learning curve on the side of the engineering students (1)

These responses confirm issues in communication between engineering and architecture students, but also a significant learning curve and time constraints. Results were either handed over too late or inconsistently due to implementing different simulation settings in the first and second half of the design studio. The degree to which simulations influenced the design is detailed in the next section.

3.3. Overall evaluation of the process and lessons learned

The last section of the survey was concerned with the integration of simulation results into the design process to inform design decisions. In the following, results are presented on challenges and benefits to multidomain simulation workflows and trade-offs between different performance measures and architectural design constraints. The engineering and architecture students were asked to name: a.) the biggest obstacles they faced to integrating simulations in the design process, b.) the biggest perceived benefits of accompanying and integrating simulations in the design process, c.) juxtaposing performance metrics, where increasing one

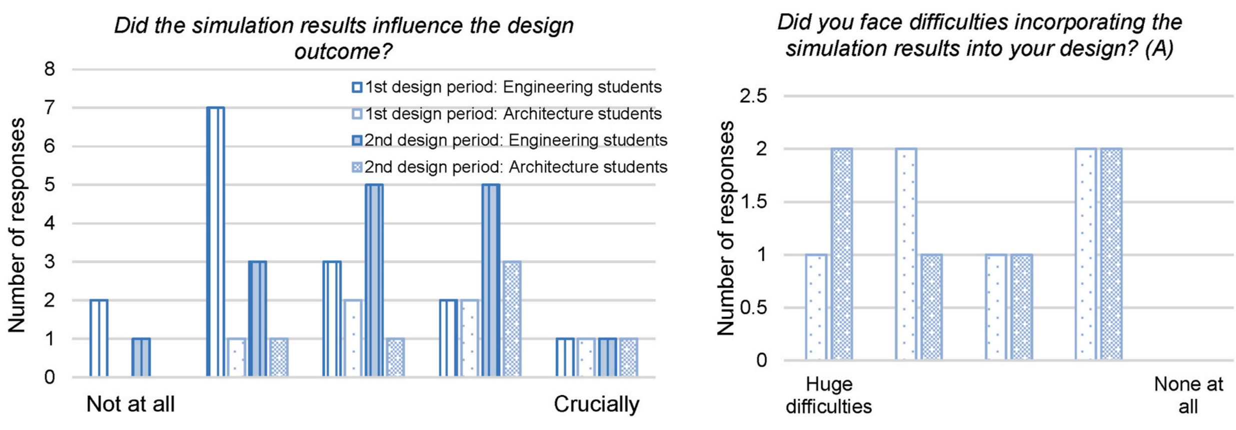

Fig. 12. Perceived impact of simulations on design outcome (to the left), and perceived difficulty of incorporating the simulation results (to the right).

performance metric would decrease another performance metric, d.) reconcilable performance metrics, where synergy effects could be exploited, as increasing one performance metric would also increase another, e.) performance metrics that conflicted with design constraints, and lastly f.) performance metrics that aligned well with design constraints. For c.) to f.), students were additionally asked to name examples in follow-up questions. Students provided responses in free text form. Key arguments are paraphrased and summarised below. The respective number of mentions and student group (E for engineering student and A for architecture student) are noted following the responses.

3.3.1. Perceived obstacles of integrating simulations in the design process

Students were asked to name the biggest obstacles to integrating simulations in the design process. A number of engineering students mentioned interoperability issues (E:4), i.e. compatibility issues between software or issues when importing model definitions for use in simulations. Another obstacle mentioned was the time required for remodelling or setting up the simulation model (E:3, A:1). In addition to modelling and simulation-based time-constraints, a few students also mentioned a lack of skills in the beginning (E:2, A:1). Faulty simulation results were also mentioned (E:1, A:1). In addition to technical issues, communication problems with the other student group were pointed out (E:2, A:1). Engineering students noted that simulation results did not fulfil the expectations of the architecture students (E:1), and that the architecture students held more decision power and would not implement design changes (E:2). Engineering students also indicated having difficulties in keeping up with the iterative design approach of the architecture students and the constantly required adjustments in the simulation model (E:2). Vice versa, architecture students pointed out that they received simulation results too late (A:2). Finally, both engineering and architecture students mentioned difficulties in understanding and interpreting the simulation results (E:2, A:3).

3.3.2. Perceived benefits of integrating simulations in the design process

As for the perceived benefits of integrating simulations in the design process, numerous students mentioned the ability to quantitatively assess design options and support design decisions (E:4, A:5). Similarly, students noted that the simulations aided in developing the design, for example when designing the façade (E:2, A:1). Two students acknowledged that incorporating simulations in the design process helped them understand the influence of design decisions (E2). One engineering student pointed out that it became possible to influence design decisions of the architecture students early on and therefore potentially save the time required for design changes at later stages (E:1). A few students responded that one of the biggest benefits to incorporating simulations was in improving the design in terms of heating, cooling, or other performances aspects (E:4). One student noted that simulations aided in ensuring compliance (E:1).

3.3.3. Conflicting performance metrics

Students were asked to name juxtaposing performance metrics, where one performance metric improved in detriment of another according to their own experience. Additionally, students were explicitly asked to include any findings from within their group, and not limit answers only to simulations performed by the responding student. Answers were requested in the following format: '(performance) improved in detriment of (performance)'. In a follow-up question, students were asked to give specific examples.

Table 1 provides an overview of the responses. X indicates where a conflict between metrics was mentioned by the engineering (X in

Table 1
Overview of performance metrics that conflicted during the design. An X in dark or light blue indicate that the conflict was mentioned by an engineering or architecture student, respectively.

	… in detriment of …				
Improvement of …	Daylighting	Building energy consumption	Cooling energy consumption	Heating energy consumption	Thermal comfort
Daylighting	-	X X	X -	X -	- X
Building energy consumption	X X	-	-	-	- X
Cooling energy consumption	X -	-	-	X -	-
Heating energy consumption	X -	-	X -	-	-
Solar gains	-	-	-	-	- X

dark blue) or architecture (X in light blue) students. Several students responded that the performance metrics for daylighting conflicted with overall building energy consumption (E:1, A:2), cooling energy consumption (E:3) and heating energy consumption (E:4). In their examples, students indicated that larger window areas led to greater transmission losses in the winter, but also greater heat gains in the summer. One student additionally indicated that shading design improved cooling demands but affected daylighting conditions. Other pairs of conflicting metrics pointed out by students were thermal comfort and overall building energy consumption (A:2), thermal comfort and daylighting (A:1), and thermal comfort and solar gains (A:1). No examples were given for the first mentioned conflicting metrics. As for thermal comfort and daylighting, insufficient thermal properties of windows were specified. The student who pointed out an increase in solar gains on the façade (presumably referring to the PV-potential of the façade) explained that the inclined façade led to overheating issues. Lastly, one other pair of conflicting metrics was mentioned: heating and cooling energy consumption (E:1). As an example, the student wrote that larger window areas reduced heating energy demand but increased the cooling demand.

To give context to and illustrate the answers, an example is given from the student's work. Part of the simulations for the example were rerun to ensure quality of results and consistency in simulation settings across the variations.

The results in Fig. 13 show how the constellation of buildings to each other affected daylighting (Fig. 13, comparing design 1 to design variant 1a, less daylight reached the building block to the north as a result of the obstruction). Adjustments in spacing and having multiple buildings blocks improved daylighting at the cost of increasing heating energy consumption (Fig. 13 1a and 1b). The increased heating energy consumption is likely due to a lower form factor (higher exterior-surface-to-volume-ratio), resulting from the expanded heat loss area relative to the useable floor area by increasing the external surface area through the division into multiple building blocks. In comparison, cooling energy consumption improved with the arrangement into multiple building blocks and lower form factor, likely resulting from the increase of surface area for heat dissipation. A further increase in heating energy consumption with an improvement in daylighting occurred with the inclination of the façade (see Fig. 13, design variants 1c and 1d). This again may have been a result of the lower form-factor resulting from the inclination. In this case, cooling energy consumption significantly increased with the inclination due to larger heat gains from the change in the solar incident angle from vertical to horizontal. In the presented example and subsequent results, exorbitantly high cooling demand values were observed. It is important to note that Revit's energy optimization tools are known for inconsistencies in energy simulation results for cooling loads, leading to substantial over-estimations of 2,5 times too high in cooling demand [27]. However, the trends observed with changes in orientation, inclination, and resulting solar radiation are sensible. Therefore, students were advised to disregard the absolute cooling values due to their inflated

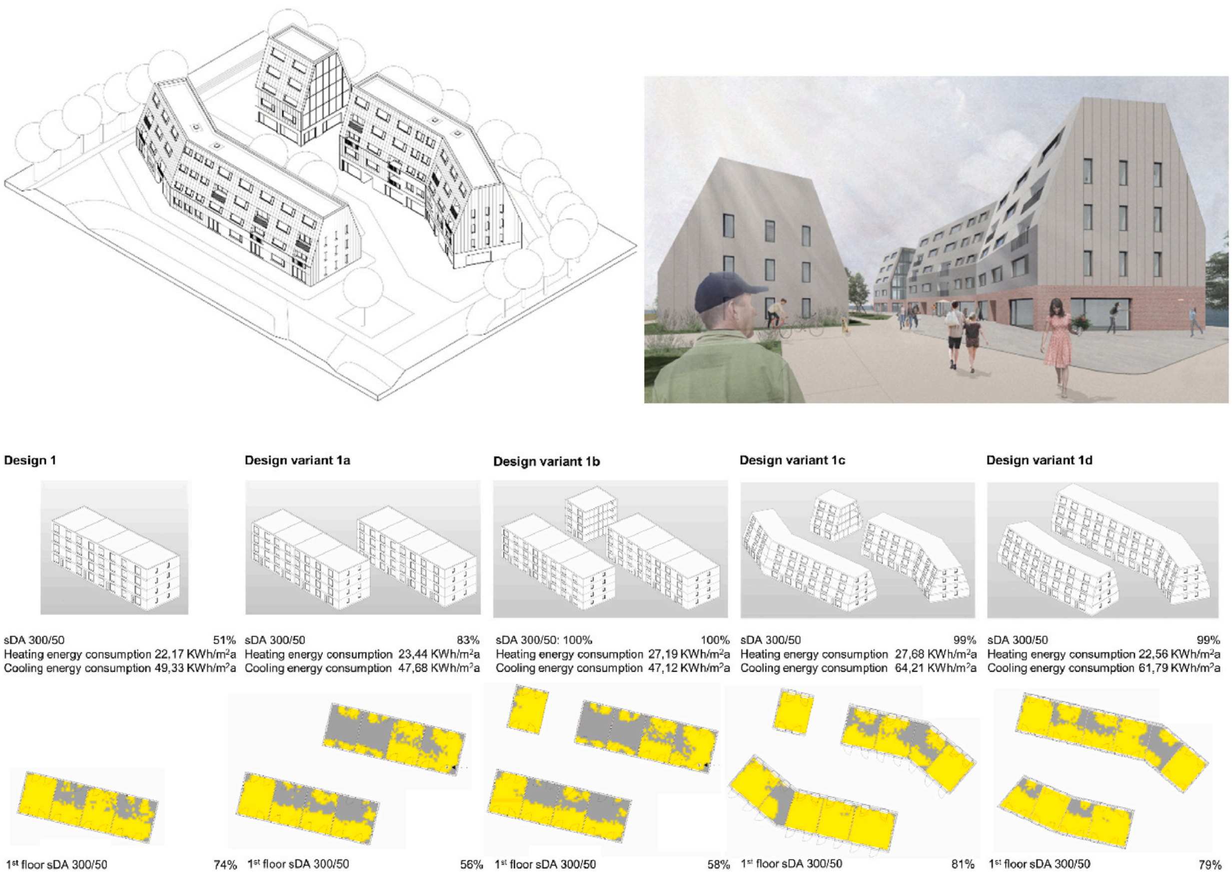

Fig. 13. Performance comparison of design variants. By E. Albrecht, M. Lümmen, J. Yu, and W. El Sabbagh.

nature, also because buildings in the Netherlands are typically constructed without the implementation of active cooling systems. Fig. 14 shows CFD simulations performed for Fig. 13, design variants 1c and 1d. Metric results aligned with performance results for daylighting but conflicted with building heating and cooling energy consumption.

3.3.4. Synergies between performance metrics

In the above, conflicting performance measures were discussed and some of the trade-offs in the design decision making process were illustrated. By way of contrast, and as already made apparent in the above example, there were also performance metrics that aligned well with each other. Students were asked to name such performance metrics in their design project, where increasing the performance of one metric would also increase the performance of another. Students were explicitly asked to include any findings from within their group, and not limit answers only to simulations performed by the responding student. Answers were requested in the following format: '(performance) improved and (performance) also improved'. Table 2 provides an overview of the responses. In a follow-up question, students were asked to give specific examples.

Several students noted that heating energy consumption and daylighting were complementary to one another (E:4), as both could be improved simultaneously with design changes. One student however added that the improvement in heating energy consumption was only marginal. The examples given by students pointed towards the benefits of larger window areas, which led to more daylight and solar heat gains. Additionally, adjusting building orientation appeared to have produced this result. In a similar context, two students pointed out that improving daylighting increased solar gains, as assessed with solar radiation analysis on the façade or roof (E:2). One reason given for this was changes to floor area and geometry, which increased the roof area. It was not clarified to what extent this improved daylighting, but one might assume the improvements to be the result of more shallow plans. Another reason for this was the inclined façades, which resulted in more daylight and solar gains due to the change in solar incident angles. Next to the complementary performance metrics mentioned thus far, students pointed out that heating and cooling energy demand improved with each other (E:3). Material choices and exterior wall construction were named as examples for design changes that resulted in the improvement of both. Another student named shading design, which reduced cooling energy consumption. It was not specified to what extent this improved the heating energy consumption. One student pointed out that an improvement of thermal comfort was possible alongside an improvement of building energy consumption (A:1). As an example, the student noted that improving the thermal properties of the external wall led to less heat loss in the winter and fewer heat gains in the summer, which improved thermal comfort. Lastly, one student answered that the daylighting performance metrics with different thresholds (e.g. 300 or 100 lux) were easily reconcilable (E:1) as a simple result of increasing the window area.

To illustrate the answers, an example is given from the students' work. Part of the simulations for the example were rerun to ensure quality of results and consistency in simulation settings across the variations.

The performance results in Fig. 15, initial design 1 to design variant 1c show an improvement in daylighting based on two design changes: inclination of the façade and building orientation. Results show a deeper daylight penetration for the inclined façade (compare Fig. 15 1 and 1a). Likely as a result of the additional solar gains from the change in incident angle, this also reduced heating energy consumption, however at the cost of increasing cooling energy consumption. The reduction in heating energy consumption was not reflected within the heating load calculations according to DIN EN 12831, as these do not take into account solar gains. Access to the apartments was provided on the north-facing back of the building, where walkways and stairs were located. These created overhangs and overshadowing. Thus, the north side of the building received less daylight for the southward orientation. A change in orientation from south to south-east consequently improved daylighting conditions for the now north-west facing backside of the building (compare Fig. 15 1a to 1b). At the same time, cooling energy consumption could be reduced, however at the cost of a marginal increase in heating energy consumption. Thus, while some performance metrics align, others may remain in conflict. The impact on total energy consumption would need to be evaluated in combination with material choices and glazing properties. What was expected of the students was to understand that an increase in solar gains can lead to an increase in cooling energy consumption, but it also has the potential to reduce heating energy consumption (e.g., Fig. 15). However, this reduction could be marginal, possibly due to a lower form factor. For instance, the surface-area-to-volume ratio may have changed as a consequence of an inclined façade, resulting in a

Fig. 14. CFD simulations for design 1d and 1e. The arrow indicates the direction of wind. Spacing is arranged such that there is ventilation in the courtyard to reduce heat-island effects, and at the same time reduced speed to ensure comfort.

Table 2
Overview of performance metrics that improved simultaneously with each other. An X in dark or light blue indicates a mention by the engineering or architecture student, respectively.

Improvement of …	… also improved … Daylighting	Building energy consumption	Cooling energy consumption	Heating energy consumption	Thermal comfort	Solar gains
Daylighting	X -	-	X -	X -		X -
Building energy consumption	-	-	-	-	- X	-
Cooling energy consumption	-	X -	-	-	-	-
Heating energy consumption	X -	-	X -	-	-	-
Thermal comfort	-	- X	-	-	-	-

larger surface area and more heat loss. Additionally, the inclination might have increased the glazing surface area, meaning a higher proportion of materials with poorer U-values. In particular, in the example of Fig. 14, and contrary to the example in Fig. 15, there was no reduction in heating energy consumption due to the inclination, presumably for these reasons. The architecture students additionally assessed ventilation strategies for their design to improve indoor temperatures and adaptive comfort (Fig. 15 bottom figures).

3.3.5. Insights from student responses on conflicting and synergising performance metrics

Interestingly, as identified in previously presented examples, complementary performance metrics can become conflicting metrics depending on design changes. This also became evident from the survey results. The combination of daylight and heating energy performance particularly stands out, with four students each reporting these metrics as complementary and conflicting. For the former scenario, students reported that larger window areas led to greater heat losses and therefore increased heating energy consumption, whereas for the latter scenario, students reported that larger window areas or a change in orientation led to more daylighting and solar heat gains, thereby reducing heating energy consumption. Students were thus able to show that with the correct combination of parameters (e.g. larger window areas only in specific orientations combined with an overall airtight building, or going by the design examples, buildings with a southward oriented inclined façade while staying within certain thresholds for material U-values and the form factor) could shift trends in performance and reduce trade-offs between commonly conflicting performance metrics.

Overall, the responses of the engineering students were more varied than those of the architecture students. This may have been due to the difference in number of responses, but also because simulation work varied between engineering and architecture students and may have not been adequately discussed across student groups. This is apparent in both directions: none of the engineering students provided examples involving thermal comfort, which was a focus of the architecture students, and vice versa, there was a lack of examples from architecture students involving simulation results the engineering students focused on. Additionally, one student noted that they could not provide more detailed information because responsibilities for daylight and energy performance simulations had been divided between them and another engineering student, suggesting a lack of shared understanding or discussion about the broader consequences of their simulations on other performance metrics. Thus, simulation results may have also been evaluated and discussed poorly, not just between the engineering and architecture students, but also among the engineering or architecture students themselves. Therefore, responsibility distribution may carry the risk of disinterest in the 'problems of others'. This occurred despite an alignment of goals and potential mutual benefit arising from it (e.g. the competition). It may, however, also have been because students were overwhelmed with the task and had not yet developed sufficient skills and knowledge to perform simulations smoothly and understand the results in a practical way, as indicated in the student responses about the obstacles to integrating simulations in the design process. Regardless, communication remained a problematic core aspect of trans-disciplinary workflows for solution finding.

3.3.6. Performance metrics conflicting with design constraints

Next to meeting performance targets, students also had to fulfil architectural design criteria, e.g. relating to urban constraints, building structure, layout considerations. Hence, students were asked about performance metrics that conflicted with design constraints in their projects. Answers were requested in the following format: '(performance) improved in detriment of … '. In a follow-up question, students were asked to give specific examples. Results are paraphrased and summarised below.

From the perspective of several students, reducing building energy consumption conflicted with the design concept (E:4). Examples

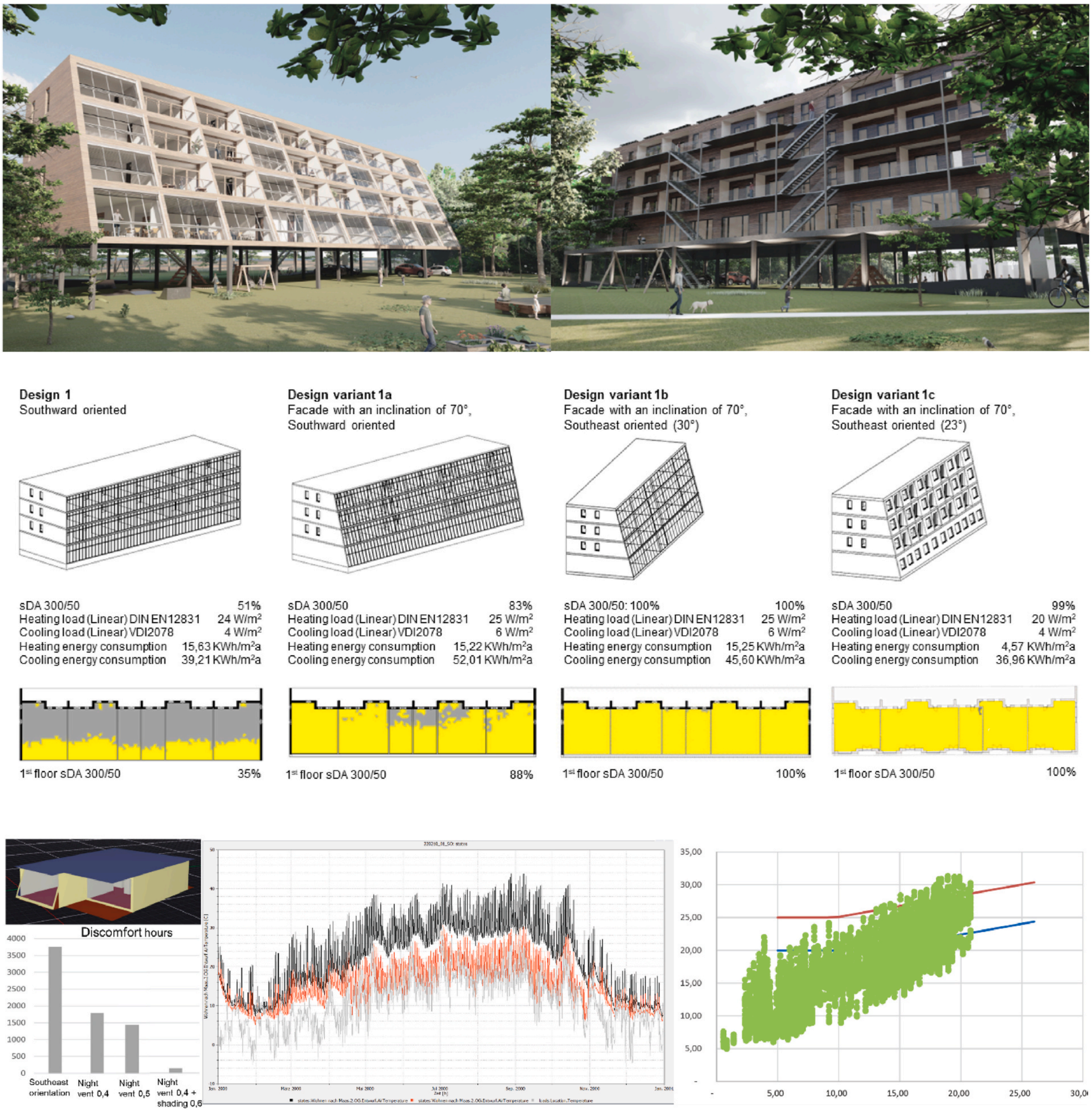

Fig. 15. Performance comparison of design variants. By M. Kühn, M. Mauel, N. Flücht, K. Heib. The top row shows the comparison of daylight and energy performance results for variations in façade inclination and orientation. The bottom row of figures shows the thermal comfort analysis. From left to right: discomfort hours for the final design, with a night ventilation rate of 0,4 and 0,5, and static external shading of 0,6; indoor temperatures before (black) and after (orange) ventilation and shading; comfort range indicated in between the red and blue lines, with hours falling in or outside the range indicated in green. Cold temperatures were seen as less problematic, as the building would be heated.

included conflicts with heating/cooling/ventilation design concepts. For example, it was noted that the placement of PV panels and inclination of the façade made it difficult to place stacks for ventilation. Similarly, daylight performance was perceived to conflict with the design concept (E:2, A1). As an example, it was specified that the inclined façade did not satisfy aesthetic requirements. Also, daylighting was found to conflict with the design in terms of location or orientation, as noted by both an architecture and an engineering student (E:1, A:1). The energy performance metric was found to conflict with layout design (E:2, A:1), and designing for views (A:1). As an example, an architecture student specified that design with multiple building blocks and larger windows increased energy consumption. In a similar vein, daylighting was found to conflict with the layout design (E1). It was indicated that internal layout and the placement of interior walls reduced daylight. Another student pointed out that improving the heating capacity of the water loop for underfloor heating conflicted with M&E design constraints (E1), as permitted surface temperatures for the floor would have been exceeded. Lastly, an architecture student pointed out that daylighting conflicted with the steel construction design (A:1). Overall, students pointed out design constraints that had to be navigated. Several of the constraints mentioned related to the location (or views) and layout design. Besides this, however, responses from the engineering students suggested that they thought that architecture students prioritized design concept and aesthetics. This notion may need to be addressed to improve communication and discussions in integrated workflows between engineering and architecture disciplines.

3.3.7. Performance metrics aligning with design constraints

Both engineering and architecture students reported on the challenges they faced when aligning performance with architectural design criteria. However, the simulations also provided an opportunity to aid architectural design goals. Hence, students were asked about performance metrics that aligned well with design considerations in their projects. Answers were requested in the following format: '(performance) improved and … also improved'. In a follow-up question, students were asked to give specific examples. Results are paraphrased and summarised below.

Overall, only a few examples were given. Students noted that daylighting helped in making design choices related to geometry (E:1), building façade (E:1), and building layout. As examples, students specified that daylight simulations helped make decisions on window-to-wall ratio (WWR), and on building layout in terms of the geometric shape of the layout. Students also found that improving simulated energy performance helped with form-finding (E:3). Examples for this include justification of the 70° façade, and form-finding in relation to improving the PV-potential.

4. Discussion

An integrated design approach to multidomain BPS was evaluated in a teaching experiment within the context of design education with students from architecture and engineering disciplines. Challenges are discussed from 1) a simulation and performance-measure-orientated point of view, 2) a technological point of view, and 3) an integrated-workflow-oriented point of view.

Regarding 1) a simulation and performance-measure-orientated point of view, several benefits to integrating simulations in the design process were highlighted. As students had pointed out in answers to survey questions, potential benefits included using simulations to develop the design and inform design decisions. As seen in the design examples, the use of simulations also showed potential for improving performance, and thus the impact on environment and occupant comfort. Still, it is unclear how the design would have developed without simulations, as we do not have a control group with the same design task. Nonetheless, another benefit of integrating simulations across different domains was the learning outcome for students, as it allowed them to understand the impact of design decisions and experience trade-offs between design choices and performance metrics.

In terms of applying multiple performance metrics, students had to deal with conflicting performance metrics and also those that aligned well with each other. Interestingly, when students were asked to specify conflicting and complementary metrics, some were named in both scenarios. Going by the number of mentions, one example in particular stood out: students on one hand found that daylighting could improve in detriment of heating energy consumption and vice versa, yet on the other hand, students also pointed out that improving daylighting could improve heating energy consumption and vice versa. As one learning outcome, it therefore follows that trade-offs between conflicting performance metrics can be mitigated with the correct combination of parameters (for the specified case, e.g. inclination of façade, increase in window area only in sunny orientations, choice of material with properties permitting solar gains and good heat capacity, airtight construction). The evaluation of design strategies that can shift trends in performance to reduce trade-offs between typically conflicting performance metrics could be an avenue for future investigations. Next to known passive design strategies mentioned here, the potential of inclined façades could be a design parameter worth investigating further.

In the current study, students performed simulations for only a few variations. While the objective of the simulations was to see the trend in performance when changing a design parameter (e.g. does performance improve or worsen when going from a square to rectangular geometry and so on), the number of simulations may have been too small to truly understand performance trends. Additionally, the simulations performed by the students accompanied the design in a sequential manner (as shown in Fig. 2). This means that simulations were selectively performed on the suggested design parameters at each design stage, reducing the number of evaluated combinations (i.e. geometry and orientation was varied and a preferred solution selected, then façade design was varied and a preferred solution selected, and so on). It may thus be interesting to reevaluate student learning outcomes for design explorations or optimizations performed on larger design solution spaces, particularly because some of the findings revealed that the combination of design parameters matters (i.e. to mitigate heat loss through windows through passive design strategies). Furthermore, in terms of informed design decision making, the current approach also raised the question of how many simulations or variations are needed to meaningfully understand performance trends.

Regarding 2), a technological point of view, the survey responses in this study underline findings from previous surveys (Galasiu and Reinhart, 2008b; [15]). Challenges most mentioned across surveys were time and cost constraints. Additionally, difficulties interpreting and communicating simulation results stood out (see section 3.3). Although reasons for the latter were revealed to be partly due to the lack of knowledge and skills of students, it is also tied to interface design. Furthermore, pointing towards interoperability issues, errors were reported when dealing with IFC and data exchanges. On this aspect, commonly reported errors referred to data loss during exchanges, such that modelled information could not be read by the software to which it was imported. Therefore, where software lacks in exchange options, possible solutions lie in improvements to the IFC-schema or repeating the plea to software developers to improve interfaces between tools.

Regarding 3, an integrated-workflow-oriented point of view, the main questions of our evaluation pertain to the value of multidisciplinary exchange, when performed from an early stage, and undertaken continuously through the design process. To incentivise students toward a common goal, the design work was to be submitted to a student competition. However, the survey results highlighted communication and student interaction as a challenging factor. For example, survey results showed discrepancies in responses between the engineering and architecture student group (e.g. Section 3.2 Fig. 9, where architecture students reported providing the models more often than the engineering students reported receiving them). Additionally, architecture students reported that it remained difficult to incorporate the simulation results (see Fig. 12). Although student responses revealed that this was partly due to the initial learning curve for the engineering students and their lack of skills, other responses suggest that interpretation of the results and discussion of their implications for the design appear to have remained lacking (Section 3.3 on challenges to integrating simulations). Additionally, questions on conflicts and synergy effects between performance metrics and performance metrics and design constraints appear to have been reported mostly from a personal perspective rather than as group findings, despite the question being framed to encourage group responses. In the context of communication, a contributing factor may have been COVID-19 restrictions, which may have made in-person meetings more difficult. As reported in Section 3.1 (Fig. 6), a large number of students never met in person to discuss the design. Another challenge to interaction between the disciplines was that the engineering students reported difficulties in being able to keep up with the iterative design process of the architecture students. The difficulty was increased by the fact that the engineering students were supposed to spend less time than the architecture students on the design, as the participation in the architecture module was awarded with three times the credit of the engineering module. Thus, the process may have benefitted from more clarifications, such as the variants the architecture students wished to have investigated and those that the engineering students would recommend investigating, the deadline for analysis, and the preferred format of result or feedback. Finally, another issue that was revealed relates to the power difference when it came to making design decisions, based on which better performing solutions may have not been selected (see Section 3.3 on challenges to integrating simulations). This raises the question of how to align the interests of the two student groups, for example so that the value of simulations is acknowledged by the architecture students, while the design constraints are acknowledged by the engineering students.

Limitations of this work pertain to the small sample of students. Additionally, the success of the investigated integrated and simulation-based approach was not compared against a control group. We therefore invite others to share their teaching experience and approaches and to validate them. Future research could explore the role of Building Performance Simulations (BPS) in design education, particularly in fostering interdisciplinary collaboration and facilitating evidence-based decision making. Evaluating integrated workflows that improve interdisciplinary communication and support engagement with iterative design processes could provide valuable insights into overcoming current challenges in simulation-driven design practice. In particular, comparing integrated approaches to non-integrated ones could help highlight their relative advantages, such as improved coordination, reduced trade-offs between conflicting performance metrics, and enhanced decision-making efficiency. In that regard, questions that could be addressed in future teaching experiments include: 1) an assessment of the number of simulations or design variations needed to reasonably inform decisions, 2) the time and frequency of simulations that is required to support an iterative design process, 3) sensible definitions of responsibilities between disciplines to improve coordination, 4) sensible design and performance objectives between the disciplines and simulation domains at each iteration, and 5) methods for the effective communication of simulation results and trade-offs between simulation domains. These limitations and avenues for future research underscore the importance of refining interdisciplinary approaches to enhance the educational and practical applications of simulation-driven design workflows.

5. Conclusions

The current work evaluated and discussed challenges and benefits of integrated design workflows for multi-domain simulations from a simulation and performance-measure-oriented point of view, a technological point of view, and an integrated-workflow-oriented point of view. Findings in general confirmed challenges in the interdisciplinary application of BPS found in the literature in terms of time-based constraints, and issues with interoperability and results visualization. Results on integrated workflows, in particular, highlighted communication as a core requirement for the successful integration of multi-domain considerations, as results could not be used appropriately. Trans-disciplinary communication within the design workflows, particularly to facilitate solution finding, remained challenging. To some extent, this was attributed to the teaching experiment being undertaken for the first time, with the students' skills, particularly those of the engineering students, not yet at a level to effectively employ simulations. Extending such teaching experiments and improving student proficiency are therefore essential for the broader implementation of integrated workflows for multidomain BPS in the future.

CRediT authorship contribution statement

Clara-Larissa Lorenz: Writing – review & editing, Writing – original draft, Visualization, Methodology, Conceptualization. **Marcel Schweiker:** Writing – review & editing, Writing – original draft, Methodology, Conceptualization. **Royem Kuçin:** Writing – original draft, Visualization, Methodology. **Fahimeh Hajati:** Visualization, Methodology. **Christoph van Treeck:** Writing – review & editing.

Relationships

The authors report a relationship with RWTH Aachen University, where three of the authors are employed.

Patents and intellectual property

There are no patents to disclose.

Patents and intellectual property

There are no additional activities to disclose.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix

List of questions from the online questionnaire provided to the engineering students, translated into English. The questionnaire for the architecture students was analogous, with certain questions adapted to address the architectural counterpart:

Questionnaire title:

Integrated Workflows for Incorporating Multidomain Simulations into the Design Process.

Part I: General Questions.

1. Which simulations did you perform yourself?
   - Daylight analysis
   - Energy performance simulation
   - Thermal simulation
   - Wind simulation
   - Other (indicate which one)
2. Which software did you use to run the simulations?
   - Revit Lighting
   - Revit Solar
   - Energy Optimization for Revit
   - Revit LINEAR
   - Autodesk CFD
   - SIM-VICUS
   - Other (indicate which one?)
3. What were your Revit skills like before the start of the module?
   - No experience
   - Little experience
   - Experienced
4. How much time did you approximately need to familiarize yourself with the installations, Revit, and the simulation tools, and to achieve initial results?
   - 2 weeks
   - 2 weeks to 1 month
   - 1–2 months
   - More than 2 months
5. In which file format did you receive the design from the architecture students?
   - DWG
   - IFC
   - RVT
   - PLN
   - The model was recreated by us
6. The design models from the architecture students were processed in Revit to be used as simulation models. How did you proceed in this regard?
   - The models from the architecture students were used as a template in Revit and remodeled
   - The models from the architecture students could partially be used and were modified to create the simulation models
   - The models from the architecture students could be used directly in Revit to generate the simulation models and perform the simulations

7. Did you instal an IFC plugin as an additional module for Revit to improve IFC import and export functionalities?
   - Yes
   - No
   - I don't know
8. Did the IFC plugin help improve the IFC import functionalities and make post-processing in Revit easier?
   - Yes
   - No
   - I don't know
   - Not applicable
9. Over which platform were the design documents exchanged?
   - Email
   - Autodesk Construction Cloud
   - Sciebo
   - Other cloud storage platform
   - WhatsApp

   10. What kind of communication did you use?
   - Zoom
   - Teams
   - Email
   - Phone call
   - WhatsApp
   - In person

Part II: Communication and Coordination in the First Half of the Design Studio*

1. How often did you communicate with the architecture students?
   - Irregularly, less than once a week
   - Once a week
   - 2 to 3 times a week
   - More than 3 times a week
2. How often did discussions involve the following topics?

Design options and design decisions.

- Never
- Rarely
- Occasionally
- Often
- Very Often

Issues with data exchange.

- Never
- Rarely
- Occasionally
- Often
- Very Often

Simulation results.

- Never
- Rarely
- Occasionally
- Often
- Very Often

Issues with simulations.

- Never
- Rarely
- Occasionally

- Often
- Very Often

3. How often did you receive models from the architecture students?
   - Once per month
   - 2 to 3 times per month
   - 3 to 5 times per month
   - More than 5 times per month
4. How much time on average did you require to set up an architectural model for performance analysis?
   - Less than 30 min
   - Less than an hour
   - 1–3 h
   - 3–5 h
   - More than 5 h
   - Not applicable
5. If you worked with IFC files from the architecture students: What kind of errors occurred when importing the files for simulation?
6. What errors did you yourself frequently make during post-processing or remodelling of the architectural model for simulation?
7. Did the simulation results influence the design outcome?
   - 1 = not at all
   - 2
   - 3
   - 4
   - 5 = crucially
8. Which aspects of building design did the simulations influence?
   - Building form/geometry
   - Building orientation
   - Slope of the facade
   - Window area/window position
   - Shading design
   - Material of exterior walls/choice of glazing
   - Choice of materials for interiors (ceiling, floor, walls)
   - Atrium
9. Who made changes to the design for the variant analysis (building shape, orientation, façade design, details, etc.)?
   - Engineering students
   - Architecture students
   - Both

Part III: Communication and Coordination in the Second Half of the Design Studio.
Question in Part II are repeated for the second half of the design studio and are thus not presented here.
Part IV: Overall Process and Lessons Learned.

1. What were the greatest challenges to integrating simulations in the design process?
2. What did you find to be the greatest benefit of simulations for the design decision-making process?
3. Were there simulation results that were difficult to reconcile because one value improved while another worsened? Please respond with 'Improvement of xxx at the expense of xxx.' (The answers should be based on the experiences of the entire group, not just on individually conducted simulations).
4. Please provide specific examples of these conflicts.
5. Were there simulation results that were easy to reconcile because one value improved while another also improved? Please respond with 'Improvement of xxx alongside improvement of xxx.' (The answers should be based on the experiences of the entire group, not just on individually conducted simulations).
6. Please provide specific examples.
7. Were there simulation results that were difficult to reconcile with **design criteria** because one aspect improved while another worsened? Please respond with 'Improvement of xxx at the expense of xxx.' (The answers should be based on the experiences of the entire group, not just on individually conducted simulations).
8. Please provide specific examples of these conflicts.
9. Were there simulation results that were easy to reconcile with **design criteria** because one aspect improved while another also improved? Please respond with 'Improvement of xxx alongside improvement of xxx.' (The answers should be based on the experiences of the entire group, not just on individually conducted simulations).
10. Please provide specific examples.

Data availability

The data that has been used is confidential.

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