Integrating Thermal, Energy, Lighting, and Acoustics in Building Design Approach: Lesson Learned from Students Assignments

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Abstract

This paper aims to report results and lesson learned from students assignments in integrating thermal, energy, lighting, and acoustic performance in a building simulation project. The objectives are to observe the students approach in obtaining the baseline, target, and optimum performance in all mentioned aspects, and to analyse the differences between the submitted design proposals. The students were asked to simulate and predict the baseline and target values of thermal, energy, lighting (all using *Sefaira*) and acoustic (using *CATT* v9) aspects of a hypothetical classroom and to optimise the interior material properties. Based on the submitted reports, only 50% of the students modified the interior materials by considering the four aspects simultaneously. Among the aspects, lighting performance ($sDA_{300/50\%}$) is the most consistently predicted, with the coefficient of variance (CV) of 0.16 (baseline) and 0.07 (optimum). Meanwhile, thermal performance (annual overheating hours) is the least consistent, with CV of 1.28 (baseline) and 1.82 (optimum).

Key Innovations

- Analysis of students assignments in integrating thermal, lighting, and acoustic performance
- Application of thermal, energy, lighting (in *Sefaira*) and acoustic simulations (in *CATT* v9) simultaneously for a design project
- Observation of the most consistently predicted performance indicators among all aspects

Practical Implications

Consider the acoustic aspect along with the thermal, energy, and lighting aspects in building design projects. Be aware that simulation results of thermal and energy performance indicators may be less consistent than the daylighting and acoustic ones.

Introduction

In architecture and engineering education, the use of building performance simulation (BPS) as a tool to understand the importance of integrated building design approach is now common in many universities worldwide. The use of BPS tools is nowadays relatively ‘easy’, even for first-time users (Beausoleil-Morrison and Hopfe, 2015; Beausoleil-Morrison, 2018); although achieving accurate and reliable results can at times be problematic (Guyon, 1997; Berkeley et al. 2014; Strachan et al. 2016; Imam et al., 2017). Solid understanding of the underlying principles of building science, as well as collaboration, co-creation (as in creative teaching methods (Reinhart et al., 2012; Reinhart et al., 2015)) and interaction with practitioners are thus required to overcome the problem of accuracy and reliability of BPS’s outcomes (Beausoleil-Morrison, 2018).

In the case of most architecture and engineering postgraduate courses, however, an integrated BPS approach that simultaneously considers thermal, energy, lighting, and acoustic performance altogether in a single building design course is not very common. Integrating the first three mentioned aspects is indeed popular and is supported by current simulation tools, but the acoustic aspect is often not considered at the same time, i.e. the acoustics subject is only taught in a different course. In the acoustic-related courses, the topic of BPS may be introduced, for instance in simulating room acoustics, but the relation with other aspects of building performance is rarely mentioned in the activity.

In the literature, research involving thermal, lighting, and acoustic aspects altogether nonetheless exist, though mostly related with field experiments with real building occupants (e.g. Buratti et al., 2018; Ricciardi and Buratti, 2018; Yang and Mak, 2020) or with in-situ building performance (e.g. Krüger and Zannin, 2004; Cotana et al. 2014). In terms of full BPS studies, only a few involve all of the aforementioned aspects (e.g. Bo et al., 2015; Cui et al. 2016). To some extent, this is also the case in professional design practice, because many BPS practitioners are usually experts in only one or two specific fields of the building science (e.g. thermal and energy in buildings).

Despite the current practice, it is nonetheless worthwhile to consider giving an integrated approach of BPS involving all aspects of building performance, in postgraduate courses attended by mostly young students, who are potential BPS practitioners in the future. This paper therefore aims to report results and lesson learned from a small case of students assignments in integrating thermal, energy, lighting, and acoustic performance in a postgraduate course on integrated building design. The objectives are to observe the students approach in obtaining the baseline, target, and optimum performance in all mentioned aspects, and to analyse the differences between the submitted design proposals.

The findings are expected to offer an insight on how graduate students (in architecture or building science/ engineering), integrated and optimised all of those four aspects altogether, in an attempt to modify a given room in a given building, using BPS tools.

Methods

Case study

The postgraduate course reported in this paper is named 'Integrated Building Design Project', taught in the second semester of the first year of Master Program in Engineering Physics (with concentration on Building Physics) in the authors' university. During the second semester of the academic year 2019/2020, a total of six students enrolled in this course. Among the six students, one has a background in architecture, while the remaining five have a background in engineering (applied) physics, electrical engineering, or pure physics. Two students had already worked in architectural/building engineering consultant firms, while the rest were fresh graduates.

During the course, the students were exposed to several BPS tools related with thermal, energy, and lighting aspects (with *Sefaira* (Trimble, Inc., 2020)), and acoustic aspect (with *CATT* v9 (CATT, 2020)). In the final project assignment of the course, the following problem was assigned to the students.

Consider the baseline scenario of a classroom with internal size of 30 m (length) × 15 m (width) × 5 m (height), with two glazed windows, measuring 13 m (length) × 2 m (height) each. Both windows are separated by 2 m, at 1 m above the floor. The classroom is situated on the second floor (i.e., one story above the ground) of a third-story building of 72 m (length) × 21 m (width).

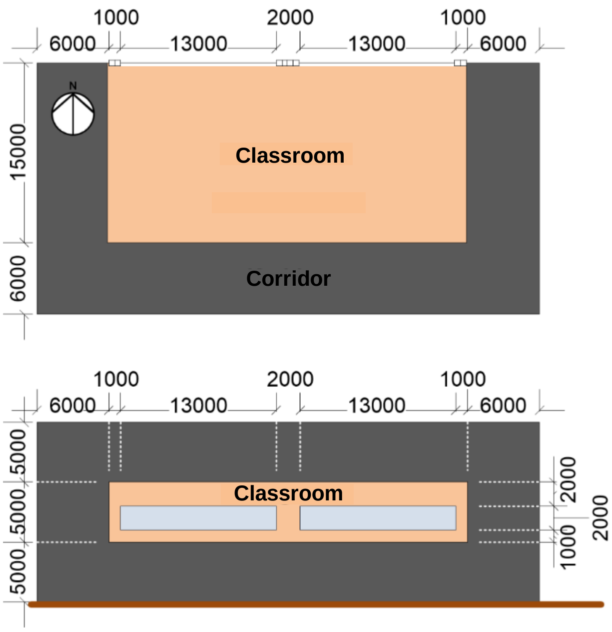


Figure 1: Floor plan and elevation views of the modelled classroom building; units in mm

The north side of the room is exposed to the exterior, whereas the other three sides are adjacent to an unconditioned corridor. Figure 1 displays the floor plan and elevation views of the assigned classroom building (in mm).

The classroom is set to be located in Jakarta, Indonesia (6°S, 107°E), which belongs to the Af (tropical rainforest) climate type. Thermal and lighting properties, i.e., thermal conductivity (k), light reflectance (ρ), and light transmittance (τ) of the relevant material surfaces in the baseline scenario are given in Table 1, whereas the acoustic properties are given in Table 2.

Table 1: Thermal conductivity (k), light reflectance (ρ), and light transmittance (τ), of relevant material surfaces in the baseline scenario

Surface	Material	k [W/(m·K)]	ρ [-]	τ [-]
Ceiling	Gypsum 12mm	0.17	0.80	-
Wall	Painted concrete 250mm	1.45	0.50	-
Floor	Marble 12mm	1.30	0.20	-
Window	Clear glass 3mm	1.05	-	0.85

Table 2: Acoustic properties of relevant material surfaces in the baseline scenario

Surface	Material	Sound absorption coefficient [-]					
		125 Hz	250 Hz	500 Hz	1 kHz	2 kHz	4 kHz
Ceiling	Gypsum 12mm	0.29	0.10	0.05	0.04	0.07	0.09
Wall	Painted concrete 250mm	0.10	0.05	0.06	0.07	0.09	0.08
Floor	Marble 12mm	0.01	0.01	0.01	0.01	0.02	0.02
Window	Clear glass 3mm	0.18	0.06	0.04	0.03	0.02	0.02

For other relevant parameters not included in Tables 1 and 2, the values are to be assumed by the students, based on reliable references or standards. Any relevant settings for the building utilities (cooling, ventilation, and lighting) shall be also assumed properly. For acoustic calculation, the sound source is located at 1.5 m high in the front part of the room, whereas the receiver is at 1.2 m in the centre of the room.

The following questions are provided:

1) Define the specific **target** values of the following performance indicators:
   - Percentage of annual overheating hours (%OH), which in this case defined as:

$$\%OH = \frac{t_{T>T_{max}}}{t_{total}} \times 100\% \quad (1)$$

where $t_{T>T\max}$ is the duration (in hours) when the dry bulb temperature in the room exceeds the maximum target temperature $T_{\max}$, and t_{total} is the total occupied hours.

- Spatial daylight autonomy with target 300 lx, 50% ($\text{sDA}_{300/50\%}$), knowing that:

$$\text{sDA}_{300/50\%} = \frac{A_{\text{DA}_{300}\geq 50\%}}{A_{\text{total}}} \times 100\% \approx \frac{n_{\text{DA}_{300}\geq 50\%}}{n_{\text{total}}} \times 100\% \quad (2)$$

where $A_{\text{DA}300\geq 50\%}$ and $n_{\text{DA}300\geq 50\%}$ are the workplane area and the number of sensor points with DA_{300} of at least 50%, while A_{total} and n_{total} are the total workplane area and number of sensor points in the room.

- Total annual energy use intensity (EUI), annual cooling energy intensity (CEI), and annual lighting energy intensity (LEI) [kWh/m^2/yr].
- Reverberation time (RT_{60}) [s] at the receiver point at frequencies 125, 250, 500, 1000, 2000, and 4000 Hz, knowing that:

$$\text{RT}_{60} = \frac{0.161V}{\sum_{i=1}^{n} S_i \alpha_i} \quad (3)$$

where V is the room's volume, S_i and α_i are the surface area and sound absorption coefficient of the i-th surface in the room interior. In actual measurement, the decay of 60 dB as the base to determine RT_{60} is difficult to achieve. It is thus common to approach RT_{60} with any of the three indicators: Early Decay Time (EDT), T_{20}, or T_{30}; which use the extrapolation of sound decay at 5, 20, and 30 dB, respectively.

2) Determine the values of the aforementioned performance indicators for the **baseline** scenario.
3) Re-design the classroom, by modifying the type and/or surface area of the interior materials only, considering the defined target of all performance indicators.
4) Compare the **optimum** values of all performance indicators to their defined targets, and to the baseline scenario. Provide your analysis.

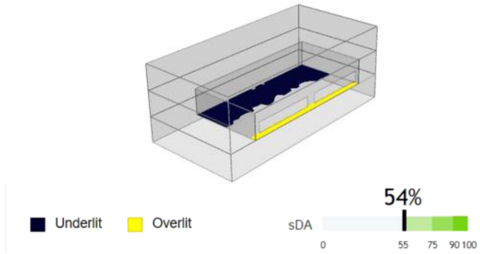
Observation

Based on the submitted simulation reports, the entire performance indicators are listed for all students. The mean, standard deviation (SD), and coefficient of variance (CV) are evaluated across all students, for each performance indicator. Despite the fact that the number of students is too few to represent the general population, CV values are needed to compare the deviations of the results obtained across the students, so that one can determine the performance indicators that are the most consistently predicted.

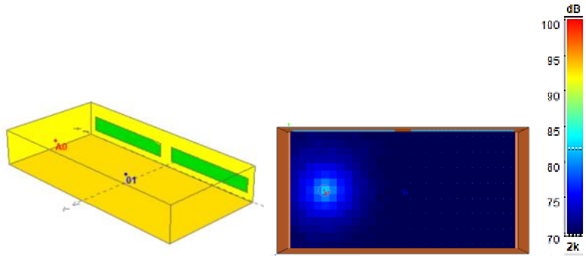
The analyses are conducted separately for the target, the baseline, and the optimum values. Further analysis and discussion are also made with regard to the choice of target values and how the optimum values are obtained.

Results

To give an illustration of the submitted results, Fig. 2 displays typical 3D visualisations of the daylighting simulation results in *Sefaira* and the geometric model for acoustic simulation in *CATT* v9.



(a)



(b)

Figure 2: Typical visualisations of (a) the daylighting simulation results in Sefaira and (b) the acoustic simulation results in CATT v9

The target values of %OH, EUI, CEI, LEI, and $\text{sDA}_{300/50\%}$ as specified by all students are summarised in Table 3, while the specified target values of RT_{60} at all frequencies are summarised in Table 4.

Table 3: Target values of %OH, EUI, CEI, LEI, and $\text{sDA}_{300/50\%}$ specified by all students

#	%OH [%]	EUI [kWh/m²/yr]	CEI [kWh/m²/yr]	LEI [kWh/m²/yr]	$\text{sDA}_{300/50\%}$ [%]
1	*	≤173.5	*	*	≥55
2	*	≤80	*	*	≥55
3	*	*	*	*	≥55
4	≤10	≤116	≤44	≤15	≥55
5	≤2	≤250	*	*	≥55
6	≤1	*	*	*	≥55

* not submitted or specifically mentioned by the student

Table 4: Target values of RT_{60} at frequencies 125, 250, 500, 1000, 2000, 4000 Hz specified by all students

#	RT_{60} [s] 125Hz	RT_{60} [s] 250Hz	RT_{60} [s] 500Hz	RT_{60} [s] 1kHz	RT_{60} [s] 2kHz	RT_{60} [s] 4kHz
1	0.8~1.2	0.8~1.2	0.8~1.2	0.8~1.2	0.8~1.2	0.8~1.2
2	0.7~0.8	0.7~0.8	0.7~0.8	0.7~0.8	0.7~0.8	0.7~0.8
3	*	*	0.6~0.8	0.6~0.8	*	*
4	≤0.49	≤0.49	≤0.49	≤0.49	≤0.49	≤0.49
5	*	*	0.7~1.4	0.7~1.4	*	*
6	*	*	0.6~0.8	0.6~0.8	*	*

* not submitted or specifically mentioned by the student

Based on the student reports, the baseline values of %OH, EUI, CI, LI, and $sDA_{300/50\%}$ as obtained by all students are summarised in Table 5, while the obtained baseline values of RT_{60} at all frequencies are summarised in Table 6.

Lastly, the optimum values of %OH, EUI, CI, LI, and $sDA_{300/50\%}$ as proposed by all students after the modifications are summarised in Table 7, while those of RT_{60} at all frequencies are summarised in Table 8.

Table 5: Baseline values of %OH, EUI, CEI, LEI, and $sDA_{300/50\%}$ obtained by all students

#	%OH [%]	EUI [kWh/m²/yr]	CEI [kWh/m²/yr]	LEI [kWh/m²/yr]	$sDA_{300/50\%}$ [%]
1	8.8	188	86.8	31.1	66
2	99.0	142	67.0	30.9	43
3	*	178	94.9	24.8	67
4	71.4	165	62.0	21.0	69
5	1.0	442	*	*	65
6	0.2	178	81.5	20.8	68
Mean	36.1	216	78.4	25.7	63
SD	46.0	112	13.7	5.1	10
CV	1.28	0.52	0.17	0.20	0.16

* not submitted or specifically mentioned by the student

Table 6: Baseline values of RT_{60} at frequencies 125, 250, 500, 1000, 2000, 4000 Hz obtained by all students

#	RT_{60} [s] 125Hz	RT_{60} [s] 250Hz	RT_{60} [s] 500Hz	RT_{60} [s] 1kHz	RT_{60} [s] 2kHz	RT_{60} [s] 4kHz
1	1.96	4.82	6.18	5.88	3.70	2.52
2	1.82	4.48	5.68	5.43	3.50	2.43
3	1.64	3.79	5.00	4.85	3.16	2.28
4	2.53	5.28	6.22	5.86	3.72	2.55
5	2.50	5.19	6.23	5.87	3.73	2.55
6	1.98	4.76	6.06	5.76	3.64	2.49
Mean	2.07	4.72	5.90	5.61	3.58	2.47
SD	0.36	0.54	0.48	0.41	0.22	0.10
CV	0.18	0.11	0.08	0.07	0.06	**0.04**

Table 7: Optimum values of %OH, EUI, CEI, LEI, and $sDA_{300/50\%}$ proposed by all students

#	%OH [%]	EUI [kWh/m²/yr]	CEI [kWh/m²/yr]	LEI [kWh/m²/yr]	$sDA_{300/50\%}$ [%]
1	5.4	175	78.1	31.1	62
2	*	100	34.2	31.1	54
3	*	177	*	*	57
4	70.5	149	54.0	21.0	62
5	0	312	*	*	65
6	0	162	68.8	20.8	58
Mean	19.0	179.2	58.8	26.0	60
SD	34.4	70.9	19.1	5.9	4
CV	1.82	0.40	0.33	0.23	**0.07**

* not submitted or specifically mentioned by the student

Table 8: Optimum values of RT_{60} at frequencies 125, 250, 500, 1000, 2000, 4000 Hz proposed by all students

#	RT_{60} [s] 125Hz	RT_{60} [s] 250Hz	RT_{60} [s] 500Hz	RT_{60} [s] 1kHz	RT_{60} [s] 2kHz	RT_{60} [s] 4kHz
1	0.85	0.74	0.87	0.77	0.91	0.98
2	0.88	0.80	0.87	0.73	0.70	0.68
3	1.06	1.09	0.70	0.79	0.76	0.78
4	1.30	1.04	0.74	0.40	0.46	0.46
5	1.30	1.40	0.90	1.00	0.95	0.95
6	1.13	0.73	0.81	0.77	0.71	0.75
Mean	1.09	0.97	0.82	0.74	0.75	0.77
SD	0.20	0.26	0.08	0.19	0.18	0.19
CV	0.18	0.27	0.10	0.26	0.23	0.25

Notice that the values of several performance indicators are not submitted or specifically mentioned by some of the students. In that case, the mean and SD values of those performance indicators are evaluated only across the submitted values.

Analysis and Discussion

Target values

Several remarks can be made regarding the submitted reports. From Tables 3 and 4, it is observed that several students failed to describe specifically their target values for all performance indicators. Exception is found for $sDA_{300/50\%}$, for which all students unanimously chose 55% as the minimum target, following the recommendation of LEED v4 (USGBC, 2020).

For thermal comfort, the students assigned the target criteria of %OH according to recommendations of, among others, the Passivhaus Institute (2020), SNI 6390:2011 (BSN, 2011) and Sattayakorn et al. (2017), with the target temperature range of 21~27°C or 21~24°C.

For energy intensity, various target criteria were assigned based on, among others, the criteria recommended by the Green Building Council of Indonesia for commercial buildings (GBCI, 2020) of 250 kWh/m^2/yr, the Commercial Buildings Energy Consumption Survey (CBECS) baseline for education buildings in 2003 (US EIA, 2020) of 173.5 kWh/m^2/yr (55 kBtu/ft^2/yr), and the CBECS challenge target for 2030 of 80 kWh/m^2/yr (25 kBtu/ft^2/yr).

For acoustic performance, the students based the design of RT_{60} based on, among others, the ANSI/ASA standard (ASA, 2020) or SNI 03-6386-2000 (BSN, 2000), according to the given room volume. The majority of the students did not assign different RT_{60} targets for different sound frequencies, i.e. the target values were set equal for all frequencies. The remaining students defined the RT_{60} targets only for the frequencies of 500 and 1000 Hz, which are the most relevant for speech activities.

Baseline values

From Tables 5 and 6, it is observed that reported simulation results of the baseline scenario are different from each other. In terms of thermal comfort and energy use, the differences are mainly due to the various assumptions of the thermal properties that are not listed in Table 1, as well as natural ventilation, infiltration, and (mechanical) HVAC systems. The CV of %OH is very large (1.28), because at one extreme, one of the students predicted %OH of as large as 99%, while at the other extreme, a student predicted %OH of less than 0.5%. Upon further reading of the report, it is found that the students who predicted high %OH assumed a naturally-ventilated room without air-conditioning, and/or somehow failed to properly describe or assume the insulation for the roof material, so that the observed classroom is quickly heated during the day. Meanwhile, those who predicted low %OH already assumed an air-conditioning system for the room in the baseline scenario.

Among the energy uses, the smallest CV is obtained for the cooling energy intensity (CEI), where the obtained standard deviation (SD) across the six students is 17% of the obtained mean values. The CEI values themselves lie between 62 and 95 kWh/m^2/yr. The total EUI has a CV of 0.52, with actual values ranging from 142 to 442 kWh/m^2/yr. Again, this variation is mostly related with the assumed ventilation and air-conditioning systems.

The sDA$_{300/50\%}$ has the CV of 0.16, with actual values ranging from 43 to 69%. However, if the report from student #2 (Table 5) is removed from the analysis, the remaining predicted sDA$_{300/50\%}$ values are very close to each other (65~69%). It is unclear from the report as to why that student predicted a relatively lower value; it was possibly due to different assumption of glazing layers of the windows, or incorrect weather data. For daylighting simulation, *Sefaira* incorporates a set of default ambient parameters (Truesdell, 2018). These default parameters have been tested against various sets of ambient parameters typically used in *Radiance*-based tools and have shown relatively good agreements. Moreover, in this case study, the students were not guided to change the ambient parameters. Thus, the impact on the variability observed in the daylighting simulation results is expected to be small, if not non-existent.

As for the acoustic aspect, the CV of all RT$_{60}$ (represented with either EDT, T_{20}, or T_{30}) in the baseline scenario are relatively small, between 0.04 for the frequency 4000 Hz and 0.18 for 125 Hz (Table 6). The differences between students results occur mainly due to different assumptions of material used in the simulation.

In fact, among all performance indicators evaluated for the baseline scenario, the RT$_{60}$ at 4000 Hz is the one with the smallest CV. The RT$_{60}$ at 2000 and 1000 Hz come with the second and third smallest CV; giving suggestion that the prediction of room reverberation time at mid-high frequencies, for the provided room geometry, is the most reliable in this small case study.

Optimum values

In the assignment, the students are specifically asked to modify only the material properties, including changing the surface areas, in order to achieve the target and yield the optimum. From Tables 7 and 8, it is observed that reported simulation result of the optimum scenario also differs from each other. In general, since the performance indicators values in the baseline scenario already differ between students, the proposed optimum values are also expected to differ, although the CV values in the optimum scenarios are not necessarily larger than those in the baseline scenario.

The smallest CV value (0.07) among all performance indicators in the proposed optimum design is achieved by the sDA$_{300/50\%}$, which actual values are found between 54 and 65%. Interestingly, the CV value is smaller than the corresponding value in the baseline scenario, meaning that the optimisation efforts have successfully ended up with rather similar optimum values of around 55%, as per LEED v4 recommendation.

With regard to the acoustic performance, it is observed from Table 6 that the RT$_{60}$ in the baseline scenario are arguably much higher than the recommended maximum value of approximately 1.2 s. Higher RT$_{60}$ means longer reverberation, which can create serious problem in rooms where speech intelligibility is important, such as classrooms. Thus, from the acoustic perspective, the room interior surface shall be covered with materials with higher sound absorption coefficient (e.g., gypsum or EPS boards), in order to reduce the reverberation. However, from the thermal and energy perspective, introduction of the sound-absorbing material surfaces/panels may also influence the heat balance within the room, and hence also the thermal comfort and energy use. Therefore, ideally, the thermal properties of the proposed sound-absorbing panels shall be considered altogether in the thermal and energy simulations and optimisation. Unfortunately, half of the students failed to exercise this logic in their design strategy. Instead, those students performed a 'sequential' optimisation process: all non-acoustic performances are optimised first in *Sefaira*, e.g. by adding new layers of materials with respect to the thermal transmittance (U) values, and only after that, they continued with modifying the acoustic properties of the 'optimum' material in *CATT* v9, without realising that the latter modification can bring unwanted effects to the thermal and energy performances. In such cases, the optimised RT$_{60}$ may be valid (as they are optimised the latest), but the assumed optimised thermal and energy use intensity may be not, because the assumed indoor environment conditions are not exactly the same anymore. In any case, the students were not asked to quantify whether the impact on thermal comfort and energy use is great or not; however, it is important to anticipate the possible impact, by conducting an iterative simulation process, instead of a sequential one.

Meanwhile, the modification of sound absorption coefficient of the interior material shall not necessarily influence the daylighting performance, unless when the light reflectance of the surface finishing is also changed. In the case of 'sequential' optimisation as previously mentioned, the sDA$_{300/50\%}$ shall not be influenced even though the sound absorption coefficients are modified. This explains why the proposed optimum sDA$_{300/50\%}$ values among all students have the smallest CV value, regardless of whether the students performed the optimisation sequentially or simultaneously.

To give a better visualisation on how the values of $sDA_{300/50\%}$ and RT_{60} (which results are likely to be the most reliable) are changed from the baseline to the optimum scenario, Fig. 3 displays the box plots (across all students) for the mentioned performance indicators, showing the minimum, the first, second, and third quartiles, and the maximum values of each.

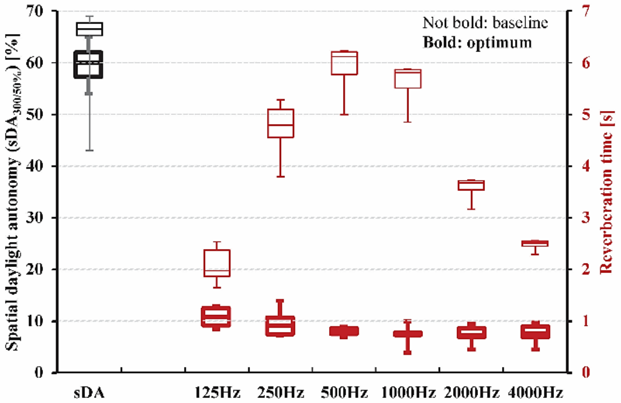


Figure 3: Box plots of the baseline (printed non-bold) and the optimum (printed bold) values of $sDA_{300/50\%}$ and RT_{60} at all frequencies

Figure 3 suggests that the baseline value of $sDA_{300/50\%}$ already satisfies the minimum criterion of 55%, so that major modifications are not required with respect to daylighting, as long as the target is still achieved.

In contrast, the RT_{60} values are all way beyond the recommended values, thus requiring further attention. All of the proposed optimised RT_{60} values are close to the target of 1.2 s, with relatively small deviation within students.

For a more realistic approach, the introduction of background noise and sources in adjacent rooms and/or outdoor noise sources may demonstrate the capability of the walls in terms of sound insulation performance, and how it can be optimised with respect to thermal performance. In this case study, however, we focus on the prediction of the room acoustic performance, which among others can be indicated with the RT_{60}, without considering noise sources other than the main one. The external noise is omitted due to the limitation of *CATT-Acoustic*, which cannot simulate the noise condition in the room due to the external noise. The interior noise can be calculated manually based on theoretical calculation with the data of transmission loss of various frequencies. Nonetheless, consideration of external noise sources shall add the value of this exercise and shall be added to the list of future development of the study.

General discussion

Some lessons can be learned from this small study. First of all, while the sample size of the participants is rather small, it is nonetheless clear that the obtained values of performance indicators differ between students, even for the baseline scenario. The discrepancy is mainly due to incomplete description of building material properties and utilities such as ventilation and mechanical air-conditioning systems. Of course, the more complete the information, the smaller the resulting discrepancy. However, this kind of situation with little to no information about relevant details is not uncommon in building practice, which creates unique challenges and is an important take-home message for the students. In practice, it is therefore important that the building designers clearly state their assumptions and communicate them with the clients or users.

Even though all aspects of building performance are important to consider, care should be given particularly in interpreting the prediction of thermal comfort and energy use, because there are many uncertain input parameters that may be entirely or partially unknown in the design stage, but do influence the outcome. This has been well reflected and confirmed in the literature (e.g. Beausoleil-Morrison and Hopfe, 2015; Reinhart et al., 2015; Imam et al., 2017; Beausoleil-Morrison, 2019). Moreover, the criteria of thermal comfort and energy use intensity often differ in various standards, codes, and regulations; all of which yield another risk of uncertainty in the outcomes.

Meanwhile, the (simplified) criteria for daylighting and acoustic performance are, to some extent, more straight-forward to compute. There are of course other relevant performance indicators in both aspects, for instance the annual sunlight exposure ($ASE_{1000,250}$) and daylight glare probability (DGP) may be added as limits to $SDA_{300/50\%}$, while other room acoustic indices such as clarity (C_{80}), definition (D_{50}), and speech transmission index (STI) are important in indoor spaces with dominant speech activities such as classrooms. Nevertheless, the main idea of the assigned student project is to observe whether the students are able to, at the first place, think in an integrated way, in the sense of all building performance aspects; instead of only partially. In this case, the project description was announced as the final assignment of the course. The students were given four weeks to finish the project and write the final report. During the project announcement, it was mentioned that the project shall be worked individually, but students were free and encouraged to discuss the design process and strategy with the lecturers and fellow students. It was also underlined that the project required integrated design in terms of all relevant building performance aspects. Two weeks later, the students presented the progress of their project, in which the lecturers could give comments and feedback on the work. Some remarks had been given regarding the possible interaction between the acoustic and thermal/energy simulation results, because at that particular time most students were still working with the *Sefaira* model. This is important because, as mentioned in the previous subsection, modifications with respect to one aspect may influence the performance of other aspects; thus a simultaneous and integrated optimisation approach is required.

The choice (by some of the students) to perform a sequential optimisation seems like a typical beginner's mistake in BPS, but it can actually happen in real building design practice, where BPS is conducted for each particular aspect by specialists, i.e. those who are experienced BPS users but do not master all of the building performance aspects altogether. Communication is therefore very important; in this case study, the academic background of the six enrolled students were quite diverse, ranging from architecture to pure physics. The students were also free to discuss with each other about their project, although the report should be written individually. Using this way, interdisciplinary interactions, as well as the idea of iterative design process, were expected to happen prior to executing the simulation plans. Apparently, at least from this study, the results are not always as expected. Therefore, clear guidance and constructive discussion are also required throughout the project to ensure that the proposed solutions are appropriate.

This fact creates challenges and opportunities for BPS educators, not only on how to teach deep understanding of the particular aspect in which BPS is required to model and optimise, but also on how to ensure broad and sufficient knowledge and understanding on the whole spectrum of building performance aspects, and how those aspects interact and influence each other.

Moreover, it is also important for the BPS educators to think about and create a project that brings students to the discovery of strong interdisciplinary interactions and the need for an iterative process in order to obtain the optimum solution. In-depth discussion shall also be encouraged to ensure that the proposed final solution will be acceptable and realistic.

Conclusion

Analysis of student reports on an integrated BPS approach in combining thermal, energy, lighting, and acoustic aspects has been reported in this study, for the case study of a hypothetical classroom. Among the aspects, lighting performance ($sDA_{300/50\%}$) is the most consistently predicted, with the coefficient of variance (CV) of 0.16 (baseline) and 0.07 (optimum). In opposite, thermal comfort indicator (annual overheating hours) is the least consistent, with CV of 1.28 (baseline) and 1.82 (optimum).

Based on the submitted reports, it is found that only 50% of the students modified the interior materials by considering the four aspects at the same time, so that the results were optimum for all aspects. The remaining 50% chose to optimise the materials considering the first three aspects, as they could be done in *Sefaira*, and then modified the material with respect to acoustic aspect in *CATT* v9; without realising that the last step might also influence or change the thermal, energy, and lighting performance.

In closing, the findings of this study can be applied to improve the content of BPS education by employing integrated building performance design approach. For the practitioners, it is suggested to consider the acoustic aspect along with the thermal, energy, and lighting aspects in building design projects, with the knowledge that simulation results of thermal and energy aspects may be less consistent due to greater uncertainties compared to the remaining aspects. For the simulation tools developers, it can be suggested to consider improving the capability of BPS tools in facilitating integration or iteration between building performance domains, so that the simulation results can be held more reliable.

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