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A Case Study on Passive vs. Active Strategies for an Energy-Efficient School Building Design

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Abstract: This paper presents a simulation study to reduce heating and cooling demand of a school building in Seoul Metropolitan Area, Korea. This study aims to cross-compare the impact of passive (e.g. improved thermal performance of envelopes, redesign of the building shape and orientation) vs. active (blind control, lighting control, heat exchanger, and geothermal heat pump) approaches on building energy savings using EnergyPlus simulation. It was found that the energy saving of the original school building design by lighting control is most significant. In addition, the energy saving from the original design to a new improved building design increases by 32%. It is noteworthy that energy saving potentials of each room significantly vary depending on room's thermal characteristics (window-wall-ratio, internal heat generation, ventilation requirement) and orientation. Thus, the energy saving analysis should be introduced at the level of individual space, not at the level of the whole building. Also, simulation studies must be involved for informed rational design. Finally, it was concluded that a priority should be placed on passive building design strategies, such as building orientation as well as control and utilization of solar radiation. Passive building design strategies for enhancing energy efficiency are related to urban, architectural design and engineering issues, and are more advantageous in terms of energy savings than active strategies.

Keywords: energy efficiency; passive; active; building design strategies; architectural engineering; energy simulation

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1. Introduction

The Zero Energy Building (ZEB) design has become a high and imminent priority for architects and multi-disciplinary researchers [1-2]. With no standardized definition of ZEB, Torcellini et al. [3] indicate that a good ZEB should first attempt energy efficient design, and then employ available renewable energy production on site. In particular, the integration of active and passive design elements is important to achieve the required energy efficiency and energy productivity of a ZEB. Generally the requirements of Net Zero Energy Buildings are easier to achieve than the requirements of standalone Zero Energy Buildings [4-5]. In order to achieve a net zero energy consumption of a building over the period of one year, the total renewable energy production of a building has to be at least similar or even exceed the total energy demand of the concerned building.

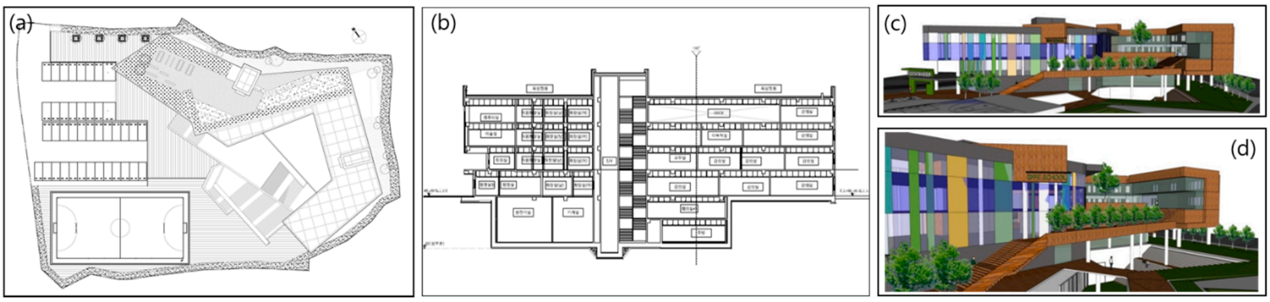
Building Energy Performance Simulation (BEPS) tools have been widely used for energy efficient building design since they take into account the dynamic thermal behavior of buildings, climatic conditions, and user behavior [6]. Several studies [7-9] have shown that the active and passive systems can be successfully simulated for informed rational decision-making.

In this paper, the authors discuss a ZEB project, in which the energy saving potential of active and passive design elements was compared using BEPS. The production of renewable energy will not be discussed in this paper. Accordingly this paper focuses on the enhancement of the energy efficiency and reduction of the end energy demand. In order to facilitate such a comparison two building designs had to be compared with each other. The process involved the identification of effective design and control strategies to achieve the ZEB concept for the concerned school building design. The energy efficiency two different building designs and different technology applications were compared by means of the program EnergyPlus [10], a widely used BEPS tools. This paper presents results and insights learned from the research and design project for the concerned ZEB building in Korea.

2. Project Description

The ZEB School building in Korea, which is discussed in this paper (Figure 1) was designed as a high school for international students. The total usable floor area of the building is 7,963 m^2. The building has four floors above ground and two underground levels. The main building orientation is towards southwest. Each room is equipped with an individual electric heat pump for cooling and heating, and LEDs for lighting. There are staff rooms, administrative rooms, and classrooms on the floors above ground. The underground floors accommodate a gymnasium, a cafeteria, a mechanical and electric equipment room, and a music room with windows to a sunken garden. The U-values of building envelopes are: 0.183 W/m^2-K for underground walls, 0.147W/m^2-K for walls above ground, 0.113W/m^2-K for roofs, and 0.795W/m^2-K for windows. The g-value of the windowpanes is 0.442. In comparison, the recommended U-values for passive house design are as follows: 0.08-0.15 W/m^2-K for underground walls, 0.06-0.15 W/m^2-K for walls above ground and 0.8 W/m^2-K for windows [11]. The underground walls and g-value of windows do not meet the passive house design criterion (The g-value for passive house is 0.5).

Figure 1. (a) Site plan. **(b)** Section. **(c)** 3D view from southeast. **(d)** 3D view from southwest.



Before attempting to apply renewable energy to the building, the original design was simulated to investigate the energy efficiency. Based on architectural drawings and specifications, the authors developed a simulation model using the program EnergyPlus (Figure 2(a)). The school is operated during five days per week, but not during the weekends and the school holiday periods. The summer and winter vacations are from Jun 27th to August 31th, and from January 1st to March 3rd respectively. Internal heat generation (people, lights, and equipment) was assumed based on the database of the program DesignBuilder [12].

Table 1 and Figure 2 (b) show the simulation results of the original school design. The total annual end-energy demand is in the range of so-called low energy buildings. Compared with conventional Korean school buildings the annual end-energy demand of 44.86 kWh/m^2-year is very low. The heating and cooling energy demand is relatively low because the thermal performance of the building envelope is excellent. Due to the low heating and cooling energy demand, the portion of lighting energy demand accounts for 44.46% (Table 1) of the total end-energy demand. Accordingly, reducing the energy demand for artificial lighting became a priority for the further reduction of the building's energy demand. Based on Table 1, the authors developed active design strategies for the reduction of the building's energy demand, which will be explained in the following section.

Figure 2. (a) Simulation model. **(b)** Energy consumption of the original school design

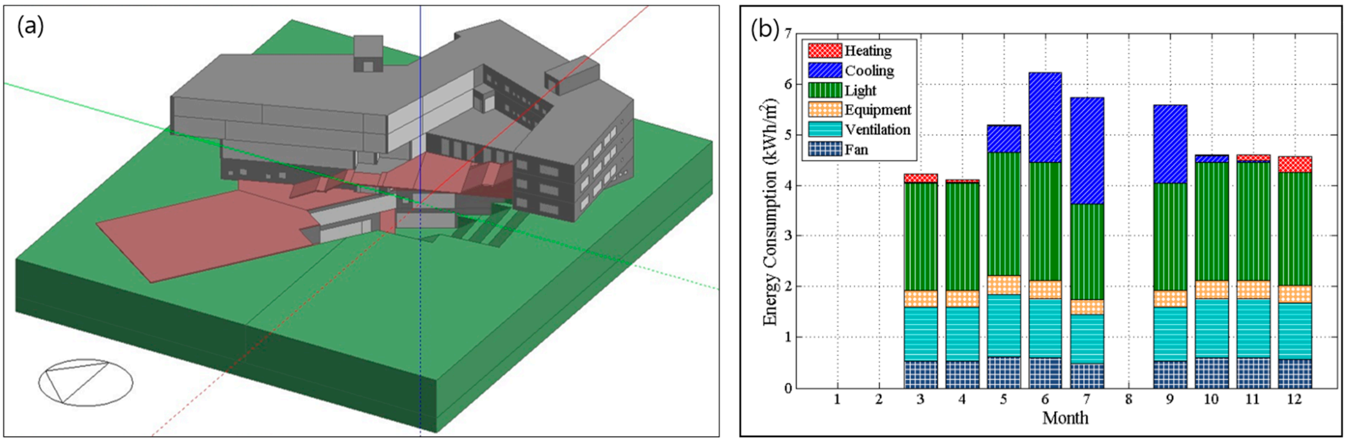


Table 1. Annual energy use of the original design

	Heating	Cooling	Lighting	Equipment	Ventilation	Fan	Total
kWh/m^2-year	0.69	6.10	19.95	3.10	10.00	5.03	44.86
%	1.53	13.60	44.46	6.90	22.29	11.22	100.00

3. Active Strategies

3.1. Application of Active Strategies

Since the initial building design was already completed and passive strategies (change of orientations, window-to-wall ratio, room relocation, etc.) require significant effort and time for redesign of the school, the authors started first to apply active strategies in order to reduce the building's end energy demand. As mentioned above, intelligent lighting control was primarily considered in this regard. In addition, dynamic blinds and controlled ventilation systems with heat recovery were also considered. The three active design strategies can be summarized as followed:

- Blinds - Dynamic exterior blinds: In cooling mode, blinds are closed (rolled down) to block incident solar radiation. In heating mode at daytime, blinds are rolled up to induce solar radiation as much as possible. In heating mode at nighttime, blinds are rolled down to minimize long wave radiation between glazing surfaces and outdoors environment (e.g. a cold night sky).
- Lights - Daylighting autonomy: If indoor daylight illuminance is higher than the thresholds (classroom: 400lx, office: 300lx), the artificial lighting is automatically turned off. If indoor illuminance is lower than the thresholds, 3 steps of dimming control is applied (33%, 66%, 100%) for artificial lighting.
- HE - Controlled ventilation with heat recovery by Heat Exchanger (HE): In the origin design, there is no mechanical ventilation system considered but windows were regarded as a mean for fresh air supply. For energy savings, a CO_2 level controlled mechanical ventilation systems with HE with demand control is introduced. The ventilation rate is set to 9.44L/s-person and the heat recovery efficiency of the ventilator with regard to total heat (both sensible and latent) is 0.8. In addition, the HE is not operated and in bypass economizer mode when outdoor air temperature is between 10℃ and 23℃.

3.2. Results

Table 2 and Figure 3 show the simulation results of active design strategies. The lighting control strategy could save 28.07% of total annual end energy consumption by reducing 25% of the cooling energy and 55% of the lighting energy demand. The cooling energy demand can be significantly reduced by dynamic blinds and lighting control. In contrast, the heating energy demand increases since the exterior blinds prevent transmission of part of solar radiation, and lighting control reduces heat generation from luminaries.

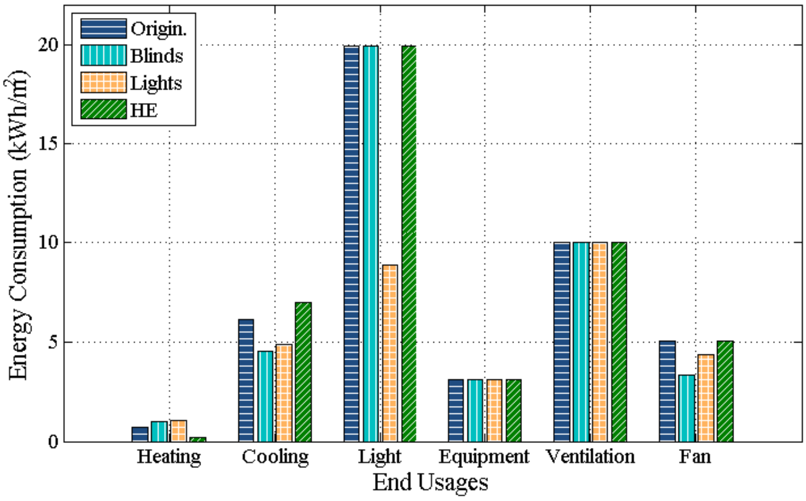
The introduction of controlled ventilation system with HE was efficient in heating mode, but increased the cooling energy demand due to introduction of hot and humid outdoor air during the summer.

Table 2. Annual simulation results of active strategies (kWh/m^2-year).

	Heating	Cooling	Lighting	Equipment	Ventilation	Fan	Total	Saving (%)
Orig.	0.69	6.10	19.95	3.10	10.00	5.03	44.86	-
Blinds	1.02	4.51	19.95	3.10	10.00	3.35	41.92	6.57
Lights	1.07	4.89	8.88	3.10	10.00	4.33	32.27	28.07
HE	0.22	7.01	19.95	3.10	10.00	5.03	45.30	-0.99

The results shown in Table 2 and Figure 3 are based on the simulation of the entire building. The energy saving potential of each active design strategy varies significantly depending on thermal characteristics of room type and orientation. Four classrooms and offices were randomly selected as shown in Table 3.

Figure 3. Annual simulation results of active strategies (kWh/m^2-year).



According to the finding illustrated in Tables 4 and 5, the energy saving rate of individual classrooms is higher than that of the whole building. There are interesting findings as follows:

- Energy saving potentials of dynamic blinds and artificial lighting control are significantly influenced by the room's orientation, WWR and the specific season related to the investigated months (January=Winter, May=Spring, August=Summer). For example, blinds and lighting controls are most advantageous to Room #7 since it faces south and has 100% of WWR.
- Controlled ventilation with heat recovery by Heat Exchanger (HE) is most advantageous to classrooms because due to high density of students, the required ventilation rate is higher than the required outdoor rate of the offices.
- Return On Investment (ROI) is dependent on the strategies as well as the room's thermal characteristics, e.g. WWR, the portion of specific air-conditioning modes (cooling versus. heating), the required artificial lighting level, ventilation rate, etc. Rather than following intuition or expert's judgment, simulation studies must be involved for informed rational design.
- The energy saving analysis of the aforementioned strategies (Blinds, Lights, HE) should be done at the level of individual space, not at the level of the whole building.

Table 3. Floor area and Window-To-Wall Ratio (WWR) of classrooms and offices.

	Classrooms				Offices			
	Room 1	Room 2	Room 3	Room 4	Room 5	Room 6	Room 7	Room 8
Orientation	East	West	South	North	East	West	South	North
Floor area (m^2)	127.68	134.44	121.67	161.09	57.24	97.33	60.90	50.86
WWR (%)	23.0	47.6	26.4	20.5	12.2	13.5	100.0	13.9

Table 4. Energy savings of active strategies

Room #		season	Origin.	Blinds		Lights		HE	
			Energy (kWh)	Energy (kWh)	Saving (%)	Energy (kWh)	Saving (%)	Energy (kWh)	Saving (%)
Classrooms	Room1	Jan.	84	85	-1.2	78	7.2	45	46.0
		May	128	102	20.6	89	30.8	130	-1.3
		Aug.	172	145	15.9	129	24.9	167	2.9
	Room2	Jan.	96	96	-0.3	91	5.0	53	44.8
		May	161	104	35.4	116	27.8	163	-1.1
		Aug.	212	149	29.8	166	21.8	206	2.9
	Room3	Jan.	74	74	-0.8	61	17.5	42	43.4
		May	114	91	19.8	81	28.6	115	-1.4
		Aug.	162	135	16.7	130	19.4	157	2.8
	Room4	Jan.	111	112	-1.0	103	6.8	57	48.1
		May	154	125	18.9	99	35.6	156	-1.2
		Aug.	209	179	14.7	153	26.9	202	3.4
offices	Room5	Jan.	82	82	0.9	82	0.4	77	6.1
		May	71	59	17.7	52	27.3	72	-1.3
		Aug.	85	72	15.7	64	24.5	86	-0.8
	Room6	Jan.	80	79	0.7	80	0.0	68	15.1
		May	100	92	8.3	92	8.6	101	-0.9
		Aug.	124	114	7.9	113	8.7	123	1.0
	Room7	Jan.	26	26	0.9	17	35.7	28	-9.1
		May	150	81	45.9	129	13.9	151	-0.6
		Aug.	181	101	44.3	159	11.8	181	-0.4
	Room8	Jan.	50	49	1.2	49	2.7	42	15.9
		May	74	61	17.0	54	26.6	75	-1.2
		Aug.	86	73	14.8	66	23.3	88	-2.1

4. Passive Strategies

4.1. Application of Passive Strategies

In the original building design, most rooms on the 2nd floor of the building have almost 100% of WWR. In addition, most classrooms and staff rooms are located on both sides of the corridor and face to different directions, to east, west, or north. The gymnasium and music rooms are located underground and deep inside the building, without any windows to the outside. The active design strategies that are discussed in section 3 of this paper show significant energy saving potentials. However the authors decided to re-design the building to correct the aforementioned issues such as improvement of WWR and daylighting potential for all rooms. The aim was to identify how much more energy could be saved by the application of passive design strategies in the re-design of the concerned school building.

Figure 4 shows the site plan, section and 3D of the re-designed school building, of which the size is similar to that of the original design. Compared to the shape and design of the original school building, which is long and narrow (Figure 1, 2) with comparable low compactness, the re-designed school building is more cubic and compact. In order to facilitate daylighting of central building space and rooms the building re-design is equipped with an atrium in the center of the building (Figure 4, 5a). Table 5 shows a comparison of the area, volume and WWR of the original and the re-designed school buildings. The floor area of the re-design is greater than that of the original design (re-design: 8,573m^2, original: 7,963m^2). The improved U-values of building envelopes of the re-design are as follows: 0.120 W/m^2-K for underground walls, 0.111W/m^2-K for the walls above ground and 0.111W/m^2-K for the roof. The u-value and SHGC of windows are similar to the original design.

Figure 4. (a) Site plan. **(b)** Section. **(c)** 3D picture from southeast.

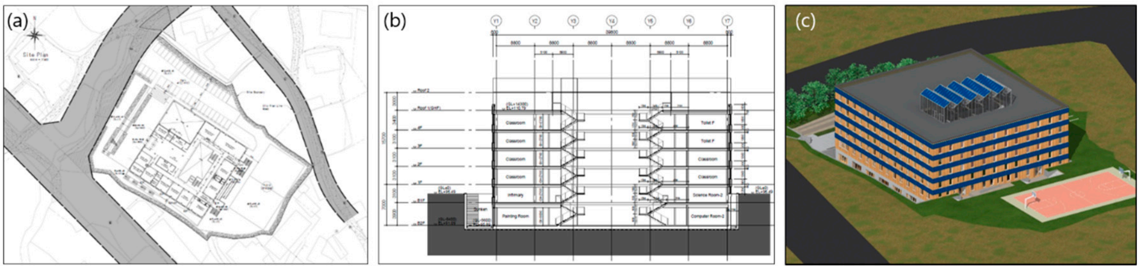


Table 5. Comparison of areas, volume and WWR of original and re-designed school building.

	Total floor area (m^2)	Exterior envelop area (m^2)	WWR (%)	Conditioned area (m^2)	Conditioned Volume (m^3)
Original design	7,693	1,958	28.24	4,599	19,841
Re-design	8,573	1,733	29.44	4,955	16,079

4.2. Results

The dynamic building simulation that was conducted on the re-designed school building with the program EnergyPlus shows the following results. The annual energy consumption of the re-design is 30.47 kWh/m^2, leading to savings in the end-energy demand of 32% compared with the original school building design. The calculated savings were achieved without including the active design strategies which have been discussed in section 3 in order to reduce the end-energy demand of the original school building design. The percentages of the end-energy demand for specific uses in relation to the total end-energy demand are illustrated in Table 6. The results show that percentages in relation to total are similar to the original school design and the values presented in Table 1. The amount of end-energy consumption of different uses in specific months is illustrated in Figure 5b.

Figure 5. (a) Simulation model. **(b)** Energy consumption of the re-designed school

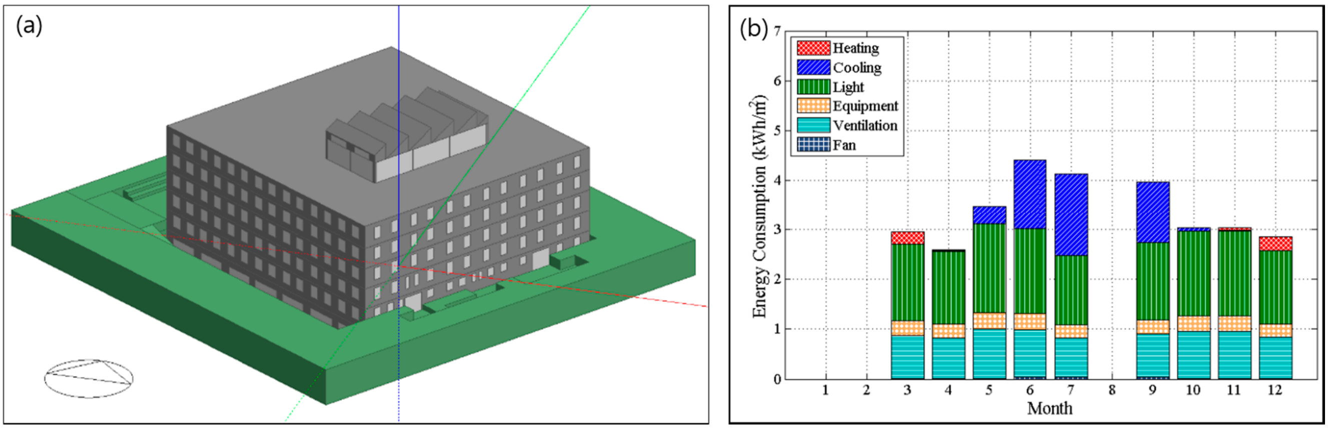


Table 6. Annual energy use of the re-design

	Heating	Cooling	Lighting	Equipment	Ventilation	Fan	Total
kWh/m^2-year	0.60	4.73	14.29	2.65	8.04	0.15	30.47
%	1.96	15.52	46.91	8.70	26.40	0.50	100.00

5. Integration of Active and Passive Strategies

The active design strategies discussed in section 3.1 were also applied to the re-designed school building. Table 7 and Figure 6 show the simulation results.

The energy saving potential (%) of each active design strategy (Table 7) of the re-designed school building is similar to the percentages of presented in Table 2. As shown in Table 2 and 7, the lighting control is most advantageous. It is noteworthy that the energy consumption of the passive design (30.47 kWh/m^2-year) is better than the best active strategy (lighting control) in the original design (32.27 kWh/m^2-year). When lighting control is applied to the re-design, the energy consumption is reduced to 21.82 kWh/m^2-year, which is close to energy saving rate of 51.36 % (Table 8).

According to the findings the effectiveness of active strategies regarding the reduction of the total end-energy demand vary significantly between the original school design and the school re-design. The end-energy saving rate by application of dynamic blinds on the original school design is for instance 6.57% while the energy saving by application of dynamic blinds on the re-designed school building is only 2.03%.

Table 7. Annual simulation results of the re-design with active strategies (kWh/m^2-year).

	Heating	Cooling	Lighting	Equipment	Ventilation	Fan	Total	Saving (%)
Passive design	0.60	0.73	14.29	2.65	8.04	0.15	30.47	-
Blinds	0.82	3.91	14.29	2.65	8.04	0.13	29.85	2.03
Lights	0.85	3.85	6.30	2.65	8.04	0.13	21.82	28.39
HE	0.06	5.36	14.29	2.65	8.04	0.15	30.56	-0.31

Figure 6. Annual simulation results of the re-design with active strategies (kWh/m^2-year).

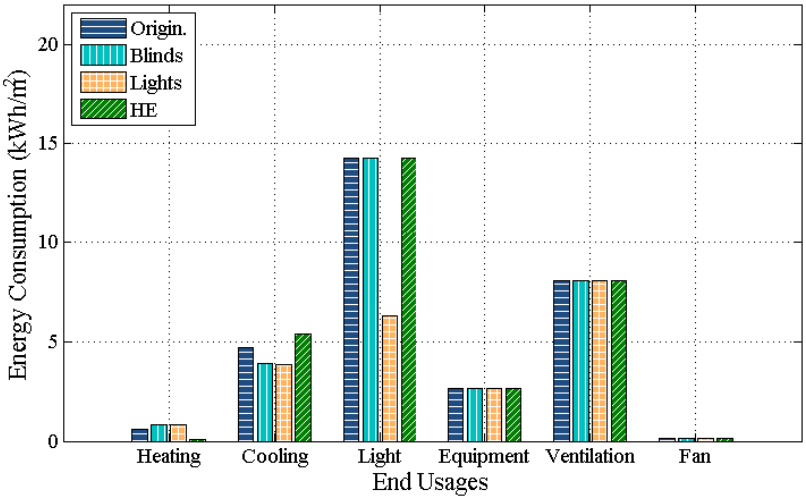


Table 8. Integration of active and passive strategies.

	Original design	Original design with active strategies		Re-design (Passive)	Re-design with active strategies	
		Best (Lights)	Worst (HE)		Best (Lights)	Worst (HE)
Energy (kWh/m^2)	44.86	32.27	45.30	30.47	21.82	30.56
Saving (%)	-	28.07	-0.99	32.08	51.36	31.88

6. Conclusions

This study addresses a ZEB school design project with application and comparison of passive and active design strategies for the reduction of the buildings end-energy demand. The following important findings were derived from the study:

- Energy saving potentials of active strategies are significantly influenced by the room's thermal characteristics such as orientation, WWR, dominant air-conditioning mode (cooling vs. heating), required ventilation rate (L/s), illuminance level, etc. Special attention should be paid to the selection of active strategies.

- The energy saving analysis should be introduced at the level of individual space, not at the level of the whole building. Also, building simulation studies must be involved for informed rational design and control.
- Passive building design strategies should be primarily addressed since passive strategies are more advantageous in terms of energy savings than active strategies. The re-designed school building according to passive design strategies, and without application of active design strategies analyzed in this study, has for instance a lower end-energy demand than the original school design with active design strategies being applied.

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Conflict of Interest

The authors declare no conflict of interest.

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