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**SCUOLA DI ARCHITETTURA, URBANISTICA
E INGEGNERIA DELLE COSTRUZIONI**

MASTER OF SCIENCE IN BUILDING AND ARCHITECTURAL ENGINEERING

Indoor comfort and energy retrofit of school buildings

A case study in Milano - via Zuara

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ABSTRACT

Public buildings are significant energy consumers considering their monumental size and intensity of usage. Being built in architectural historic styles, these facilities originate from the time period prior to The Industrial Revolution, thus the technology being used for constructing them did not include energy-saving in their building concepts. It is clear that retrofitting using new technologies would provide ways of adaptation to contemporary requirements in terms of energy-efficient building strategies. Those ways are varying from the simple first step interventions such as reducing the overall costs of maintenance and usage to more current concerns of CO_2 emissions. Schools are one of the most intensively used buildings of this type and the comfort conditions are important in order to ensure student's best possible wellbeing and productivity. The method to reach the comfort thresholds and reach the best energy usage results means to exploit the gains and reduce the losses. There are a few ways to do so: thermally insulating the building's envelope, replacing existing windows with higher performance ones, enhancing solar gains during winter and reducing them during summer, and finally, using ventilation in the most favorable way.

For the sake of this thesis, static and dynamic calculations were used in order to estimate realistic conditions in the best possible way. Inputs were calculated based on the information collected on the site in order to set the baseline - current state of the building. Retrofit strategies were applied to the baseline and each step was parallelly compared with the other in order to apply the greatest improvement. It is not possible to reach the comfort threshold with passive strategies, but aiming to achieve the most of it is beneficial in the long run.

This thesis aims to create a base point, identify possible problems, and most importantly contribute to further encouraging the discussion in this field concerning ubiquitous topics related to indoor comfort and energy retrofit of the buildings.

SOMMARIO

Gli edifici pubblici sono importanti consumatori di energia considerando le loro dimensioni monumentali e l'intensità di utilizzo. Essendo costruite in stili storici architettonici, queste strutture risalgono al periodo precedente alla rivoluzione industriale, quindi la tecnologia utilizzata per costruirle non includeva il risparmio energetico nei loro concetti di costruzione. È chiaro che il retrofit utilizzando le nuove tecnologie fornirebbe modalità di adattamento alle esigenze contemporanee in termini di strategie edilizie efficienti dal punto di vista energetico. Questi modi variano dai semplici interventi di prima fase, come la riduzione dei costi complessivi di manutenzione e utilizzo, alle preoccupazioni più attuali sulle emissioni di CO_2. Le scuole sono uno degli edifici più utilizzati di questo tipo e le condizioni di comfort sono importanti per garantire il miglior benessere e produttività possibile degli studenti. Il metodo per raggiungere le soglie di comfort e raggiungere i migliori risultati di consumo energetico significa sfruttare i guadagni e ridurre le perdite. Ci sono alcuni modi per farlo: isolare termicamente l'involucro dell'edificio, sostituire le finestre esistenti con altre più performanti, aumentare i guadagni solari durante l'inverno e ridurli durante l'estate e, infine, utilizzare la ventilazione nel modo più favorevole.

Ai fini di questa tesi, sono stati utilizzati calcoli statici e dinamici al fine di stimare condizioni realistiche nel miglior modo possibile. Gli input sono stati calcolati sulla base delle informazioni raccolte sul sito al fine di impostare lo stato di riferimento - attuale dell'edificio. Le strategie di retrofit sono state applicate alla linea di base e ogni passaggio è stato confrontato parallelamente con l'altro per applicare il miglioramento maggiore. Non è possibile raggiungere la soglia di comfort con strategie passive, ma puntare a ottenerne il massimo è vantaggioso nel lungo periodo.

Questa tesi mira a creare un punto di partenza, identificare possibili problemi e, soprattutto, contribuire a incoraggiare ulteriormente la discussione in questo campo su argomenti onnipresenti relativi al comfort interno e al retrofit energetico degli edifici.

INTRODUCTION

The construction sector is responsible for 40% of final energy consumption and 36% of greenhouse emissions in Europe. If we focuse more on re-using buildings and improving the existing ones, we could reduce number of factors that are enhancing climate change.

If we focus on buildings that are non-residential, we can see that the majority of energy consumption is taken by schools. Moreover, educational buildings are the spaces where the comfort threshold should be on a high level of respect in order to assure 100% of the undisturbed focus of attendants.

Since many schools were built before it was one of the priorities to take care of energy performance, many of those buildings have problems of energy dissipation these days. Performance of the envelope and other parts of the building is lower, as expected. To meet the current requirements of efficiency, retrofit of those buildings is advised.

In order to reach a good and accurate effect, the baseline model used as a starting point should be as precise as it could be, starting from the geometry of the school, construction of it to the loads and users profile in the building.

To be sure that the model is as close as the real building's state, a site visit has been done. By the use of the non-destructive method of research, information have been collected and transferred as input to the model in order to carry out the analysis of possible solutions.

CHAPTER 1. CLIMATE ANALYSIS

Weather analysis is one of the first steps in retrofit process. Through this kind of analysis, we can conclude what will be the main focus. By extracting the data from .epw file, there are many parameters that could be derived, but this chapter will focus shortly on temperature and heating, cooling and neutral hours, as they are the most relevant for the kind of analysis that is gonna be presented in this document. The following analysis is done for Milan, since that is the locaton of the case study.

1.1 Temperature

The relative humidity in Milan is most of the time higher than 70% and is globally higher during the cold months. The temperature for the most parts of the year stays between -8 °C and 32 °C.

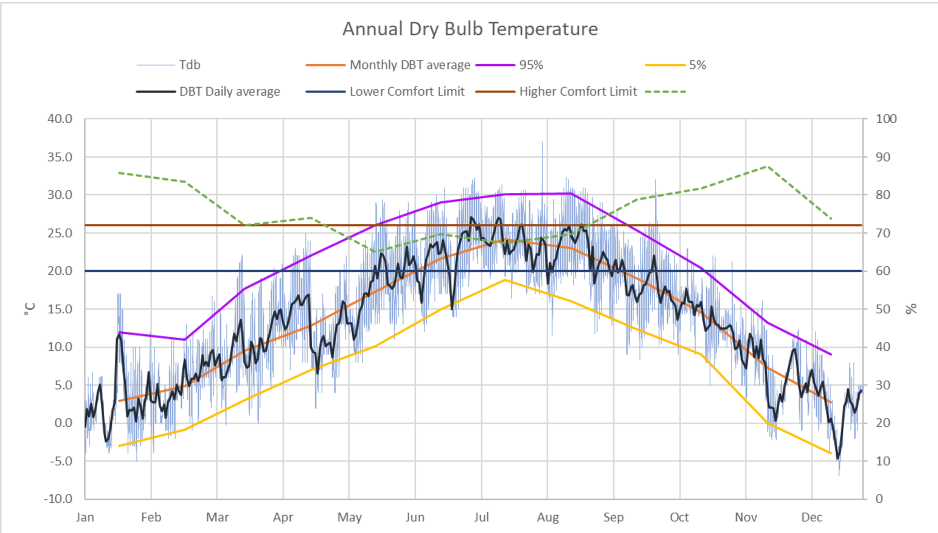

Fig. 1. Temperature and Relative Humidity distribution over the year in Milan.

By analyzing the temperature, we can see that the main concern of climate like this is heating, while on the other hand during warm months cooling is not required most of the time.

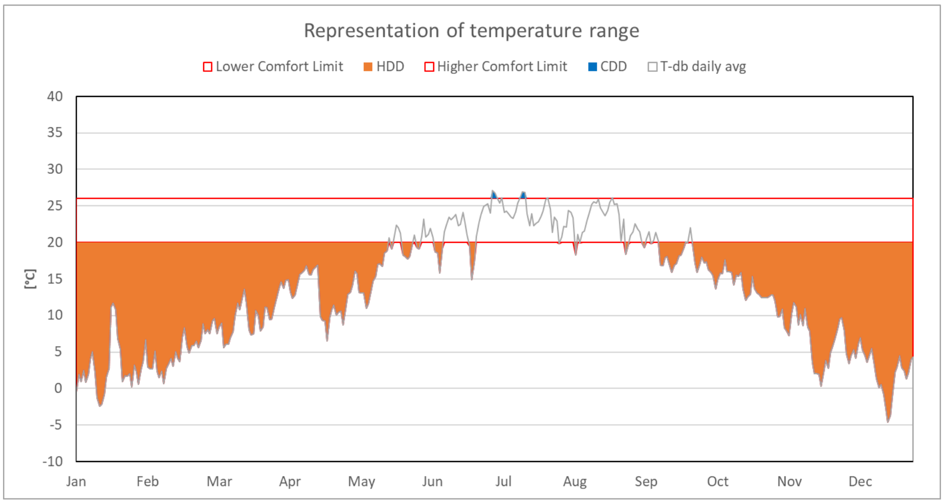

Figure 1 - Representation of temperature renge

1.2 Heating and cooling hours

Taking into consideration only working time, there are 73% of heating and only 7% of cooling hours. Neutral hours represent 20% of the total hours, and the amount is higher as we are closer to summer time.

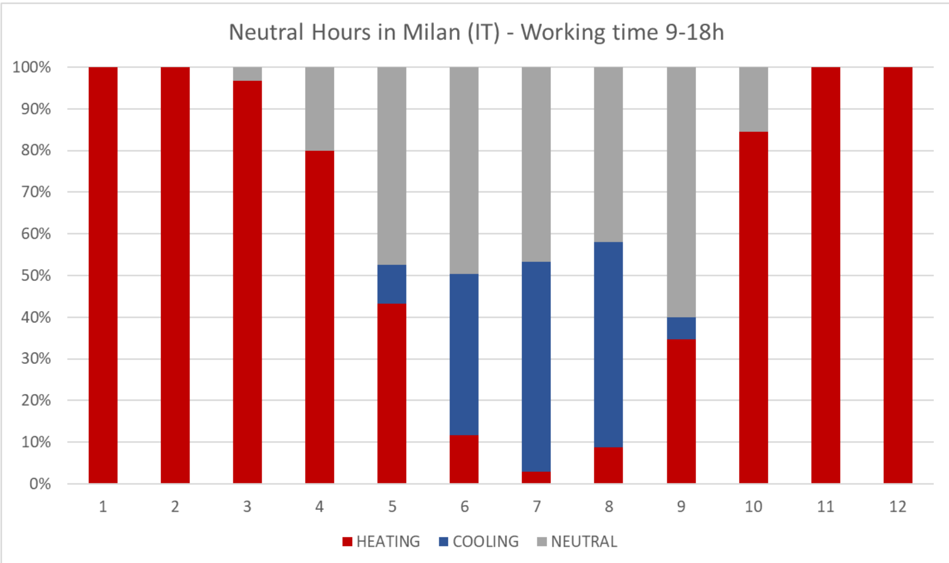

Figure 2 - Representation of heating, cooling and neutral hours of outside temperature duringworking time

CHAPTER 2. BASELINE

The subject of research is a primary school in Milan that has a total of 447 children attending the classes held by 21 teachers. The number of other staff is considered as 15. All the common areas and offices are placed on the ground floor, while the other two floors are reserved for the classrooms. Since the gym is a separate space and it is connected to the school by a small corridor, it is not considered in this analysis.

2.1 Floor plans and sections

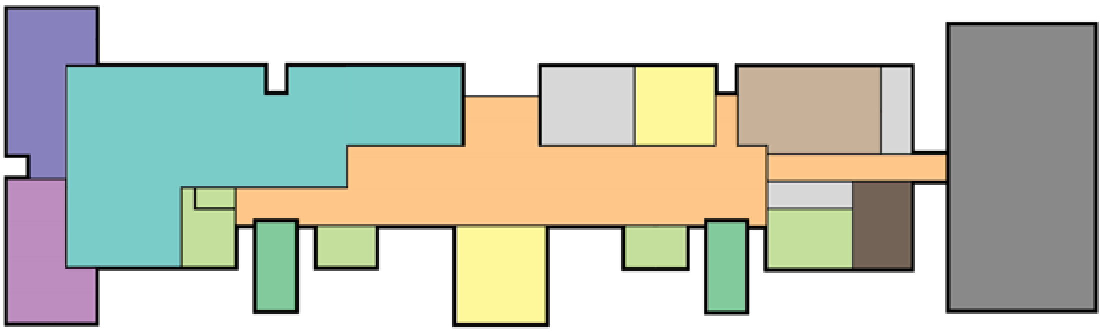

Figure 3 - Ground floor with space typologies

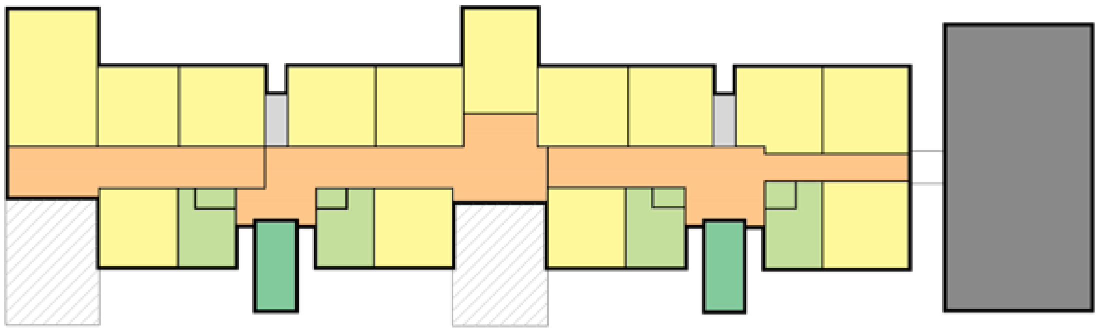

Figure 4 - 1st floor plan with space typologies

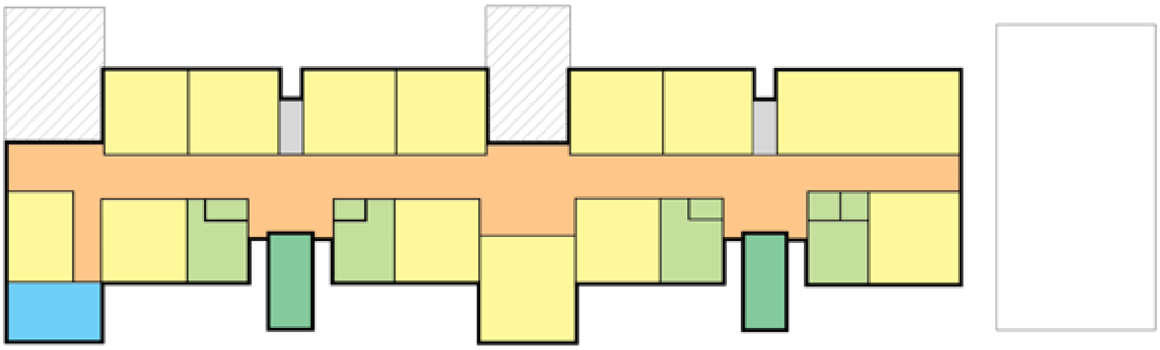

Figure 5 - 2nd floor plan and space distribution

Figure 6 - Legend of space typologies

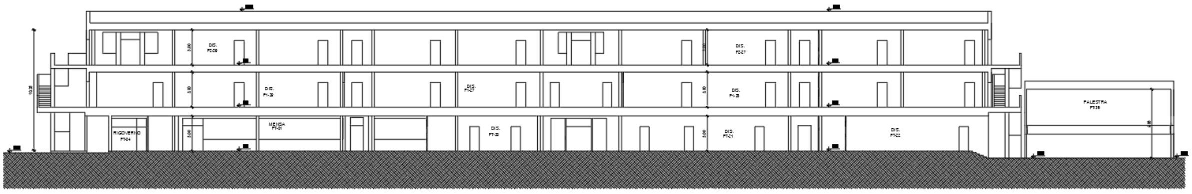

Figure 7 - Longitudinal section of the building

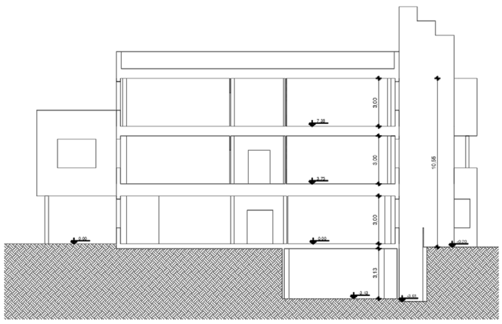

Figure 8 - Transversal section of the building

2.2 Construction, materials and properties

All the characteristic values of the materials are shown in the table. The corrected U value was used in order to take into account the impact of thermal bridges. This is done by following simple calculations that will be shown in the next chapter. New U value in IES-VE was obtained by reducing the thickness of one of the layers.

2.2.1 External walls

Figure 9 - External wall pictures

External walls of the school are assumed as prefabricated. The panels have different dimensions depending on the position. Overall thickness of the external wall is 20cm. The panel consists of prefabrisated concrete which has the gap in the middle as it could be observed in the Figure 10. Because of the complexity of the panel, the best way to consider this gap in the panel was to use equivalent values for parameters when calculating U-value.

Layers	Thickness [m]	Conductivity λ [W/mK]	Density ρ [kg/m³]	Spec. heat capacity c_p [J/Kg*K]	Thermal resistance, R [m²K/W]
External surface res.	--	--	--	--	0.04
Concrete panel	0.20	1.40	1700.00	1000	0.14
Air gap	0.03	-	-	-	0.20
Plasterboard	0.01	0.16	1800	837	0.08
Internal surface res.	--	--	--	--	0.13
total	**0.24**			**Rtot**	**0.59**
				Uvalue [W/m² K]	**1.69**
				U' [W/m2 K]	**1.98**
				R' [m2 K/W]	**0.29**
				ΔU	**0.29**
				ΔR	**0.09**
				New Thickness of concrete layer [m]	**0.076**

Table 1. U-value of external walls.

2.2.2 Internal walls

Internal partitions are assumed to be constructed with under-construction and finishing with plasterboard which means that there is the air gap. In that air gap small amount of insulation is assumed. The layers are reported in the table below.

Layers	Thickness [m]	Conductivity λ [W/mK]	Density ρ [kg/m³]	Spec. heat capacity c_p [J/Kg*K]	Thermal resistance, R [m²K/W]
Internal surface res.	--	--	--	--	0.13
Gypsum/plaster board	0.01	0.16	1800	837	0.08
Air gap	0.05	-	-	-	0.20
insulation panel (equivalent	0.05	0.040	35	800	1.25
Gypsum/plaster board	0.01	0.16	1800	837	0.08
Internal surface res.	--	--	--	--	0.13
total	**0.33**			**Rtot**	**1.87**
				Uvalue [W/m² K]	**0.53**

Table 2. U-Value of internal walls

2.2.3 Roof

While visiting the site, it was recognised that on the flat roof, additional slopes were created in order to regulate irrigation of atmospheric water. To simplify simulations, equivalen thickness of gap created under the slope was used.

Figure 10 - Picture of the roof

Layers	Thickness [m]	Conductivity λ [W/mK]	Density ρ [kg/m³]	Spec. heat capacity c_p [J/Kg*K]	Thermal resistance, R [m²K/W]
outdoor surface res. equiv.	--	-	-	-	0.10
Non insulated slope screed	0.05	1.00	1200	1000	0.05
Air gap	0.35	-	-	-	0.20
Hollow brick slab	0.20	0.45	2300	1000	0.44
Internal surface res.	--	--	--	--	0.10
total	**0.25**			**Rtot**	**0.89**
				Uvalue [W/m² K]	**1.12**
				U'	**1.57**
				R'	**0.64**
				ΔU	**0.45**
				ΔR	**0.25**
				New Thickness of concrete layer	**0.085**

Table 3. U-value of the roof

2.2.4 Internal floor

The slab is assumed as hollow brick slab. Above the slab there is a ascreed and floor finish. Below the slab there is the suspended ceiling. The characteristics of every layer are given in the teble below.

Layers	Thickness [m]	Conductivity λ [W/mK]	Density ρ [kg/m³]	Spec. heat capacity c_p [J/Kg*K]	Thermal resistance, *R* [m²K/W]
Internal surface res.	--	--	--	--	0.10
Floor finish	0.04	1.40	2100	650	0.03
Screed	0.04	0.41	1200	840	0.09
Hollow brick slab	0.20	0.45	2300	1000	0.44
Air gap	0.12	-	-	-	0.20
Gypsum/plaster board	0.01	0.16	1800	837	0.08
Internal surface res.	--	--	--	--	0.10
total	**0.41**			**Rtot**	**1.04**
				Uvalue [W/m² K]	**0.96**

Table 4. U-value of the internal ceiling/floor

2.2.5 Ground floor

Ground floor is considered as typical one with the layers repored in the table below. In IES-VE the values were inserted in order to include the ground impact to the overall U-value of ground floor. All the parameters are following the BS EN ISO 13370.

Layers	Thickness [m]	Conductivity λ [W/mK]	Density ρ [kg/m³]	Spec. Heat capacity c_p [J/Kg*K]	Thermal resistance, *R* [m²K/W]
U-value correction layer	0.82	0.05	550	1000	1.65
Screed	0.04	0.41	1200	840	0.09
Reinforced concrete slab	0.20	0.45	2300	1000	0.44
Gravel	0.1	0.36	1840	840	0.28
total	**0.34**			**Rtot**	**2.46**
				Uvalue [W/m² K]	**0.41**
				U'	**0.45**
				R'	**2.21**
				ΔU	**0.04**
				ΔR	**0.25**
				New Thickness of the correction layer	**0.07**

Table 5. U-value of the ground floor

2.2.6 Windows

The windows are consisting of 1 glass layer and aluminium frame (picture below).

Figure 11 - Window and door pictures from the site

There are eleven types of window in the building and they are:

	Length [m]	Height [m]	Number [-]	Perimeter [m]	Area [m²]
Window /type1/	4.8	1.8	32	13.2	8.64
Window /type2/	4.8	0.8	20	11.2	3.84
Window /type3/	2.4	1.8	2	8.4	4.32
Window /type4/	2.4	0.8	11	6.4	1.92
Window /type5/	1.0	1.8	12	5.6	1.80
Window /type6/	1.2	1.8	12	6.0	2.16
Window /type7/	5.4	1.8	10	14.4	9.72
Window /type8/	1.8	0.8	3	5.2	1.44
Window /type9/	7.2	0.8	1	16	5.76
Window /type10/	1.0	0.8	1	3.6	0.8
Window /type11/	1.2	0.8	2	4	0.96

Table 6. Infomration about the windows

In the table below, properties of windows are shown.

Layers	Thickness [m]	Conductivity λ [W/mK]	Resistance m2K/W	Transmittance	Outside reflacatnace	Outside reflacatnace	Outside emissivity	Inside emissivity
Internal surface res.	-	-	0.04	-	-	-	-	-
Clear glass	0.006	1.06	0.0057	0.409	0.289	0.414	0.837	0.042
Internal surface res.	-	-	0.13	-	-	-	-	-
total	**0.006**						**Rtot**	**0.18**
							Uvalue [W/m² K]	**5.17**

Table 7. U-value of windows

2.3 Characteristic detail

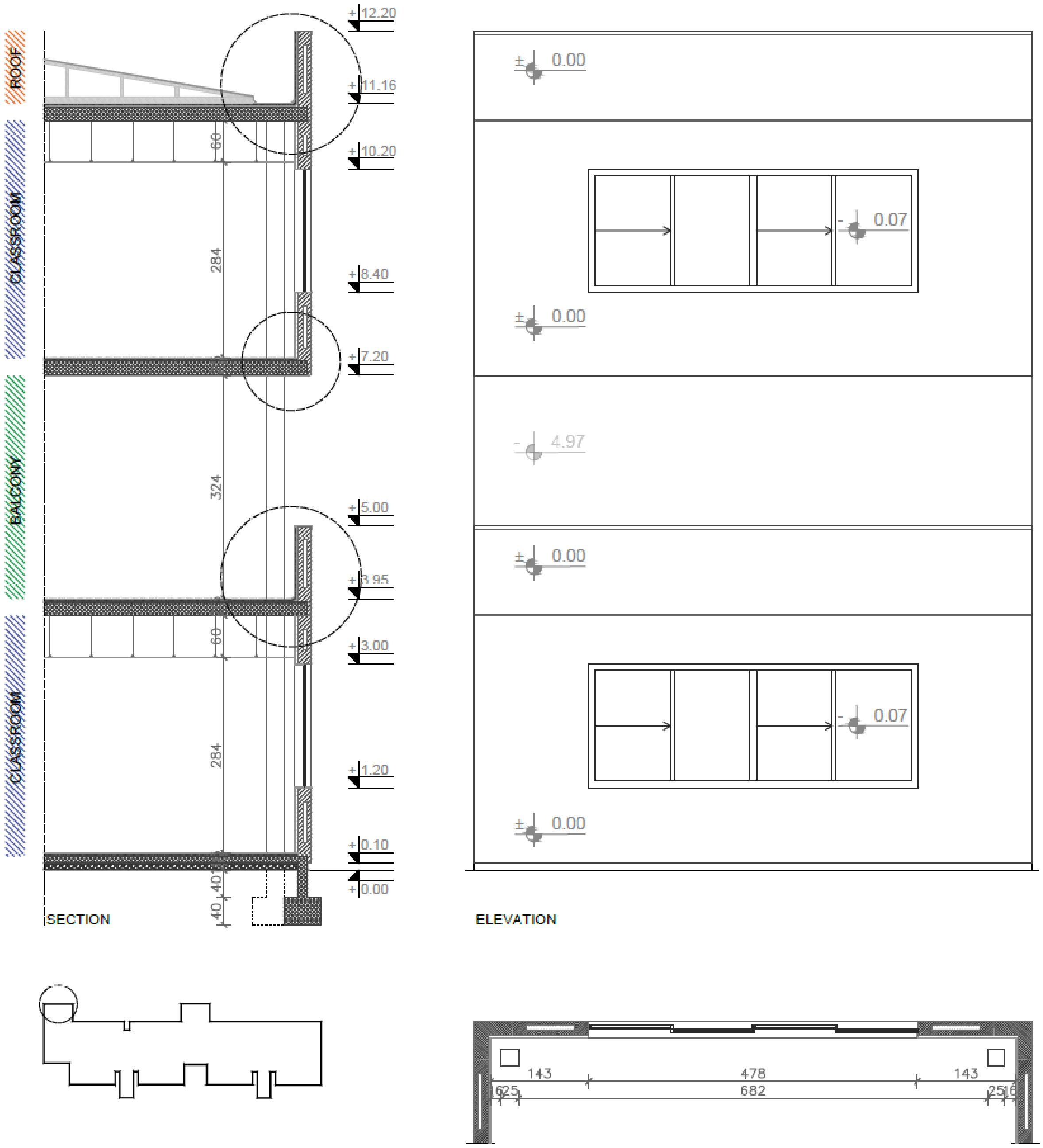

Figure 12 - Section, plan and prospect of the most characteristic part of the building

2.4 Loads

Provided data about the school in Via Zuara 9 gave us the opportunity to calculate occupany and distribution of people in the space taking into account areas, number of children and teachers. The ventilation load that was calculated represents the value as if all of the students were present in the certain space we are dealing with. Later on, the distribution of children in the school has been decided and based on that, % of people in certain space will therefor indicate also the % od maximum ventilation needed to balance indoor air quality.

2.4.1 People load

In the tables below distribution of areas in the school and number of children and staff are reported.

	Ground floor mq	1st floor mq	2nd floor mq	Total mq
Classoroom	106	754	749.3	1609
Corridor	352	314	329	995
Stairs	46	46	46	138
Toilets	102	141	141	384
Kitchen	82	0	0	82
Library	76.8	0	0	77
Mensa	369	0	0	369
Medical room	55.8	0	0	56
Archives	93	17	17	127
Teachers room	88	0	0	88
Locker room	36	0	0	36
Gym	300	0	0	300
SUM	1706.6	1272	1282.3	4260.9

Table 2 - Types of spaces and total area of them in the school

description	number
total number of children	447.00
reduction factor because of ab-sence	0.95
Number of children present	424.65

Teachers	21
Doctor	1
Hygene staff	6
Kitchen	5
Dean	1
Psychologist	1
Librarian	1
Total number of staff	36

Table 3 - Number of people in the school

Since every person is emitting certain power and CO2, basic calculations allowed us to indicate how much load out of children do we have and also what is the ventilation requirement in order to have good indoor air quality (respecting thresholds of ppm in the space). In the tables below the calculation process is reported.

PEOPLE LOAD class and corr		PEOPLE LOAD TEACHERS	
49.53	W/m^2/met	70	W/m^2/met
1.2	m^2	1.8	m^2
1.2	met	1.2	met
71.3232	W	151.2	W
447.00	children	21.00	trachers
31881.4704	W/class	3175.2	W/class
1609.3	m^2	1609	m^2
19.81076891	W/m^2	1.973031753	W/m^2
71.3232	W/P	151.2	W/P
Sendible	**Latent**	**Sendible**	**Latent**
42.8	28.5	90.7	60.5

Table 4 - People load in the school

CLASSROOM VENTILATION CHILDREN		
Weight	25	kg
Height	120	cm
Area of body	1.20	m^2
Adult	1.8	m^2
Child	1	m^2
Superficie corpo	1.20	m^2
RQ	0.83	-
Metabolismo	1.2	met
Consumption of O2	0.00414	ltCO2/sec
Production of CO2	0.00343	ltCO2/sec
	12.4	ltCO2/h
area	1609.3	mq
volume of the zone	5632.55	m^3
occupation	3.79	m^2/pers
n of people	424.65	-
production of CO2	12.4	ltCO2/h persona
external CO2 concentration	400	ppm
internal CO2 concentration	1200	ppm
potenziale di esp	0.8	ltCO2/m^3
minimum ventilation	6560.170325	m^3/h
minimum ventilation	1.16	1/h
	15.45	l/h per person
	4.29	l/s per person

CORRIDOR VENTILATION CHILDREN + toilet + stairs		
Weight	25	kg
Height	120	cm
Area of body	0.91	m^2
Adult	1.8	m^2
Child	1	m^2
Superficie corpo	0.91	m^2
RQ	0.83	-
Metabolismo	1.2	met
Consumption of O2	0.00314	ltCO2/sec
Production of CO2	0.00260	ltCO2/sec
	9.4	ltCO2/h
area	1517	mq
volume of the zone	5309.5	m^3
occupation	3.393736018	m^2/pers
	447	people
n of people	447.0	-
production of CO2	12.0	ltCO2/h persona
external CO2 concentration	400	ppm
internal CO2 concentration	1200	ppm
potenziale di esp	0.8	ltCO2/m^3
minimum ventilation	6705	m^3/h
minimum ventilation	1.26	1/h
	15	l/h per person
	4.17	l/s per person

CORRIDOR VENTILATION CHILDREN + toilet + stairs		
Weight	25	kg
Height	120	cm
Area of body	0.91	m^2
Adult	1.8	m^2
Child	1	m^2
Superficie corpo	0.91	m^2
RQ	0.83	-
Metabolismo	1.2	met
Consumption of O2	0.00314	ltCO2/sec
Production of CO2	0.00260	ltCO2/sec
	9.4	ltCO2/h
area	1517	mq
volume of the zone	5309.5	m^3
occupation	3.393736018	m^2/pers
	447	people
n of people	447.0	-
production of CO2	12.0	ltCO2/h persona
external CO2 concentration	400	ppm
internal CO2 concentration	1200	ppm
potenziale di esp	0.8	ltCO2/m^3
minimum ventilation	6705	m^3/h
minimum ventilation	1.26	1/h
	15	l/h per person
	4.17	l/s per person

MENSA VENTILATION 100%		
Weight	25	kg
Height	120	cm
Area of body	0.91	m^2
Adult	1.8	m^2
Child	1	m^2
Superficie corpo	0.91	m^2
RQ	0.83	-
Metabolismo	1.2	met
Consumption of O2	0.00314	ltCO2/sec
Production of CO2	0.00260	ltCO2/sec
	9.4	ltCO2/h
area	369	mq
volume of the zone	1291.5	m^3
occupation	0.825503356	m^2/pers
	447	people
n of people	447.0	-
production of CO2	12.0	ltCO2/h persona
external CO2 concentration	400	ppm
internal CO2 concentration	1000	ppm
potenziale di esp	0.6	ltCO2/m^3
minimum ventilation	8940	m^3/h
minimum ventilation	6.92	1/h
	20	l/h per person
	5.56	l/s per person

KITCHEN VENTILATION		
Weight	70	kg
Height	180	cm
Area of body	1.89	m^2
Adult	1.8	m^2
Child	1	m^2
Superficie corpo	1.89	m^2
RQ	0.83	-
Metabolismo	1.2	met
Consumption of O2	0.00652	ltCO2/sec
Production of CO2	0.00541	ltCO2/sec
	19.5	ltCO2/h
area	82	mq
volume of the zone	287	m^3
occupation	16	m^2/pers
	5	m^2 per persona
n of people	5	-
production of CO2	20.0	ltCO2/h persona
external CO2 concentration	400	ppm
internal CO2 concentration	1200	ppm
potenziale di esp	0.8	ltCO2/m^3
minimum ventilation	125	m^3/h
minimum ventilation	0.44	1/h
	25	l/h per person
	6.94	l/s per person

Table 5 - Calculation of ventilation needed for regulating CO2 concentration

The distribution of people in the model has been supposed on the general behavior of children in the school. The starting point was 2 possible behaviors, that were combined to derive one unique profile of users. It has to be mentioned that during weekends, the school was considered empty, so the overall load was 0. The annual profile was containing of weekly profiles like this, the holidays were not taken into account.

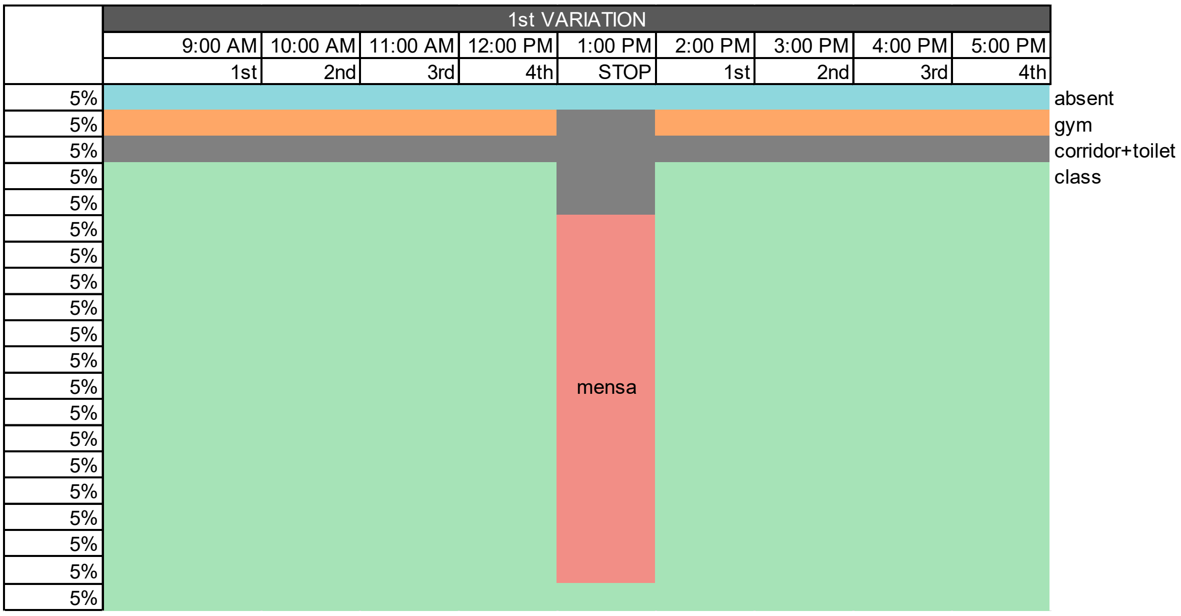

Table 6 - 1st possible distribution of people in the building

5% of all the children were considered absent for all the working time. During all day except the lunch break, 5% of people were supposed to be in the gym. 5% of people during the working time was considered to be in the toilets, corridors or stairs and the rest in the classroom, which is 85%. On the contrary, during lunch break, 5% of children were supposed in the classroom, 20% on the corridors, stairs, or in the toilets, and 70% in mensa. The lunch break in this case was considered from 13:00h to 14:00h.
The second profile was the same except for the change in the time of the brake which was in that case from 14:00h to 15:00h.

	2nd VARIATION									
	9:00 AM	10:00 AM	11:00 AM	12:00 PM	1:00 PM	2:00 PM	3:00 PM	4:00 PM	5:00 PM	
	1st	2nd	3rd	4th	5th	STOP	1st	2nd	3rd	
5%										absent
5%										gym
5%										corridor+toilet
5%										class
5%										
5%										
5%										
5%										
5%										
5%										
5%										
5%						mensa				
5%										
5%										
5%										
5%										
5%										
5%										
5%										
5%										

Table 7 - 2nd possible distribution of people in the building

By supposing that some of the children are going on the lunch break from 13:00h to 14:00h and the others from 14:00h to 15:00h, profiles were combined and the following % of children are assigned to different types of spaces:

	COMBINED PROFILE FOR CHILDREN								
time	9:00 AM	10:00 AM	11:00 AM	12:00 PM	1:00 PM	2:00 PM	3:00 PM	4:00 PM	5:00 PM
hour	1st	2nd	3rd	4th	STOP	STOP	1st	2nd	3rd
5%	absent - 5%								
5%	gym - 5%				corridor + toilets		gym - 5%		
5%	5%				10%		5%		
5%									
5%									
5%									
5%					mensa 42.5%				
5%									
5%									
5%									
5%									
5%	class 85%						class 85%		
5%									
5%									
5%									
5%					class 42.5%				
5%									
5%									
5%									
5%									

Table 8 - The final distribution of people in the building

2.4.2 Lighting load

By counting the number of light units and bulbs contained in it the classroom the lighting load is obtained considering the nominal power of the bulb. For what concerns the load of the light in the corridors, it is considered half of the one in the classrooms since the same was observed during the visit of the school. The calculation is reported in the table below.

LIGHING LOAD		
Nominal power	40	W
N. Of lights	12	-
Area of classrooms	50	m2
Lighting load	9.6	W/m2

Table 9 - Lighting load of the classroom

2.4.3 Equipment load

The value of the equipment load is taken from the standard ISO 18523-1.

Equipment load	0.5	W/m2

Table 10 - Equipment load of slassroom

CHAPTER 3. Thermal bridges in the baseline configuration

There are 3 characteristic spots (besides the connection between the window and the wall) that are important to focus on while developing technology of the details. Those are :

1. Roof detail
2. Balcony-ceiling detail
3. Balcony-floor detail

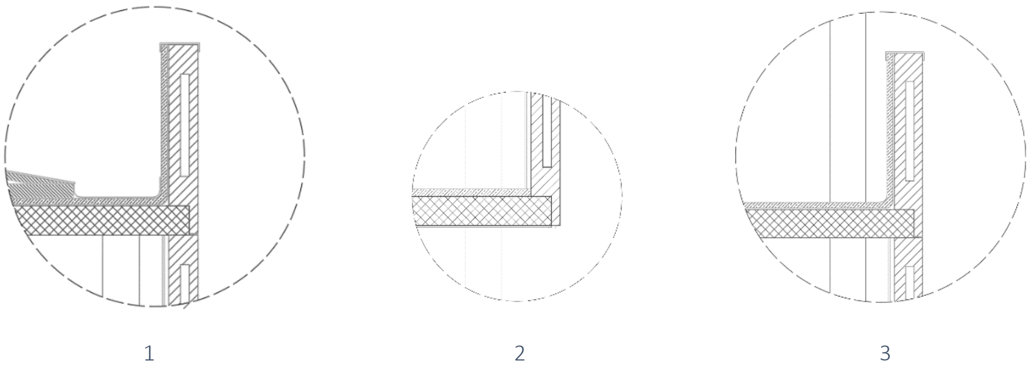

Figure 13 - Characteristicdetails of the building

In order to take into consideration, the impact of thermal bridges in the baseline delta U value is calculated using simple formulas and BS EN ISO 14683. The calculation was performed using an Excel file and inserting characteristic values that are shown in the table below.

It is important to note that there are many different types of windows in this building. Areas and lengths are collected and summed up to simplify the process.

Element code	Description	surface/lenght	unit	Uvalue/psi	number	S/L TOT	H	attribution	attribution %	attributed
WI	windows	540.6	mq	5.17	1	540.6	2794.7	WI	1	2794.7
TBw	windows	1060.0	m	0.5	1	1060.0	530.0	WA	1	530.0
WA	wall	3948.7	*mq*	1.47	1	3948.7	5804.6	WA	1	5804.6
RO	roof	1367.6	*mq*	1.27	1	1367.6	1736.8	RO	1	1736.8
TBro	roof	275.2	*m*	0.75	1	275.2	206.4	RO	0.5	103.2
								WA	0.5	103.2
SL	slab	2951.0	*mq*	0.97	1	2951.0	2862.5	SL	1	2862.5
TBsl	slab	326.5	*m*	0.7	2	653.1	457.2	WA	1	457.2
GF	ground floor	1753.4	*mq*	0.43	1	1753.4	754.0	GF	1	754.0
TBgf	ground floor	296.6	*m*	0.5	1	296.6	148.3	WA	0.5	74.2
								GF	0.5	74.2
CO1	corner	3.8	*m*	-0.15	70	262.5	-39.4	WA	1	-39.4
CO2	corner inverted	3.8	*m*	0.12	60	225.0	27.0	WA	1	27.0

Figure 14 - List of the elements and thermal bridges

	Stot	U	H	H'	%	U'	DeltaU
WA	197434.5	1.47	290228.7	346441.4	9.54%	1.8	0.285
WI	57299.36	5.17	296237.7	296237.7	0.00%		
RO	1367.59	1.27	1736.8	1840.1	0.02%	1.3	0.075
GF	1753.38	0.43	754.0	828.1	0.01%	0.5	0.042

Figure 15 - Calculation of change in U-value caused by thermal bridges

It could be recognized that the thermal bridges have the biggest impact on the walls rising their U-value by 0.285. In comparison to the walls, the roof and the ground floor are impacted by thermal bridges much less, 0,075 and 0,042 respectively.

After a derived change in U-value, the reverse calculation was performed to reach the equivalent thickness of construction layers in order to set the corrected U-value caused by thermal bridges. This equivalent thickness is reported in the tables of previous chapter.

CHAPTER 4. Results of the baseline

In order to analyze the first results after setting the baseline, two classrooms on the top floor are selected:

1. Space 83 (South-West oriented)
2. Space 93 (North-East oriented)

4.1 Energy balance

The energy balance will tell us how the building behaves with the loads that are present in it and the losses that occur. The energy balance of thermal zones is given in the following two figures.

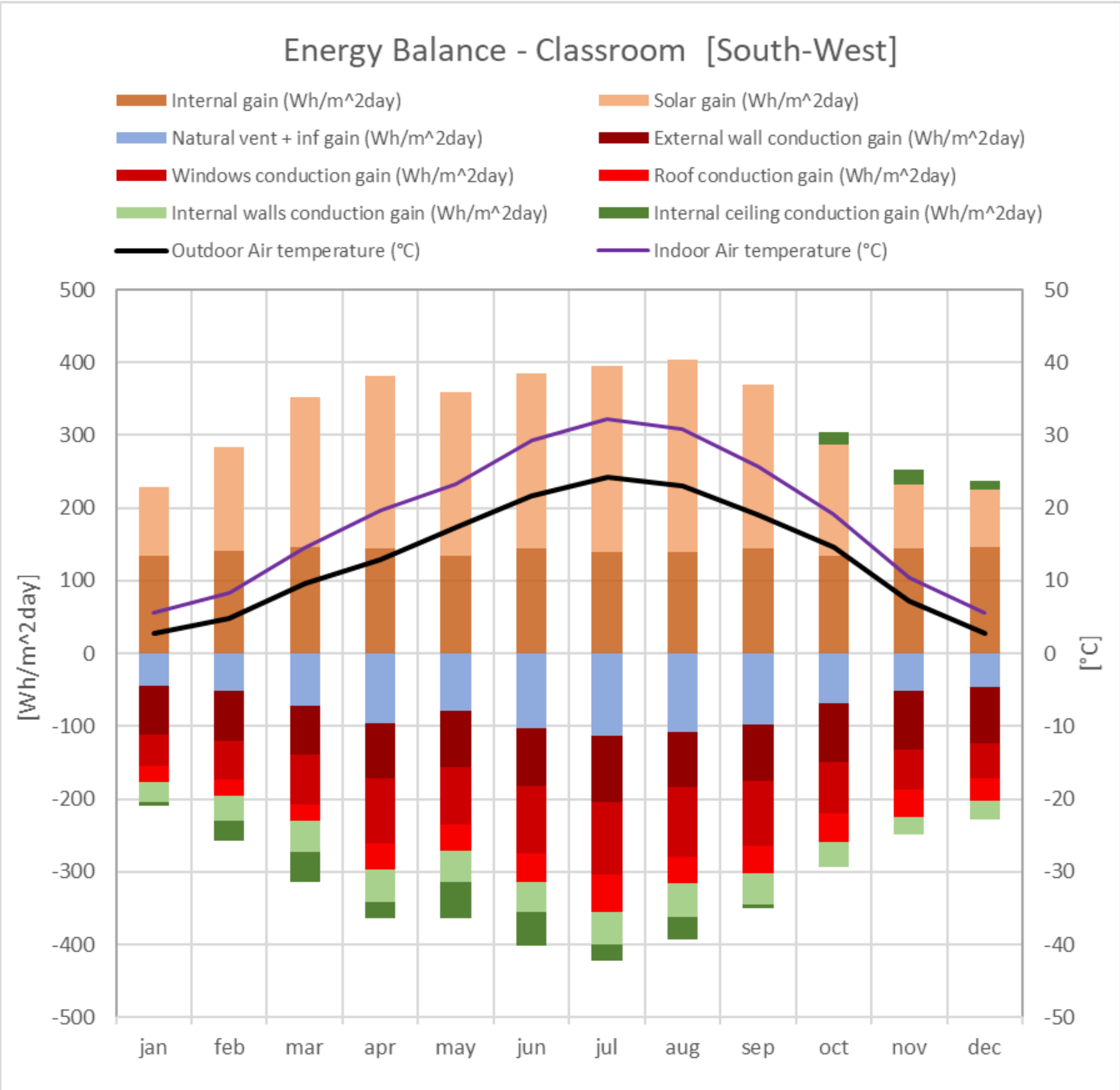

Figure 16 - Eneegy balance of Space 83

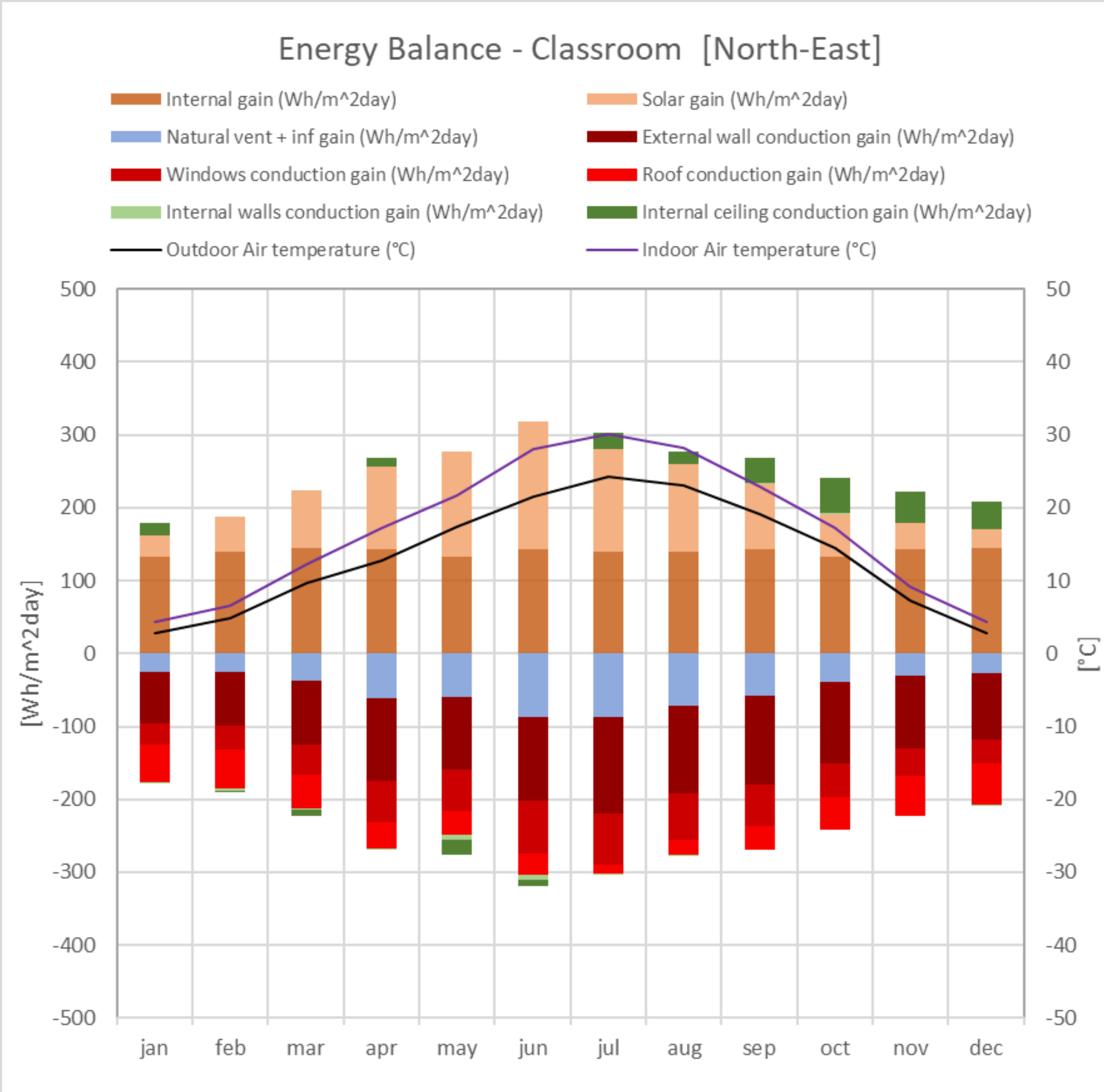

Figure 17 - Energy balance of Space 93

Comparing the two graphs showing the energy balance, we have proved that if the space is oriented towards the South it will receive more sun and therefore the bars showing those gains are taller in the case of Space 83. Besides that, since the North-oriented classroom is colder, through internal ceiling and walls we have gains, opposite to the South oriented space (warmer one) which is mostly losing energy through internal partitions.

Since these two spaces are on the top floor, in order to see every contribution to losses and gains, the energy balance of the whole building was done. The results are shown in the figure below.

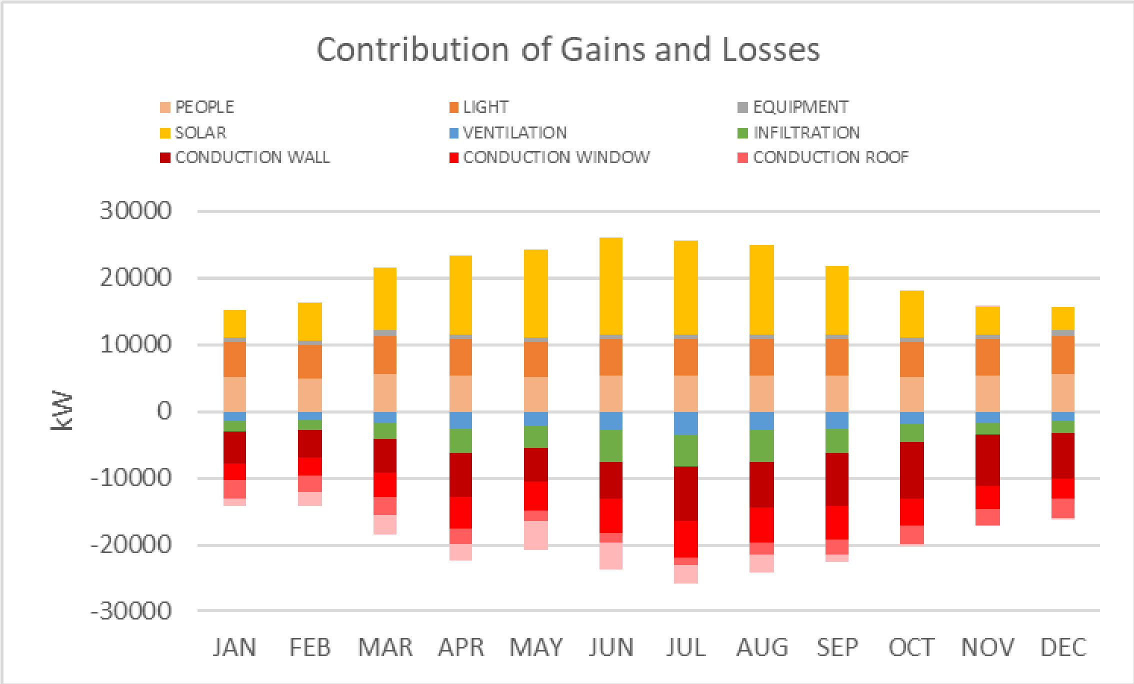

Figure 18 - Energy balance of the school

As expected, the solar gains are bringing the most energy into the building and right after solar gains, people are contributing the most to the energy gains.
What we should focus on are the losses in order to see which retrofit scenarios would be the most appropriate for this case.
During wintertime conduction losses through external walls is predominant and the losses through the windows are right after. As we are getting closer to the summertime, losses from the external walls and windows are becoming similar.
What could be said is for sure that the focus should be put on insulating the envelope and replacing the windows with higher performance ones.
Losses through the roof are present too, especially during wintertime, so insulating this envelope part is needed too.
Losses through the ground are small compared to the other ones during wintertime. During summer, these losses are becoming bigger, which is favorable.
As previously mentioned, the focus could be put also on natural ventilation, since minimizing it during wintertime could bring us higher temperatures and promoting it during summer will bring the temperature down.

4.2 CO2 concentration

Comfort is defined by many parameters. One of them is CO2 concentration. The minimum ventilation rate was provided in order to regulate ppm of CO2 in the air. In the following figures, we will focus on it for a few thermal zones.

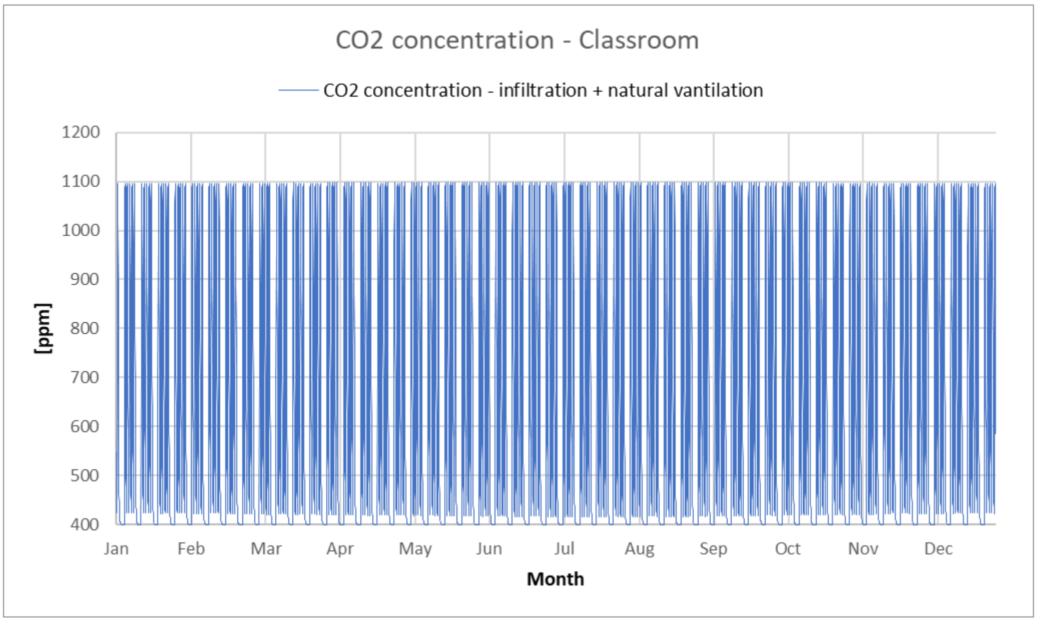

Figure 19 - CO2 concentration in the classroom after applying minimum ventilation rate calculated in the chapter 2

Since we can see that the CO2 concentration is not crossing the value of 1100 ppm when we apply natural ventilation, we can say that the air quality regarding this concern is achieved. Now, we can focus on one month and see what would happen if we didn't apply the natural ventilation.

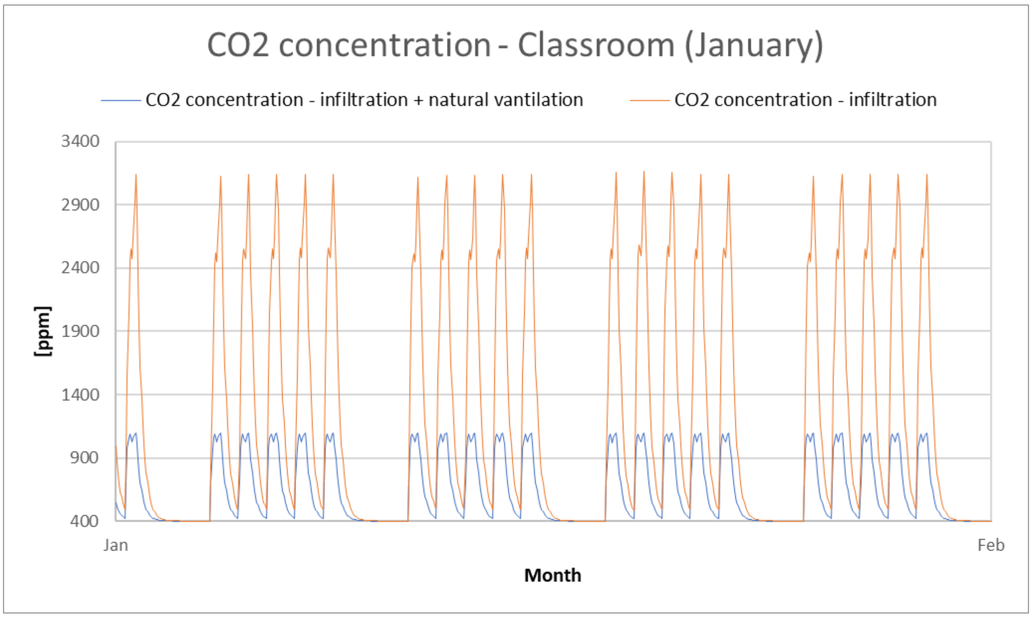

Figure 20 - CO2 concentration in the classroom before and after applying minimum natural ventilation rate

It could be concluded that natural ventilation has regulated the CO_2 concentration and that without it, the ppm of CO_2 would cross the threshold.
The same conclusion could be derived from the results of CO_2 concentration in Mensa. Even though the space is used differently, the peak of occupancy is bringing a high concentration of CO_2 that must be regulated by natural ventilation. Different occupation density and occupation time are leading to different CO_2 concentration even after applying minimum ventilation rate.

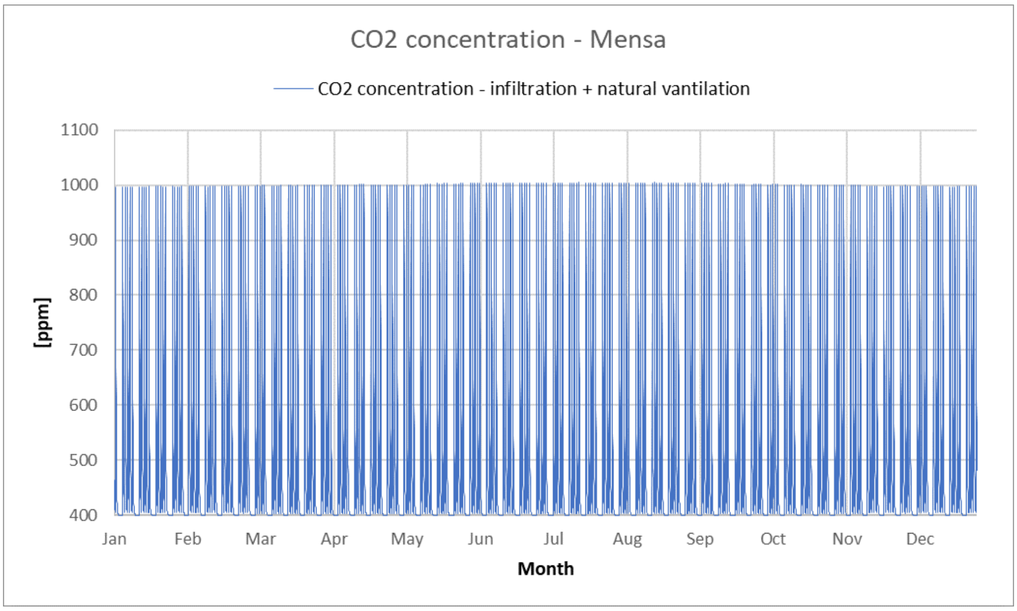

Figure 21 - CO2 concentration in the mensa after applying minimum ventilation rate calculated in the Chapter 2

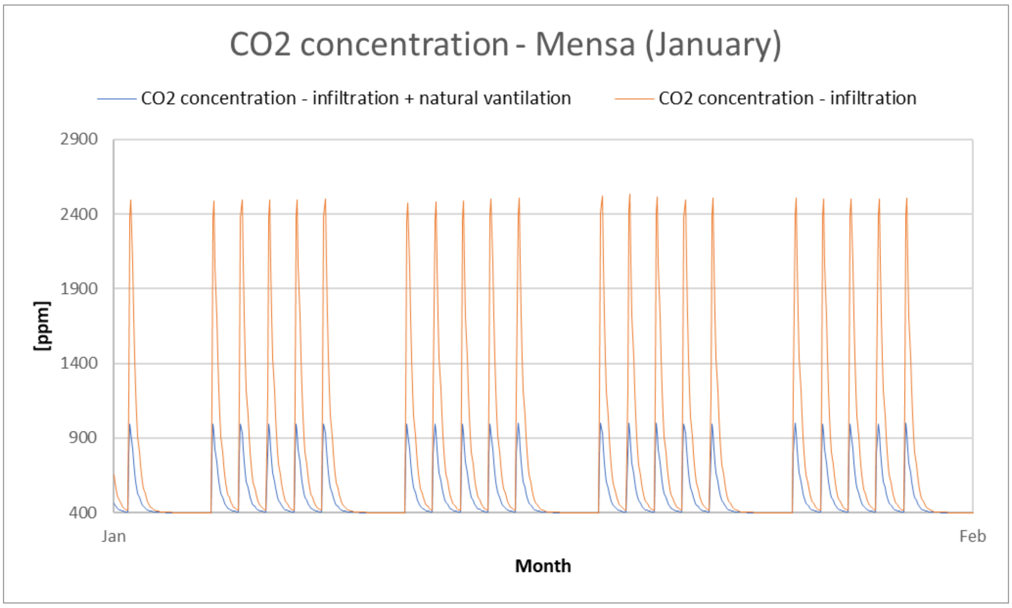

Figure 22 - CO2 concentration in the mensa before and after applying minimum natural ventilation rate

When it comes to the corridor. The number of people that are present in this space is most of the day very low and the peak is during lunchtime. The occupation is short and not particularly high, which leads us to the conclusion that natural ventilation is not needed in order to regulate it. This is supported by the results below.

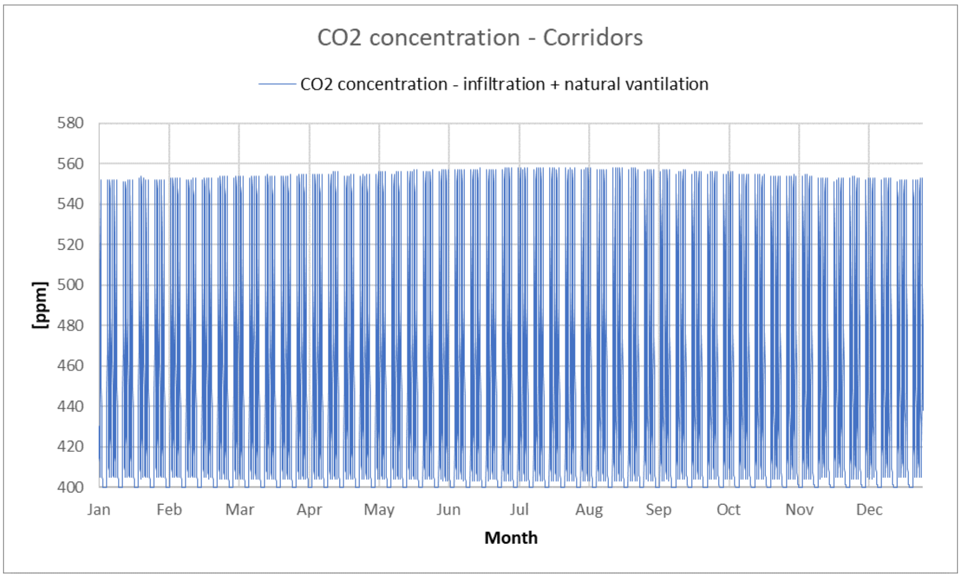

Figure 23 - CO2 concentration in the corridor after applying minimum ventilation rate calculated in the chapter 2

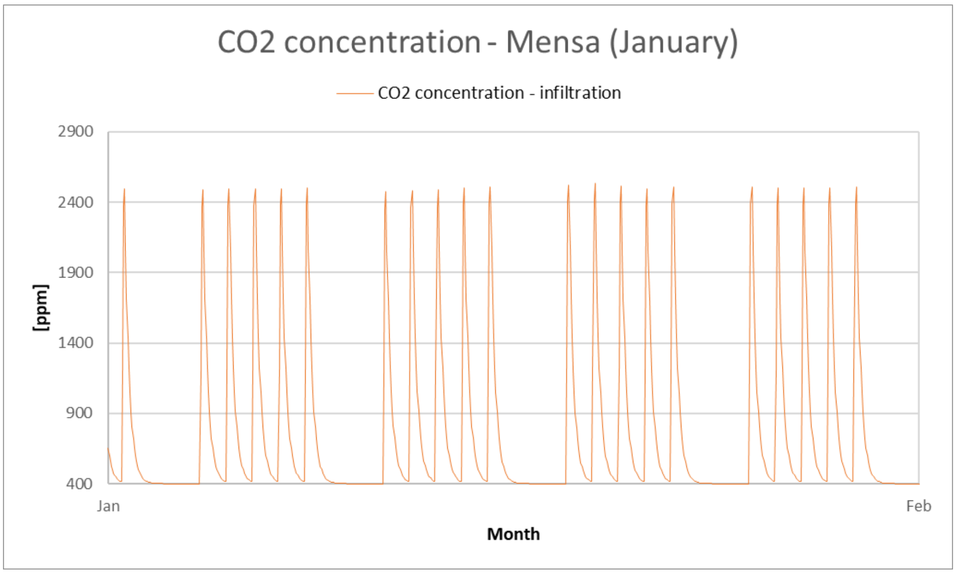

Figure 24 - CO2 concentration in the corridor without ventilation

CHAPTER 5. RETROFIT STRATEGIES

Following the previously derived energy balance of the building, the path of retrofit has been defined. As the biggest losses were through external walls and the third ones through the roof, the first thing to consider is to insulate the envelope. The next step would be considering changing windows to higher-performing ones.
The retrofit strategies will be analyzed separately and after that, retrofit packages will be created and they will include a combination of strategies depending on their separate effect. The results of retrofit strategies were analyzed for the North-East oriented classroom since it is the coldest one on the top floor.

5.1 Insulating external walls

Nowadays, especially as the climate change effects are getting more and more serious, the embodied energy of the products became one of the important parameters when considering the options. Frequently used products such as polystyrene foams and boards contain a high amount of embodied energy. To be eco-friendly, while insulating external walls, the considered material was cellulose thermal insulation which has a conductivity of 0.04 W/mK. This conductivity is close to the ones of the products frequently used for thermal insulation, but since this is the natural material, the process of getting to the final product requires less energy. One more thing to be mentioned is that if we want to achieve the same effect of polystyrene thermal insulation, the thickness of cellulose one should be higher.

Thicknesses that were used to check the effect of this retrofit strategy are 5cm, 10cm, and 20cm. Since this is natural-based material, it requires certain protection to avoid contact with the water and therefore degradation. The protection is achieved with additional covering layers.

With additional thermal insulation of the wall, a change in the U value of the wall is reported in the table below. The starting point was the U-value of the wall with effect of thermal bridges.

Wall configuration	U-value (W/m2K)
Baseline	1.98
Baseline+10cm of thermal insulation on external wall	0.34
Baseline+15cm of thermal insulation on external wall	0.24
Baseline+20cm of thermal insulation on external wall	0.18

Table 11 - U-values of different wall configurations

The simulations were launched just with changed external walls configurations and the results that will be shown in the table below represents a change in monthly temperature average between the baseline and 3 scenarios of an additional 10cm, 15cm, and 20cm of cellulose thermal insulation.

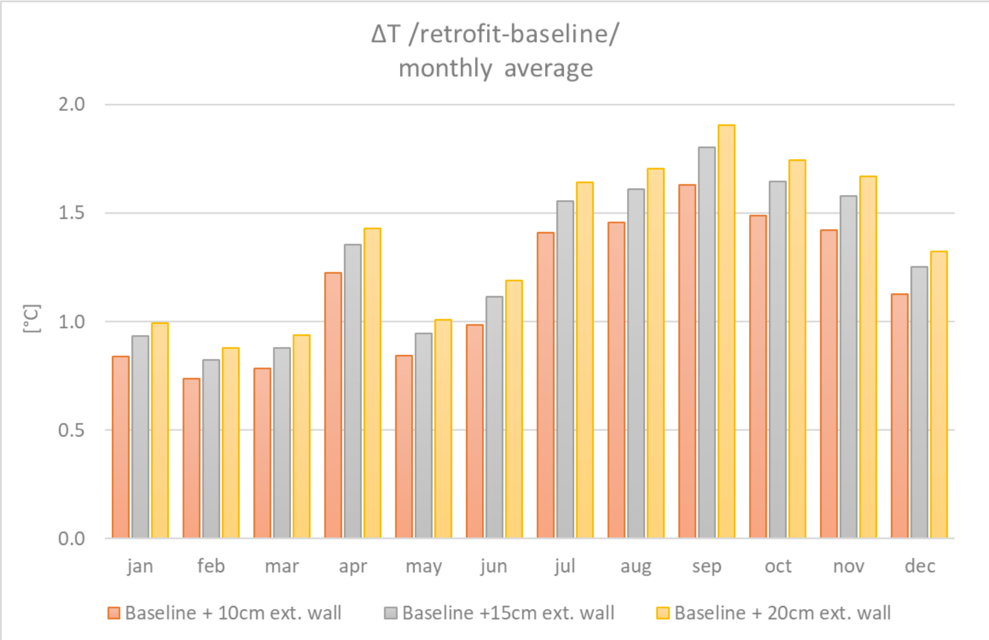

Figure 25 - Temperature differance between retrofit scenario and baseline of the external wall

With the change in thickness of thermal insulation applied, the rise of delta temperature is noticed. The biggest difference could be seen when the biggest thickness is applied (20cm). The other thing that could be seen is that the change in temperature between applying 5cm and 10cm and applying 10cm and 20cm is not the same, even though the change in thickness is the same between those two. The conclusion is that even if we would continue to increase thermal insulation thickness, the difference between every additional step would be lower and lower.

5.2 Insulating the roof

The roof is the target place where the water could be stuck due to many reasons. Because of this fact, natural material such as cellulose for thermal insulation was avoided. Instead of it, mineral wool was considered, because it has lower embodied energy (16.6 MJ/kg) in comparison to the usually used polystyrene (about 88.6 MJ/kg).

The conductivity of thermal insulation used on the roof is 0.035 W/mK. Examined thicknesses are 10cm, 15cm and 20cm. With additional thermal insulation of the roof, a change in U value of the roof is reported in the table below.

Roof configuration	U-value (W/m2K)
Baseline	5.17
Baseline+10cm Roof	0.25
Baseline+15cm Roof	0.18
Baseline+20cm Roof	0.14

Table 12 - U-values of different roof configurations

The simulations were launched just with changed roofs configuration and the results that will be showed in the table below represent a change in monthly temperature average between the baseline and 3 scenarios of additional 10cm, 15cm and 20cm of mineral wool thermal insulation.

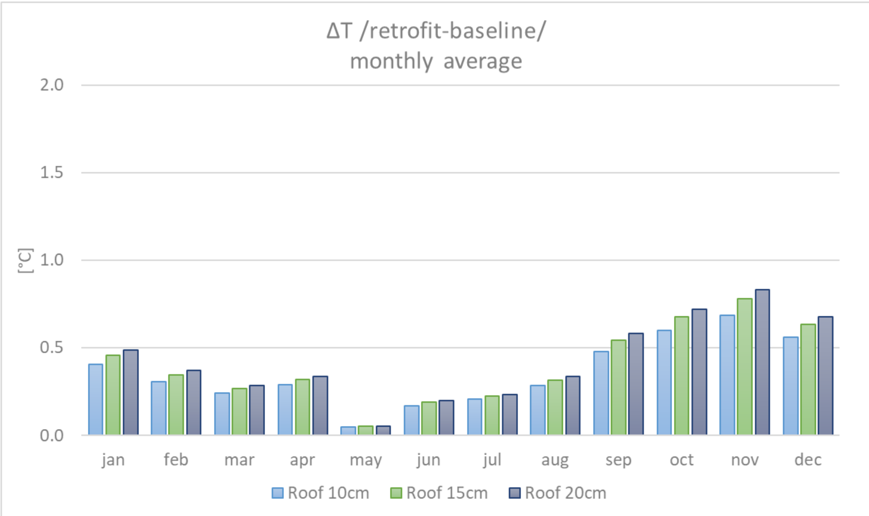

Figure 26 - Temperature differance between retrofit scenario and baseline of the roof

It could be noted that the raise in monthly temperature average when applying thermal insulation on the roof is lower than the one when the thermal insulation is applied on the external wall. This supports the energy balance of the whole building since the losses through the roof are much lower than those through external walls. Also, the same thing that was noted in the previous retrofit about the temperature rise with rising of thickness could be noticed.

5.3 Changing the windows

The second biggest losses were the ones through the windows. During summertime, they were almost equal to the ones of the external walls. The current state of the building includes single glazed windows and Aluminum frames. Technologies that were considered for retrofit possibilities are double and triple glazing, both with Argon-filled cavity since this became more usual. Additionally, options with applied low-E coating on the inner glass pane were introduced. The frame was considered 10%. For Double Glazing, the U value of the frame was taken as 1,02 W/m2K and for Triple Glazing 0,83 W/m2K (Values taken from Nauffer company). Overall U-values of different window configurations are reported in the table below.

Windows configuration	U-value (W/m2K)
Baseline (Single glazing)	5.17
Double Glazing+Argon	2.43
Double Glazing+Argon+lowE	1.03
Triple Glazing+Argon	1.58
Triple Glazing+Argon+lowE	0.83

Table 13 - U-values of different window configurations

The simulations were launched just with changed windows configuration and the results that will be shown in the table below represent a change in monthly temperature average between the baseline and 4 scenarios of replacing existing windows with higher-performing types reported in the legend.

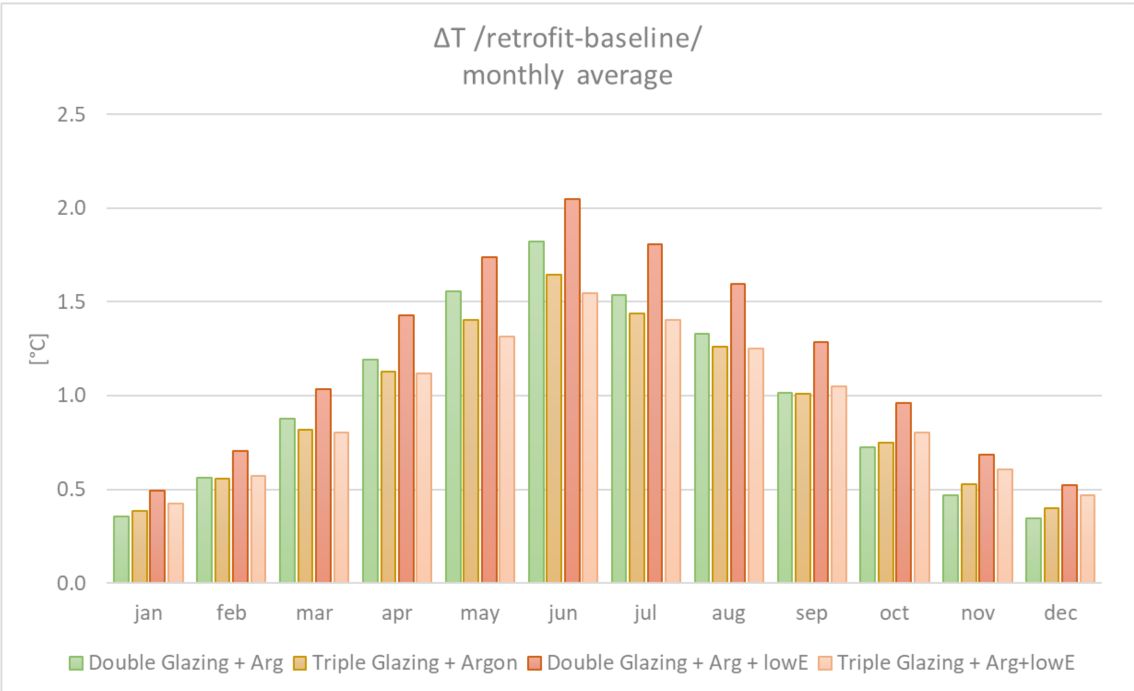

Figure 27 - Temperature differance between retrofit scenario and baseline of windows

What is interesting to be mentioned from this analysis is that even though triple glazing sometimes means a better U-value, it doesn't always project as rising of the temperature higher than one of double glazing. This can happen due to the transmittance of window panes. More window panes mean lower transmittance and therefore lower sun gains. Exactly this happened in this case, so we can conclude that double glazing with Argon and lowE coating seems like the best option from the average monthly temperature view.

A thought about the transmittance of double glazing and triple glazing affecting solar gains is supported by solar gain analysis of the classroom where those types of windows were introduced.

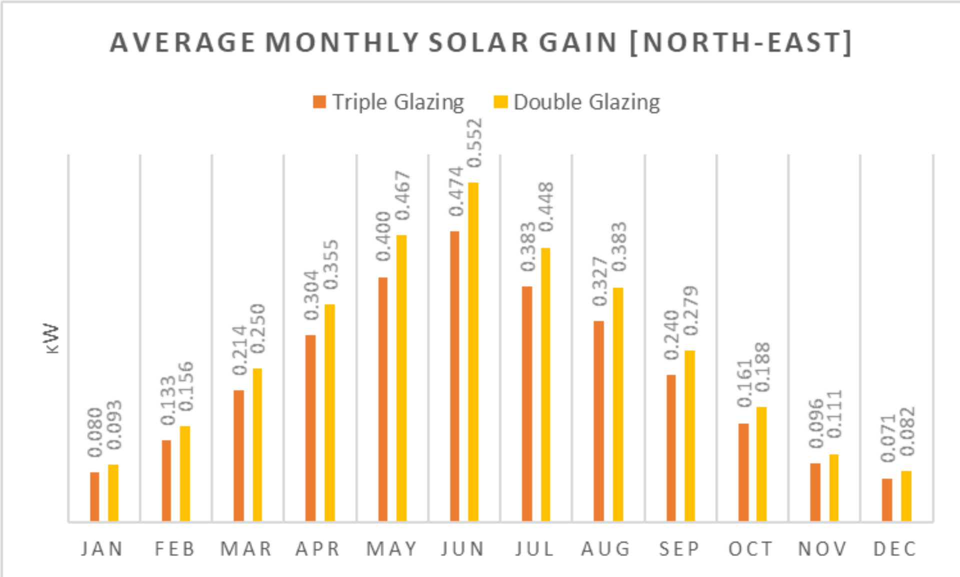

Figure 28 - Solar gains of thermal zone depending on the type of the window

5.4 Retrofit packages

Based on the results of the analysis that every single retrofit is bringing, three retrofit packages were created. Even though a change in temperature between adding 15cm and 20cm of thermal insulation on the roof and on the external wall is small, 20cm of thermal insulation was chosen to be examined in further analysis in order to see what would be the maximum possible effect with combined maximum proposed solutions. Therefore, double glazing with Argon and low E coating was chosen for the first simulation. The second one was with the same thickness of 20cm thermal insulation, but with triple glazing with Argon and low E coating in order to see if the change to triple glazing will have a better effect when it is combined with good thermal insulation. The last one that was chosen to be simulated was the minimum proposed improvement, 10cm of thermal insulation on the external wall and roof and double glazing with Argon in the cavity.

The results of chosen packages are shown in the table below in terms of the difference in temperature between the retrofit package and baseline.

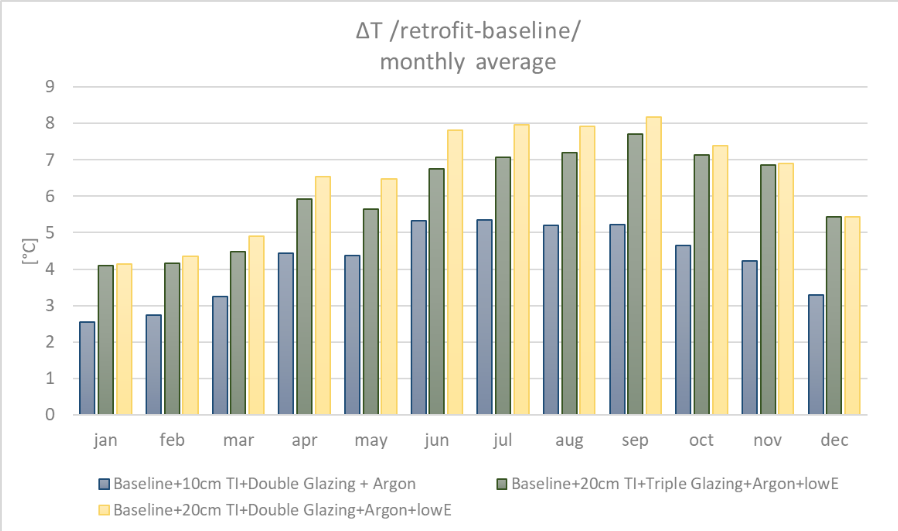

Figure 29 - Temperature differance between retrofit pacages and baseline of windows

In comparison to single retrofit solutions (for example, just additional thermal insulation on the walls) combining single retrofit strategies into packages is bringing significantly better results in terms of rising the temperature. As the retrofit package is stronger (improved R-value), the results are better.

It could be recognized that the retrofit package with the lowest examined improvements (blue in the chart) is not favorable in terms of raising the temperature. On the other hand, it could be favorable from other points of view. For sure from the General Cost point of view. This, together with other points of view like Life Cycle Assessment, Embodied energy and so on, could be the topic to deepen more.

However, the difference between the two strong retrofits (green and yellow) is not so visible during winter, but as we are closer to the summer months, it becomes clear that double glazing is allowing the space to gain more energy from the sun.

CHAPTER 6. COMPARING STATIC AND DYNAMIC ANALYSIS

The results achieved by retrofitting in terms of temperature seemed too low, so it has been decided to create a static model of one room and check what is the potential that the retrofit can bring in terms of temperature change. The chosen classroom to be analyzed was North-East oriented one on the top floor, Space 93.

6.1 Baseline – creating a static model

The dimensions of the thermal zone analyzed and surfaces (Space 93, North-East oriented classroom) were taken from the model. All U-values were inserted as the ones calculated in Chapter 2. By using U-values and areas calculated, heat loss coefficients are derived. The classroom is located on the top floor and its East and North oriented walls are the external ones. The window is placed just on the North-East oriented wall with dimensions of 4,8x1,8m. Since this thermal zone is in contact with another one in the way that it has the common walls and floor, the U-values of this construction parts are set as 0, as we consider just the losses towards the external environment. The values used are reported in the tables below.

	Area		U-value		Hd	
Floor	46.24	m^2	0	W/m^2 K	0.00	W/K
Roof	46.24	m^2	1.12	W/m^2 K	51.79	W/K
SOUTH wall	23.63	m^2	0	W/m^2 K	0.00	W/K
WEST wall	23.98	m^2	1.98	W/m^2 K	47.47	W/K
NORTH wall	14.95	m^2	1.98	W/m^2 K	29.61	W/K
EAST wall	23.98	m^2	0	W/m^2 K	0.00	W/K

Table 14 - Areas, U-values and Heat loss coefficients of envelope parts

The window is placed on the North-East facade and it has an area of 8,67m2. This is another part of the envelope that has an impact on the losses, so its heat loss coefficient is calculated too.

	Area		U-value		Hd	
NORTH window	8.67	m^2	5.17	W/m^2 K	44.83	W/K

Table 15 - Area, U-value and Heat loss coefficient of the window

The total Heat loss coefficient is the summation of the ones that every single component contributes. It is 173,96 W/K.

This ventilation Heat loss coefficient is the last one to be taken into account and for this, we need information about the volume of the building, ventilation rate and specific heat of the air. The ventilation rate in the dynamic model was inserted as the peak one, which is further regulated by modulating profile (different % of peak ventilation rate is applied at a different times of the day depending on the occupation rate), so the ventilation rate applied in the static calculation was taken as the weighted average of the one applied in the model.

AVERAGE VENTILATION				
Number of hours	15	7	2	h
Amount of ventilation	0.25	1.24	0.62	1/h
Total ventilation for hours	3.75	8.65	1.23	
Average ventilation rate			0.57	1/h

Table 16 - Method for calculating weighted average of ventilation rate

Cp air	0.34	Wh/m^3
Volume	161.83	m^3
n	0.57	1/h
Hv	31.24	W/K

Table 17 - Calculating ventilation heat loss coefficient

The final, real heat loss coefficient is calculated as the summation of the previous two, so it has a value of 204.94 W/K. Now we can conclude that the envelope is responsible for 84,8% of the losses, while the ventilation is contributing the rest - 15,2%.

Talking about the gains, there are two parts, internal gains and solar gains. Internal gains are calculated as the weighted average since they are applied the same way as the ventilation is.

WEIGHTED AVERAGE PEOPLE LOAD				
Number of hours	15	7	2	
Load	0	24.23	12.11	W/m2
Total people load	0	169.58	24.23	
Average people load			8.08	W/m2

Table 18 - Method for calculating weighted average of occupants load

WEIGHTED AVERAGE LIGHT LOAD				
Number of hours	9	15		
Load	9.60	0.00		W/m2
Total light for hours	86.40	0.00		
Average light load			3.60	W/m2

Table 19 - Method for calculating weighted average of lighting load

WEIGHTED AVERAGE APPLIANCES LOAD			
Number of hours	9	15	
Load	0.50	0.00	W/m2
Total ventilation for hours	4.50	0.00	
Average people load		0.19	W/m2

Table 20 - Method for calculating weighted average of appliances load

Now that we calculated separate loads in terms of power, we got one of the inputs for the calculation of internal gains. The other ones are floor area and time.

Qi	9.40	kWh/day
w	8.47	W/m^2
Sfloor	46.24	m^2
t	24	h/day

Table 21 - Calculation of internal gains

The second part are the solar gains, for which the average daily irradiation is derived from the weather file of Milan used for dynamic simulations.

	Average daily irradiation kWh/m^2 day				
	HORIZONTAL	SOUTH-V	WEST-V	NORTH-V	EAST-V
jan	1.5	2.3	1.0	0.4	0.7
feb	2.4	3.1	1.5	0.6	1.2
mar	4.0	3.7	2.3	0.8	1.8
apr	5.5	3.7	3.0	1.1	2.2
may	6.8	3.4	3.4	1.4	2.9
jun	7.4	3.2	3.6	1.5	2.9
jul	7.3	3.4	3.6	1.3	2.8
aug	6.1	3.8	3.2	1.1	2.5
sep	4.5	3.8	2.6	0.9	1.8
oct	3.0	3.4	1.6	0.6	1.5
nov	1.9	2.9	1.1	0.5	1.0
dec	1.2	1.9	0.7	0.4	0.7

Table 22 - Average daily irradiation for every orientation

Average daily radiation is further combined with area of the window and g value to get the correct value of monthly solar gains.

	jan	feb	mar	apr	may	jun	jul	aug	sep	oct	nov	dec	
I_north_v	0.43	0.58	0.80	1.06	1.41	1.46	1.33	1.06	0.88	0.63	0.46	0.37	kWh/m^2 day
Area	8.67	8.67	8.67	8.67	8.67	8.67	8.67	8.67	8.67	8.67	8.67	8.67	m2
g-sol	0.49	0.49	0.49	0.49	0.49	0.49	0.49	0.49	0.49	0.49	0.49	0.49	
Qsol	1.84	2.47	3.41	4.51	5.97	6.19	5.64	4.51	3.73	2.67	1.94	1.57	kWh/day

Table 23 - Calculation of solar gains

Total internal gains are the sum of Qi and Qsol and they are reported in the table below.

Qgain,tot	11.25	11.88	12.82	13.91	15.37	15.59	15.04	13.91	13.13	12.08	11.34	10.97	kWh/day

Table 24 - Total internal gains

By combining internal gains and ventilation losses and summing them with average external temperature, we can estimate the average internal one. From the start, we wanted to compare the static and dynamic model results, in the next table the average monthly temperatures are reported and the difference between those two is calculated.

Tio, baseline	5.141	7.244	12.247	15.667	20.457	24.787	27.280	25.863	21.701	16.984	9.560	4.992	°C
Tio, base model	4.282	6.594	12.287	17.170	21.773	27.973	30.058	28.145	22.928	17.152	9.132	4.387	°C
delta T	0.860	0.650	-0.040	-1.503	-1.316	-3.187	-2.778	-2.282	-1.227	-0.169	0.428	0.605	°C

Table 25- Compareson of temperatures between static and dynamic model

The variation in results is expected, and moreover, they are larger as we are moving to the summer season. The reason behind this could be the variation of solar gains, the thermal mass of the building and so on. In any case, the differences are reasonable, so we are stating that there is no mistake in the dynamic model.

6.2 Improvement of the baseline – envelope improvement

In order to see what is the difference between static and dynamic models even for retrofit solutions, the same values used in simulations were inserted in the static model. Just heavy retrofit is considered for comparison.
This retrofit includes 20cm od thermal insulation on the wall and on the roof together with replacing the windows with double glazing ones with Argon in the gap and low-E coating applied.

	U-value		Hd	
Floor	0	W/m^2 K	0.00	W/K
Roof	0.14	W/m^2 K	6.47	W/K
SOUTH wall	0	W/m^2 K	0.00	W/K
WEST wall	0.18	W/m^2 K	4.32	W/K
NORTH wall	0.18	W/m^2 K	2.69	W/K
EAST wall	0	W/m^2 K	0.00	W/K
Windows	1.03	W/m^2 K	8.93	W/K

Table 26 - U-values and heat loss coefficients after applying strong retrofit

The ventilation rate was kept the same asin the baseline in order to track the impact of just construction retrofit. The results are reported in the table below.

month	jan	feb	mar	apr	may	jun	jul	aug	sep	oct	nov	dec
Tio, strong rerofit	12.2	14.9	20.7	25.1	31.3	35.8	37.8	35.3	30.5	24.8	16.7	11.8
Tio, strong retrofit model	8.6	11.0	17.1	23.3	27.7	35.2	37.4	35.5	30.8	24.6	16.3	10.2
delta T	3.6	3.9	3.7	1.9	3.6	0.6	0.4	-0.2	-0.3	0.2	0.4	1.6

Table 27 - Differance between applying strong rerofit in static and dynamic model

As we are introducing retrofit strategies the difference in average monthly results between static and dynamic models are increased too. This is happening and is especially emphasized due to the fact that input parameters in the static model are averaged. The actual behavior of users, which is concentrated in the middle of the day has much impact on the dynamic results especially negative in terms of temperature behavior.

6.3 Final step – regulating temperature with ventilation rate

In order to achieve thermal comfort (since as of now, the iAQ is not taken into consideration), especially in the winter months, the lower ventilation – the better. So for January and December, the ventilation rate was set to 0.1 ach/h. During summertime, in order to lower the indoor temperature, a high ventilation rate was used, even up to 7.5 ach/h.

	jan	feb	mar	apr	may	jun	jul	aug	sep	oct	nov	dec
n	0.10	0.15	0.30	0.60	1.50	3.50	7.50	4.50	3.00	0.60	0.20	0.10
Tio, strong rerofit + ventilation	20.8	22.4	24.9	24.8	24.5	25.2	25.9	25.5	22.3	24.5	22.4	20.1
Tio, strong rerofit + ventilation, m	11.6	13.7	18.9	23.1	23.5	25.7	26.2	25.6	22.4	22.3	18.1	13.4
delta T	9.2	8.7	6.1	1.7	1.0	-0.5	-0.3	-0.1	-0.1	2.2	4.4	6.7

Table 28 - Differance between static and dynamic model of heavy retrofit with regulated ventilation

As expected, the difference in temperature is even higher in comparison with the previous one, especially during winter. Still, we can see the difference between dynamic models, but what we are more interested in is what is happening day by day and even hour after hour.

6.4 Compareson of HDh of the baseline and retorift configuration

To get a better view of what is happening inside the building, heating degree hours were calculated from the results obtained in dynamic simulation. For now, the focus is on heating degree hours because we almost exploited every retrofit improvement and we are still far from comfort, while during summer, the ventilation rate could be higher and moreover shading strategies could be introduced. It would have a significant impact on on the temperature since during summertime solar gains are the most responsible ones for heat gains.

HDh working		Milan	Baseline	Baseline + strong re-torift	Baseline + strong retrofit + ventilation from static analy-sis
MONTH	n	HDh	HDh	HDh	HDh
jan	1	4950	4646	3355	2351
feb	2	3826	3477	2259	1486
mar	3	2552	2031	602	277
apr	4	1844	721	0	0
may	5	707	204	0	16
jun	6	117	0	0	0
jul	7	17	0	0	0
aug	8	120	0	0	1
sep	9	478	32	0	39
oct	10	1325	727	0	10
nov	11	3528	3016	1006	496
dec	12	5023	4578	2873	1772
total		24487	19432	10095	6448

Table 29 - Compareson of Heating Degree hours

The results reported in the table are the ones concerning just the working hours of the school. Through this analysis, we can see that amount of Heating Degree Hours is lowering with the introduction of retrofit strategies so that in the end all the months besides winter ones almost don't have a problem with reaching the comfort threshold of 20°C. We have to notice a small raise in heating degree hours after applying different ventilation rates for every month. This is happening because the same ventilation rate was set for every day of every month separately, so if there is a short period of higher temperature drop, the ventilation is still the same and for those exact moments temperature reaches out of the comfort threshold.

What is important to say is that this is not how the ventilation actually works in this kind of building. It is more relevant to use modulating profile. There are many ways to determine ventilation. This will be the topic of the next chapter.

CHAPTER 7. Natural ventilation simulation – Dynamic mode

7.1 Supposing achivable ventilation rates with existing configuration

In the beginning, the ventilation rate has been set with a help of static calculation in order to regulate indoor CO_2 concentration. This is maybe one of the things we can propose. What is the real situation when we are talking about the user's behavior is that they are opening windows a certain amount of minutes per hour, or if the temperature is higher than a certain value.
In order to regulate internal temperature, the ideal situation is that the windows are operating automatically by receiving a signal from the sensors. The degrees of opening were analyzed to get the feeling what is the maximum ventilation rate that could be achieved if the windows are opened by exact degrees if the internal temperature is higher than 26°C.
It has to be mentioned that all the following simulations were done after applying strong retrofit solutions (20 cm of thermal insulation on the roof and on the wall and changing windows to double glazing with Argon fill and low-E coating),

In order to enhance the saving of energy, the limit of opening the window was set if the temperature crosses the value of 26°C. The window was divided into three equal parts. At first, it has been decided that just one of them is openable (side hung), so the openable area was set as 33%. Further, the threshold of 26°C was held while the opening angle was varying from 10° to 70°. The results are reported in the table below.

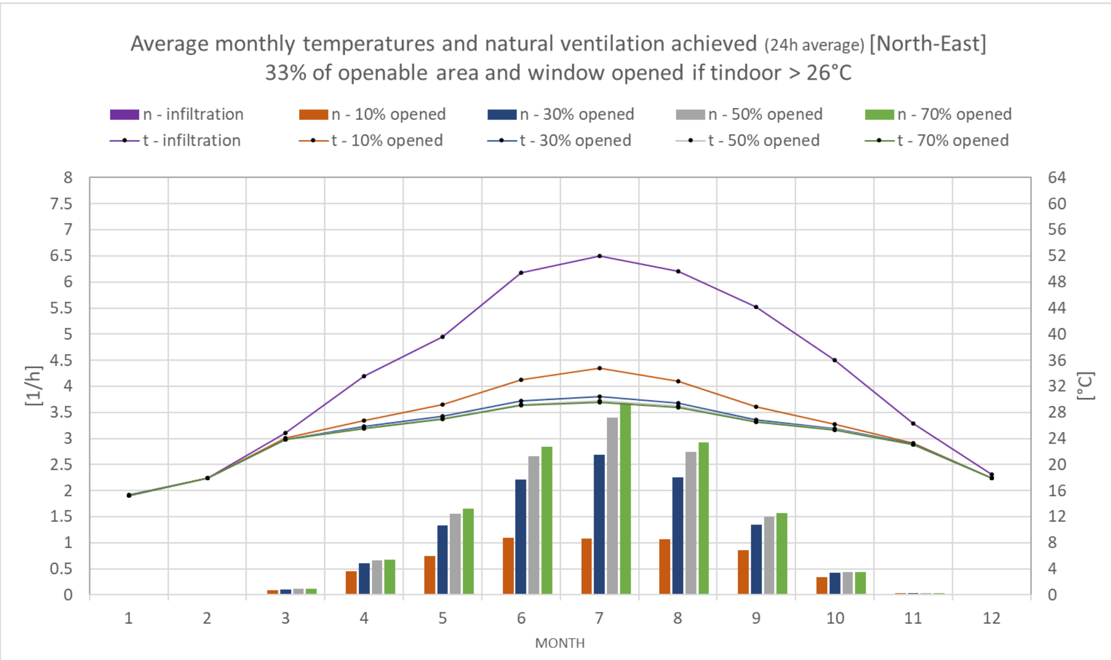

Figure 30 - Average monthly temperature and average monthly ventilation rate

Before any operational profile, just the values of infiltration were extracted to see how the temperature behaves. As expected, if we keep all the windows closed, the temperature during summer is far above the limit, even doubled. Immediately, when we apply 10° of opening on

if the temperature is higher than 26°C, the temperature drop between just infiltration and this profile during summer is very high. As we move forward to a higher degree of opening the difference between every next one becomes lower and lower. This is similar to the situation where applying, for example, thermal insulation led to a lower temperature difference every time we improve the thickness. In this case, it could be indicated that there is a maximum possible amount of air that could be exchanged with the external environment in a specific situation where just 33% of the window is openable.
The only way to increase ventilation rate and therefore decrease indoor temperature during summer is to provide larger openable area.
During wintertime, we can see that there is no difference between different opening configurations and this is simply because the threshold for the opening was set as 26°C, which is the temperature hardly reached during the cold time in this specific case. The problem that opens at this moment is indoor air quality, especially CO2 concentration during winter. If the windows are closed, the Co2 concentration will just rise, since just infiltration is not enough to regulate it. One of the solutions could be the use of a cross-flow heat exchanger, so to use indoor air to preheat the fresh, incoming one in order to minimize temperature drop.

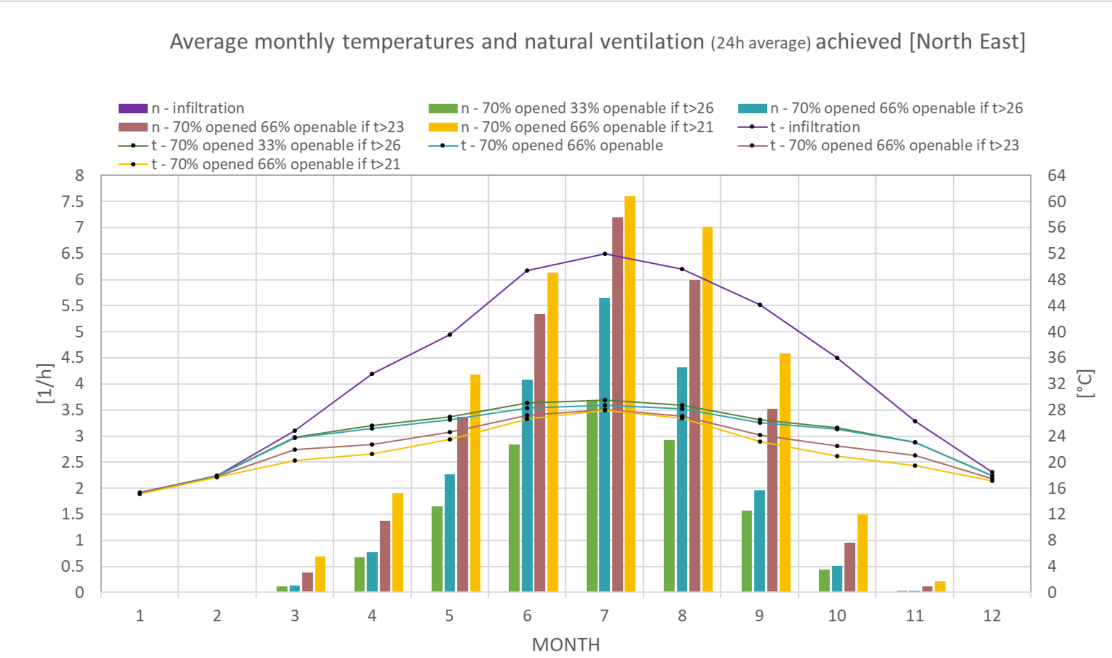

Figure 31 - Average monthly temperature and average monthly ventilation rate

In the next step, increasing the openable area to 66%, we can see that not much has been changed, so another modification has been introduced. The temperature threshold was set to 23°C and finally 21°C. We can notice that this modification has the biggest impact during spring and fall. This is reasonable since, during these seasons, indoor air temperature is below 26°C more than it is during summer, so the window opening is activated more frequently. Also, what could be said about summer is that we can notice higher air exchanges when changing the opening profile, but no big change in temperature. This can be caused by a small difference between internal and external temperatures. The conclusion is that applying a different opening profile to every season would be the best option. As summer is coming, the degree of the opening is becoming bigger, and when we are closer to winter months it is reducing proportionally with temprature.

CHAPTER 8. WINDOW ENGINEERING

The results achieved in previous simulations are indicating that during wintertime we are still out of our comfort zone, but at the same time, the temperature that we have to reach is not so far. When retrofitting and replacing the windows, we can think about changing the dimensions too. Especially during cold times, this will bring more solar gains in classrooms, helping the temperature to be in between comfort limits. Of course, this will mean even higher temperatures during summer. To take care of this, some kind of solar protection should be introduced, together with a strategy of opening the window to provide the needed ventilation rate.

8.1 Solar gains and temperature with new dimensions

For now, the ventilation profile that is gonna be used is the last one, 66% of the openable area, 70% opened when the temperature is higher than 21°C.
The existing window has dimensions of 4.8x1.8m. If the parapet is removed and instead of it new window becomes the one that goes all the way to the floor, the new dimensions are 4.8x2.7cm. Talking about percent, the new window would be enlarged by 50% of the existing area of the window.
The new simulation has been represented with a simple model of one window with no vertical or horizontal profiles that divide the window. This window was applied also to the surrounding rooms in order to include their effect on temperature change.

The results are showing that solar gains are higher, as expected.

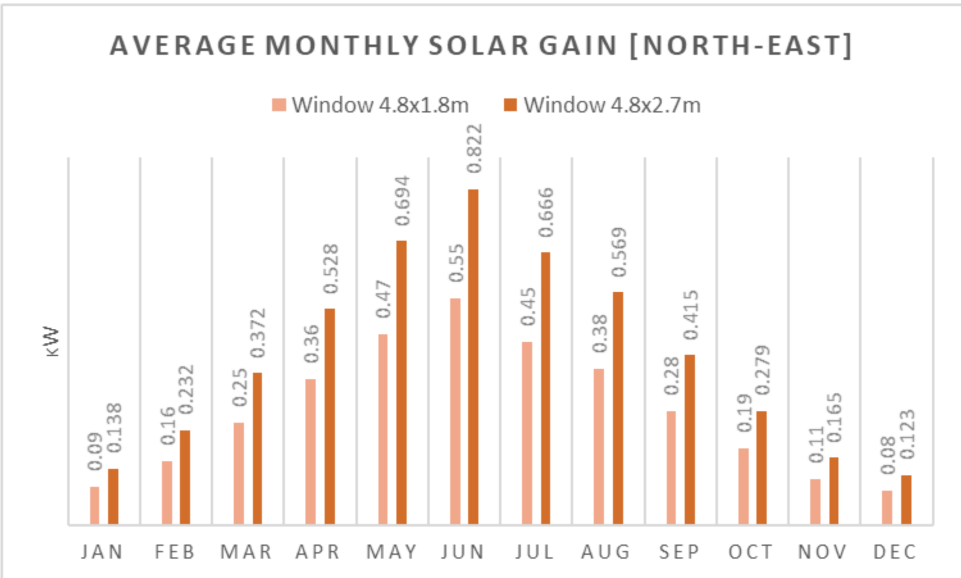

Figure 32 - Solar gains of windows

Anyway, talking about the temperature, a change is not so significant in terms of average monthly temperature. There is a raise, especially during summer and important notice of higher temperature is happening during February.

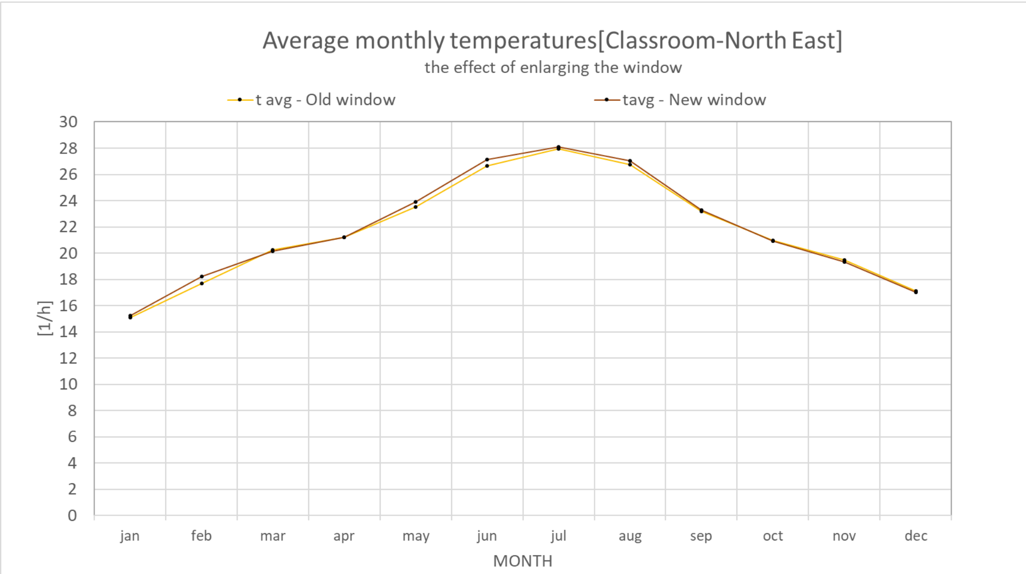

Figure 33 - Effect of enlarging the window on average monthly temperature

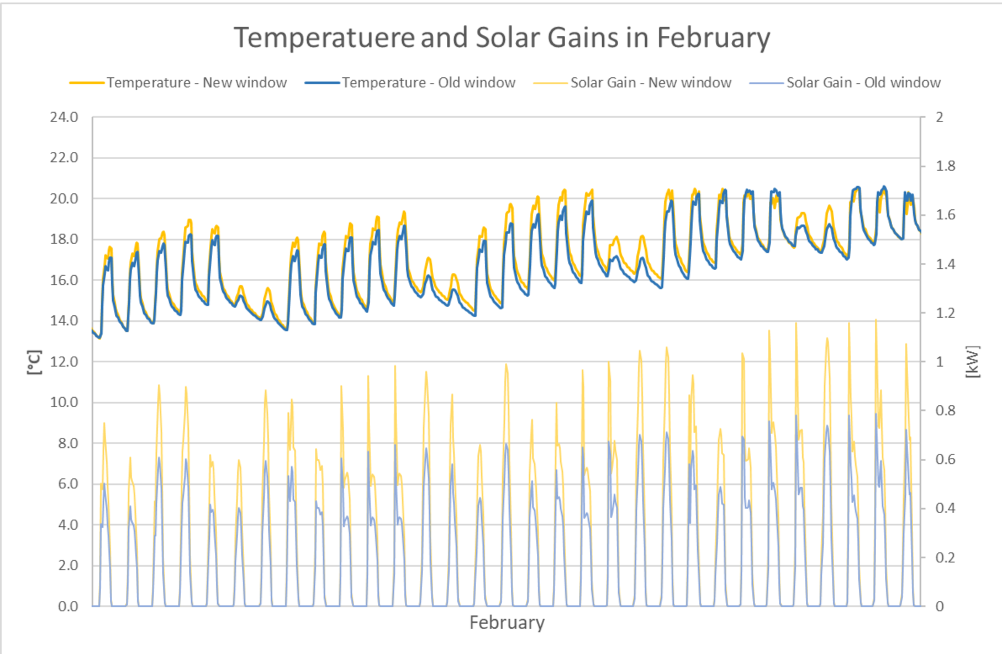

Figure 34 - Temperature and Solar Gain in February for North-East oriented classroom

In order to make sure that the change in February is reasonable, the month of January is plotted and is the subject of comparison. In January there is a slight change in the temperature average, while in February we can notice a bigger change. By plotting the results of temperature and solar gain the answer is given. Firstly Solar gains are lower than in February, therefore the Solar gain improvement by enlarging the window is lower compared to February which leads to a difference in temperature raise looking at two months.

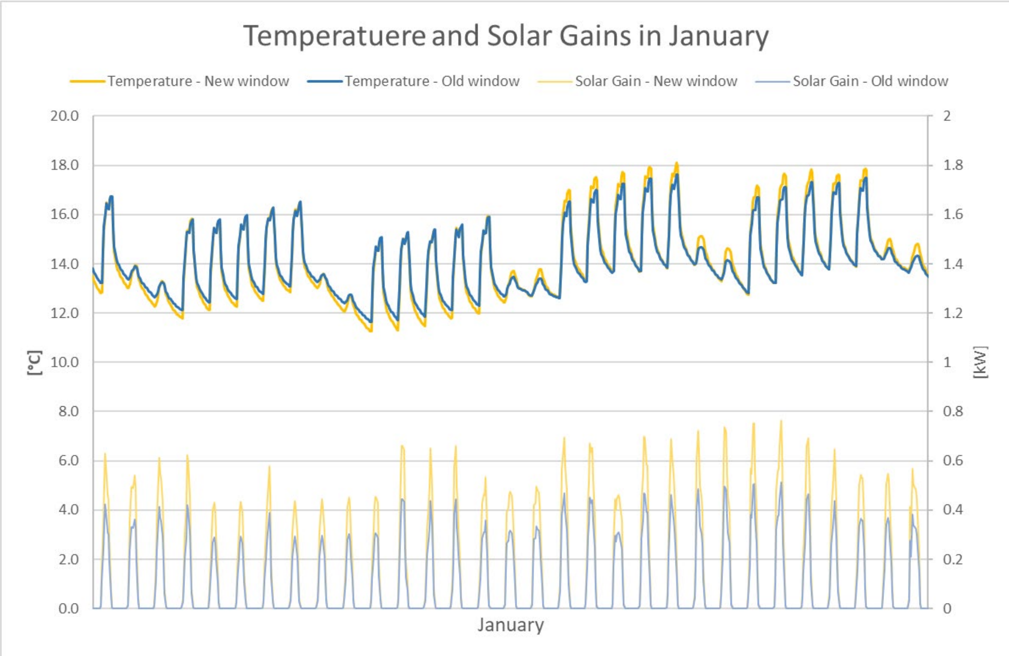

Figure 35 - Temperature and Solar Gains in Januaryfor North-East oriented classroom

8.2 ONE STEP BACK – abolition of the ventilation while retrofiting

The change in temperature perceived in the previous analysis is low. This led to a thought: "Is there something wrong?". Eventually, by using ventilation, the raise in temperature can hardly be seen, so it is time to step back. The start will be the results of indoor temperature, HDh, CDh and ventilation rate of the hottest space placed on the South-East side on the top floor, but with windows closed all the time. The infiltration is taken into account. It will be reported as ventilation rate. Firstly, suitable strategies were applied on the South-West side, and later on the North-East side, since those two orientations are predominant in the building.

8.2.1 South-West orientation

Enlarging the window

The original window dimensions of 4.8x1.8m were enlarged to 4.8x2.7m by removing the parapet and using that area for the window too. The window has been divided into smaller openable parts to explore the possibility of air changes later. It is expected to have higher sun gains, which is favorable for winter. Since for the summer that's not the case, the overhangs with a depth of 35cm were placed in front of every one of three horizontal profiles of the window. (Figutre 38)

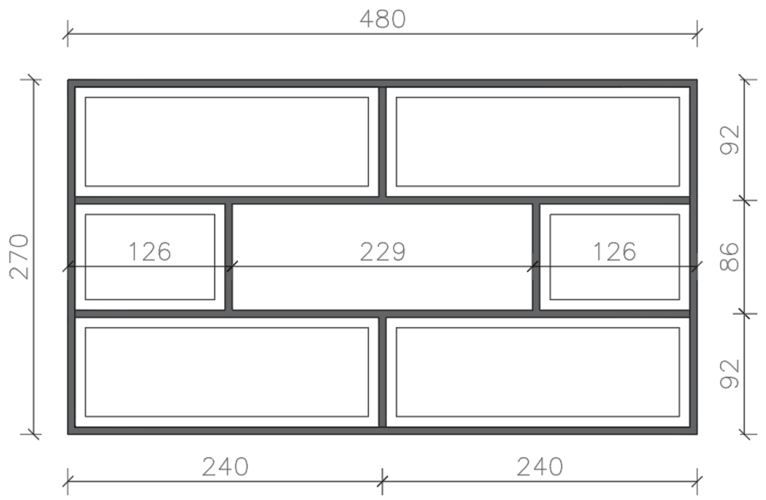

Figure 36 - Enlarged window prospect

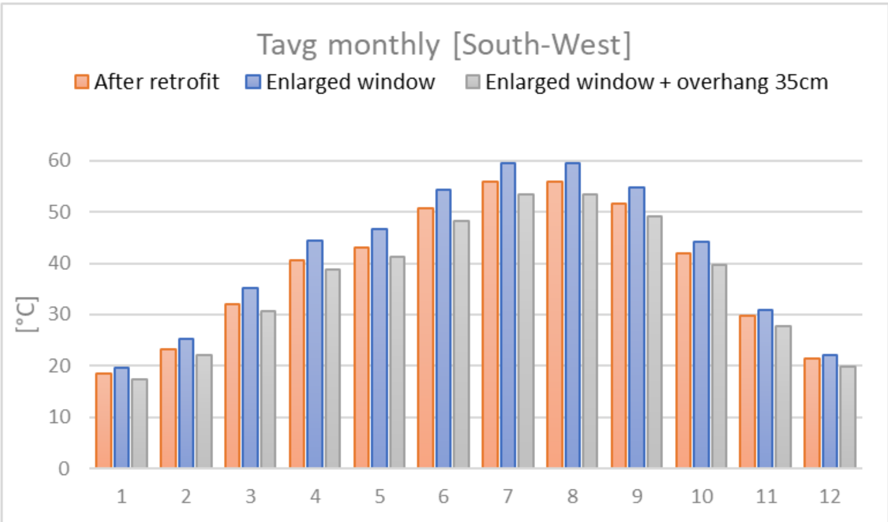

Figure 37 - Average monthly temperature during working hours

It could be recognized that the change of window dimensions brought a rise in average monthly temperature, but also, the introduction of the overhang reduced it to an even lower one. The dimensions were kept since the bigger area will be favorable for manipulating the natural ventilation.

	Retrofit				Enlarged window				Enlarged window + overhang 35cm			
MONTH	tavg working	n (1/h)	HDh	CDh	tavg working	n (1/h)	HDh	CDh	tavg working	n (1/h)	HDh	CDh
jan	18.5	0.013	604	0	19.7	0.017	481	21	17.4	0.036	836	0
feb	23.2	0.012	59	125	25.3	0.018	27	352	22.0	0.037	128	78
mar	32.0	0.013	0	1698	35.2	0.019	0	2574	30.7	0.040	0	1383
apr	40.6	0.015	0	3943	44.3	0.022	0	4937	38.9	0.045	0	3473
may	43.1	0.014	0	4765	46.5	0.021	0	5732	41.1	0.042	0	4224
jun	50.7	0.015	0	6677	54.4	0.021	0	7661	48.3	0.044	0	6032
jul	55.9	0.015	0	8334	59.6	0.022	0	9369	53.4	0.045	0	7654
aug	55.8	0.016	0	8323	59.5	0.023	0	9344	53.4	0.047	0	7645
sep	51.6	0.016	0	6921	54.9	0.023	0	7791	49.1	0.047	0	6235
oct	42.0	0.015	0	4462	44.2	0.021	0	5064	39.6	0.044	0	3801
nov	29.8	0.014	0	1178	30.9	0.019	0	1438	27.8	0.040	8	775
dec	21.3	0.012	202	36	22.1	0.018	157	98	19.8	0.037	407	7
			866	46462			665	54381			1378	41307

Table 30 - Monthly averafes of temperature during working hours, ventilation rate, HDh and CDh

Firstly, with enlarging the window we will focus on HDh since the aim of that change was a reduction, which could be observed from the table. Secondly, adding overhangs was introduced to lower heating hours, which could be observed from the table too. Overall, we can state that the results are reasonable and expected.

Curtains

The next step was to introduce another strategy to reduce solar gains, which is using curtains. Three regulating profiles were created which are activating the curtains depending on the internal temperature:

1. Curtains on if internal temperature is higher than 26°C
2. Curtains on if internal temperature is higher than 23°C
3. Curtains on if internal temperature is higher than 21°C

After simulations and analysis of the results, it became clear that changing the temperature threshold is not bringing any significant change to HDh and CDh.

In order to enhance the use of the curtains, one more control has been introduced. Incident irradiation was a trigger for activating the curtains. By taking a look at incident irradiation on the window surface derived from IES-VE, the threshold has been decided to be 500W/m2, with a variation of 100, which means that when the radiation reaches the value of 450W/m2, the curtains will be activated and when it reaches the value of 550 W/m2 they will be closed. This threshold was set by taking care not to go too low and bring the students into situations where the curtains are down all-day.

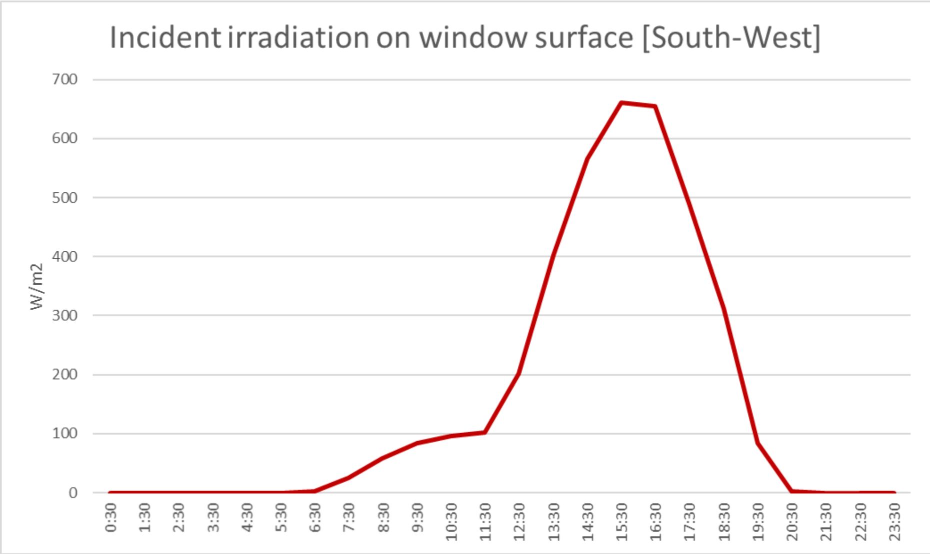

Figure 38 - Incident irradiation on the window surface - August 18th

This threshold in this particular case, which is August the 18th, will mean that the curtains will be activated from 14:00h and will go up after 17:00h.

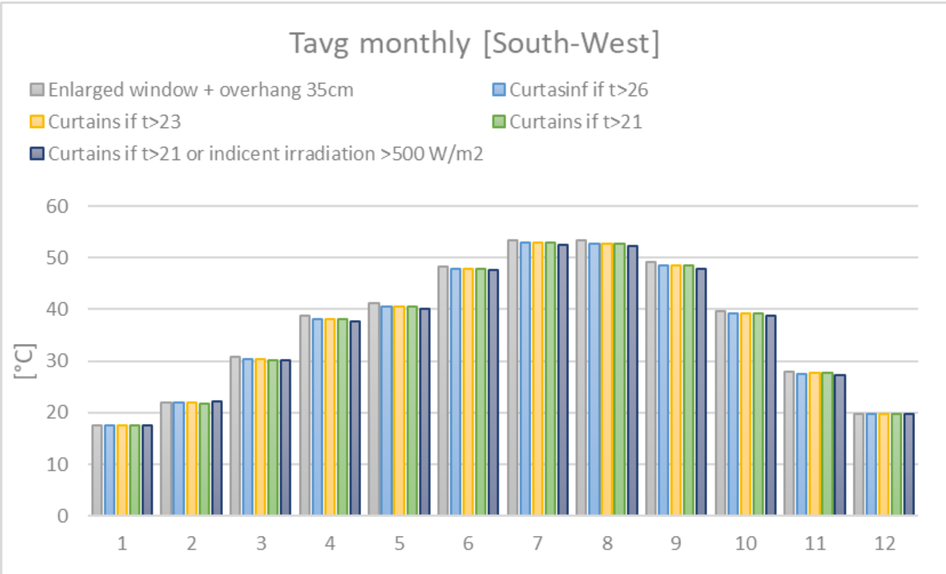

Figure 39 - Average monthly temperature during working hours

The results in terms of temperature change are mostly the same for all the operating profiles, so the nig change is not expected from the HDh and CDh neither.

	Enlarged window + overhang 35cm				Enlarged window +overhang + curtains t>26				Enlarged window +overhang + curtains t>23				Enlarged window +overhang + curtains t>21			
MONTH	tavg working	n (1/h)	HDh	CDh	tavg working	n (1/h)	HDh	CDh	tavg working	n (1/h)	HDh	CDh	tavg working	n (1/h)	HDh	CDh
jan	17.4	0.036	836	0	17.5	0.036	825	0	17.5	0.036	833	0	17.4	0.036	843	0
feb	22.0	0.037	128	78	22.0	0.036	128	90	21.9	0.036	143	76	21.7	0.036	155	68
mar	30.7	0.040	0	1383	30.4	0.039	0	1299	30.3	0.039	0	1276	30.2	0.039	0	1270
apr	38.9	0.045	0	3473	38.2	0.044	0	3283	38.1	0.044	0	3280	38.1	0.044	0	3280
may	41.1	0.042	0	4224	40.4	0.041	0	4024	40.4	0.041	0	4024	40.4	0.041	0	4024
jun	48.3	0.044	0	6032	47.8	0.043	0	5896	47.8	0.043	0	5896	47.8	0.043	0	5896
jul	53.4	0.045	0	7654	52.8	0.045	0	7486	52.8	0.045	0	7486	52.8	0.045	0	7486
aug	53.4	0.047	0	7645	52.8	0.046	0	7464	52.8	0.046	0	7464	52.8	0.046	0	7464
sep	49.1	0.047	0	6235	48.5	0.046	0	6083	48.5	0.046	0	6083	48.5	0.046	0	6083
oct	39.6	0.044	0	3801	39.2	0.043	0	3674	39.2	0.043	0	3674	39.2	0.043	0	3674
nov	27.8	0.040	8	775	27.6	0.040	10	736	27.6	0.040	10	742	27.6	0.040	10	743
dec	19.8	0.037	407	7	19.8	0.037	409	9	19.7	0.037	427	6	19.6	0.037	438	5
			1378	41307			1372	40044			1413	40008			1446	39993

Table 31 - Average monthly temperature during working time, vantilation rate, HDh and CDh

Even though the change is not significant, the best results in terms of CDh are with using two triggers for profile operation, so this profile will be used in further analysis.

Change of opening configuration

Since the HDh have been raised, the thought of reducing window frame percentage was introduced. By changing percentage from 30,86% to 25,6%. This has been done by making the middle part of the window fixed, so the dimensions needed for the openable profile are no longer present. The picture of the prospect of the window is reported in Figure 40.

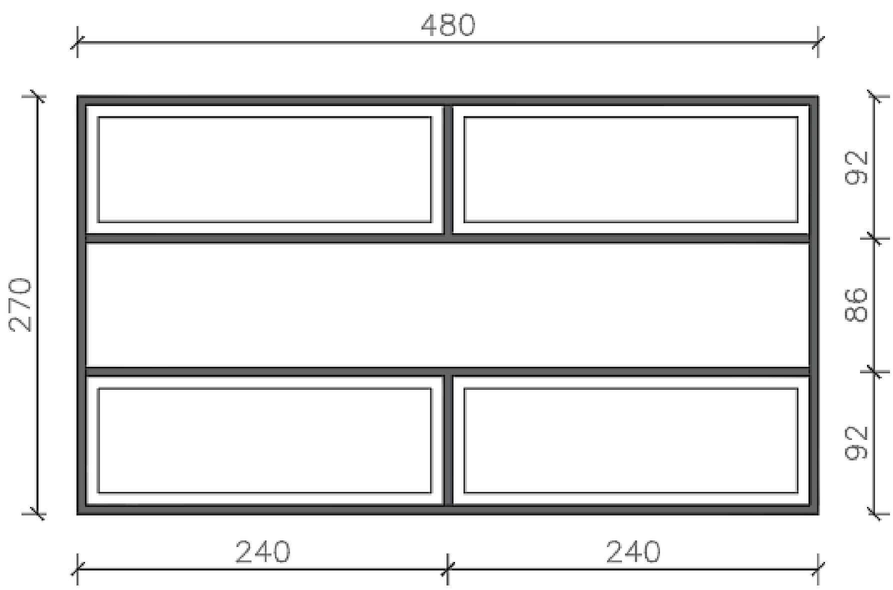

Figure 40 - New window configuration, middle part fixed

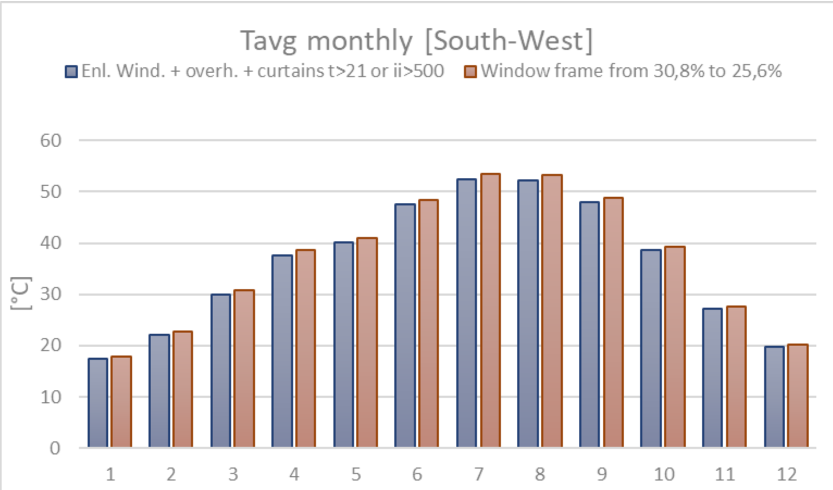

Figure 41 - Average monthly temperature during working hours

	Window frame 30,8%				Window frame 30,8%			
	Enl. Wind. + overh. + curtains t>21 or ii>500				Enl. Wind. + overh. + curtains t>21 or ii>500			
MONTH	tavg working	n (1/h)	HDh	CDh	tavg working	n (1/h)	HDh	CDh
jan	17.5	0.036	825	0	17.9	0.037	758	0
feb	22.1	0.037	122	84	22.7	0.037	95	120
mar	30.0	0.039	0	1207	30.8	0.040	0	1393
apr	37.7	0.044	0	3155	38.6	0.044	0	3390
may	40.1	0.040	0	3925	40.9	0.041	0	4151
jun	47.5	0.042	0	5818	48.4	0.043	0	6044
jul	52.5	0.044	0	7395	53.4	0.045	0	7657
aug	52.3	0.046	0	7330	53.2	0.046	0	7599
sep	47.9	0.046	0	5916	48.8	0.046	0	6157
oct	38.7	0.042	0	3532	39.3	0.043	0	3718
nov	27.2	0.040	14	666	27.6	0.040	10	745
dec	19.8	0.037	409	6	20.2	0.037	364	12
			1371	39035			1227	40985

Table 32 - Average monthly temperature during working hours, ventilation rate, HDh and CDh

The temperature rise is obvious even during winter, but also is of CDh in general. This will be regulated by opening the window and providing air changes of fresh air from outside.

The window was divided into 3 parts. 90% of the upper window area is openable by top hung 90° maximum. The middle part is fixed, this allowed us to reduce the frame percentage. The lower third of the window is 90% openable by bottom hung 30° maximum. Every openable window is openable only towards inside.

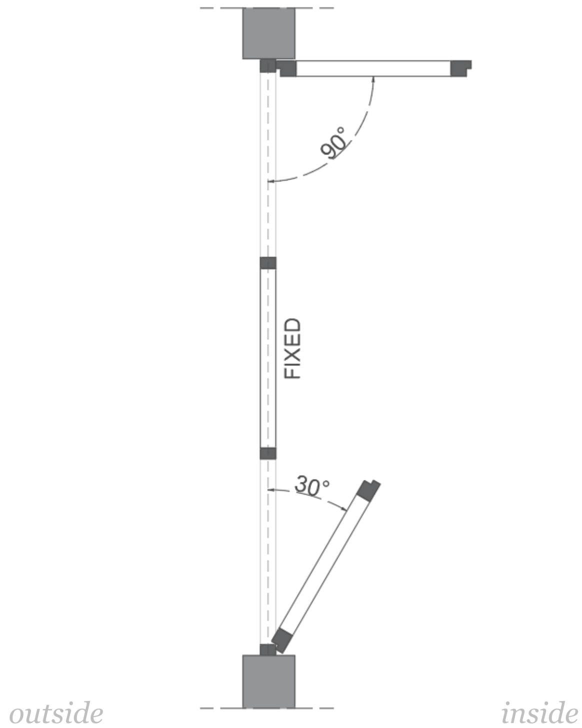

Figure 42 - Scheme of opening profile of the window

Introducing ventilation

Throughout all previous simulations, windows were closed in order to have a clear view of the effect of strategies we are applying such as curtains, their operating profile, overhang and so on. Now that the profiles are set and the improvement of the window is set, the ventilation profile has been decided in order to lower the CDh.

To see the effect of the ventilation, the operating profile that has been applied was that the openable windows are on maximum if the internal temperature crosses the value of 21°C.

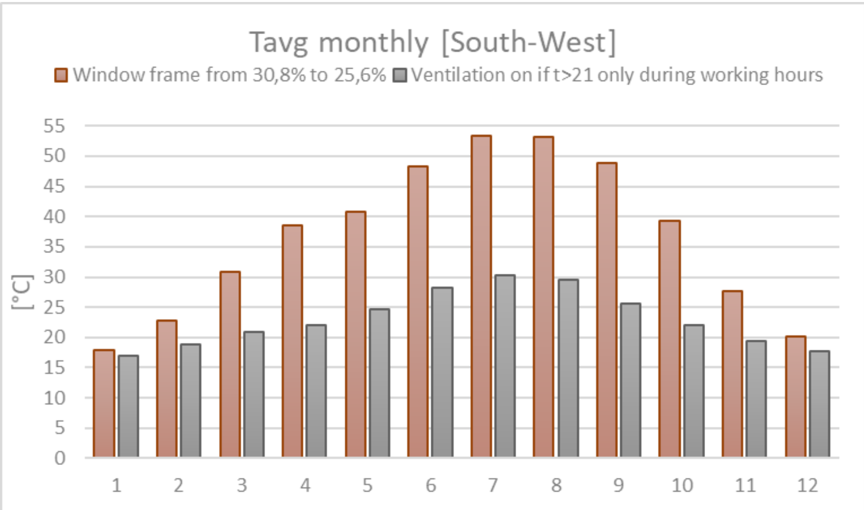

Figure 43 - Average monthly temperature durign working hours

As expected, the drop of temperature, especially during summer is significant, and further looking at HDh and CDh tables, we can see that CDh have been reduced 10 times. On the other hand, during winter, ventilating is not favorable and this will mean that in next stpes the ventilation will be off during that time.

					Ventilation on if t>21 only during working hours			
	Window frame from 30,8% to 25,6%				Window frame from 30,8% to 25,6%			
	Curtain profiles on Mar-Nov				Curtain profiles on Mar-Nov			
	Enl. Wind. + overh. + curtains t>21 or ii>500				Enl. Wind. + overh. + curtains t>21 or ii>500			
MONTH	tavg working	n (1/h)	HDh	CDh	tavg working	n (1/h)	HDh	CDh
jan	17.9	0.037	758	0	16.9	0.159	883	0
feb	22.7	0.037	95	120	18.9	0.597	329	0
mar	30.8	0.040	0	1393	20.8	2.075	100	35
apr	38.6	0.044	0	3390	22.1	3.506	59	90
may	40.9	0.041	0	4151	24.7	4.677	8	341
jun	48.4	0.043	0	6044	28.3	6.455	0	843
jul	53.4	0.045	0	7657	30.3	7.069	0	1275
aug	53.2	0.046	0	7599	29.5	7.078	0	1169
sep	48.8	0.046	0	6157	25.5	5.956	2	425
oct	39.3	0.043	0	3718	22.1	3.110	16	68
nov	27.6	0.040	10	745	19.5	0.760	198	0
dec	20.2	0.037	364	12	17.7	0.245	647	0
			1227	40985			2243	4247

Figure 44 - Average temperature durign working hours, ventilation rate, HDh and CDh

Also, the temperature drop is significant, but in the summer months, maximum possible ventilation during working hours is not enough to bring the temperature between the comfort thresholds. There is the option to keep the windows open even after working hours. How many hours they should be opened and what is the effect will be reported in the next chapter.

Night ventilation

Night ventilation should have a great impact since during the time of ventilating, the outside temperature reaches the lowest value of that day. Since during nighttime, sun gains are not present, ventilating is even more effective. There are a few questions about this kind of ventilation. The first is how much ventilation should be used during spring and fall since the outside temperature could be very low during the night and therefore cause discomfort during the beginning of the working hours. Also, there is a question of safety, but as of now, it is not the focus.

Firstly, the additional ventilation was applied from 19:00 to 24:00 to see if this change would be enough. Secondly, it was applied all night during certain months. The yearly schedule of ventilation is reported in the table below. It has to be mentioned that the decision has been brought to not open the window during winter at all since it has no good effect in terms of temperature. The problem of CO_2 concentration that this decision will bring would have to be solved by an effective heat exchanger which would preheat the external air to provide good indoor air quality, but at the same time not affect the temperature in unfavorable way.

	Ventilation on if t>21 only during working hours Window frame from 30,8% to 25,6% Curtain profiles on Mar-Nov Enl. Wind. + overh. + curtains t>21 or ii>500				Dec-Feb NO Mar-May if t indoor > 21 Jun-Aug if t indoor > 21 andopened all night Sept-Nov if t indoor > 21				Dec-Feb NO Mar-Apr if t indoor > 21 May if t indoor >21 and opened 19-24h Jun-Aug if t indoor > 21 andopened all night Sept if t indoor >21 and opened 19-24h Oct-Nov if t indoor > 21			
MONTH	tavg working	n (1/h)	HDh	CDh	tavg working	n (1/h)	HDh	CDh	tavg working	n (1/h)	HDh	CDh
jan	16.9	0.159	883	0	17.9	0.035	759	0	17.9	0.0	759	0
feb	18.9	0.597	329	0	22.8	0.035	94	124	22.8	0.0	94	124
mar	20.8	2.075	100	35	20.9	2.165	100	35	20.9	2.2	100	35
apr	22.1	3.506	59	90	22.1	3.509	59	90	22.1	3.5	59	90
may	24.7	4.677	8	341	24.7	4.676	8	341	24.2	7.2	8	258
jun	28.3	6.455	0	843	27.6	8.870	0	684	26.9	12.1	0	530
jul	30.3	7.069	0	1275	29.6	9.718	0	1099	28.9	13.1	0	937
aug	29.5	7.078	0	1169	28.9	9.743	0	1005	28.2	13.4	0	850
sep	25.5	5.956	2	425	25.4	5.900	2	407	24.9	8.2	2	313
oct	22.1	3.110	16	68	22.1	3.108	16	68	22.0	3.1	16	56
nov	19.5	0.760	198	0	19.5	0.751	195	0	19.5	0.8	198	0
dec	17.7	0.245	647	0	19.6	0.034	419	3	19.6	0.0	419	3
			2243	4247			1653	3859			1656	3199

Table 33 - Average monthly temperature during working hours, ventilation rate, HDh and CDh

We can notice that night ventilation has an impact on reducing CDh, but still, the temperature is not lower than 26°C. A big change in the average monthly ventilation rate is observed. It might be strange that the temperature reduction is not so drastic as the change in ventilation rate, but this is because the temperature is calculated as average during working hours and the ventilation rate as a pure monthly average.
Since there is still a need for reduction of temperature during summer, night ventilation is set all night and again there is a big change in the average monthly ventilation rate since now the ventilation is on during the whole night. Reduction in CDh is reported, so we can say that this method has its benefits.

Shutters

Still, there is a way to save energy in the building during cold nights. By introducing shutters to a window, when they are all the way down, the window has additional resistance, where the window of value that is 1,05 W/m2K to 0,8 W/m2K. If the shutters are used in the hours when the school is not working during wintertime, the expectations are that the energy will be stored. The simulation was launched and the results are reported in the table below. The rise in temperature could be noticed during winter months even by 1°C. Since there is no ventilation during winter, especially during February, the temperature is reaching levels high enough to cross the boundary and increase overall CDh. Also, the difference between the last two columns is indicating that applying the same strategy to same-oriented rooms will have an impact when comparing if the strategy is applied just to one room and surrounding ones.

MONTH	Dec-Feb NO Mar-Apr if t indoor > 21 May if t indoor >21 and opened 19-24h Jun-Aug if t indoor > 21 andopened all night Sept if t indoor >21 and opened 19-24h Oct-Nov if t indoor > 21				Introducing shutters in winter 19-08h				Shutters during winter nights New windows applied on the whole school			
	tavg working	n (1/h)	HDh	CDh	tavg working	n (1/h)	HDh	CDh	tavg working	n (1/h)	HDh	CDh
jan	17.9	0.0	759	0	18.8	0.0	582	1	18.8	0.0	590	1
feb	22.8	0.0	94	124	23.8	0.0	46	184	23.8	0.0	45	185
mar	20.9	2.2	102	37	20.9	2.2	104	38	20.8	2.1	103	29
apr	22.1	3.5	59	90	22.1	3.5	59	90	21.8	3.2	56	67
may	24.2	7.2	8	258	24.2	7.2	8	258	23.8	6.8	11	192
jun	26.9	12.1	0	530	26.9	12.1	0	530	26.3	11.3	0	398
jul	28.9	13.1	0	937	28.9	13.1	0	937	28.2	12.4	0	775
aug	28.2	13.4	0	850	28.2	13.4	0	850	27.5	12.5	0	685
sep	24.9	8.2	2	313	24.9	8.2	2	313	24.3	7.5	2	209
oct	22.0	3.1	16	56	22.0	3.1	16	56	21.5	2.6	18	27
nov	19.5	0.8	198	0	19.5	0.8	196	0	19.2	0.6	248	0
dec	19.6	0.0	419	3	20.4	0.0	274	10	19.9	0.0	342	3
			1656	3199			1288	3268			1414	2572

Table 34 - Average monthly temperature during wirking hours, ventilation rate, HDh and CDh

Overview of window engineering for South-West orientation

As there was a chance of gaining more sun by enlarging the window, this option was under exploring. The window was divided into smaller parts, which led to a high frame percentage. This was solved by making one-third of the window zone fixed and two others openable. This made the situation better. The next focus was on reducing CDh with the use of overhangs and curtains. The overhang of 35cm on each horizontal profile and curtains are activated if the indoor air temperature is higher than 21°C or incident irradiation higher than 450 W/m2. This was effective, but still, without using ventilation, the parameters were far from the comfort. By making a certain scheme of opening the window and providing the maximum possible opening of that configuration, a strong drop in temperature during summer happened as expected. Still, this was not enough to bring summer temperature between 20°C and 26°C. The last strategy for reducing CDh was introducing night ventilation. The profile that was used for the ventilation was the following:

Dec-Feb NO
Mar-Apr if t indoor > 21
May if t indoor >21 and opened 19-24h
Jun-Aug if t indoor > 21 and opened all night
Sept if t indoor >21 and opened 19-24h
Oct-Nov if t indoor > 21.
This led to even lower CDh during the year.
For the last step, the addition of a shutter was performed, which brought additional resistance to the window when they are closed (during non-working hours in winter).
The ratio between HDh and CDh of all the steps are reported in the table below.

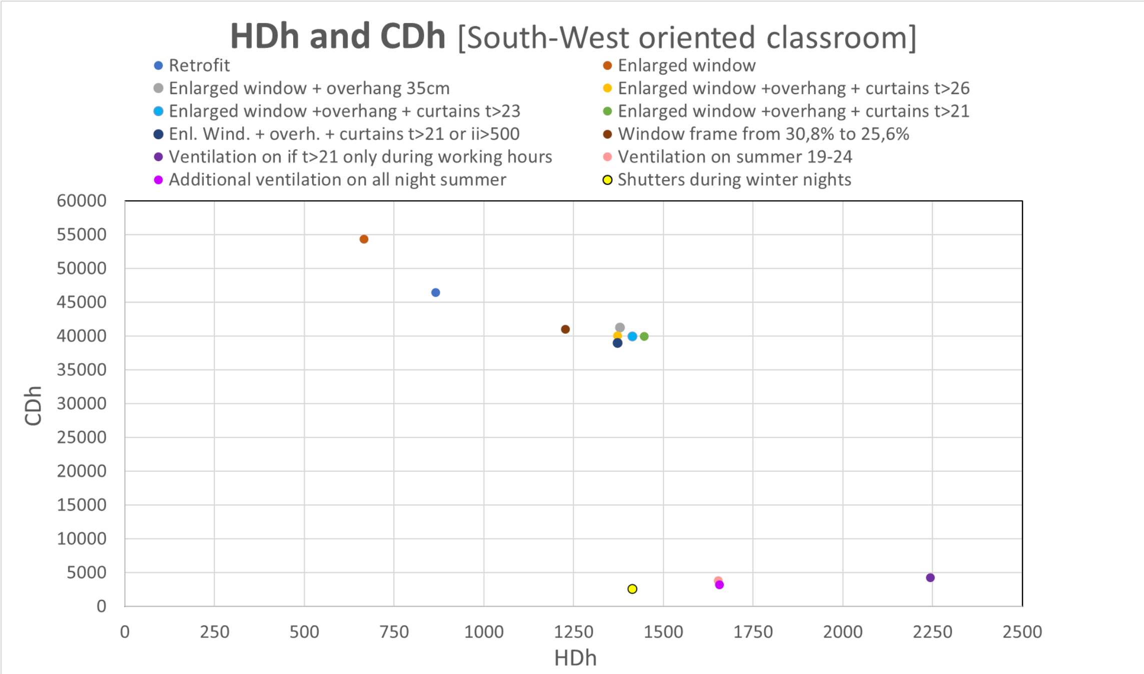

Figure 45 - HDh and CDh of window improvements

Looking at the balance chart, we can recognize that the highest gains the room is receiving from the sun and people. The biggest losses are present as the summer is closer and those are ventilation losses. It can be recognized that losses towards other thermal zones are high. This is mostly because the classroom analyzed is the hottest one, but also has a common wall with the corridor which is significantly colder since the occupation is low and concentrated during lunch break. moreover, the corridor is long and has windows just on the sides, which means that sun gains are low too.
We can see higher losses through the walls, windows and roof during winter, this is because the temperature difference between indoor and outdoor temperatures is high, so the losses are higher too.

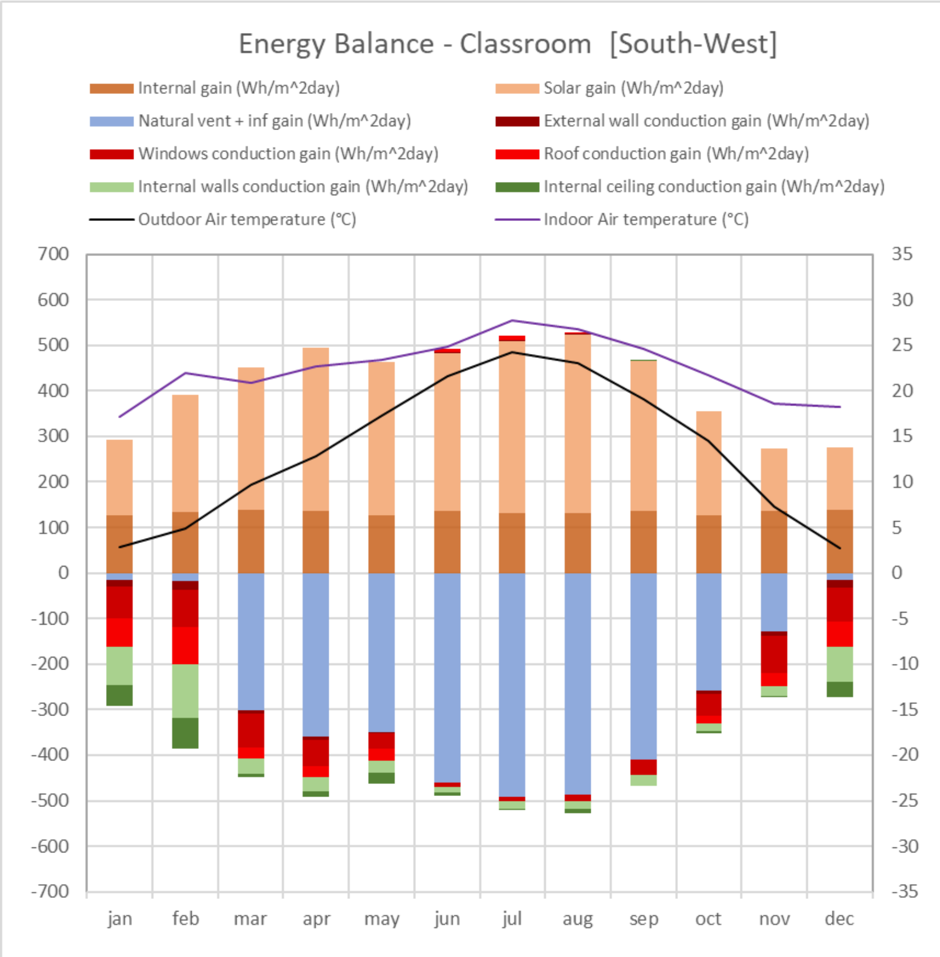

Figure 46 - Energy balance of South-East oriented classroom after retrofit

8.2.2 North-East orientation

Enlarging the window

The original window dimensions of 4.8x1.8m were enlarged to 4.8x2.7m by removing the parapet and using that area for the window too. The window has been divided into smaller openable parts to explore the possibility of air changes later. It is expected to have higher sun gains, which is favorable for winter. Since this is the North-East side and the sun gains are much lower, the overhangs were not the option to go for.

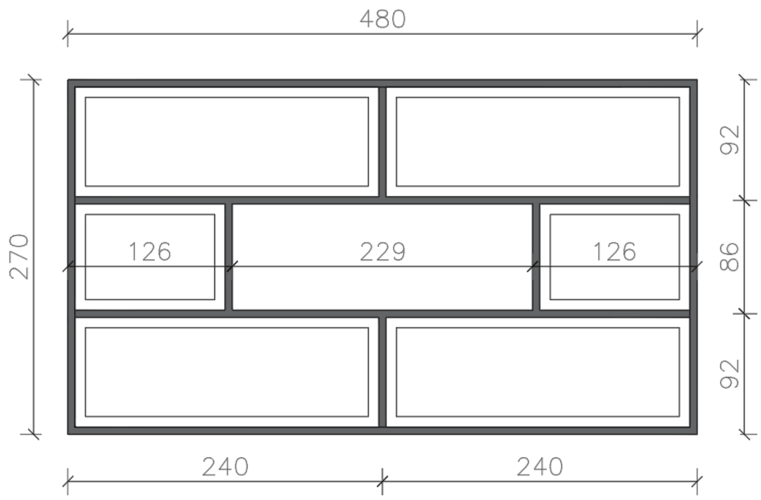

Figure 47 -Enlarged window prospect

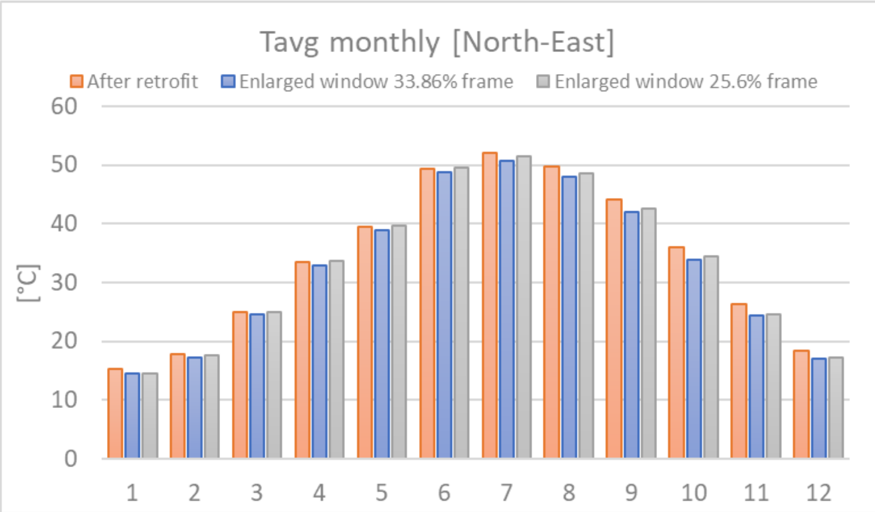

Figure 48 - Average monthly temperature during working hours

It could be recognized that the change of window dimensions had the opposite effect t the one on the South-West side. After the window enlargement, a temperature drop has occurred. This has happened because the rise in solar gains is not significant as losses through the window in this case. Due to that loss, % of the frame has been decreased immediately to 25,6% by making the middle part of the window fixed. This action has caused the rise in temperature.

	Retrofit				Enlarged window 33.86% frame				Enlarged window 25.6% frame			
MONTH	vg working	n (1/h)	HDh	CDh	vg working	n (1/h)	HDh	CDh	vg working	n (1/h)	HDh	CDh
jan	15.3	0.011	1302	0	14.4	0.033	1552	0	14.6	0.033	1500	0
feb	17.9	0.009	553	0	17.3	0.031	689	0	17.6	0.031	627	0
mar	24.9	0.010	1	183	24.6	0.033	3	148	25.0	0.033	1	198
apr	33.6	0.012	0	2044	33.0	0.038	0	1888	33.6	0.039	0	2049
may	39.6	0.012	0	3781	38.9	0.039	0	3591	39.6	0.040	0	3808
jun	49.4	0.013	0	6323	48.7	0.043	0	6124	49.6	0.044	0	6384
jul	52.0	0.013	0	7246	50.6	0.042	0	6876	51.5	0.043	0	7112
aug	49.7	0.013	0	6600	47.9	0.042	0	6116	48.6	0.042	0	6319
sep	44.2	0.013	0	4906	42.1	0.040	0	4339	42.6	0.041	0	4493
oct	36.0	0.012	0	2792	34.0	0.038	0	2219	34.4	0.038	0	2333
nov	26.3	0.012	1	434	24.3	0.037	35	193	24.6	0.037	29	223
dec	18.5	0.011	536	0	17.0	0.034	870	0	17.2	0.034	824	0
			2392	34309			3148	31495			2982	32918

Table 35 - Average temperatre during working hours, ventilation rate, HDh and CDh for different configurations

Changing type of the glass

The orientation that we are analyzing now is North-East. Since the window is losing more than gaining from the sun, the fixed, middle part of the window was changed to triple glazing to have improved the U-value.

	Enlarged window 25.6% frame				Enlarged window 25.6% frame + triple			
MONTH	tavg working	n (1/h)	HDh	CDh	tavg working	n (1/h)	HDh	CDh
jan	14.6	0.033	1500	0	14.7	0.034	1467	0
feb	17.6	0.031	627	0	17.6	0.031	613	0
mar	25.0	0.033	1	198	25.0	0.033	1	191
apr	33.6	0.039	0	2049	33.5	0.039	0	2023
may	39.6	0.040	0	3808	39.5	0.040	0	3760
jun	49.6	0.044	0	6384	49.4	0.044	0	6317
jul	51.5	0.043	0	7112	51.3	0.043	0	7072
aug	48.6	0.042	0	6319	48.6	0.042	0	6302
sep	42.6	0.041	0	4493	42.7	0.041	0	4507
oct	34.4	0.038	0	2333	34.5	0.039	0	2367
nov	24.6	0.037	29	223	24.8	0.037	25	240
dec	17.2	0.034	824	0	17.3	0.034	781	0
			2982	32918			2887	32780

Table 36 - Average tempeature during working hours, ventilation rate, HDh and CDh of different configurations

Even though if looking at the temperature, we can say that rise is minimal, generally looking at total HDh, the drop has occurred.

Curtains

The next step was to introduce another strategy to reduce solar gains, which is using curtains. Three regulating profiles were created which are activating the curtains depending on the internal temperature:

4. Curtains on if internal temperature is higher than 26°C
5. Curtains on if internal temperature is higher than 23°C
6. Curtains on if internal temperature is higher than 21°C

After simulations and analysis of the results, it became clear that changing the temperature threshold is not bringing any significant change to HDh and CDh.
In order to enhance the use of the curtains, one more control has been introduced. Incident irradiation was a trigger for activating the curtains. By taking a look of incident irradiation on

the window surface derived from IES-VE, the threshold has been decided to be 275W/m2, with a variation of 50, which means that when the radiation reaches the value of 250W/m2, the curtains will be activated and when it reaches the value of 300 W/m2 they will be closed. This threshold was set by taking care not to go too low and bring the students into situations where the curtains are down all-day.

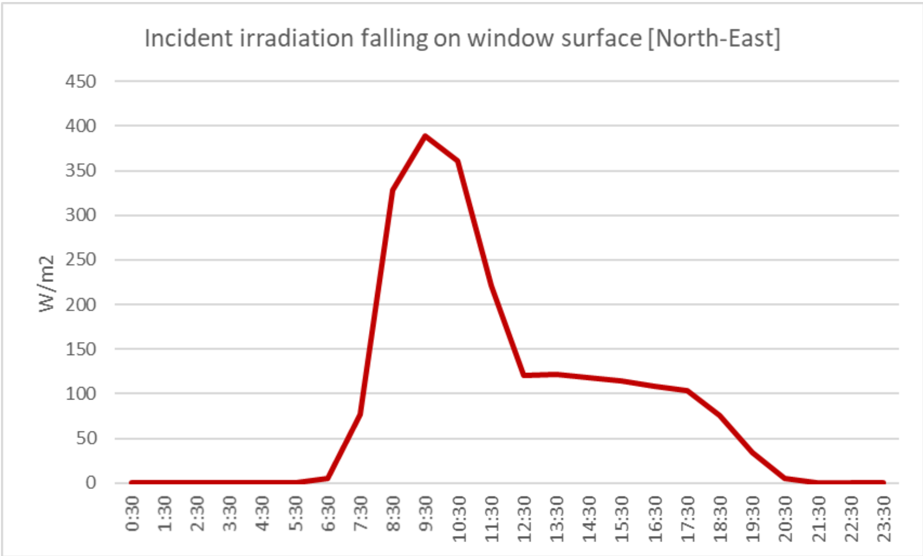

Figure 49 - Incident irradiation on the window surface - August 18th

This threshold in this particular case, which is August the 18th, will mean that the curtains will be activated from 08:30h and will go up after 11:30h.

The results in terms of temperature change are mostly the same for all the operating profiles, so the nig change is not expected from the HDh and CDh neither.

	Enlarged window 25.6% frame + triple				Enlarged window + curtains t>26				Enlarged window + curtains t>23				Enlarged window + curtains t>21				Enl. Wind. + curtains t>21 or ii>500			
MONTH	tavg working	n (1/h)	HDh	CDh	tavg working	n (1/h)	HDh	CDh	tavg working	n (1/h)	HDh	CDh	tavg working	n (1/h)	HDh	CDh	tavg working	n (1/h)	HDh	CDh
jan	14.7	0.034	1467	0	14.8	0.034	1458	0	14.8	0.034	1459	0	14.8	0.034	1459	0	14.8	0.034	1459	0
feb	17.6	0.031	613	0	17.7	0.031	602	0	17.7	0.031	602	0	17.7	0.031	603	0	17.7	0.031	602	0
mar	25.0	0.033	1	191	24.9	0.033	1	180	24.8	0.033	1	159	24.7	0.033	1	153	24.6	0.033	1	143
apr	33.5	0.039	0	2023	33.1	0.038	0	1904	33.0	0.038	0	1895	33.0	0.038	0	1893	32.8	0.038	0	1837
may	39.5	0.040	0	3760	38.8	0.039	0	3567	38.8	0.039	0	3566	38.8	0.039	0	3566	38.6	0.038	0	3524
jun	49.4	0.044	0	6317	48.5	0.043	0	6072	48.5	0.043	0	6072	48.5	0.043	0	6072	48.4	0.043	0	6049
jul	51.3	0.043	0	7072	50.6	0.042	0	6855	50.6	0.042	0	6855	50.6	0.042	0	6855	50.5	0.042	0	6824
aug	48.6	0.042	0	6302	48.0	0.042	0	6148	48.0	0.042	0	6148	48.0	0.042	0	6148	47.8	0.041	0	6080
sep	42.7	0.041	0	4507	42.3	0.041	0	4414	42.3	0.041	0	4414	42.3	0.041	0	4414	42.1	0.040	0	4336
oct	34.5	0.039	0	2367	34.3	0.038	0	2320	34.3	0.038	0	2320	34.3	0.038	0	2320	34.0	0.038	0	2235
nov	24.8	0.037	25	240	24.7	0.037	25	234	24.8	0.037	25	236	24.8	0.037	25	236	24.5	0.037	29	208
dec	17.3	0.034	781	0	17.4	0.034	775	0	17.4	0.034	775	0	17.3	0.034	778	0	17.3	0.034	782	0
			2887	32780			2861	31695			2862	31666			2866	31658			2872	31235

Table 37 - Average monthly temperature during working time, vantilation rate, HDh and CDh

Even though the change is not significant, the best results in terms of CDh are with using two triggers for profile operation, so this profile will be used in further analysis.

Introducing ventilation

Throughout all previous simulations, windows were closed in order to have a clear view of the effect of strategies we are applying such as curtains, their operating profile, overhang and so on.Now that the profiles are set and the improvement of the window is set, the ventilation profile has been decided in order to lower the CDh.

To see the effect of the ventilation, the operating profile that has been applied was that the openable windows are on maximum if the internal temperature crosses the value of 21°C.

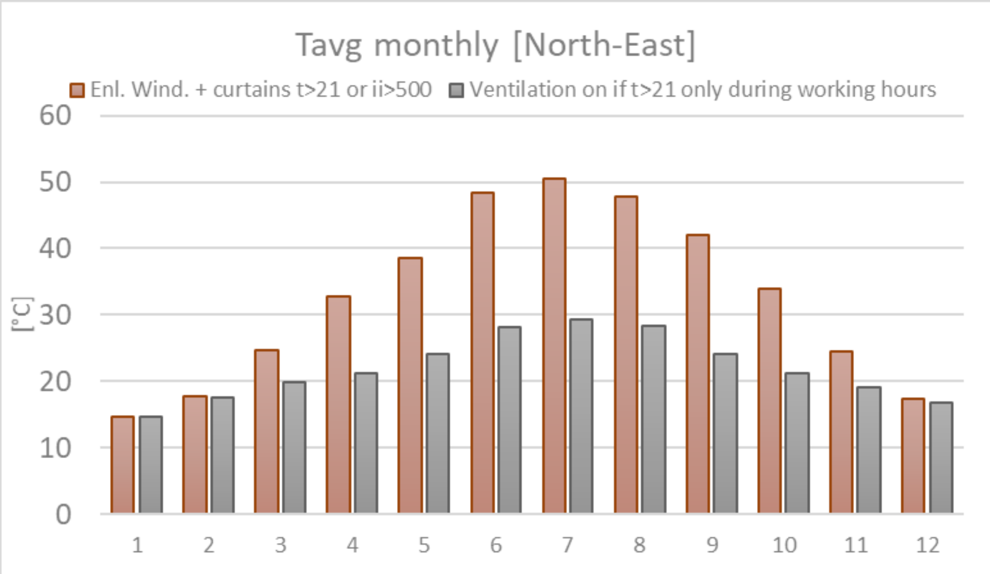

Figure 50 - Average monthly temperature durign working hours

As expected, the drop of temperature, especially during summer is significant, and further looking at HDh and CDh tables, we can see that CDh have been reduced more than 10 times.

					Ventilation on if t>21 only during working hours			
	Window frame from 30,8% to 25,6%				Window frame from 30,8% to 25,6%			
	Curtain profiles on Mar-Nov				Curtain profiles on Mar-Nov			
	Enl. Wind. + curtains t>21 or ii>500				Enl. Wind. + curtains t>21 or ii>250			
MONTH	tavg working	n (1/h)	HDh	CDh	tavg working	n (1/h)	HDh	CDh
jan	14.8	0.034	1459	0	14.8	0.032	1458	0
feb	17.7	0.031	602	0	17.6	0.054	613	0
mar	24.6	0.033	1	143	19.9	0.908	96	0
apr	32.8	0.038	0	1837	21.2	2.422	61	0
may	38.6	0.038	0	3524	24.2	4.416	9	228
jun	48.4	0.043	0	6049	28.2	6.309	0	799
jul	50.5	0.042	0	6824	29.3	6.740	0	1012
aug	47.8	0.041	0	6080	28.3	6.386	0	822
sep	42.1	0.040	0	4336	24.1	5.098	2	126
oct	34.0	0.038	0	2235	21.2	2.279	16	0
nov	24.5	0.037	29	208	19.1	0.358	232	0
dec	17.3	0.034	782	0	16.8	0.037	882	0
			2872	31235			3369	2985

Figure 51 - Average temperature durign working hours, ventilation rate, HDh and CDh

Also, the temperature drop is significant, but in the summer months, maximum possible ventilation during working hours is not enough to bring the temperature between the comfort thresholds. There is the option to keep the windows open even after working hours. How many hours they should be opened and what is the effect will be reported in the next chapter.

Night ventilation

Night ventilation should have a great impact since during the time of ventilating, the outside temperature reaches the lowest value of that day. Since during nighttime, sun gains are not present, ventilating is even more effective. There are a few questions about this kind of ventilation. The first is how much ventilation should be used during spring and fall since the outside temperature could be very low during the night and therefore cause discomfort during the beginning of the working hours. Also, there is a question of safety, but as of now, it is not the focus.

Firstly, the additional ventilation was applied May-September from 19:00h to 24:00h to see if this change would be enough. For April, October and November, the threshold for opening the window was kept at the indoor air temperature of 21°C during working hours. Just during March, the threshold was moved to 26°C, since the temperatures are colder in comparison with the other following months. It has to be mentioned that the decision has been brought to not open the window during winter at all since it has no good effect in terms of temperature. The problem of CO2 concentration that this decision will bring would have to be solved by an effective heat exchanger which would preheat the external air to provide good indoor air quality, but at the same time not affect the temperature in an unfavorable way.

	Ventilation on if t>21 only during working hours Window frame from 30,8% to 25,6% Curtain profiles on Mar-Nov Enl. Wind. + curtains t>21 or ii>250				Dec-Feb NO Mar- if t indoor > 26 Apr - if t indoor > 21 May-Sept if t indoor > 21 and opened 19-24h Oct - if t indoor > 26 Nov - if t indoor >26				Dec-Feb NO Mar-Apr if t indoor > 26 May if t indoor >21 and opened 19-24h Jun-Aug if t indoor > 21 and opened all night Sept if t indoor >21 and opened 19-24h Oct-Nov if t indoor > 26			
MONTH	tavg working	n (1/h)	HDh	CDh	tavg working	n (1/h)	HDh	CDh	tavg working	n (1/h)	HDh	CDh
jan	14.8	0.032	1458	0	14.8	0.032	1453	0	14.8	0.032	1453	0
feb	17.6	0.054	613	0	17.7	0.029	596	0	17.7	0.029	596	0
mar	19.9	0.908	96	0	22.9	0.267	1	0	22.9	0.266	1	0
apr	21.2	2.422	61	0	21.3	2.536	61	0	24.0	1.188	0	9
may	24.2	4.416	9	228	23.7	6.881	8	167	23.4	8.044	9	112
jun	28.2	6.309	0	799	27.5	8.523	0	631	26.7	11.807	0	461
jul	29.3	6.740	0	1012	28.7	9.265	0	854	28.0	12.611	0	685
aug	28.3	6.386	0	822	27.7	8.764	0	679	27.0	12.196	0	513
sep	24.1	5.098	2	126	23.6	7.101	2	66	23.6	7.026	2	54
oct	21.2	2.279	16	0	23.8	0.810	0	0	23.8	0.809	0	0
nov	19.1	0.358	232	0	21.9	0.102	53	0	22.1	0.090	51	0
dec	16.8	0.037	882	0	17.2	0.032	804	0	17.2	0.032	803	0
			3369	2985			2979	2397			2915	1835

Table 38 - Average monthly temperature during working hours, ventilation rate, HDh and CDh

We can notice that night ventilation has an impact on reducing CDh, but still, the temperature is not lower than 26°C. A big change in the average monthly ventilation rate is observed. It might be strange that the temperature reduction is not so drastic as the change in ventilation rate, but this is because the temperature is calculated as average during working hours and the ventilation rate as a pure monthly average.

Since there is still a need for reduction of temperature during summer, night ventilation is set all night from Jun toAugust now, and the concentration of High CDh was in these months. Dor May and September, the additional ventilation was kept from 19:00h to 24:00h. This orientation of the classroom is bringing different temperatures. In this case, the more suitable threshold for opening the windows was 26°C, different from the South-West side. This change allowed a lower number of HDh. The ventilation during winter has been kept off. Again there is a big change in the average monthly ventilation rate since now the ventilation is on during the whole night. Reduction in CDh is reported, so we can say that this method has its benefits.

Shutters

Still, there is a way to save energy in the building during cold nights. By introducing shutters to a window, when they are all the way down, the window has additional resistance, where the window U-value is 1,05 W/m2K to 0,8 W/m2K. If the shutters are used during the hours when the school is not working during wintertime, the expectations are that the energy will be stored. The simulation was launched and the results are reported in the table below. The rise in temperature could be noticed during winter months even by almost 1°C.

	Dec-Feb NO Mar-Apr if t indoor > 26 May if t indoor >21 and opened 19-24h Jun-Aug if t indoor > 21 and opened all night Sept if t indoor >21 and opened 19-24h Oct-Nov if t indoor > 26				Introducing shutters in winter 19-08h			
MONTH	tavg working	n (1/h)	HDh	CDh	tavg working	n (1/h)	HDh	CDh
jan	14.8	0.032	1453	0	15.7	0.033	1195	0
feb	17.7	0.029	596	0	18.7	0.031	395	0
mar	22.9	0.266	1	0	23.1	0.275	0	0
apr	24.0	1.188	0	9	24.0	1.187	0	9
may	23.4	8.044	9	112	23.4	8.051	9	112
jun	26.7	11.807	0	461	26.7	11.810	0	461
jul	28.0	12.611	0	685	28.0	12.611	0	685
aug	27.0	12.196	0	513	27.0	12.197	0	514
sep	23.6	7.026	2	54	23.6	7.029	2	55
oct	23.8	0.809	0	0	23.8	0.808	0	0
nov	22.1	0.090	51	0	22.1	0.090	51	0
dec	17.2	0.032	803	0	18.0	0.033	597	0
			2915	1835			2248	1836

Table 39 - Average monthly temperature during wirking hours, ventilation rate, HDh and CDh

Overview of window engineering for South-West orientation

As there was a chance of gaining more sun by enlarging the window, this option was under exploring. The window was divided into smaller parts, which led to a high frame percantage. This was solved by making one-third of the window zone fixed and two others openable. This made the situation better. The next focus was on reducing CDh with the use of curtains since on the North-East side the overhangs would not bring more good than bad results. The curtains are activated if the indoor air temperature is highter than 21°C or incident irradiation higher than 250 W/m2. This was effective, but still, without using ventilation, the parameters were far from the comfort. By making a certain scheme of opening the window and providing the maximum possible opening of that configuration, a strong drop in temperature during summer happened as expected. Still, this was not enough to bring summer temperature between 20°C and 26°C. The last strategy for reducing CDh was introducing night ventilation. The profile that was used for the ventilation was the following:
Dec-Feb NO
Mar-Apr if t indoor > 26
May if t indoor >21 and opened 19-24h
Jun-Aug if t indoor > 21 and opened all night
Sept if t indoor >21 and opened 19-24h
Oct-Nov if t indoor > 26
This led to even lower CDh during the year.
For the last step, the addition of a shutter was performed, which brought additional resistance to the window when they are closed (during non-working hours in winter).
The ratio between HDh and CDh od all the steps are reported in the teble below.

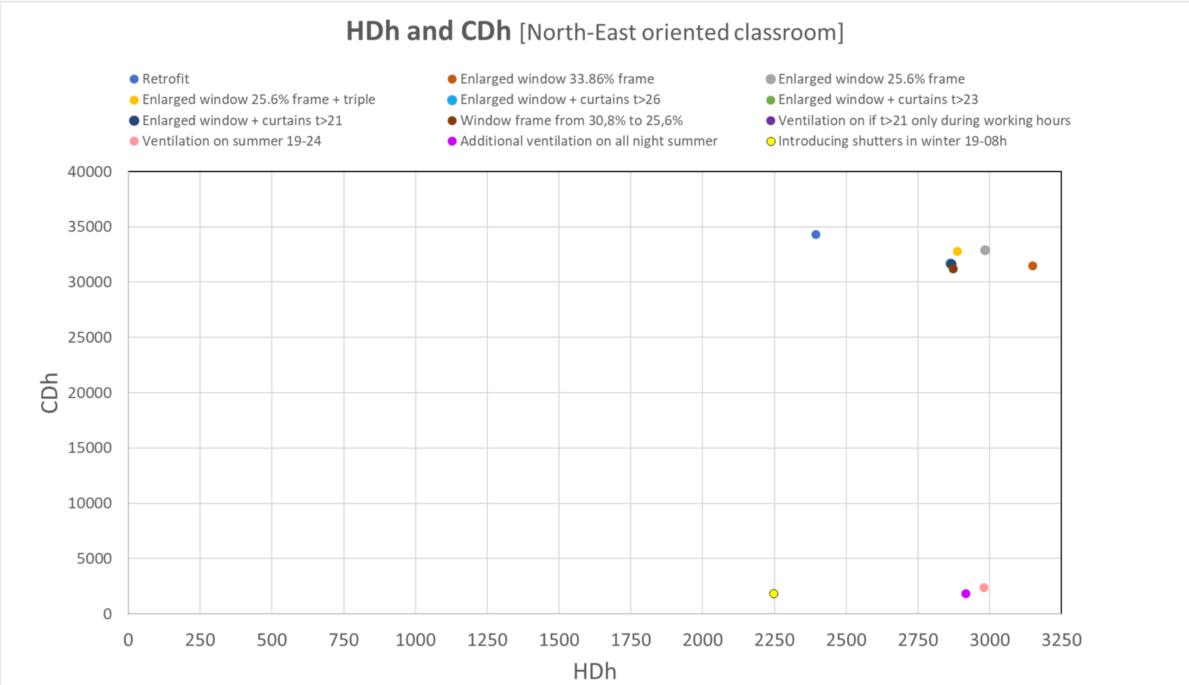

Figure 52 - HDh and CDh of window improvements

Looking at the balance chart, we can recognize that the highest gains the room receivec from the sun and people. Solar gains are much lower in comparison to the South-West side. The biggest losses are present as the summer is closer and those are ventilation losses. It can be recognized that losses towards other thermal zones are not as high as the ones in the previously analyzed classroom. This is mostly because this classroom is the coldest one on the top floor. It could be expected from this thermal zone to have gained from internal partitions, analyzed is the hottest one, but also has a common wall with the corridor which is significantly colder since the occupation is low and concentrated during lunch break. Moreover, the corridor is long and has windows just on the sides, which means that sun gains are low too.
We can see higher losses through the walls, windows and roof during winter, this is because the temperature difference between indoor and outdoor temperature is high, so the losses are higher too.

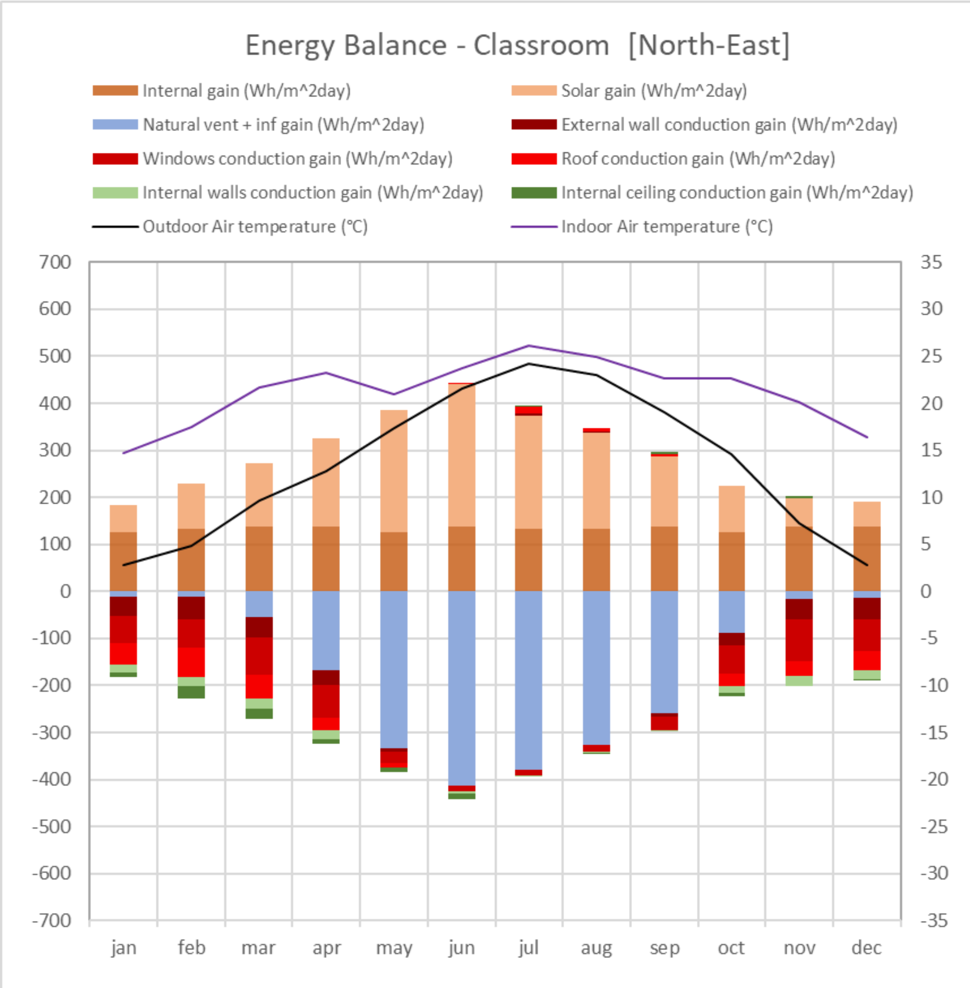

Figure 53 - Energy balance of South-East oriented classroom after retrofit

CHAPTER 9. Mechanical ventilation

The natural ventilation profile during wintertime has been off. This means that the CO2 concentration in the classrooms is very high. In order to avoid direct outside airflow which would have a very low temperature, a heat exchanger has been used. The air that's leaving the room is preheating the entering one and with the help of fans, fresh air which is preheated is introduced to the classroom, and in this way, CO2 concentration is regulated.

By using the volume of a typical classroom and needed air changes to regulate CO2 concentration which has been calculated in Chapter 2.4.1. The value of 257 m3/h has been set as a need to achieve desired conditions which would be 1000ppm or less. The commercial product Altair H.R. 301 has been selected with the following characteristics:

Figure 54 - Altair H.R. 301 Heat Exchanger

Model	air flow	Microprocessor	Nutrition	Potenza fans	Recovery efficiency the sensible heat **	efficiency class energy ***
H.R.301	330 m^3/h	CTR	230 V	71 2 x W	>93%	B
H.R.501	460 m^3/h	CTR	230 V	200 2 x W	>91%	B
HRX 301	330 m^3/h	CTRX	230 V	71 2 x W	>93%	A
HRX 501	460 m^3/h	CTRX	230 V	200 2 x W	>91%	B

Table 40 - Characteristics of the heat exchanger

The controllers were used to switch on the system if the CO2 concentration is lower than 1000ppm. The results are showing that the chosen system is regulating indoor air quality enough to be within the limits during the period from December to February.

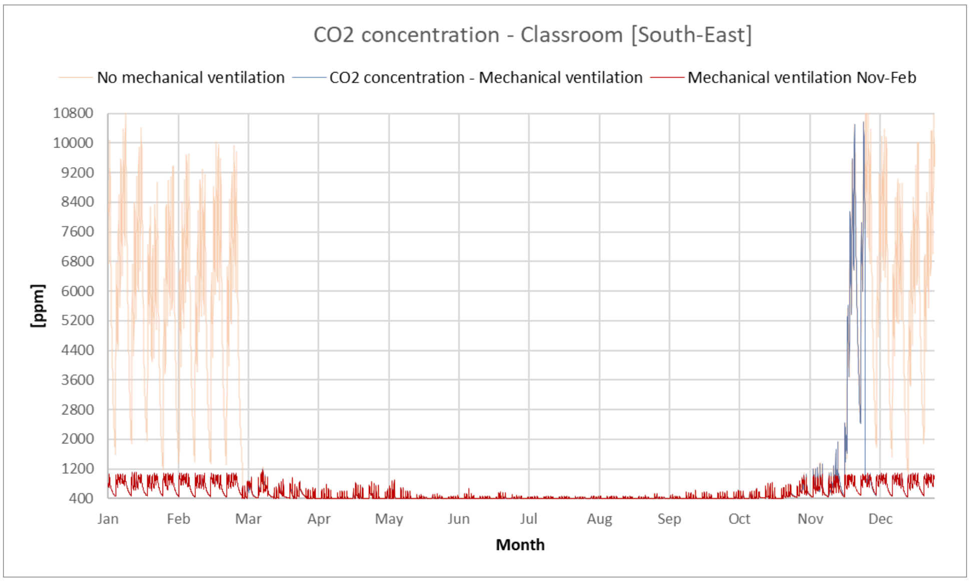

Figure 55 - CO2 concentrations for different ventilation configurations

The only problem was that still in November, there were times when the CO2 concentration was out of the limits. After applying mechanical ventilation also during November, the values of ppm became as they should be.
In terms of temperature, there is no big change since reported values of mechanical ventilation rates are very low, but anyway, a slight change is observed in HDh and CDh.

The ventilation used in the classroom can be divided into three types:

1. Ventilation during working time
2. Ventilation during non-working time
3. Mechanical ventilation

From month to month the majority of the ventilation that is regulating indoor air quality and temperature varies. The chart below is representing the results for South-West oriented room.

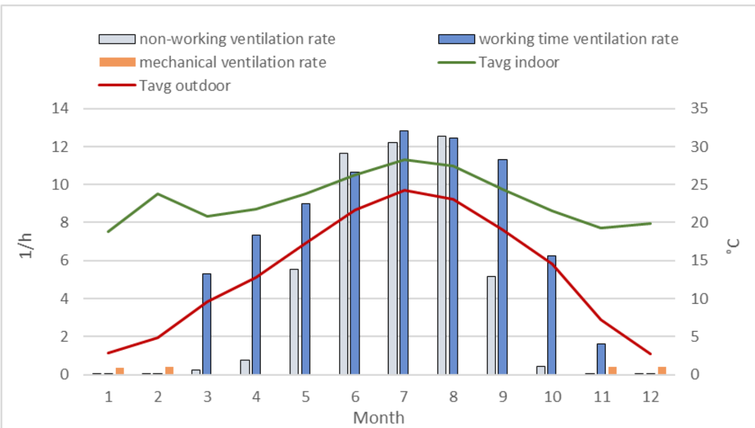

Figure 56 - Average monthly ventilation rates of different type of ventilation and average monthly temperature

The windows are closed during wintertime and that's why the night-time and day-time ventilation are not present, but in exchange, mechanical ventilation is on, so the only

ventilation rate present is due to that type of ventilation. If we take a look at March and October, the natural ventilation is the only one needed to regulate temperature and CO_2 concentration, so the daytime ventilation is the majority since the profile applied was to open the windows if the temperature is higher than 21°C during working time.
We can notice a big difference between May and September in comparison with the winter months. Since during May and September, ventilation is on during working times if the temperature is higher than 21°C and from 19:00h to 24:00h,non-working time ventilation is lower in comparison to the summer months when the windows are open all the time when the school is not working and they reach the values of working-time ventilation or even go beyond. This can happen since the night temperatures are significantly lower in comparison to the daily ones.
The situation where the attention should be put on November. In this case, natural ventilation if the indoor temperature is higher than 21°C is present and also if the CO_2 concentration is lower than 1000ppm. These two parameters should be synchronized in order to avoid the inefficiency of ventilation strategies. So, the profile of mechanical ventilation during November should be active if the temperature is lower than 21°C so that if the natural ventilation is working, it will regulate CO_2 concentration and if not, the mechanical ventilation will regulate it while the windows are closed in order to avoid loss of energy.

CHAPTER 10. ENERGY BALANCE OF THE BUILDING AFTER RETROFIT

Now that some retrofit strategies are applied on the whole building, the simulation was launched in order to extract gains and losses from the school model.

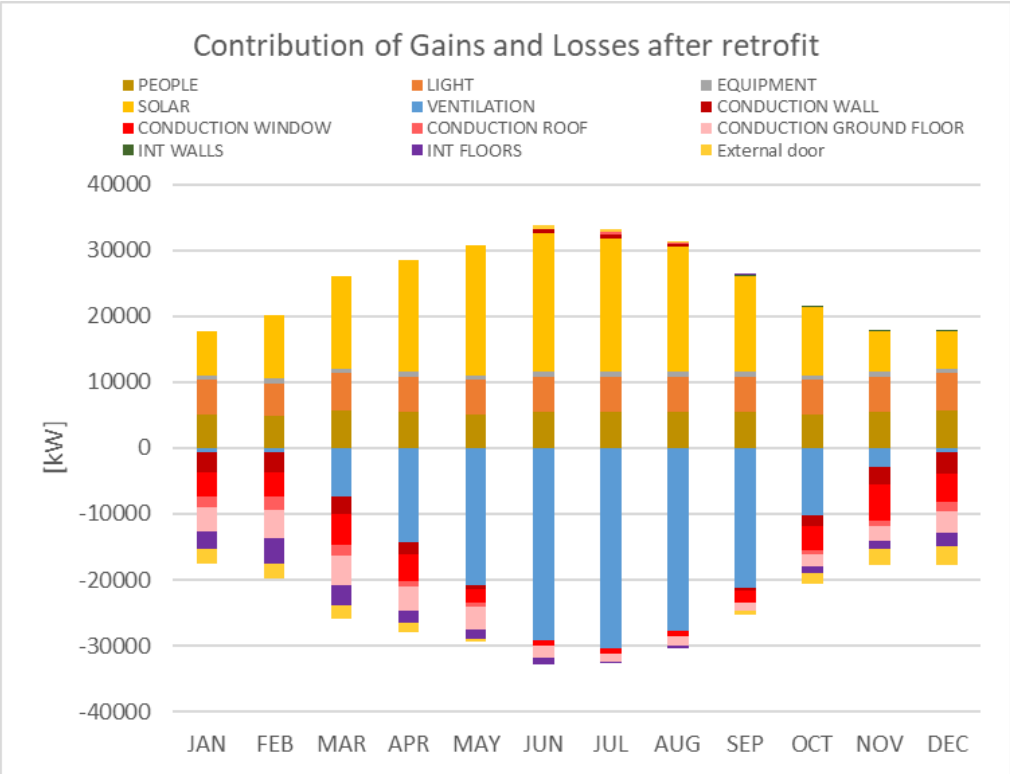

Figure 57 - Energy balance of the school after retrofit

In the end of this simulations and series of choices, the effect of strategies used up to now has been shown. Natural ventilation has a strong impact and it is the most important strategie to reduce cooling hours in the building. This is one of the reasons why configuration of the window should be developed. Effective strategie for natural ventilation is impacted by opening profile of the windows. During winter time, everything that has been done was in oder to keep the energy inside the building. The temperature rise was the result, and therefore the losses through the envelope bacame bigger too.

This is one way to choose while retrofiting. Deepening each of the strategie on the way could lead us to another solution, another configuration and another energy balance. After all, there is not just one correct answer, but the trade-off between important parameters presented in this work and not forgetting the others like CO2 emission, General Cost, Payback Period, Primery Energy Ratio and many many more.

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Note: Overview of bibliography is given in a separate document "Review of the literature (about energy retrofit of schools)"

Note: Special short overview of papers read by authors is given as separate document named "Collelctive overview of the literature"

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