Advanced insulation materials and systems in buildings, and energy savings

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Skopje, Makedonija

University of Ljubljana
Faculty of Civil and Geodetic Engineering

UNIVERSITY OF LJUBLJANA

- Established in 1919 UL100

•Among the top **500** of the world's best universities on the Shanghai, Times and Webometrics ranking lists.

•**26 full Members** (3 art academies and 23 faculties) and 3 associated Members (National University Library, University of Ljubljana Central Technical Library, University of Ljubljana Innovation-Development Institute).

In 2014
•Annual budget: **324,689,669** (EUR)
•Number of staff: **5,481**

•Number of students: **42,922**
•Number of foreign students: **1,865**

Student exchanges:

1130 students went on exchange abroad
1411 foreign students were on exchange at our University

Projects:

439 European projects
123 other international projects
156 research programmes
79 applied projects
219 basic projects
49 CRP
12 scientific meetings
648 projects with the industry/users of knowledge

1st CYCLE STUDY PROGRAMMES	2nd CYCLE STUDY PROGRAMMES	3rd CYCLE STUDY PROGRAMMES
CIVIL ENGINEERING (BA)	CIVIL ENGINEERING (MA)	BUILT ENVIRONMENT (PhD)
CONSTRUCTION MANAGEMENT (BA)	BUILDINGS (MA)	ENVIRONMENTAL PROTECTION (PhD)
WATER SCIENCE AND ENVIRON. ENGINEERING (BA)	WATER SCIENCE AND ENVIRON. ENGINEERING (MA)	
GEODESY AND GEOINFORMATION (BA)	GEODESY AND GEOINFORMATION (MA)	
TECHNICAL REAL ESTATE MANAGEMENT (BA)	SPATIAL PLANNING (MA)	

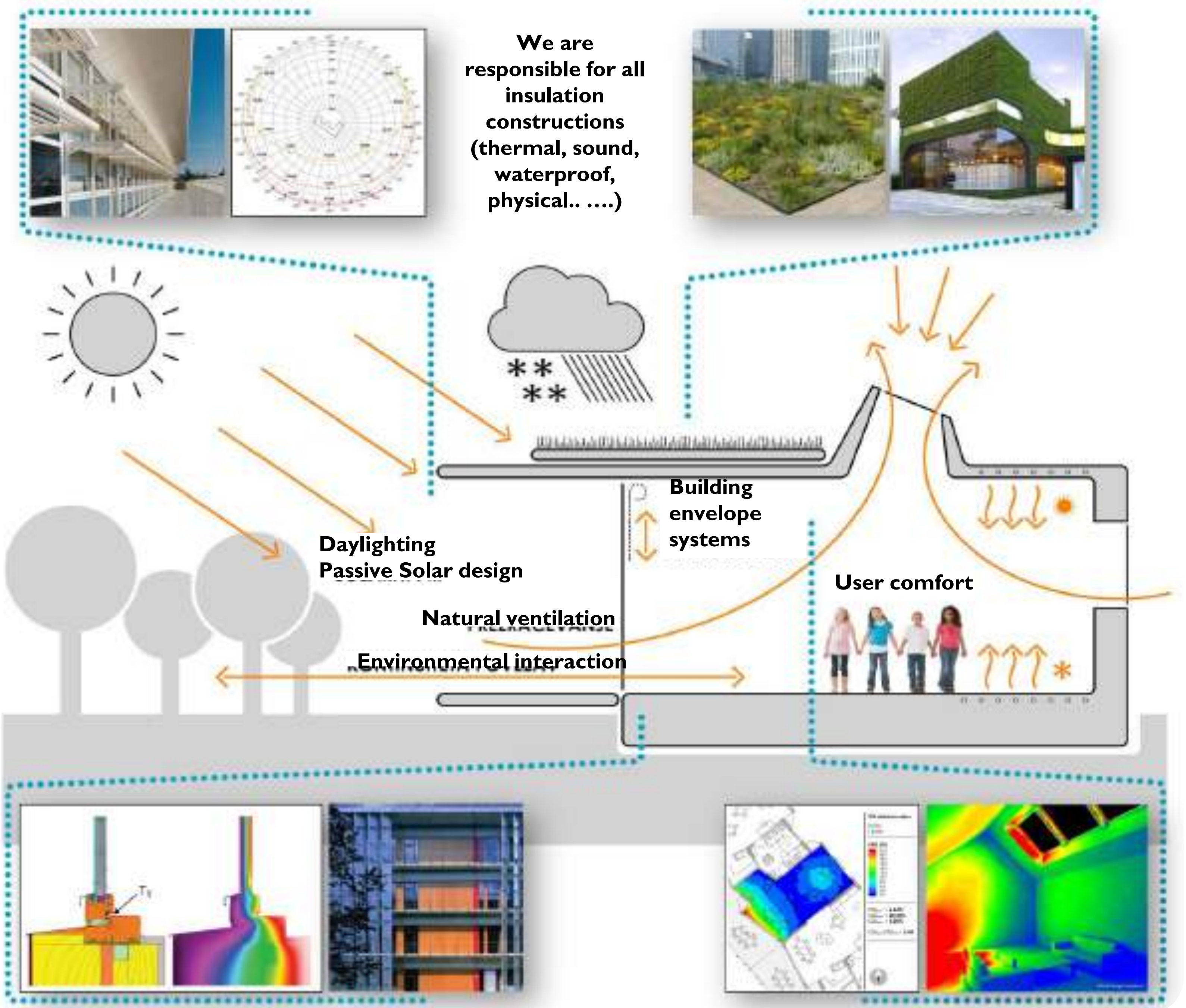
2nd Cycle: Buildings MA

The second cycle master study program **Buildings** consists of two years (four semesters) and amounts to 120 credit points. After the studies graduate acquires the professional title **MASTER ENGINEER OF BUILDINGS.**

The study program Buildings focuses on buildings – their design, construction, use and removal.

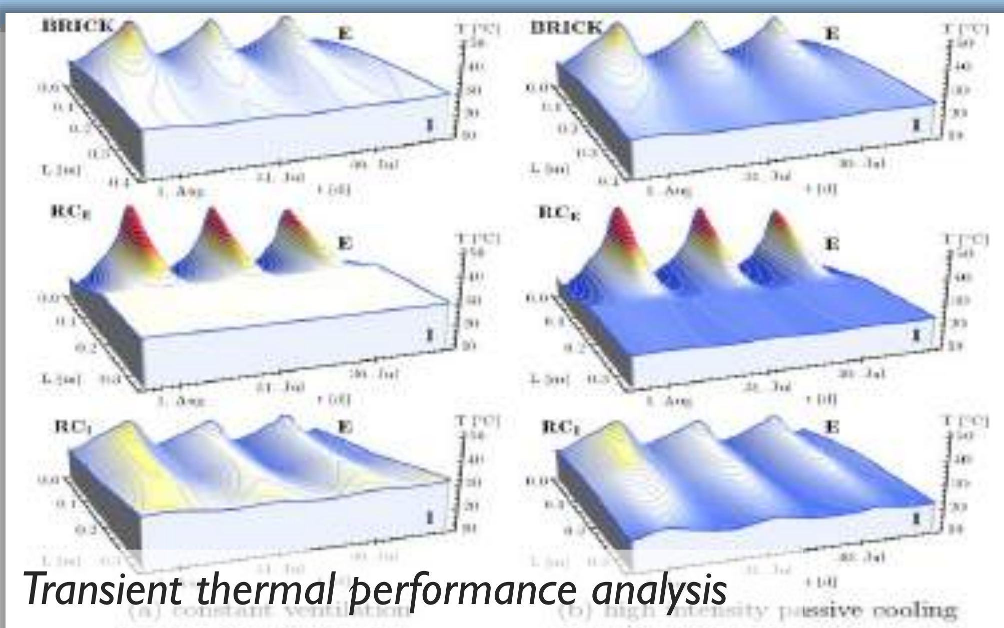
The study program Buildings is adapted to the needs and requirements of our dwelling and working environments. The basic condition and rule for the functioning of ecological systems is rationality and balance of their parts and complexes. The same is also true for socio-ecological system, part of which are also built environment and man. Architectonic artefact is an interface between natural environment and man-made environment. Building as part of the ecosystem that harmonizes different influences and conditions in the system using high technology, is the goal of all efforts of the contemporary bioclimatic design dealing with dwelling and living environment.

Focus of research and teaching at the Chair of Buildings and Constructional Complexes



Thermal performance of buildings

- **Passive Solar Architecture**
- **Bioclimatic design**
- **Smart building design** (holistic approach to building automation)
- **Stationary and transient analysis of building envelope performance**
- **Whole building energy performance simulations**
- **User centric design and human body exergy analysis**

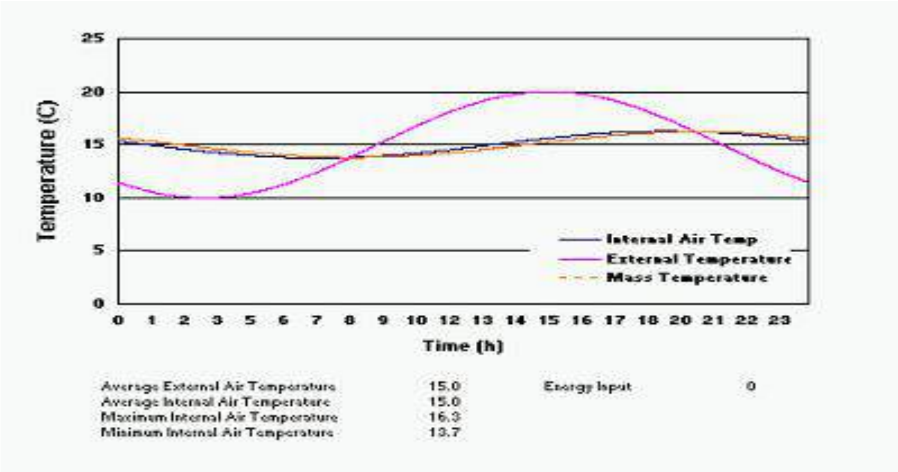


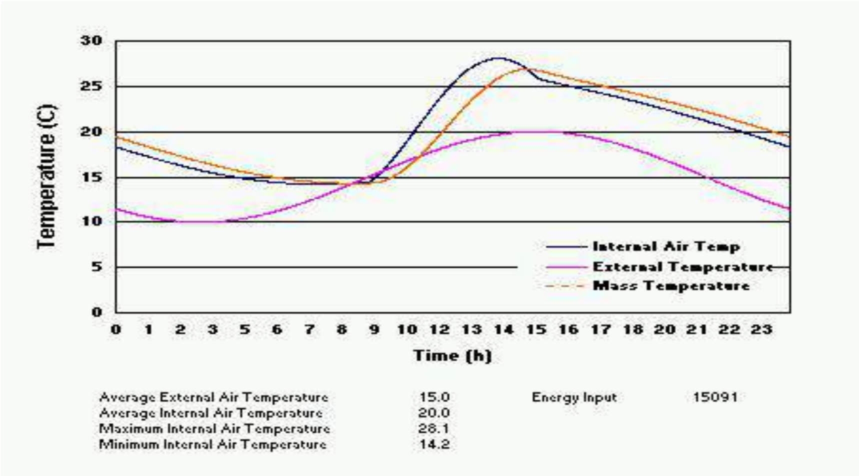
Transient thermal performance analysis

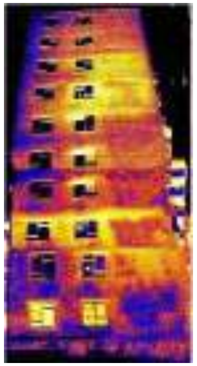
Human body exergy analysis

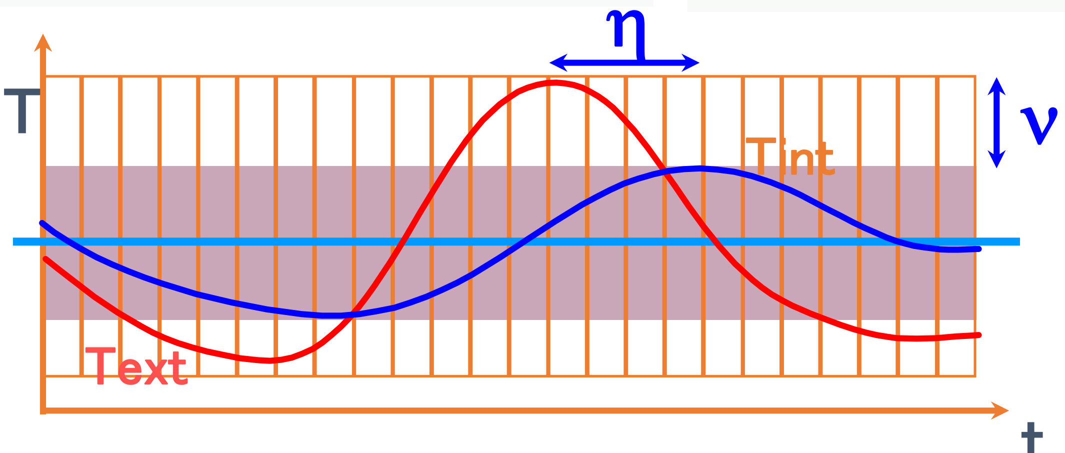
Insulation constructions

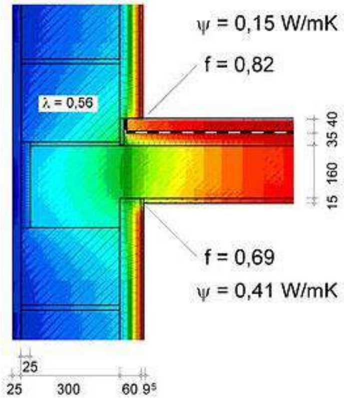
- **Thermal insulations**
- **Waterproof insulations**





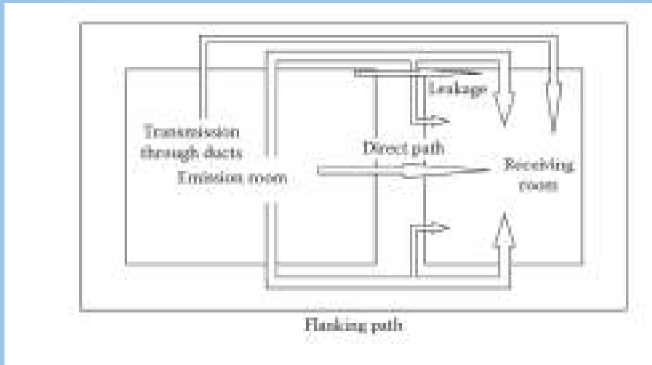






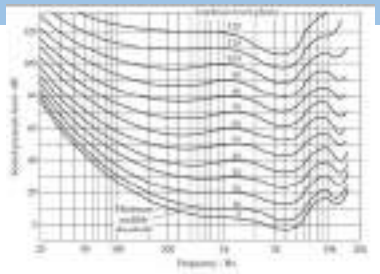
Acoustical living and working environment

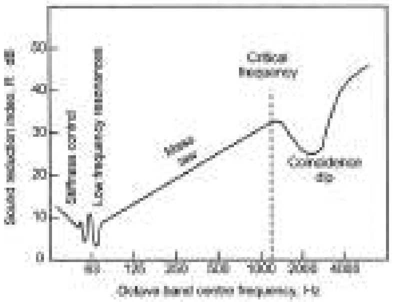
- **Sound insulation of buildings**
- **Sound insulation against airborne sound**
- **Sound insulation against impact sound**
- **Environmental (municipal) noise**
- **Vibrations in buildings**
- **Acoustics of interior space – reverberation noise**

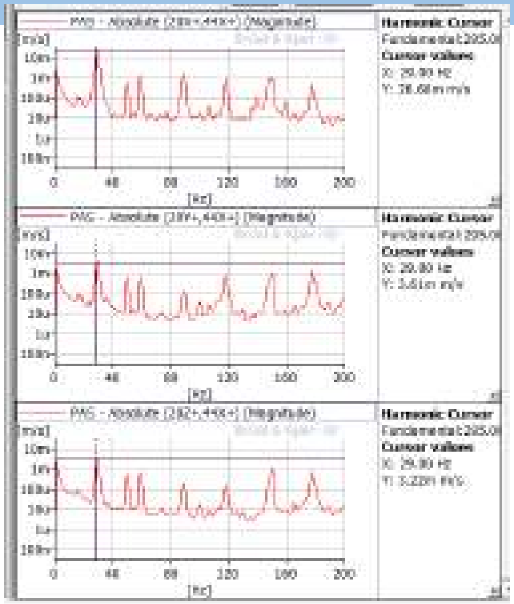


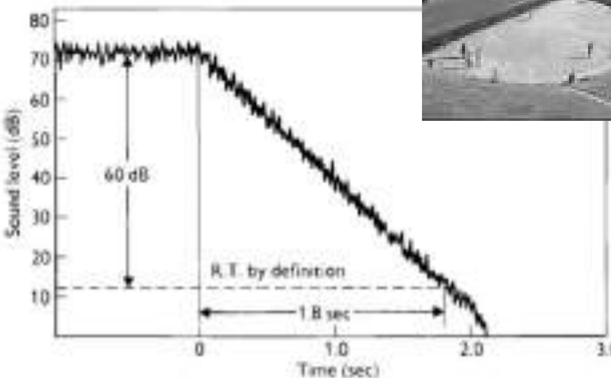
Acoustic transmission paths between spaces.

- **Design of building envelopes and interior barriers against environmental and building users noise**
- **Design of interior space against reverberation noise and exterior space against traffic noise**



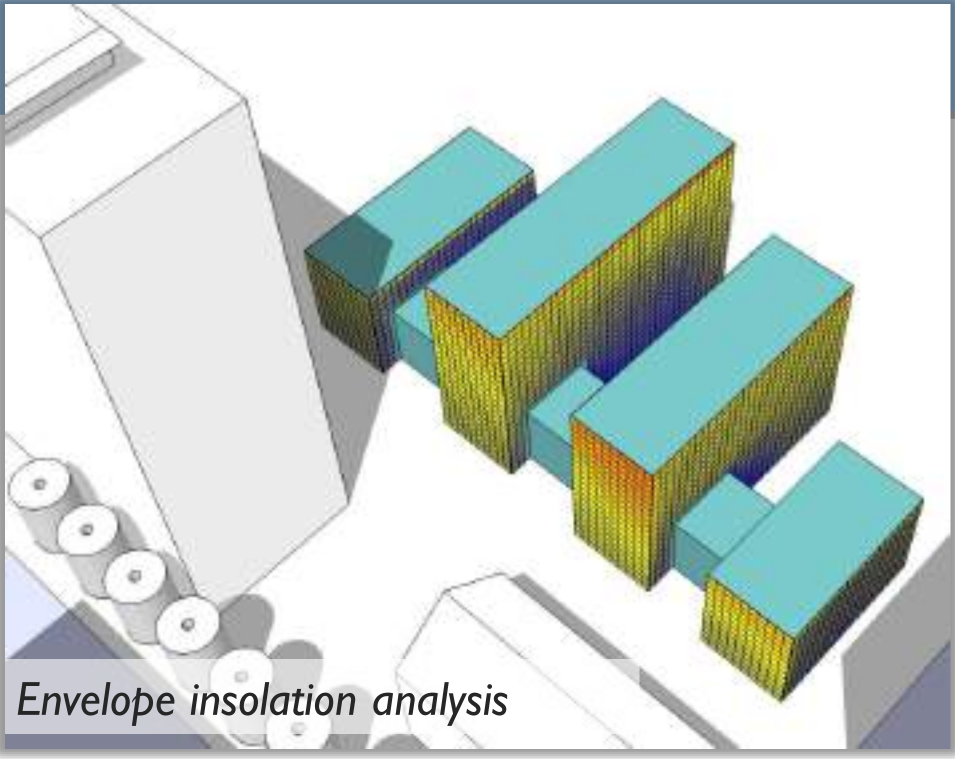




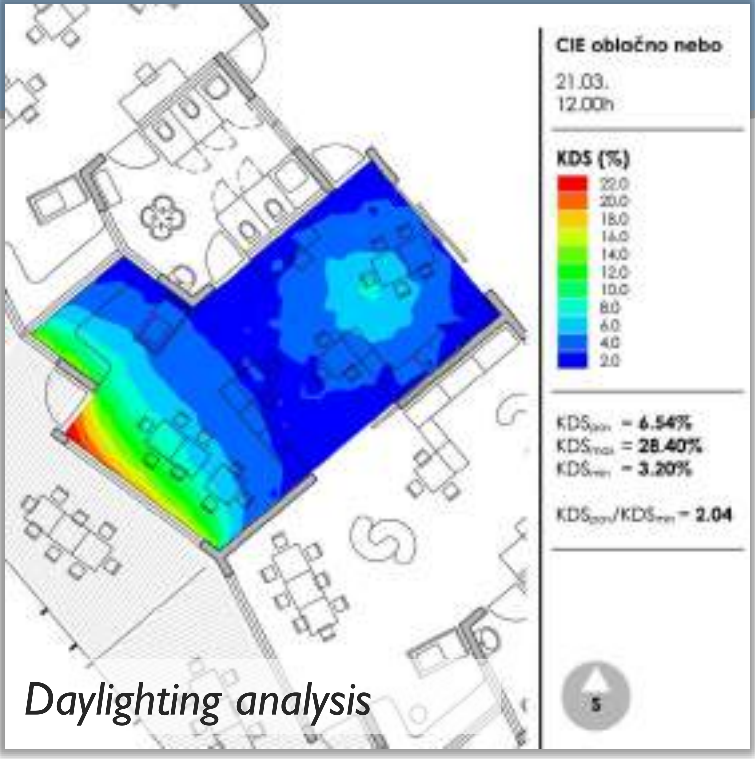


Daylighting

- **Daylighting in connection to envelope design** (design of transparent and opaque elements; widows, shading elements).
- **Daylighting and building users** (connection to the visual and non-visual performance of building users).
- **Application of conventional metrics** (daylight factor, insolation) **and climate-based daylight modeling to the building design.**

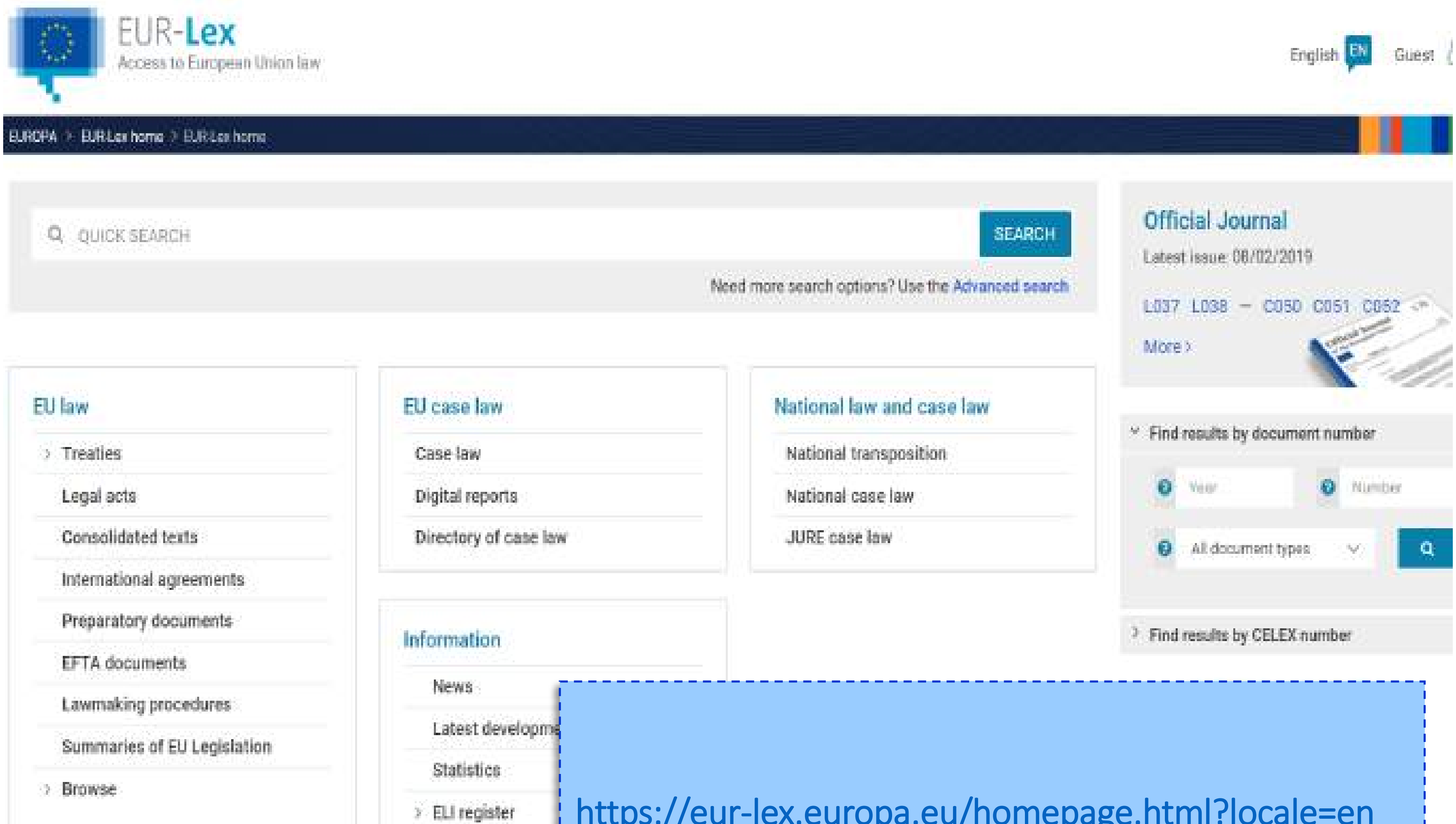


Envelope insolation analysis



Daylighting analysis

EU legislation



https://eur-lex.europa.eu/homepage.html?locale=en

Uredba (EU) št. 305/2011 Evropskega Parlamenta in Sveta z dne 9. marca 2011 o določitvi usklajenih pogojev za trženje **gradbenih proizvodov** in razveljavitvi Direktive Sveta 89/106/EGS

EPBD-R 2010/31/EU. Direktiva 2010/31/EU Evropskega Parlamenta in Sveta z dne 19. maja 2010 **o energetski učinkovitosti stavb** (prenovitev, recast)

Direktiva 2012/27/EU Evropskega Parlamenta in Sveta z dne 25. oktobra 2012 o **energetski učinkovitosti**, spremembi Direktiv 2009/125/ES in 2010/30/EU ter razveljavitvi Direktiv 2004/8/ES in 2006/32/ES

Direktiva 2009/28/ES Evropskega Parlamenta in Sveta z dne 23. aprila 2009 o **spodbujanju uporabe energije iz obnovljivih virov**, spremembi in poznejši razveljavitvi direktiv 2001/77/ES in 2003/30/ES

GZ. Gradbeni zakon (Uradni list RS, št. 61/17 in 72/17 – popr.)

PURES 2010. Pravilnik o učinkoviti rabi energije v stavbah (Ur.l.RS, 93/2008, 47/2009, 52/2010).
TSG – 1 – 004: 2010. Tehnična smernica TSG – 1 – 004: 2010. Učinkovita raba energije.

Pravilnik o zvočni zaščiti stavb (Ur.l. RS, št. 14/1999, 10/2012)
TSG-1-005: 2012. Zvočna zaščita stavb, primeri izvedbe in računski postopki.

SIST EN ISO 13790. Energy performance of buildings. Calculation of energy use for space heating and cooling.

DIRECTIVE 2010/31/EU OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL 19 May 2010

‘nearly zero-energy building’ means a building that has a very high energy performance, as determined in accordance with Annex I.

The nearly zero or very low amount of energy required should be covered to a very significant extent by energy from renewable sources, including energy from renewable sources produced on-site or nearby;

REGULATION (EU) No 305/2011 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL 9 March 2011

BASIC REQUIREMENTS FOR CONSTRUCTION WORKS

Construction works as a whole and in their separate parts must be fit for their intended use, taking into account in particular the health and safety of persons involved throughout the life cycle of the works. Subject to normal maintenance, construction works must satisfy these basic requirements for construction works for an economically reasonable working life.

1. **Mechanical resistance and stability**
2. **Safety in case of fire**
3. **Hygiene, health and the environment**
4. **Safety and accessibility in use**
5. **Protection against noise**
6. **Energy economy and heat retention**
7. **Sustainable use of natural resources**

Member States shall ensure that:

a) by 31 December 2020, all new buildings are nearly zero- energy buildings; and

b) after 31 December 2018, new buildings occupied and owned by public authorities are nearly zero-energy buildings.

Economical thickness of thermal insulation layers in building thermal envelopes

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Građevinsku delatnost na svetskom nivou karakteriše pravilo 40 %

1. Globalna građevinska industrija godišnje troši 3 milijarde tone materijala, što predstavlja 40 % od ukupne svetske potrošnje materijala
2. Tokom gradnje i korišćenja građevinski objekti troše približno 40% svih energetskih potreba u svetu
3. po završetku proizvodno - potrošniškog ciklusa građevinski otpad predstavlja 40 % svih prouzrokovanih otpada na svetu.

Održive (trajnostne) građevine su oblikovane tako da:

- Štede energiju i druge resurse, recikliraju materijale, smanjuju emisiju toksičnih materija kroz celkupni proizvodno – potrošački ciklus
- su u harmoniji – u skladu sa lokalnim klimatskim uslovima, tradicijom gradnje, kulturom i okruženjem
- su u stanju da održe i poboljšaju kvalitet života uz održavanje ekološke ravnoteže na lokalnom i globalnom nivou.

Analiza troškova

u životnom ciklusu

konstrukcijskih sklopova

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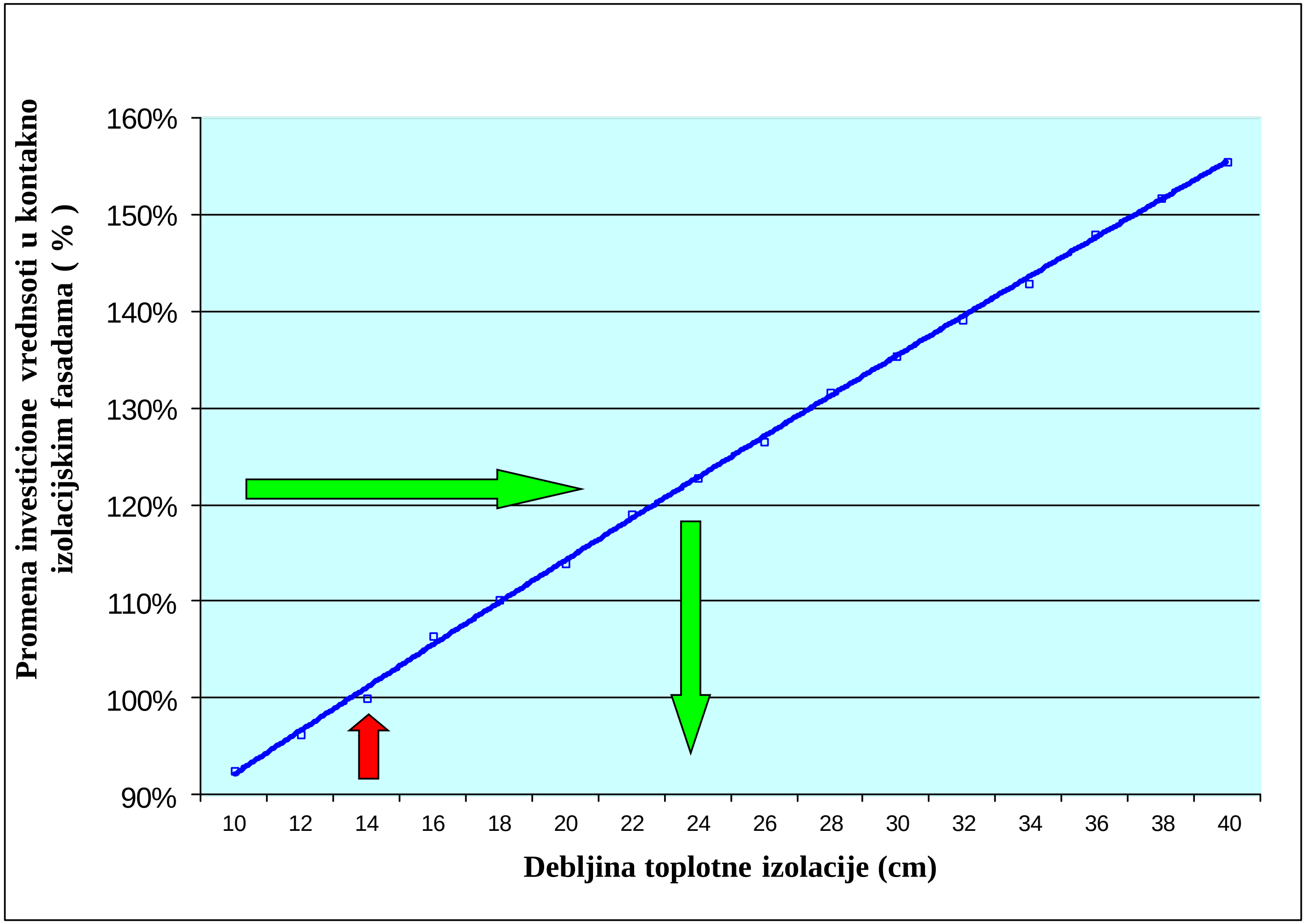
Promena investicione vrednosti u slojevima kontaktnih izolacijskih fasada izražena u procentima, shodno minimalnoj vrednosti u skladu sa propisima, t.j. 14 cm toplotne izolacije



‘Analiza troškova u životnom ciklusu’ – LCC

- da bi dobili normalan odnos cena (odlivi i prilivi), potrebno je da ih prevrednujemo – svedemo na nivo tekućih cena,
- LCC eliminiše slabosti statičnog pristupa tako, što ocenjuje troškove i doprinose u narednim godinama i tako, što ih diskontuje (prevodi) na tekuću vrednost,

LCC studija toplotne izolacije u stambenim konstrukcijama

Analiza troškova životnog ciklusa toplotne izolacije na kontakno-izolacijskoj fasadi

- metoda se temelji na shvatanju, da je evro, koji bi smo dobili (plaćali) u budućnosti, vredan manje,nego evro, koji imamo u ruci,
- Koristeći ovaj alat lako možemo uporediti različite sisteme ili različite delove a otuda i ukupne troškove objekta.

LCC odražava, predstavlja i omogućava transparentno poređenje ukupnih troškova korisnika, stanara ili vlasnika kroz celo životno razdoblje

$$LCC = C_o + \sum_{t=1}^{n} \frac{C_t}{(1+r)^t}$$

C_o …… početni ili nabavni (nediskontovani) troškovi (€)

C_t …… godišnji operativni troškovi, održavanja, tekući troškovi, troškovi energije (€)

n …… broj godina (-)

r …… godišnja diskontna stopa (%)

Procena troškova u životnom ciklusu kontaktno izolacijskih fasada

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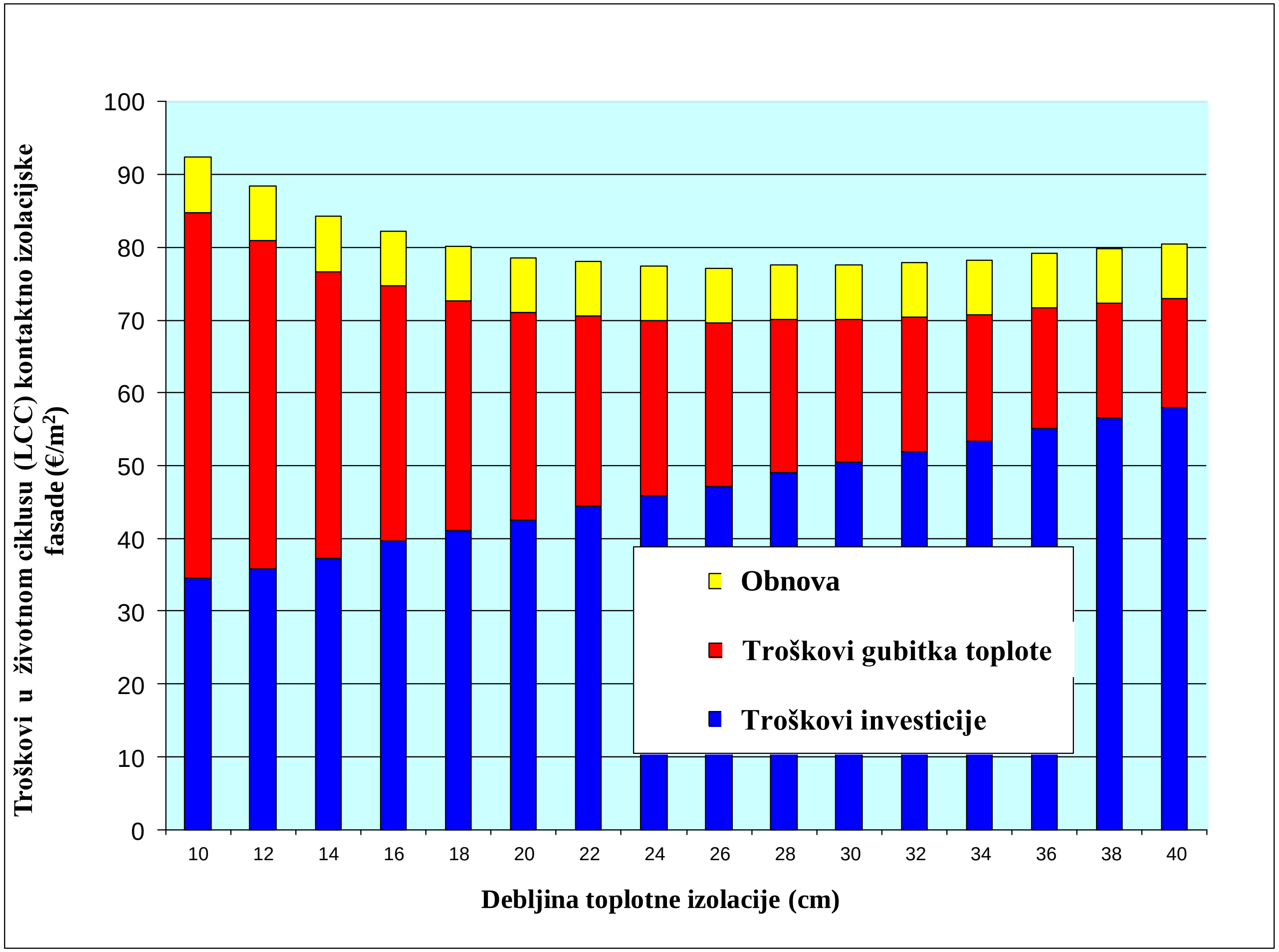
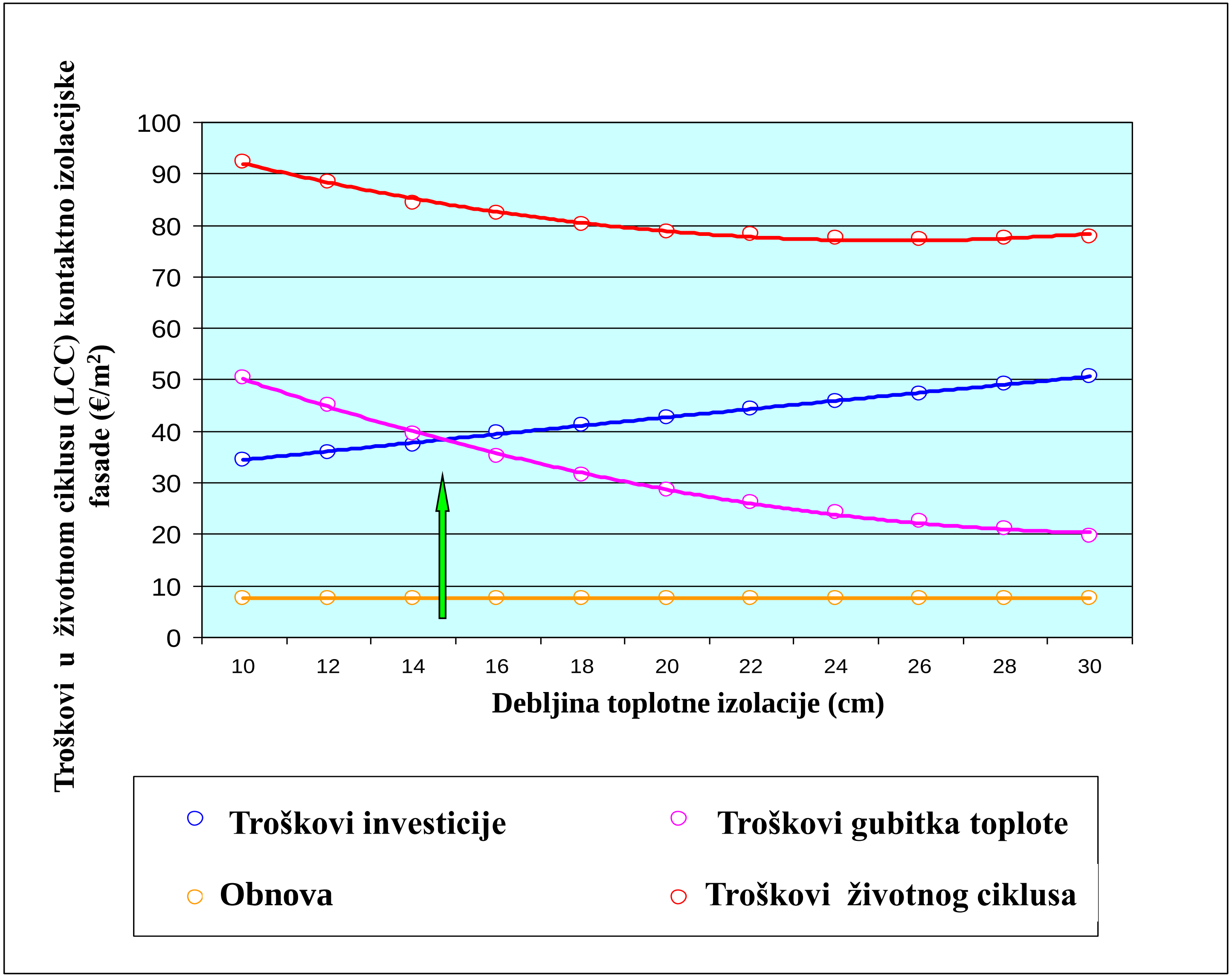
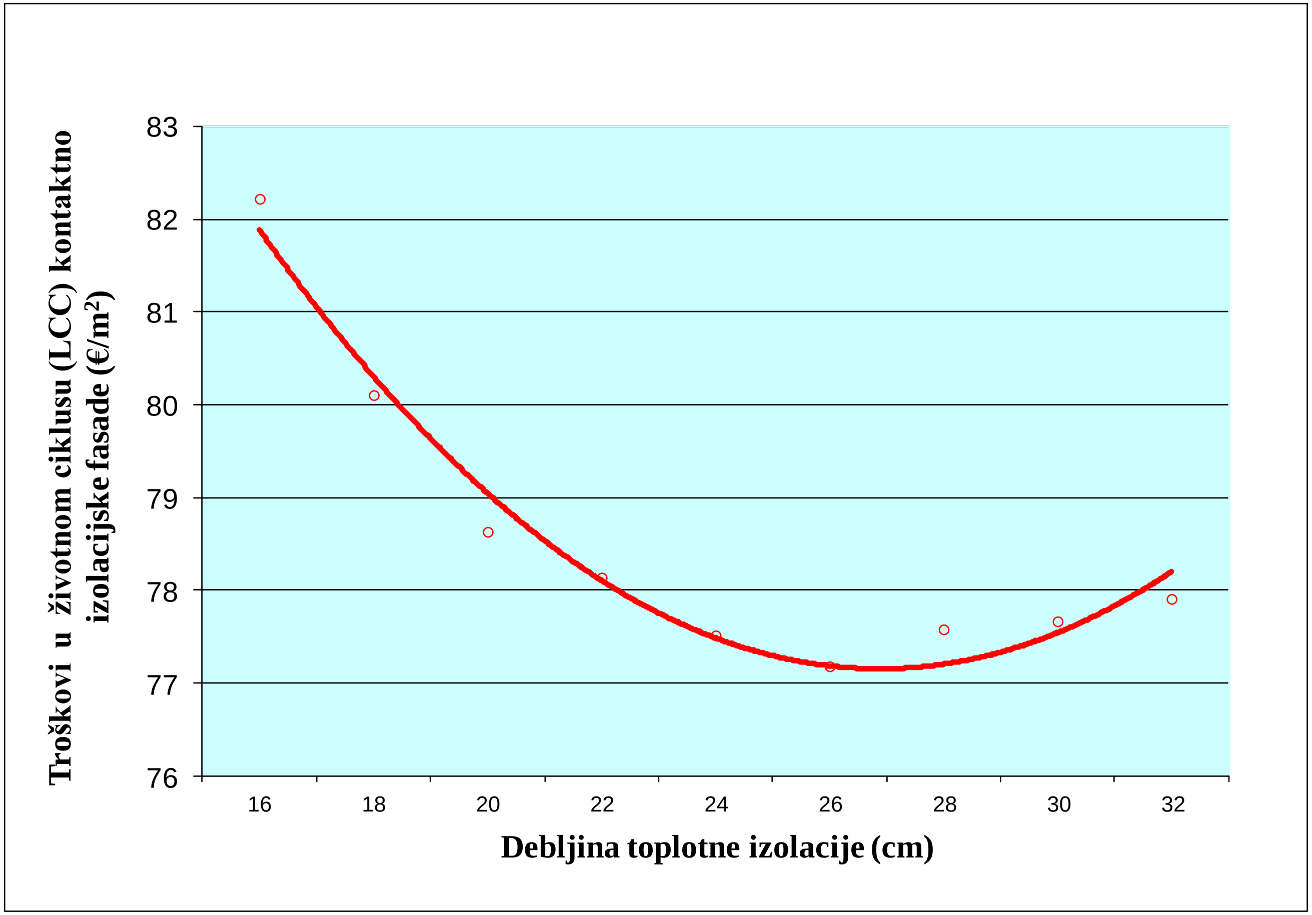
Troškovi u životnom ciklusu (LCC) kontaktno izolacijske fasade u šestdesetogodišnjem životnom veku u zavisnosti od debeljine toplotne izolacije



Troškovi u životnom ciklusu (LCC) kontaktno izolacijske fasade u životnom veku u zavisnosti od debljine toplotne izolacije



Prikaz min. ukupnih troškova u životnom ciklusu (LCC), koji se javlja na kontaktno izolacijskoj fasadi kod najekonomičnije debljine toplotne izolacije 26 cm



Ukupni investicioni troškovi ugradnje fasade sa svim materijalom, radom i iznajmljivanjem skela

- **1/3** celokupnih troškova za ugradnju fasadnog sistema predstavlja EPS toplotna izolacija debljine **22** cm
- **1/2** celokupnih troškova ugradnje fasadnog sistema predstavlja EPS toplotna izolacija pri debeljini fasade **42** cm (ostali materijali, rad i iznajmljivanje skela je druga polovina troškova)

UL100

Building thermal envelopes: thermal insulations and their environmental impact

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Differences among the thermal insulation materials

- Density variation: 15 kg/m^3 - 170 kg/m^3
  (relation 1:10)

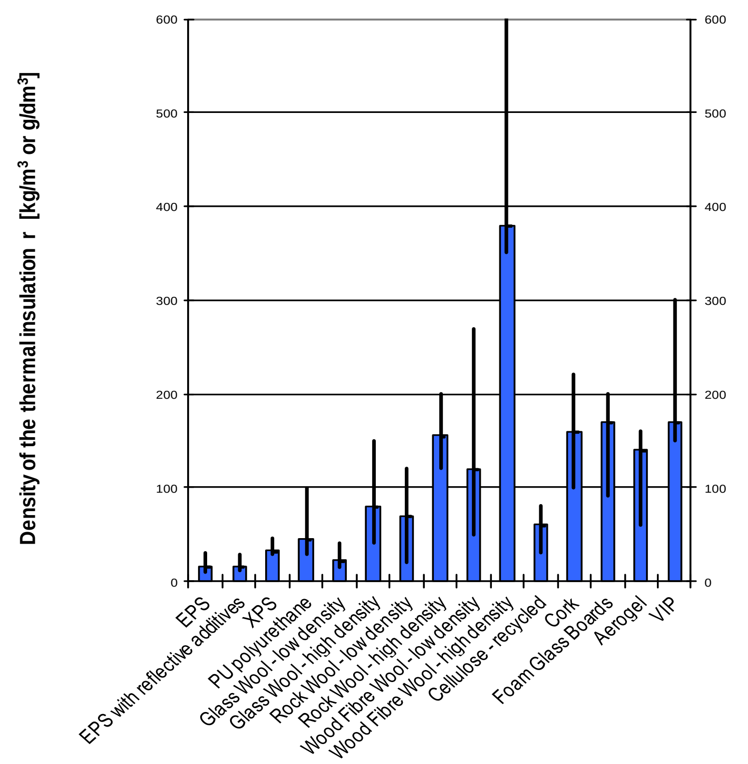
- Thermal conductivity: 6 mW/(m K) - 45 mW/(m K)
  (relation 1:7)

we have analyzed:

- Carbon footprint per mass weight of insulation material

Density of thermal insulations [kg/m³ or g/dm³]

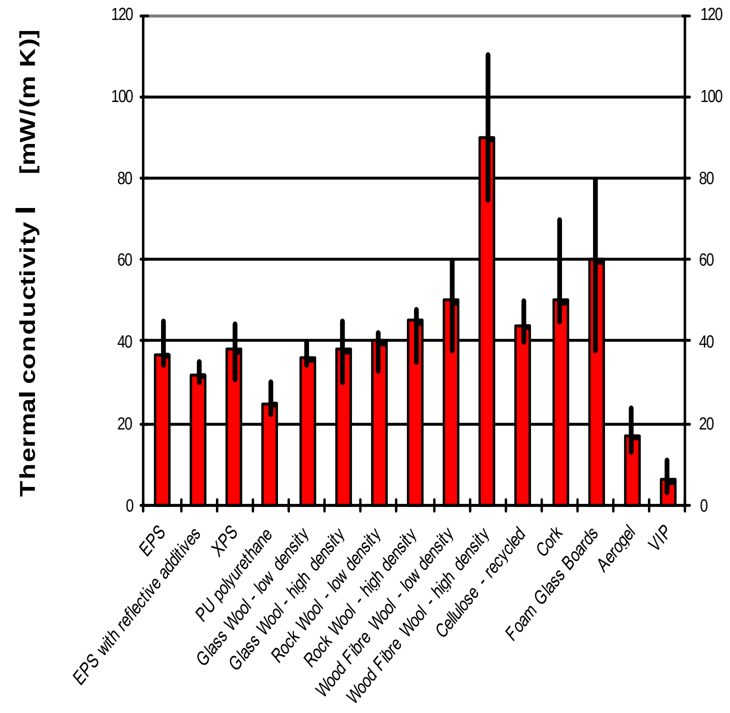
Thermal conductivity [mW/(m K)]



Relation

(min : max) =

1 : 10

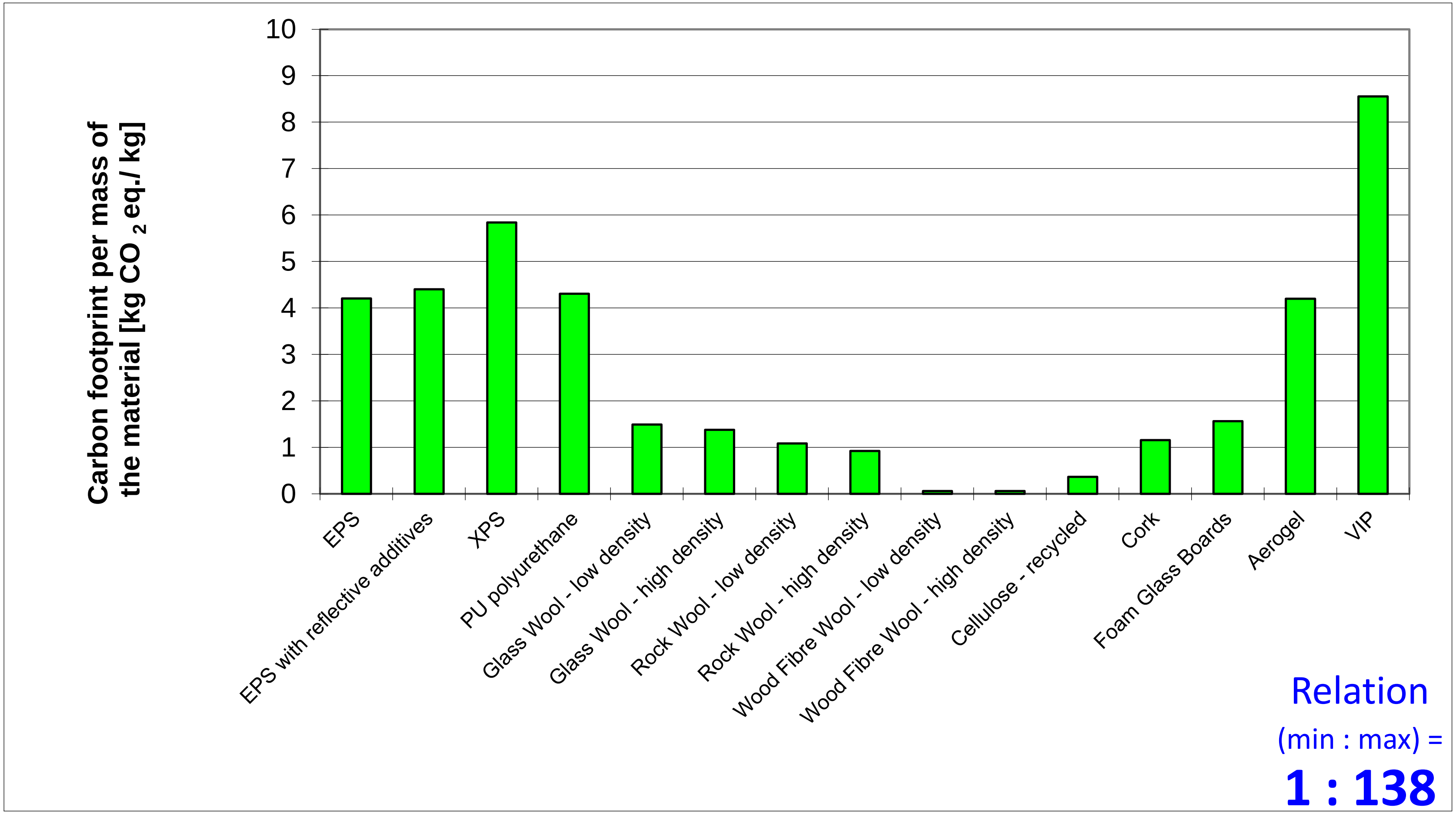


Relation

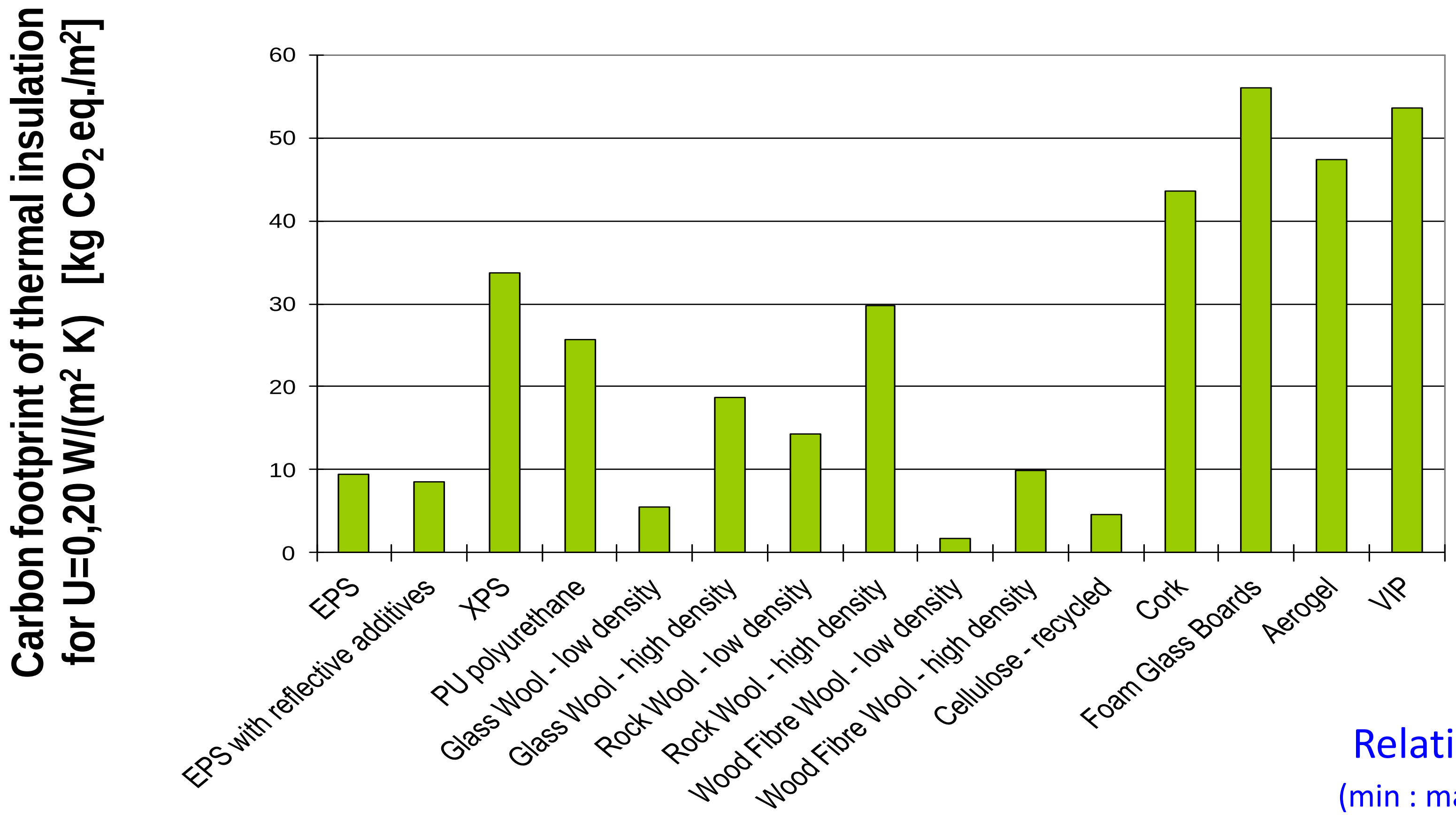
(min : max) =

1 : 7

Carbon footprint of different thermal insulation materials per kg mass of selected material [kg CO_2 eq./kg]



Carbon footprint of thermal insulation materials to achieve the value of thermal transmittance of the building envelope *U=0.20 W/(m² K)*, presented per unit area of building envelope: [kg CO_2 eq./m²]

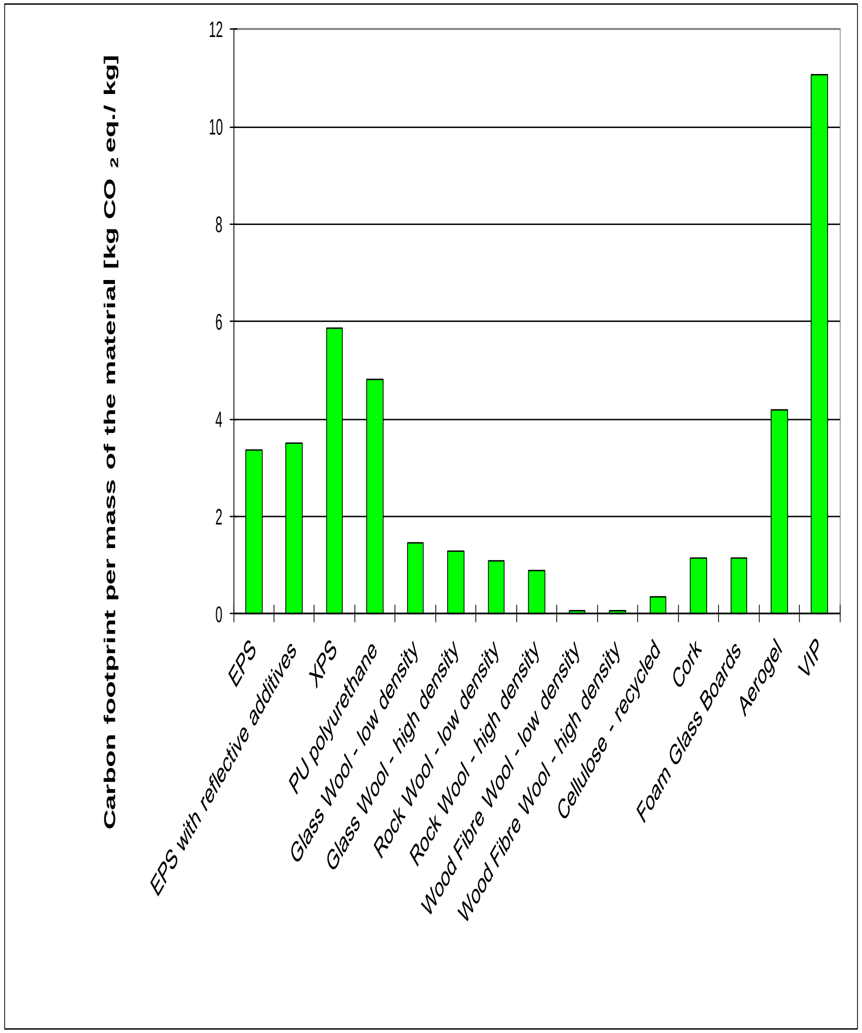


Relation

(min : max) =

1 : 42

Carbon footprint of different thermal insulation materials per kg mass of selected material [kg CO_2 eq./kg]



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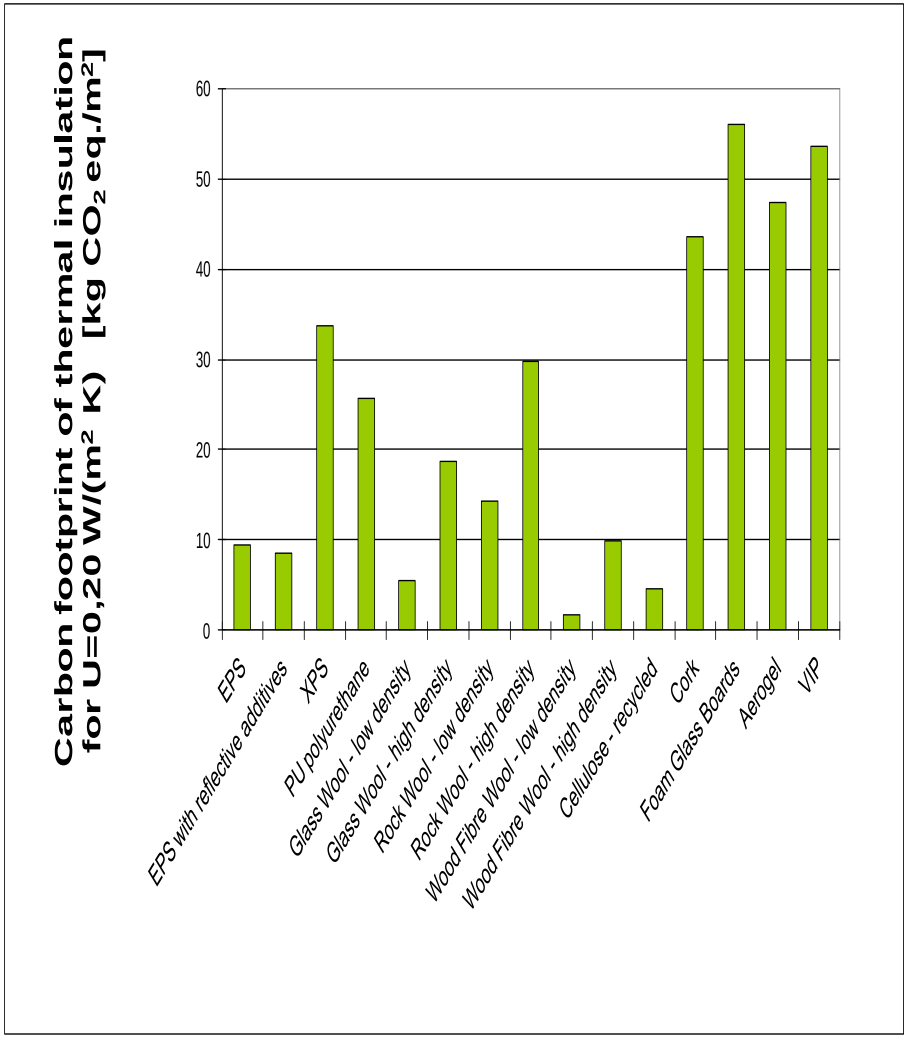


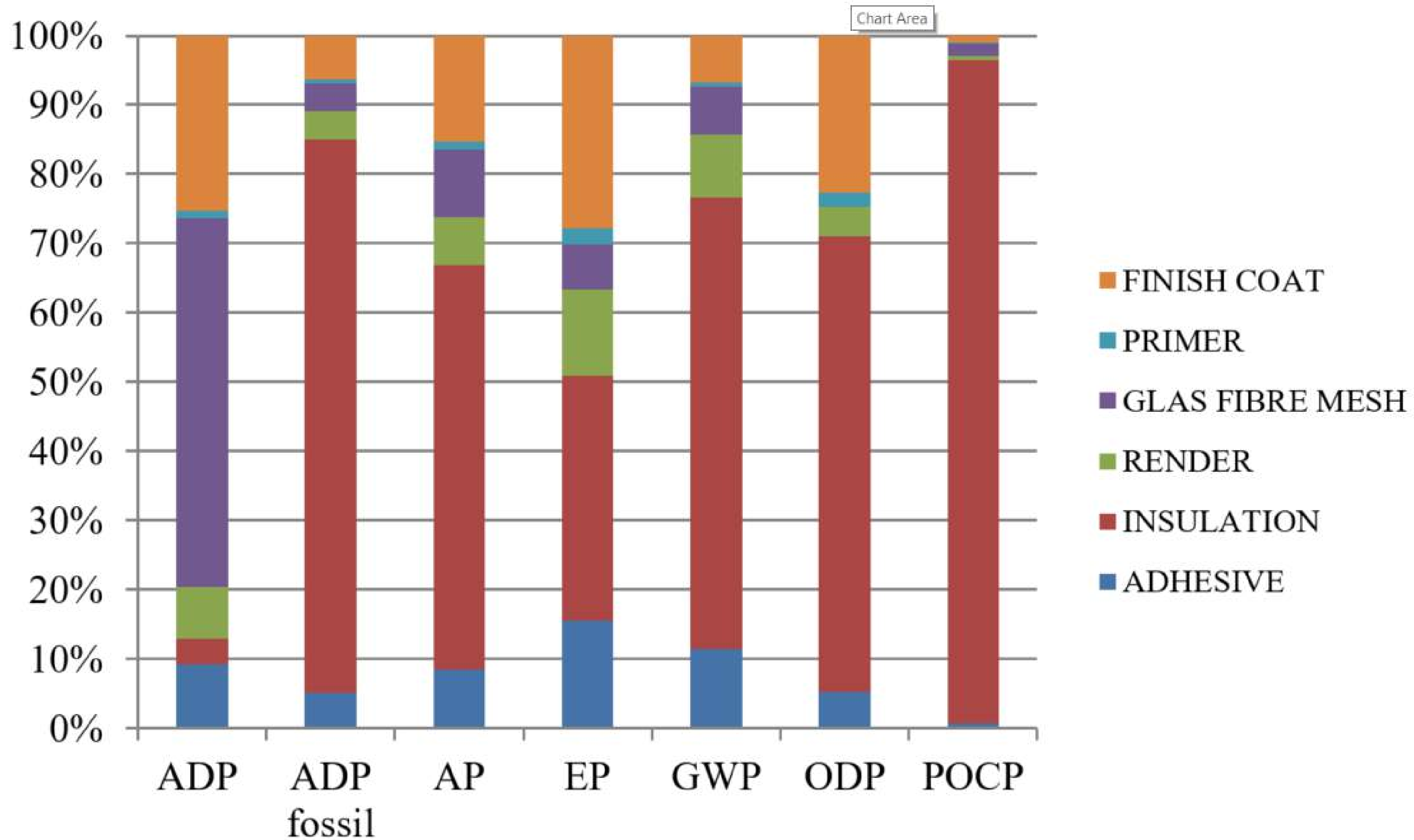
The **environmental neutrality** was defined as the time (measured in heating seasons) required to compensate the environmental impact of the production and installation of the selected insulation with the difference between the carbon footprint of the heat losses in the heating season through a currently averagely insulated external envelope and a well-insulated external envelope (U = 0.20 W/(m^2 K)) of an average building.

	kg CO2 –eq./ m2	kg CO2 –eq./ m2	kg CO2 –eq./ m2	kg CO2 –eq./ m2	kg CO2 –eq./ m2	kg CO2 –eq./ m2	kg CO2 –eq./ m2	kg CO2 –eq./ m2	kg CO2 –eq./ m2	kg CO2 –eq./ m2				
	GWP	GWP	GWP	difference										
	of thermal	ot existing	of new											
	insulation	building enve	building envelope			GWP of insulation for U-value 0,20 W/(m2 K) and difference of heat losses throug averige existing external envelope and heat losses through well-insulated (U=0,20 W/(m2 K)) external envelope								
	kg CO2 eq.	kg CO2 eq.	kg CO2 eq.	kg CO2 eq.	1	2	3	4	5	6	7	8	30	50
EPS	11.79	11.53	4.44	7.10	4.69	-2.41	-9.50	-16.60	-23.69	-30.79	-37.89	-44.98	-201.10	-343.03
EPS with reflective add	10.67	11.53	4.44	7.10	3.57	-3.53	-10.62	-17.72	-24.82	-31.91	-39.01	-46.10	-202.22	-344.15
XPS	33.62	11.53	4.44	7.10	26.53	19.43	12.33	5.24	-1.86	-8.96	-16.05	-23.15	-179.27	-321.19
PU polyurethane	22.94	11.53	4.44	7.10	15.85	8.75	1.65	-5.44	-12.54	-19.64	-26.73	-33.83	-189.95	-331.87
Glass Wool - low densi	5.60	11.53	4.44	7.10	-1.50	-8.59	-15.69	-22.78	-29.88	-36.98	-44.07	-51.17	-207.29	-349.22
Glass Wool - high dens	19.86	11.53	4.44	7.10	12.77	5.67	-1.43	-8.52	-15.62	-22.72	-29.81	-36.91	-193.03	-334.95
Rock Wool - low densit	14.34	11.53	4.44	7.10	7.25	0.15	-6.95	-14.04	-21.14	-28.24	-35.33	-42.43	-198.55	-340.47
Rock Wool - high dens	30.38	11.53	4.44	7.10	23.28	16.19	9.09	2.00	-5.10	-12.20	-19.29	-26.39	-182.51	-324.43
Wood Wool - low dens	1.76	11.53	4.44	7.10	-5.34	-12.44	-19.53	-26.63	-33.73	-40.82	-47.92	-55.01	-211.13	-353.06
Wood Wool - high den	10.01	11.53	4.44	7.10	2.92	-4.18	-11.28	-18.37	-25.47	-32.57	-39.66	-46.76	-202.88	-344.80
Cellulose - recycled	4.59	11.53	4.44	7.10	-2.51	-9.61	-16.70	-23.80	-30.90	-37.99	-45.09	-52.18	-208.30	-350.23
Cork	43.77	11.53	4.44	7.10	36.68	29.58	22.48	15.39	8.29	1.19	-5.90	-13.00	-169.12	-311.04
Foam Glass	75.59	11.53	4.44	7.10	68.49	61.39	54.30	47.20	40.11	33.01	25.91	18.82	-137.30	-279.23
Aerogel	47.33	11.53	4.44	7.10	40.23	33.13	26.04	18.94	11.84	4.75	-2.35	-9.44	-165.56	-307.49
VIP	41.30	11.53	4.44	7.10	34.20	27.10	20.01	12.91	5.81	-1.28	-8.38	-15.47	-171.59	-313.52

Environmental neutrality is time period when carbon footprint of heat losses through external envelope (m^2) is equal to carbon footprint of installed thermal insulation (m^2). In this time are environmental influences of installing thermal insulation equal to their influences of lowering heat losses on average external envelope taken into our analysis.

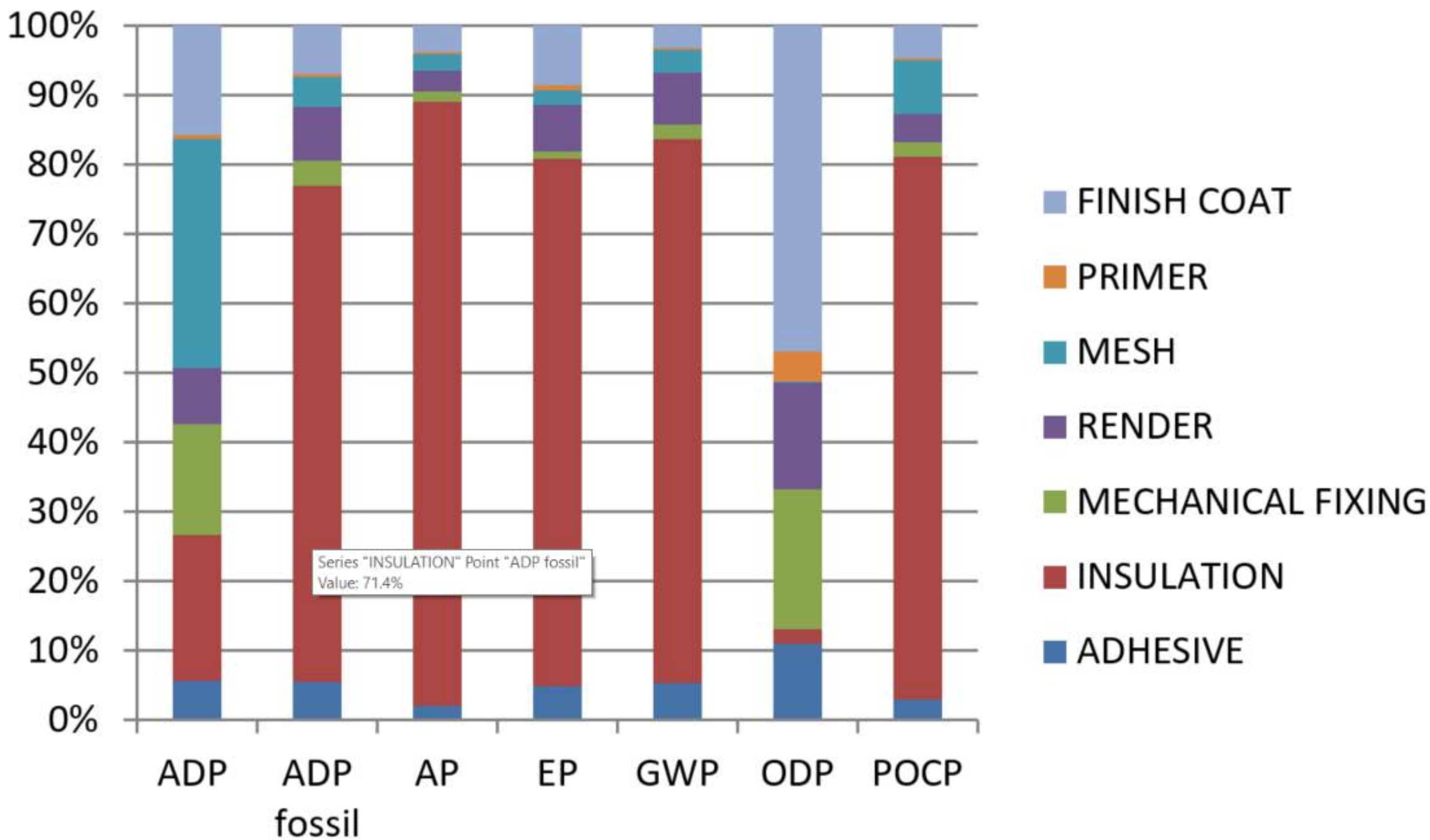
ADP(E) = Abiotic Depletion [kg Sb-eq.]
ADP Fossil = Abiotic Depletion fossil [MJ]
AP = Acidifaction Potential [kg SO_2 –eq.]
EP = Eutrophication Potential [kg Phosphate – eq.]
GWP = Global warming Potentital [kg CO_2 –eq.]
ODP = Ozone layer Depletion Potential [kg R11 –eq.]
POCP = Photochemical Ozone Formation [kg Ethene –eq.]

ETICS with EPS insulation



ADP(E) = Abiotic Depletion [kg Sb-eq.]
ADP Fossil = Abiotic Depletion fossil [MJ]
AP = Acidifaction Potential [kg SO_2 –eq.]
EP = Eutrophication Potential [kg Phosphate – eq.]
GWP = Global warming Potentital [kg CO_2 –eq.]
ODP = Ozone layer Depletion Potential [kg R11 –eq.]
POCP = Photochemical Ozone Formation [kg Ethene –eq.]

ETICS with mineral wool insulation



ADP(E) = Abiotic Depletion [kg Sb-eq.]
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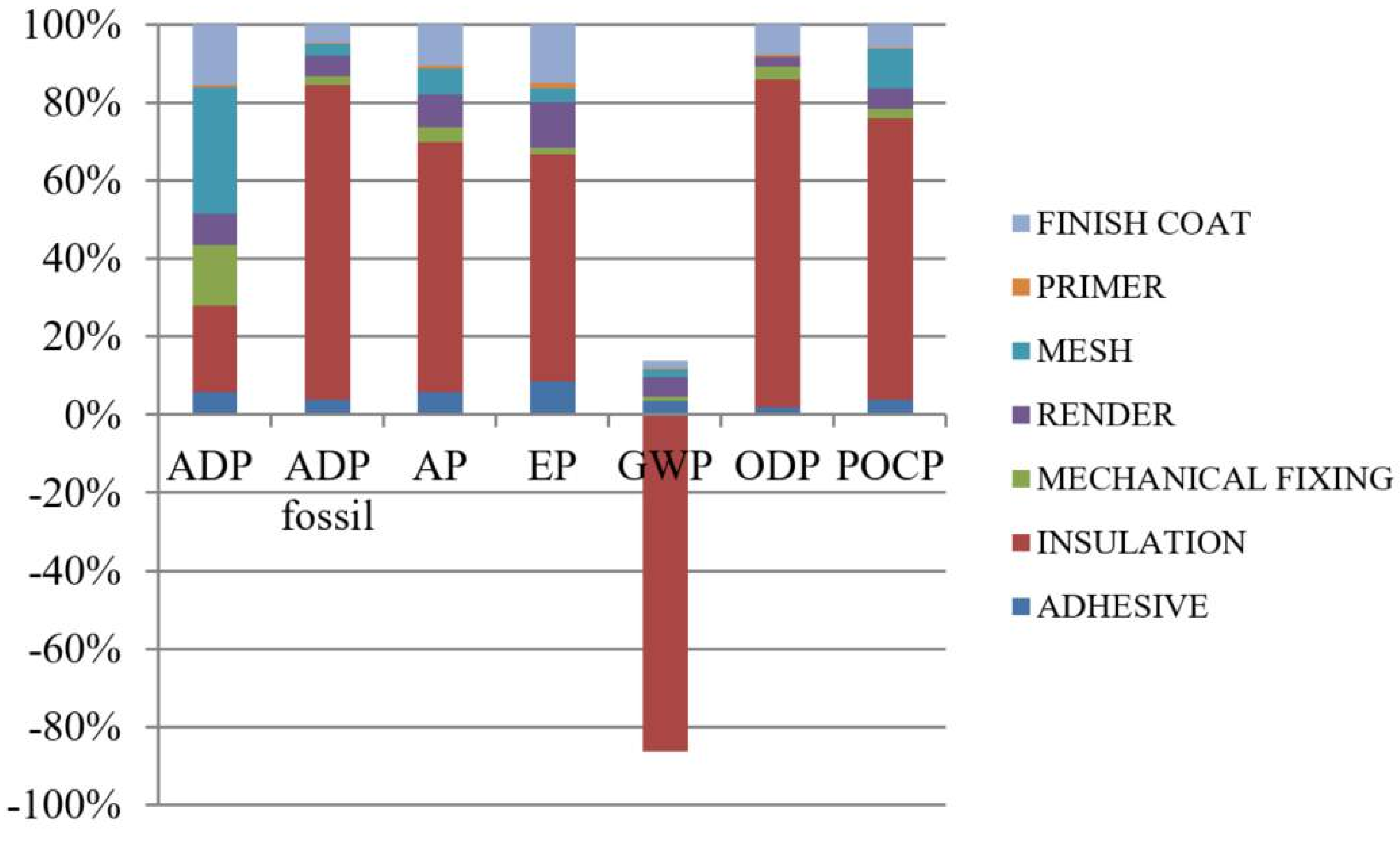
ETICS with wood fiber board insulation



Transient (dynamic) thermal response analysis of building envelopes

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Applied Energy

FEM thermal performance analysis of multi-layer external walls during typical summer conditions considering high intensity passive cooling

Blaž Hudobivnik, Luka Pajek, Roman Kunič, Mitja Košir

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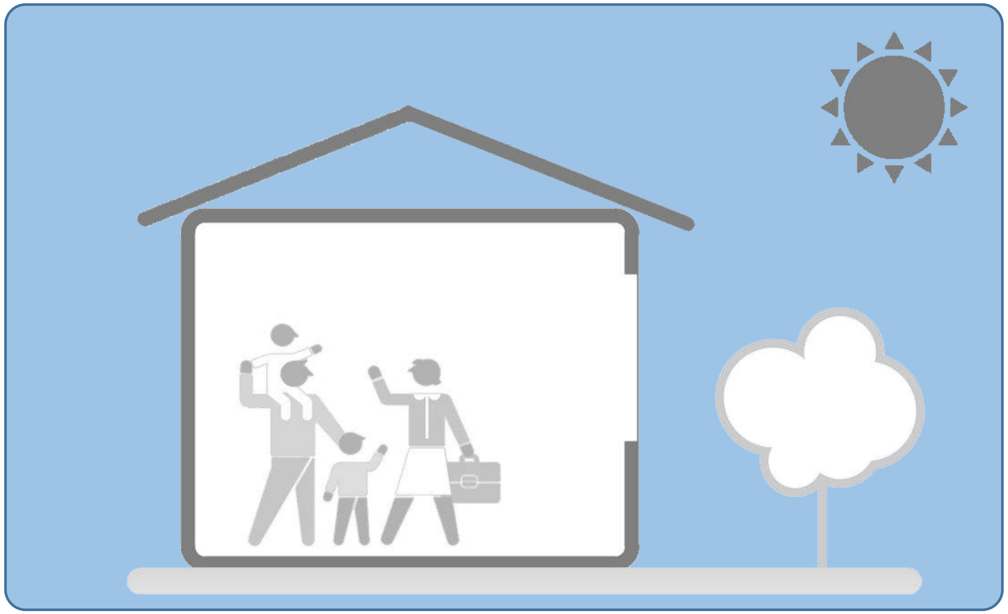
INTRODUCTION

The climate in most parts of continental Europe is favourable to make overheating of buildings completely manageable by the proper design and application of passive solar architecture features (e.g. shading, night-time ventilation, high thermal mass, etc.).

The overall performance of buildings is closely related to the thermal mass of the opaque envelope. It has been shown that in the field of energy consumption as well as indoor occupant comfort buildings with lightweight construction (LWC) and the related small thermal mass underperform compared to those with heavyweight construction (HWC) [Zhu et al., 2009; Andjelković et al., 2012; Al-Sanea et al., 2012; Buonomano et al., 2016].

STATISTICAL BACKGROUND

The statistical data of the European Union [Eurostat, 2016] show that in 2012 approximately 19% of the total population lived in dwellings not comfortably cool during summer time.
The number is a bit lower for Slovenia (17%), though overheating is much more apparent in the cities than in the rural regions.



RESEARCH MOTIVATION

AIMS

- to evaluate summer time thermal response of various building envelope construction systems under realistic climatic conditions.
- To simulate thermal performance of selected external wall segments with a non-stationary finite element analysis.

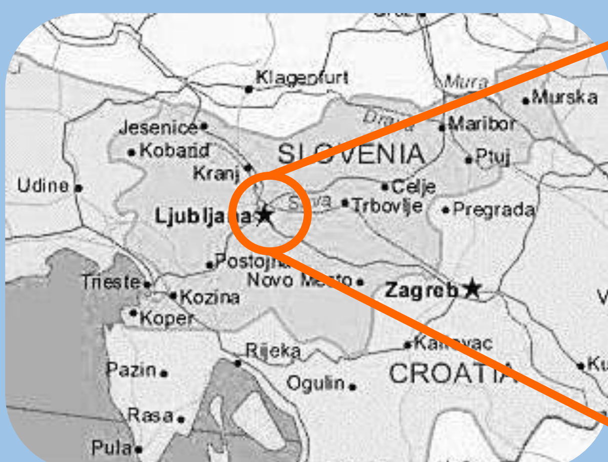
METHODS

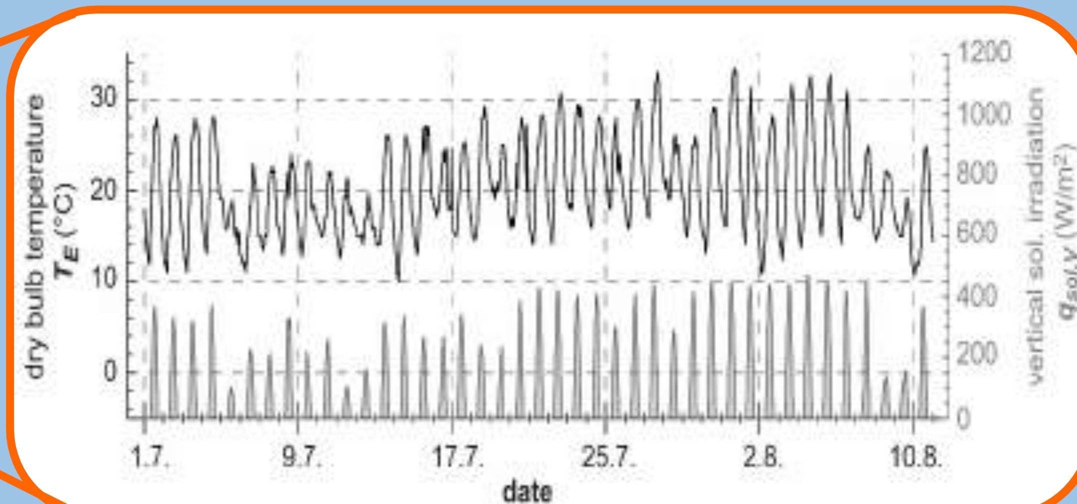
The non-stationary thermal performance of different <u>multi-layer external wall envelope</u> types was investigated <u>during summer conditions</u> (i.e. cooling season) from **June till August**.

For the executed analysis the location and climate of Ljubljana, Slovenia (N 46.05°, E 14.51°) were selected, considering daily fluctuation of dry bulb air temperatures and global solar irradiation.

CLIMATE

Climate data for the city of Ljubljana were obtained from weather file available online [EnergyPlus, 2016].





METHODS

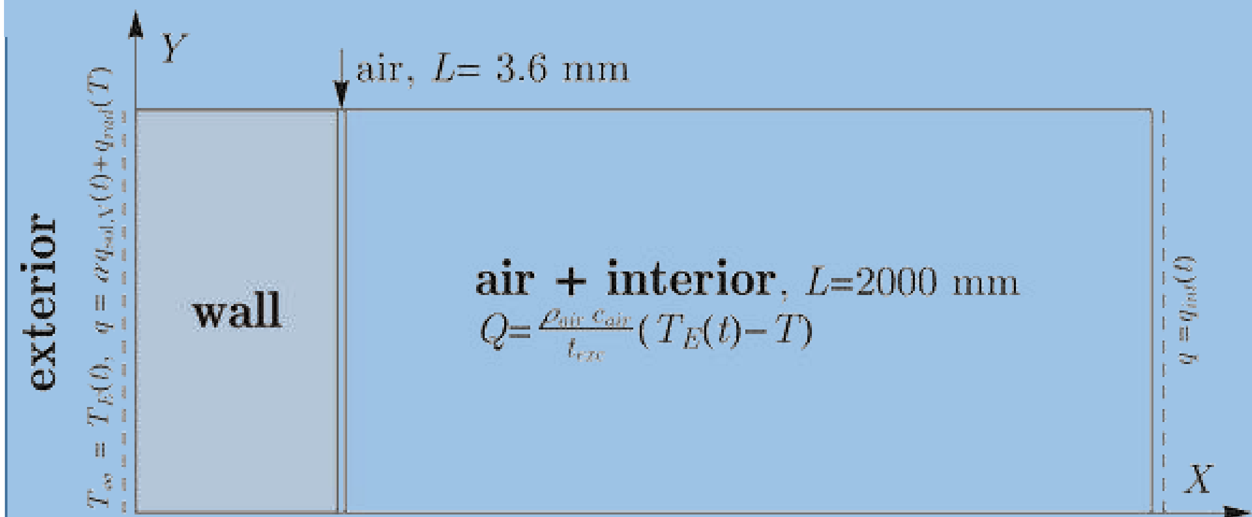
MODEL

A weak form of governing differential equation, required for the finite element method, can be written for arbitrary body B and its boundary ∂B, as presented in Hudobivnik et al. [2016].

$$\int_B \delta T \left(\left(\rho\, c\, \frac{\partial T}{\partial t} + \rho\, \Delta \mathrm{h}\, \frac{\partial S}{\partial t} - Q \right) + \frac{\partial \delta\, T^T}{\partial \boldsymbol{X}} \cdot \left(\lambda\, \frac{\partial T}{\partial \boldsymbol{X}} \right) \right) dV \;+\; \int_{\partial B} \delta\, T \left(q - \alpha_{rad} (T_{sky}^4 - T^4) + \, h\, (T - T_\infty) \right) dA \qquad (1)$$

Finite element code was derived using automatic code generation system AceGen [2011], computer algebra system Mathematica [2011] **and the numerical solver AceFEM** [2011].

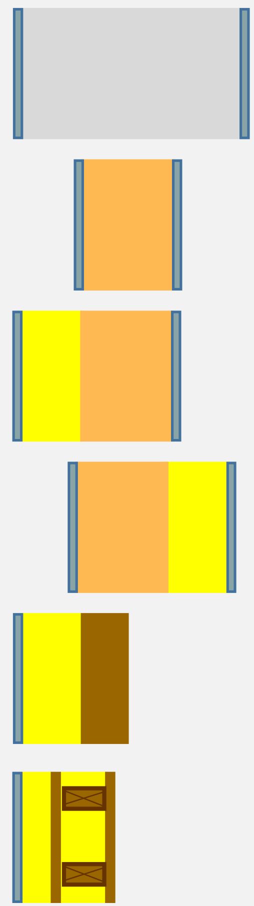
Conceptual model description



The wall was modelled either as a filigree construction (lightweight – LWC) or as a solid construction (heavyweight – HWC)

CHOSEN WALL CONSTRUCTION SYSTEMS

Construction	Label
Very thick massive stone wall w/o thermal insulation	STONE *
Hollow brick wall w/o thermal insulation	HB *
Hollow brick wall w/ external thermal insulation	HB_E
Hollow brick wall w/ internal thermal insulation	HB_I
Cross-laminated timber wall w/ external thermal insulation	X-LAM
Lightweight timber framed wall w/ external thermal insulation	LWC



* Constructions without additional thermal insulation

heavy weight construction (STONE, HB, HB_E, HB_I)

light weight construction (X-LAM, LWC)

CHOSEN WALL CONSTRUCTION SYSTEMS

Construction	Label	Thickness [mm]	U value [W/m²K]	Thermal capacity [kJ/m²K]	
Very thick massive stone wall w/o thermal insulation	STONE	530	2.17 *	980	heavy weight construction
Hollow brick wall w/o thermal insulation	HB	340	1.88 *	466	heavy weight construction
Hollow brick wall w/ external thermal insulation	HB_E	443	0.28	468	heavy weight construction
Hollow brick wall w/ internal thermal insulation	HB_I	443	0.28	468	heavy weight construction
Cross-laminated timber wall w/ external thermal insulation	X-LAM	225	0.28	117	light weight construction
Lightweight timber framed wall w/ external thermal insulation	LWC	219	0.28	102	light weight construction

* Constructions without additional thermal insulation

prescribed by Slovenian legislation

[TSG-1-004:2010: Technical guidelines for efficient energy use in buildings]

RESULTS

Environmental conditions:

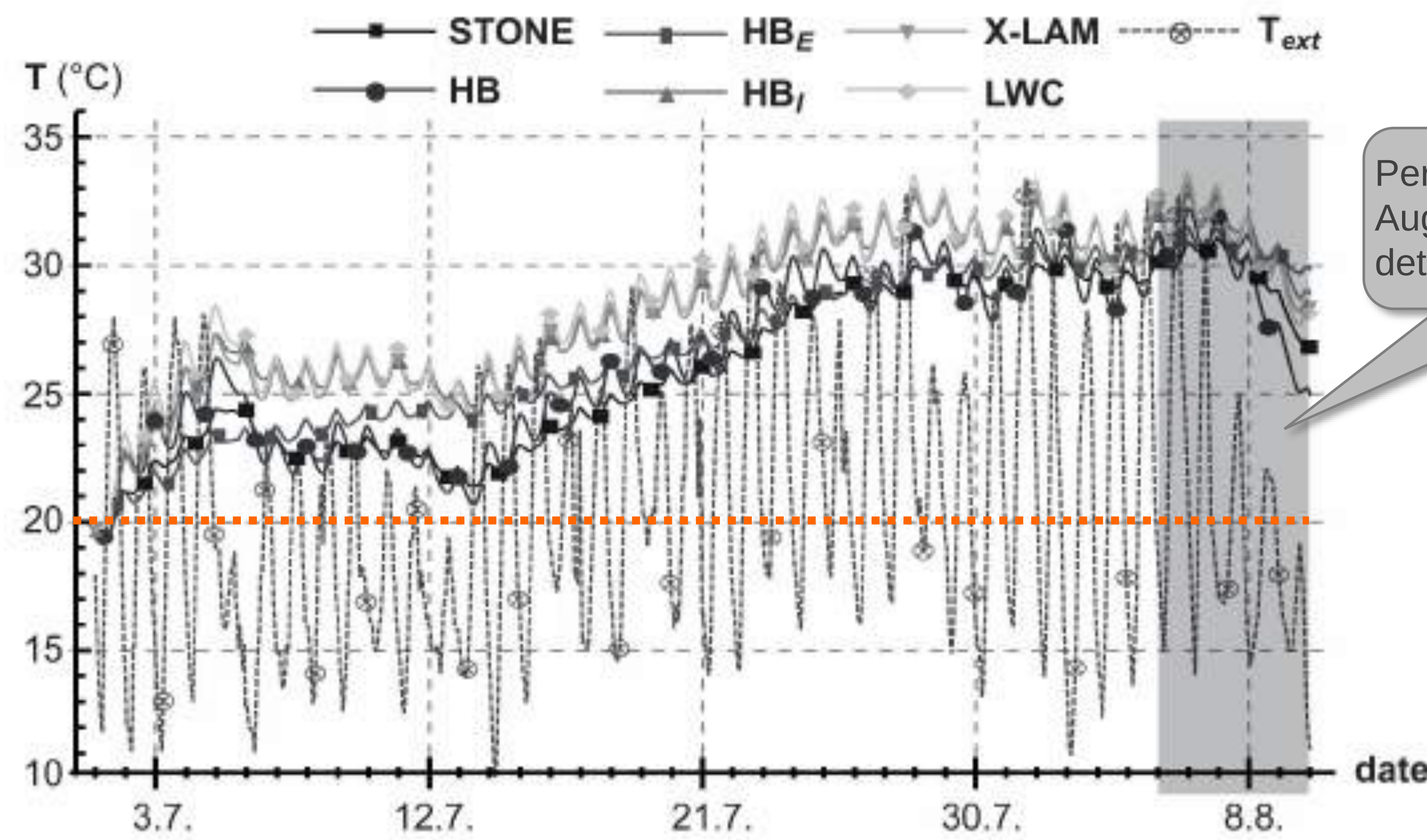
$T_{e,max}$ = 33.4 °C (31st July)

$T_{e,min}$ = 10.0 °C (14th July)

Indoor conditions:

T_{LWC}	= 29.7 °C (22:33)
$T_{X\text{-}LAM}$	= 29.5 °C (22:31)
T_{HBI}	= 29.6 °C (23:04)
T_{HBE}	= 28.2 °C (22:31)
T_{HB}	= 27.5 °C (22:52)
T_{STONE}	= 27.2 °C (23:02)

MAX. AVERAGE VALUES



Period from 5th to 10th of August (shown in greater detail on next slide)

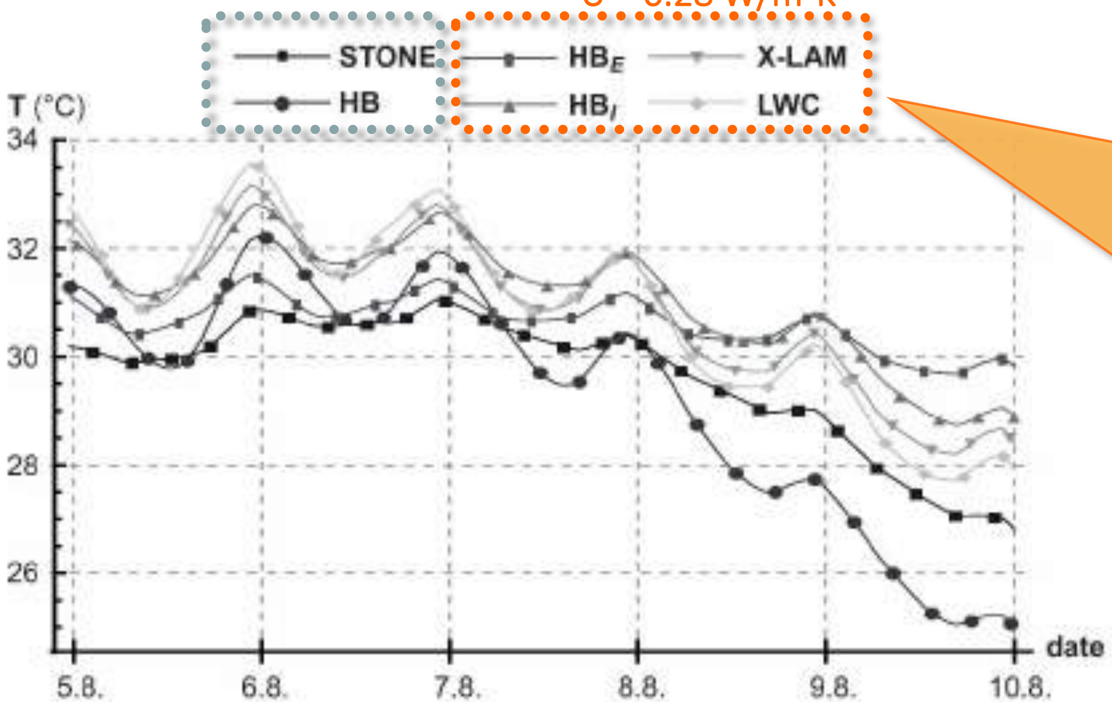
- **the <u>highest thermal stability</u>**
- **the <u>lowest average daily indoor air temperatures</u>**
- **the fastest <u>reaction to the change of external environmental conditions</u>**

AVERAGE DIURNAL TEMPERATURE FLUCTUATIONS

ΔT_{LWC} = 1.98 K
ΔT_{HB} = 1.73 K
$\Delta T_{X\text{-}LAM}$ = 1.71 K
ΔT_{HBI} = 1.25 K
ΔT_{HBE} = 0.90 K
ΔT_{STONE} = 0.73 K

No additional thermal insulation

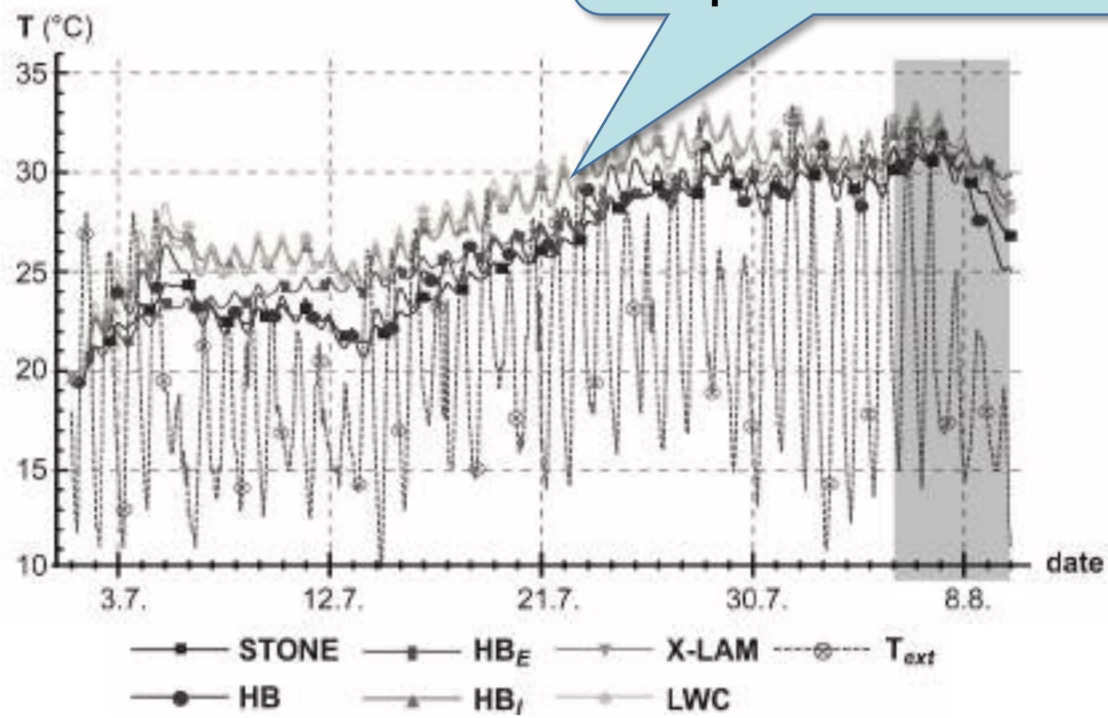
U = 0.28 W/m²K

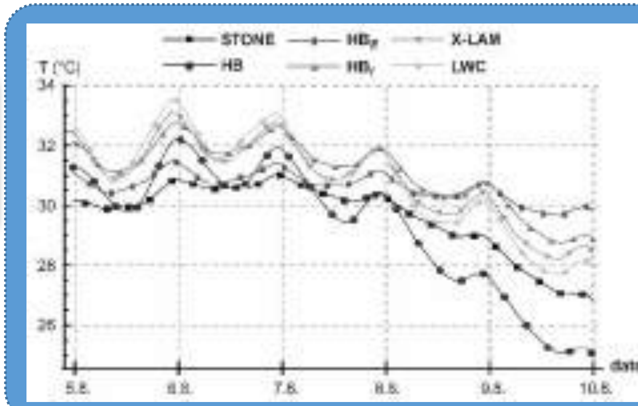


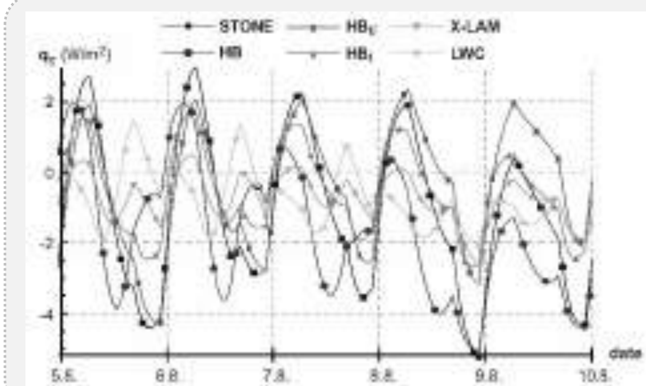
- **take longer period to cool down naturally**
- **the heat flow through the wall is low, when external temperatures fall**

LIGHTWEIGTH versus HEAVYWEIGHT

HB_I, LWC and X-LAM have similar thermal response







- lightweight envelope systems can be quickly actively or passively cooled [Hudobivnik et al., 2016]
- lightweight constructions have slower response to external temperature changes in comparison to STONE or HB (constructions without additional thermal insulation).
- lightweight timber construction (LWC) has the overall worst performance (lack of thermal capacity of inertia)

CONCLUSIONS

The understanding of summer time thermal response of buildings is very important, since the majority of legislation and design strategies are particularly focused on the heating season (i.e. winter time).

Thermal transmittance is not the only characteristic that should be taken into consideration, especially in summer time, when thermal response of buildings in free-run mode is crucially influenced by the transient thermal response.

The use of high thermal mass with a possibility of its activation is highly appreciated in summer time, when high external temperatures are reached, while the U value of construction is mostly irrelevant.

Since thermal mass can play a significant role in summer time thermal response, a thoughtful approach to building applications is necessary to ensure thermally comfortable living conditions in buildings, especially in non-mechanically cooled ones.

This is of particular interest due to a growing trend in construction industry where lightweight envelopes (LWC and X-LAM) are preferred, particularly in the construction of residential buildings.

Advanced insulation materials and systems in buildings, and energy savings

Many thanks !

Any questions?

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University of Ljubljana
Faculty of Civil and Geodetic Engineering

UL100

UL100

Sound insulation, building and architectural acustics

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Sedanji predsednik (od 2019 dalje):
Izr. prof. dr. Roman Kunič, Univerza v Ljubljani, FGG, KSKE

Sound is longitudinal vibration

c (m/s) **= f** (Hz) **. λ** (m) = const. = ~ 340 m/s

Speed of light is ~ 300 000 000 m/s i.e. 880 000 x more

$$\text{Wavelength (ft)} = \frac{\text{Speed of sound (ft/sec)}}{\text{Frequency (Hz)}} \qquad (1\text{-}1)$$

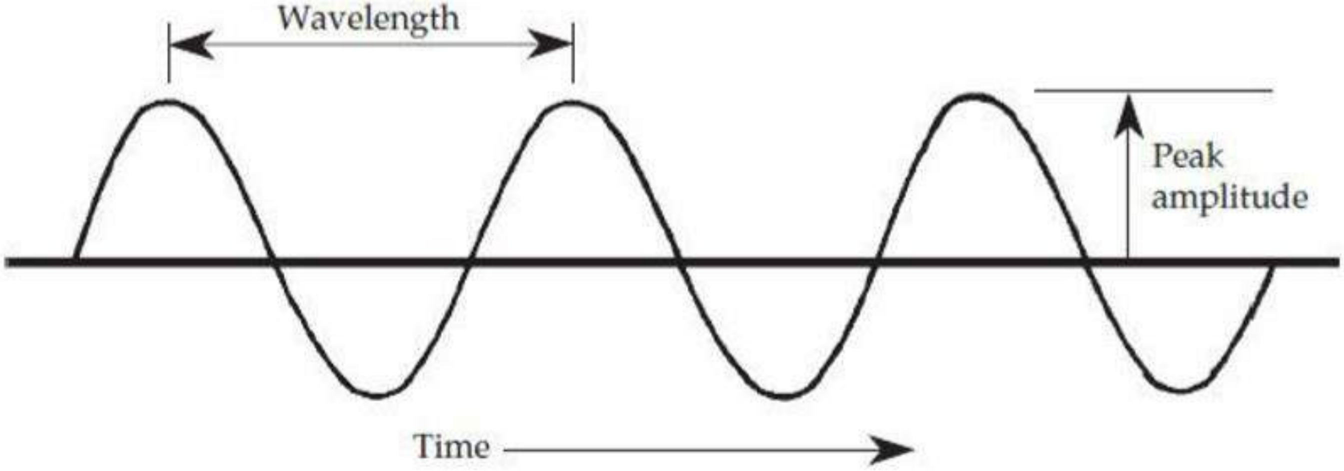


Figure 1-7 Wavelength is the distance a wave travels in the time it takes to complete one cycle. It can also be expressed as the distance from one point on a periodic wave to the corresponding point on the next cycle of the wave.

Changes in atmospheric pressure

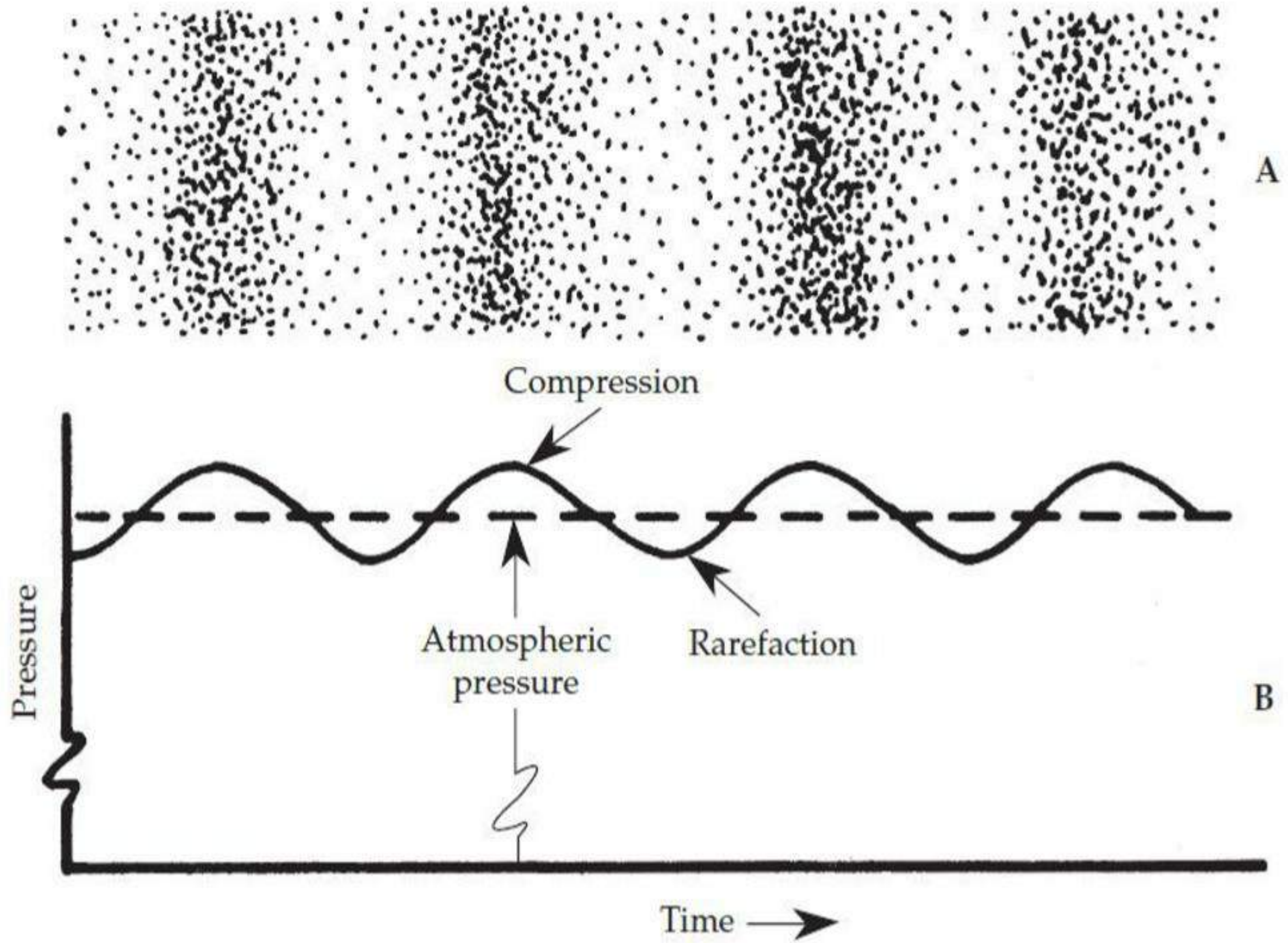
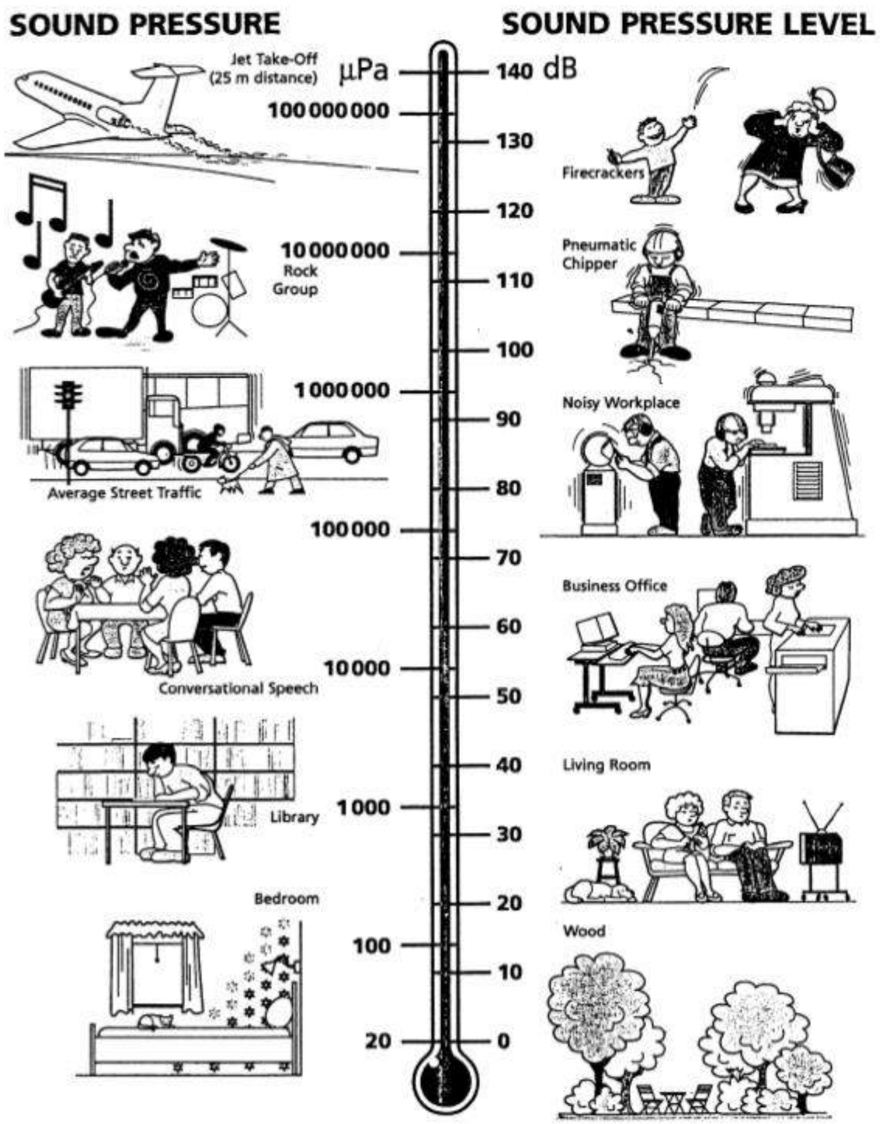
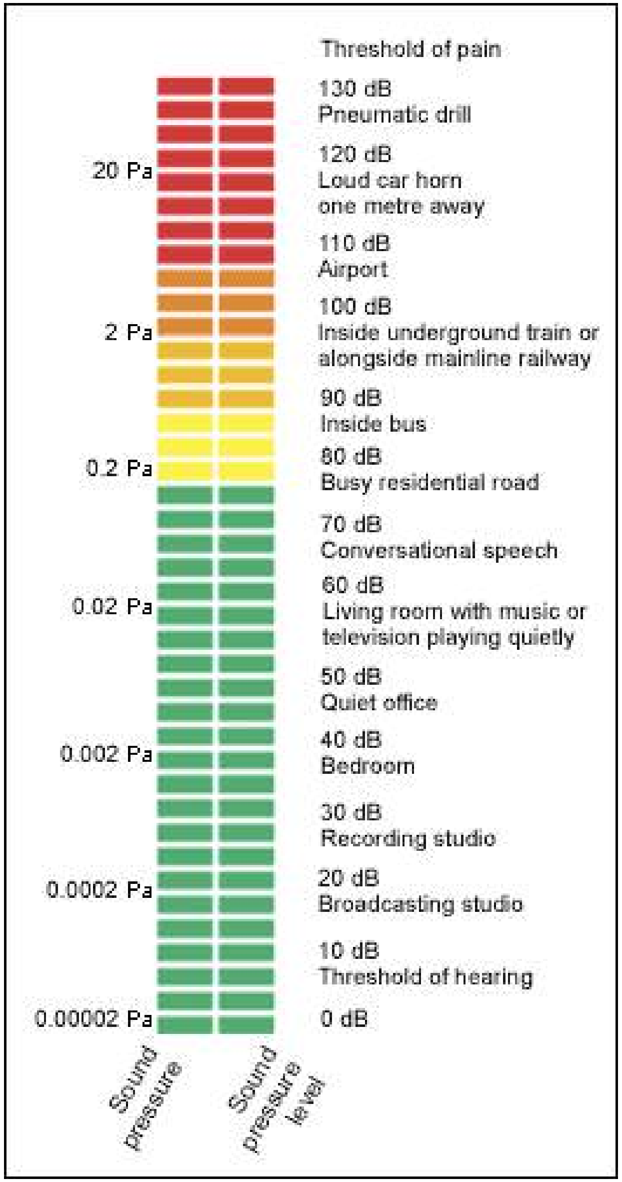


FIGURE 1-6 Pressure variations of sound waves are superimposed on prevailing barometric pressure. (A) An instantaneous view of the compressed and rarefied regions of a sound wave in air. (B) The compressed regions are very slightly above and the rarefied regions very slightly below atmospheric pressure.





Sound Pressure Level: SPL = 20 . log (p_{RMS} / p_o)

Reference pressure: p_o = 20 µPa = 0,00002 Pa = 20 . 10^{-6} N/m^2

Problem of noise in EU (source: WHO)

>40% of population is daily exposed to >65dB(A) and through nights >50dB(A)

>20% of working population is exposed to more than acceptable noise levels (more than one half to >80dB(A))

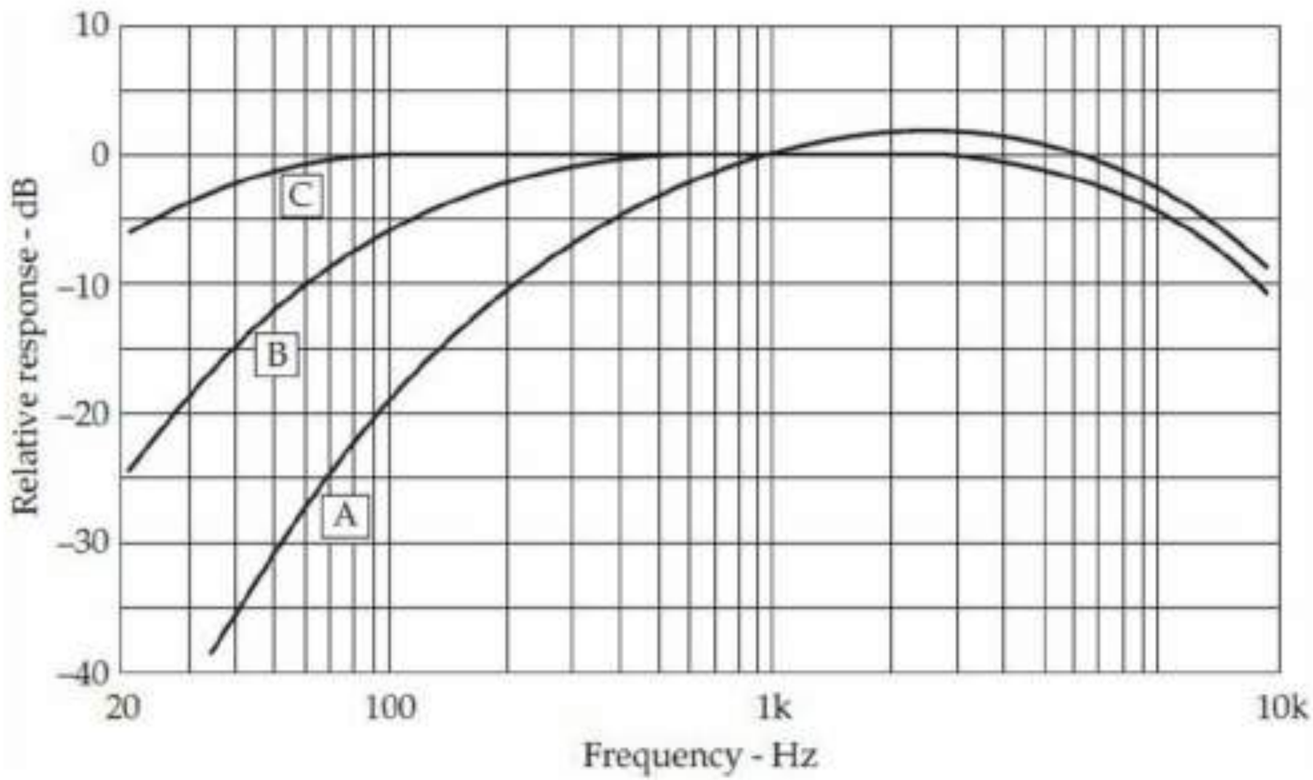
Facts:

Noise **<65 dB(A)** on long period normally **does not lead to permanent hearing failures**. Short exposure generally does not lead to permanent hearing loss. Short exposures do not have detachable effects on temporary hearing loss.

Noise **>65dB(A)** exposure for years **may lead** to problems with hearing loss

Noise **>80B(A)** exposure for many years leads to **great certainty** to permanent hearing loss

A, B & C weighting



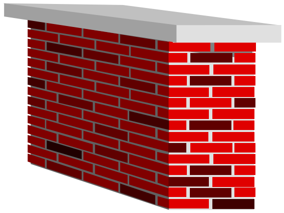
dB(A)
dB(B)
dB(C)

FIGURE 2-3 The A, B, and C weighting response characteristics for sound-level meters. (ANSI S1.4-1981.) A weighting is most commonly used.

- For sound-pressure levels of 20 to 55 dB, use network A.
- For sound-pressure levels of 55 to 85 dB, use network B.
- For sound-pressure levels of 85 to 140 dB, use network C.

Sound insulation of buildings

- Sound insulation against airborne sound ✓
- Sound insulation against impact sound ✓
- Sound insulation against vibrations of installations ✓
- Sound insulation against environmental (municipal) noise ✓
- Acoustics of interior space (reverberation noise) ✓



Sound insulation against airborne noise:

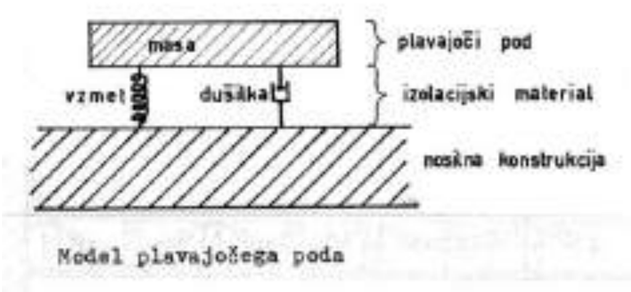
- **Emitter:** sound vibrations in the air (speech, audio speaker, musical instruments ...)
- **Transmitter:** from the air, through solid construction material, partition walls, doors, windows and sound in the air again
- **Receiver:** airborne sound in receiving room (ear, microphone of measuring instrument…)

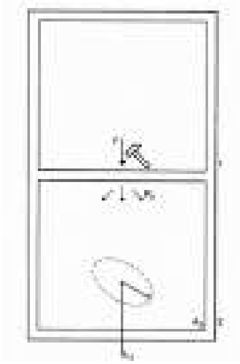
- **Basic rule:** maximizing the mass of the wall, ceiling or intermediate barriers per unit area leads to higher sound insulation values.

Noise reduction insulation materials (mainly porous) do not directly affect the reduction of sound propagation against airborne sound. Those materials are primarily used for lowering noise level by reducing echo effect and to lower reverberation time of the interior spaces

Sound insulation against impact sound:

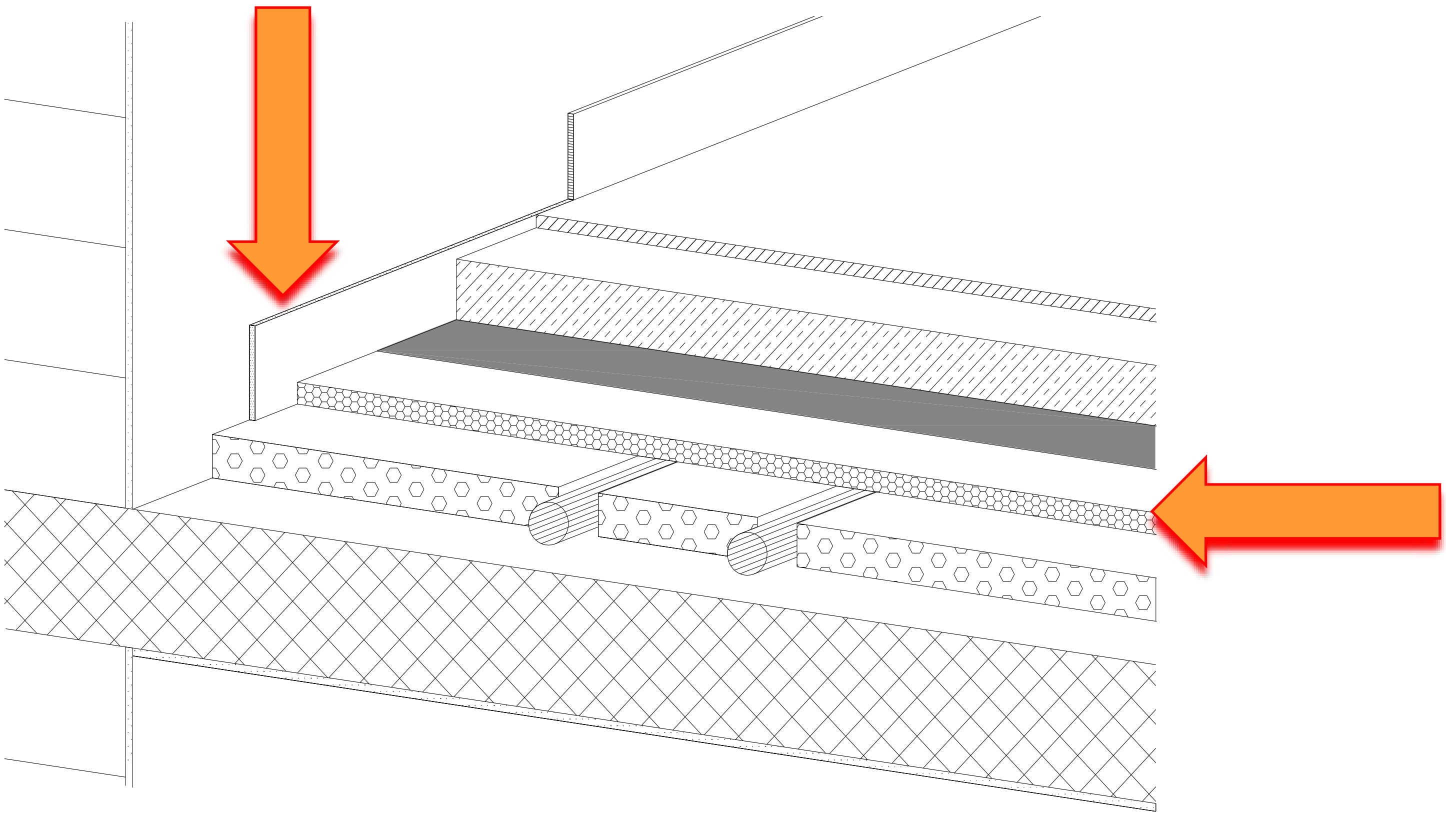
- **Emitter:** vibrations, walking, different bumps, moving chairs and furniture, various assembly and finishing construction works
- **Transmitter:** massive solid construction material and sound in the air
- **Receiver:** sound in receiving room (ear, microphone of measuring instrument…)





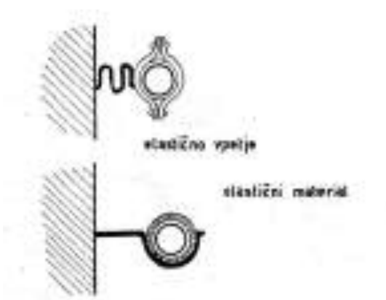
- **Basic rule:** to prevent access of impact sound to enter into massive construction (floor or wall constructions) – all other preventive approaches are much less effective

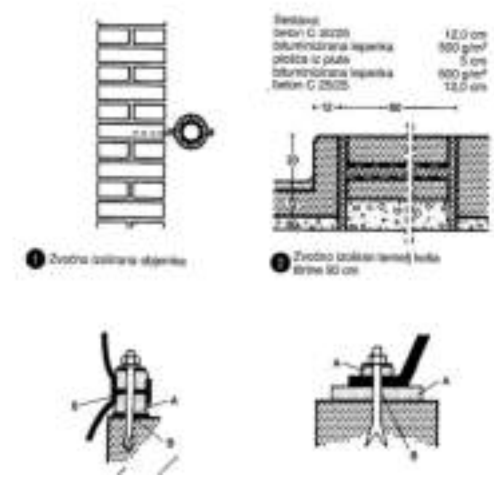
Floated floor



Sound insulation against vibrations and installations

- **Emitter:** vibrations and forced vibrations of installations and other operating equipment, vibrations transmitted from the air or impact sound into installation lines,
- **Transmitter:** installation lines, direct connections of installation lines into massive bearing constructions,
- **Receiver:** sound in receiving room (ear, microphone of measuring instrument…)





- **Basic rule:** to prevent the access of sound into installations.

To minimize transfer and sources of forced oscillations or vibrations.

All passages of installations through constructions should be sealed with elastic and acoustic insulated materials.

Insulation against environmental (municipal) noise

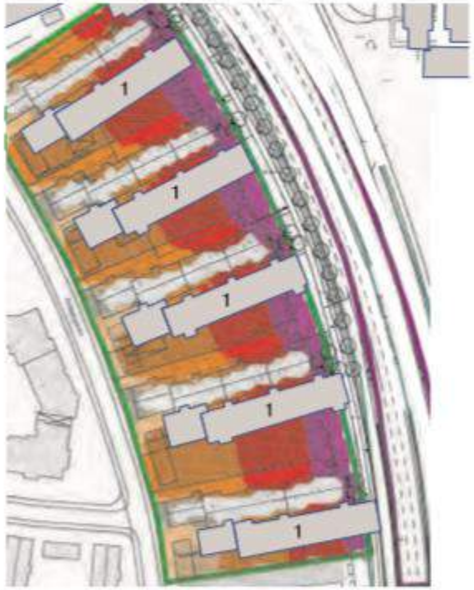
- **Sources of the noise are usually: transport (road, railway, airplane, sea transport…), industry, children's playgrounds, sport or other events…**

- **Barriers against noise are normally used**

We distinguish between:

- **Active noise protection** (reduction of noise at the source side) – very effective and less costly
- **Passive noise protection** (reduction of noise at the receiver side) – less effective and more expensive

Insulation against environmental noise starts with urban design



2a

b

c

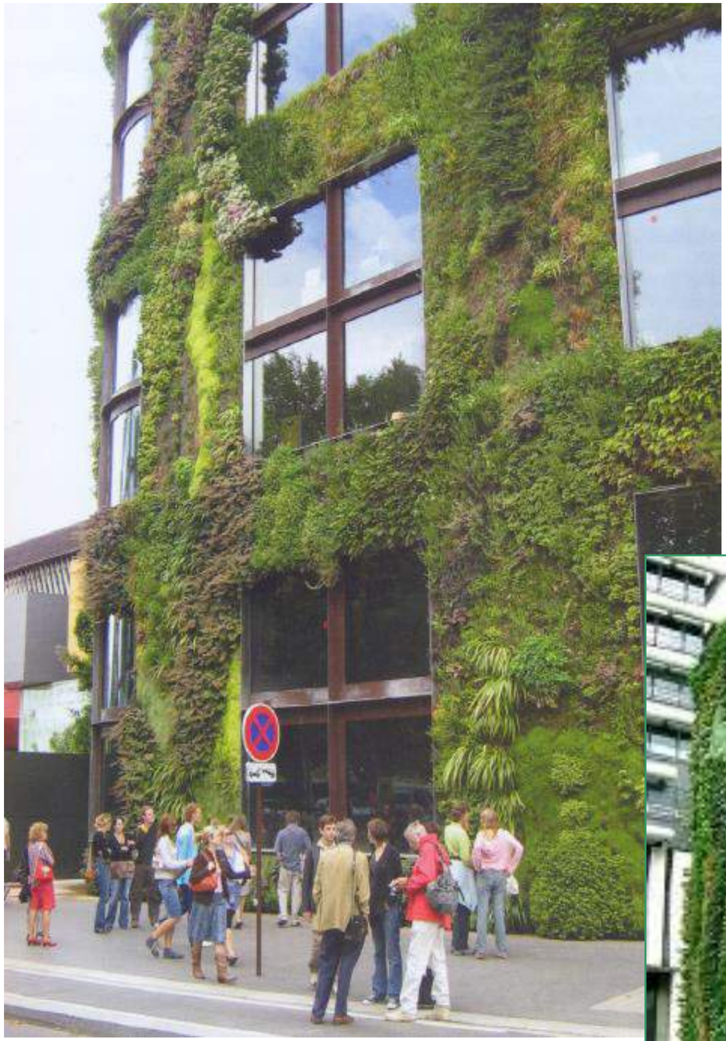
d

d

Case of glass facade designed as a noise barrier for protecting facade of offices and atrium

München

Green facades are also good noise absorbers



Reverberation time is lower and consequently also noise disturbance is lower

Acoustics of interior space (reverberation noise):

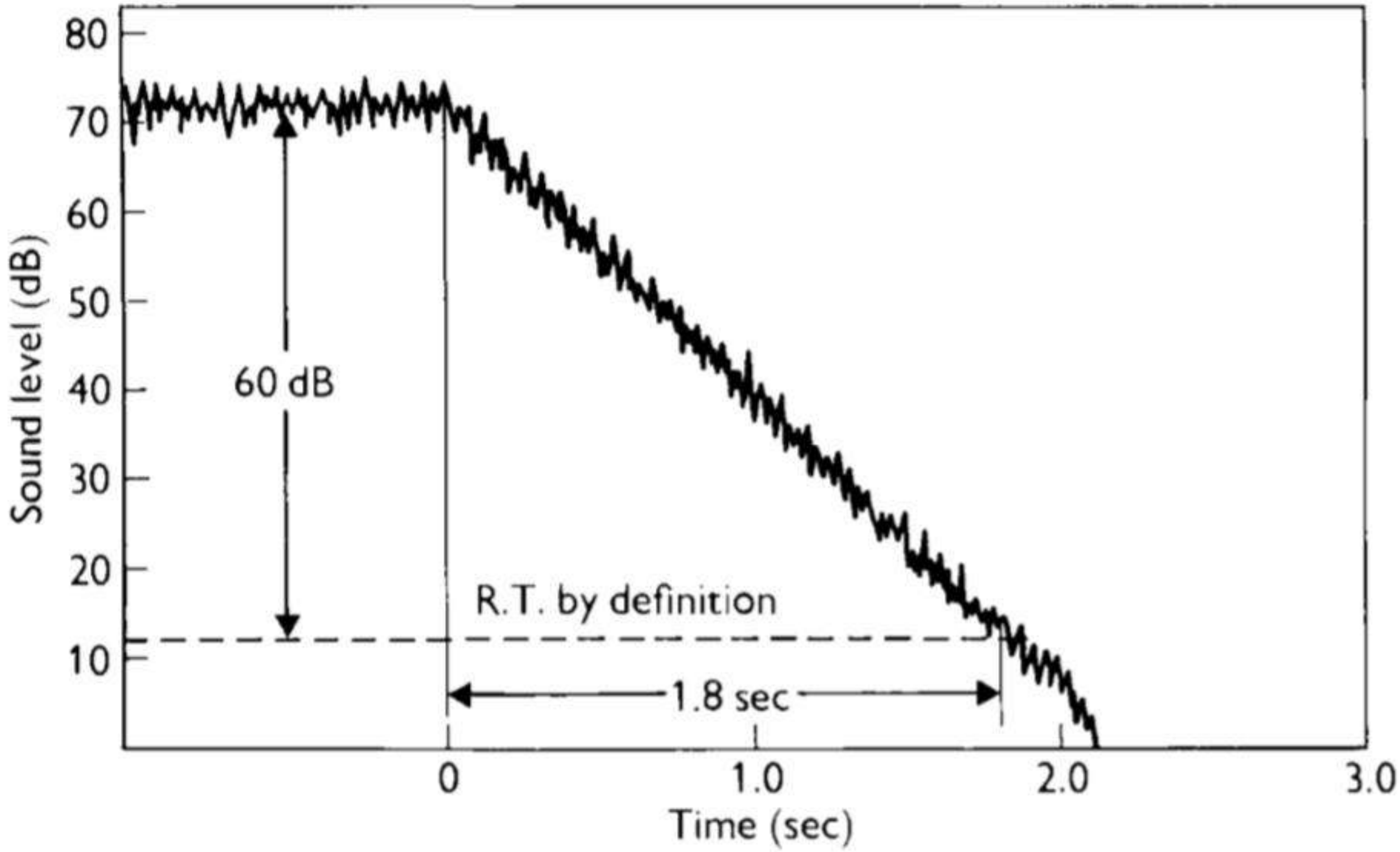
- **A goal is to control (to lower) reverberation time of interior space (indoors)**

We distinguish between:

- **Acoustics of spaces intended for speech** (importance of clarity and understanding of human voice or speaker – comprehensibility)
- **Acoustics of spaces intended for music** (importance of various aesthetic and artistic criteria)

Reverberation time is reduced by installing absorbent surfaces on walls, ceilings and floors of interior space

Acoustics of interior space (reverberation noise)

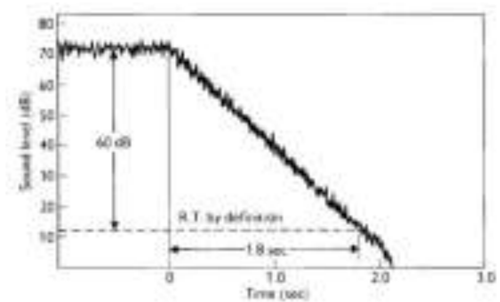


Sabin equation for reverberation time of interior space (Wallace Clement Sabine, 1868-1919)

$$RT_{60} = 0.161\ V\ (m^3) / A\ (m^2) \quad (s)$$

also: $RT_{60} = (0{,}163\ V) / (A + 4mV)$

$$A = \Sigma\, \alpha_i \times S_i \quad (m^2)$$



V ………………… Volume (m^3)
$A = \Sigma\, \alpha_i \times S_i$ ….. Equivalent absorption area (m^2)
α_i ………………. Absorption coefficient of certain surface (-)
S_i ………………. Absorption area of certain material (m^2)
4mV ………….. Absorption of sound in the air

Eyring formula:

$$TR_{Ey} = (0{,}163\ V) / (-S * \ln(1 - \alpha_{AV}) + 4mV) \quad (s)$$

S ………… sum of all surfaces in room
α_{AV} ………average absorption coefficient of all surfaces of certain room
4mV ……. Absorption of sound in the air

Ideal values of the reverberation time in dependence on the volume of the interior space

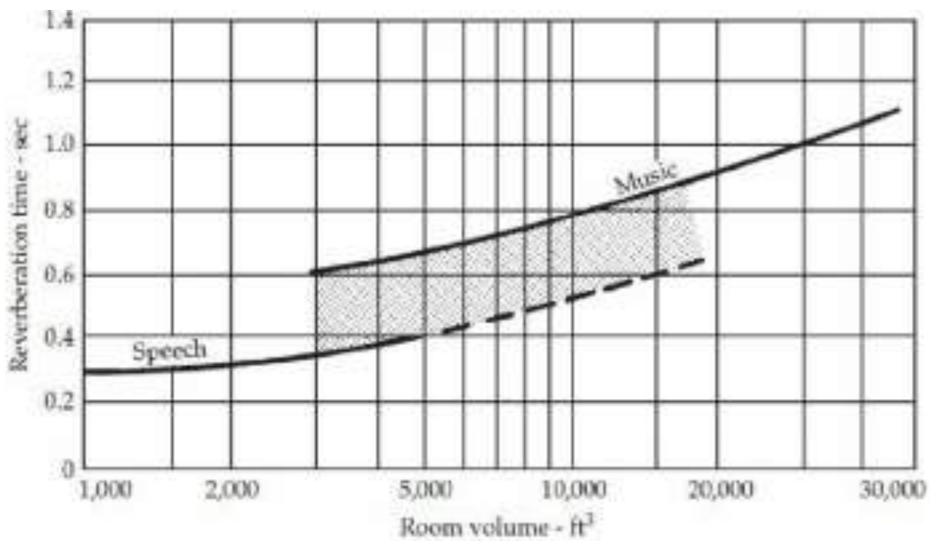
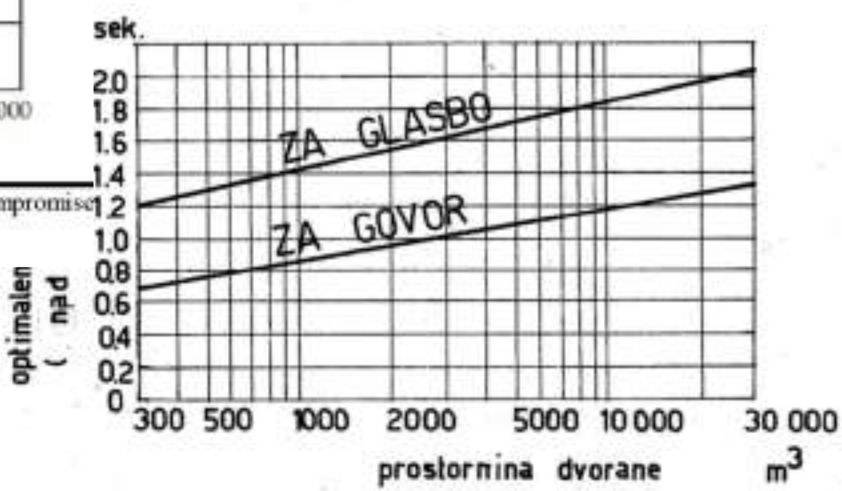


FIGURE 22-3 Suggested reverberation times for recording studios. The shaded area is a compromise region for studios in which both music and speech are recorded.



Ideal values of the reverberation time of interior space for recording are considerably smaller (shorter reverberation time)

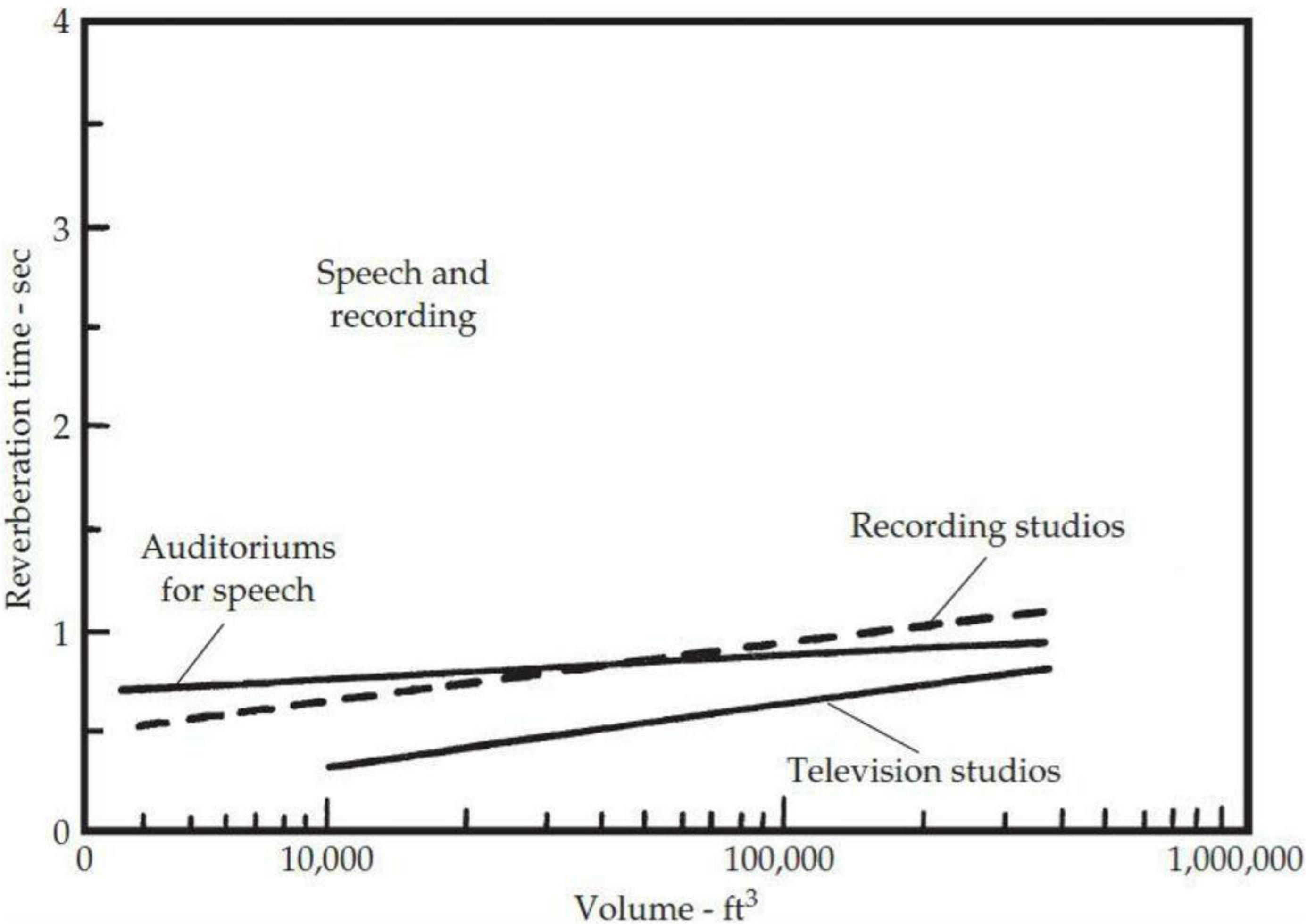
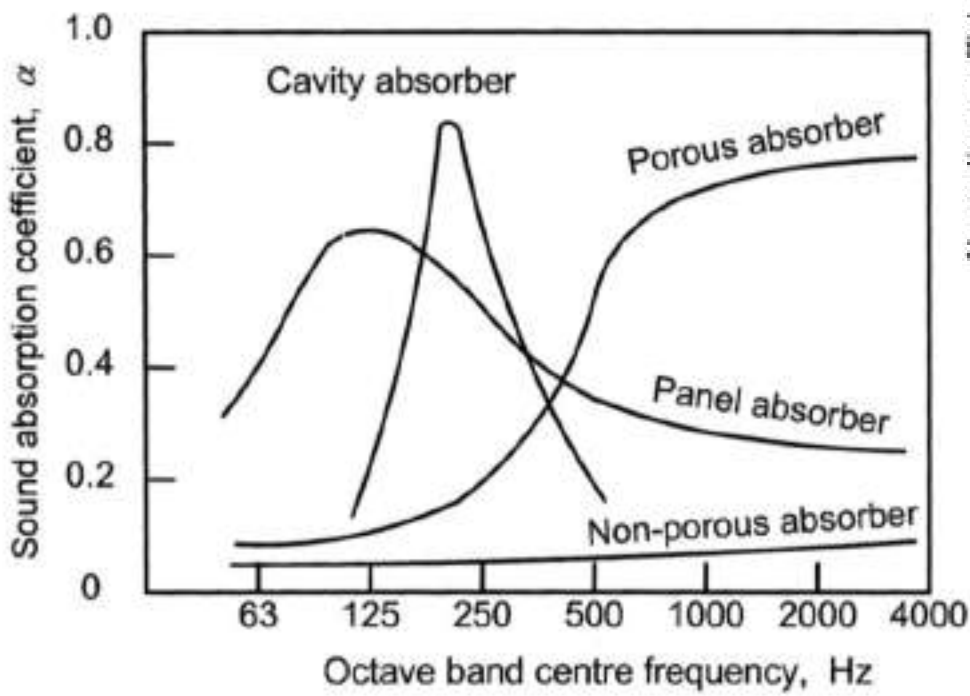
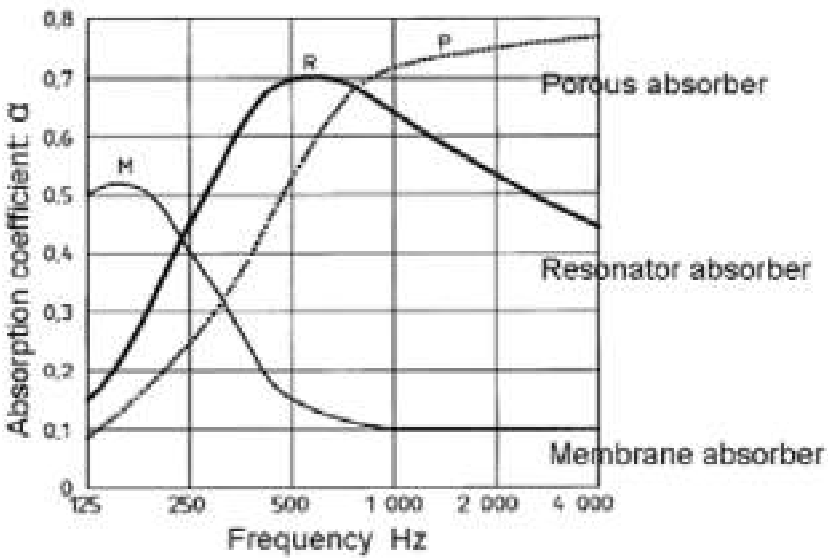


FIGURE 11-15 Spaces designed for speech and music recording require short reverberation times.

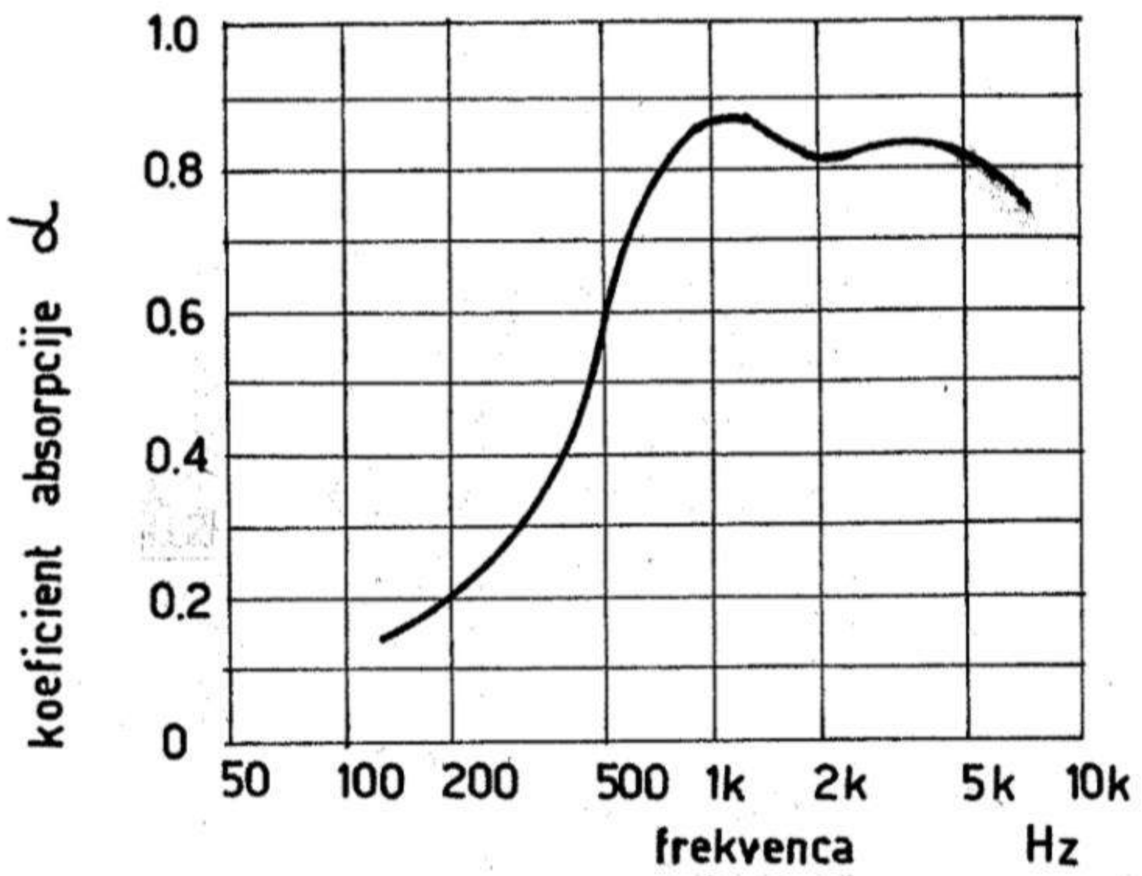
Types of absorbers: porous, membrane, Helmholtz, comprehensive (integrated)

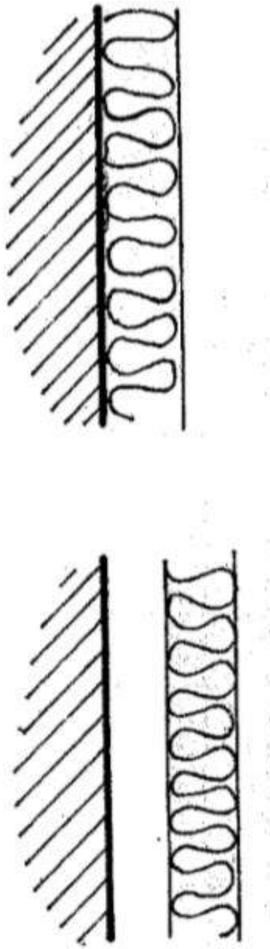


Characteristic frequency absorption curves.

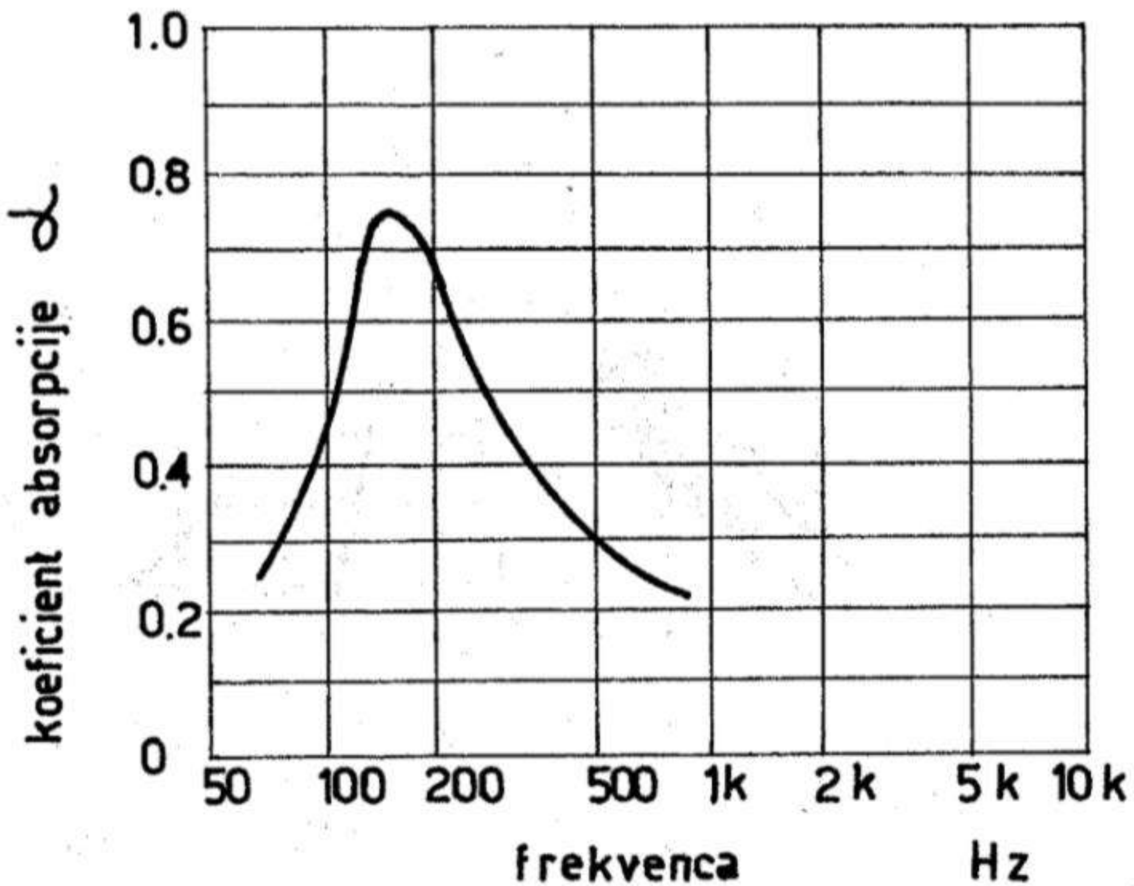


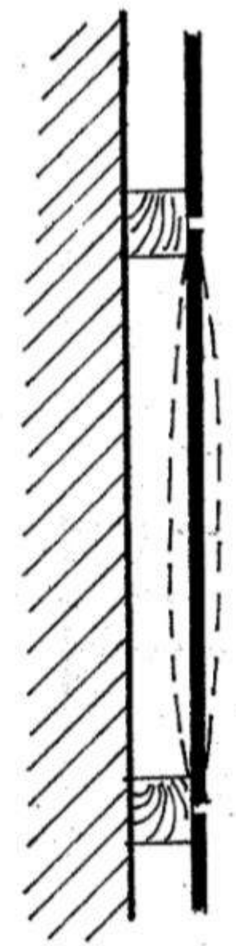
Porous absorber



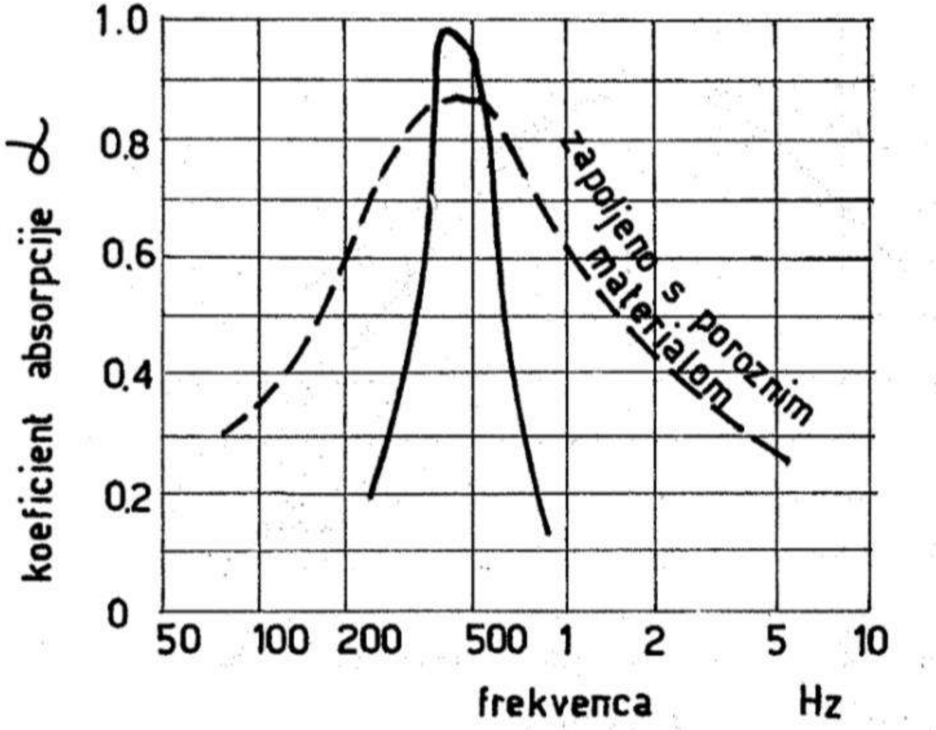


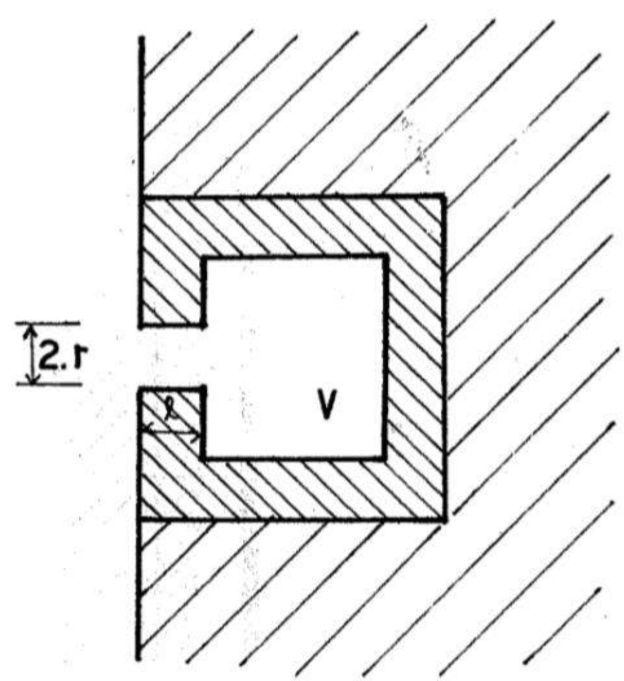
Membrane absorber



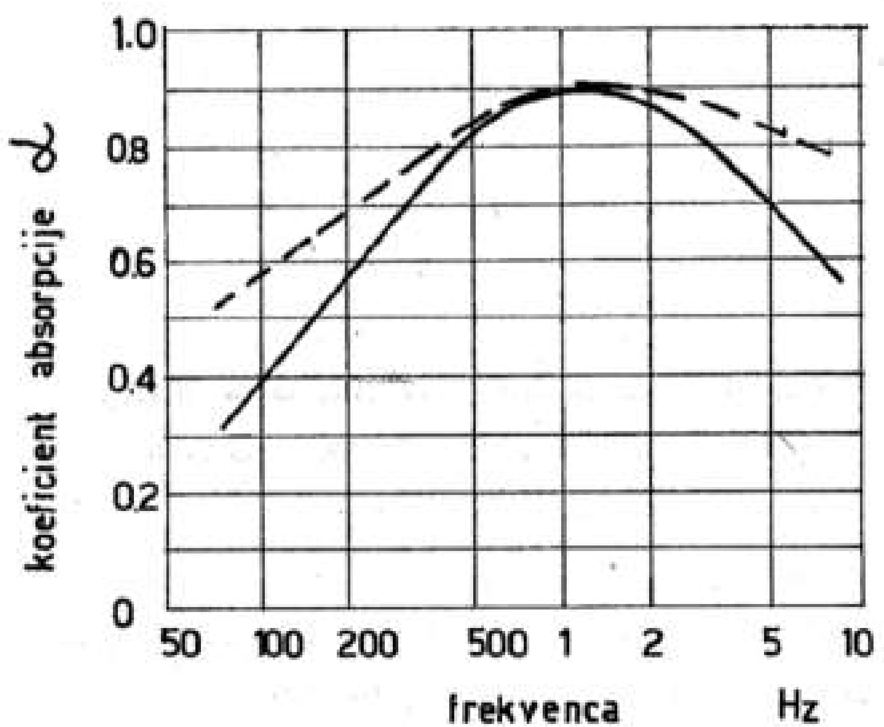


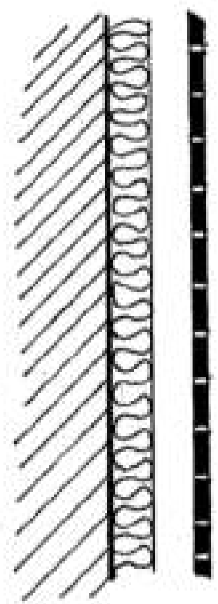
Helmholtz absorber / resonator

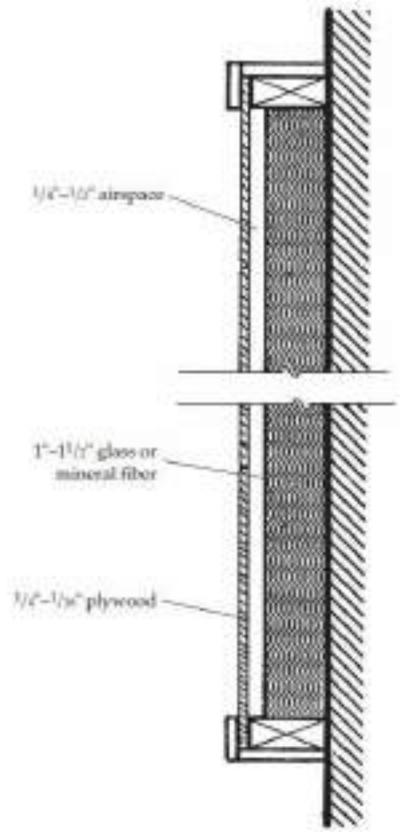




Comprehensive (integrated) absorbers:
acoustical plates, acoustical panels







Typical resonant panel absorber with wall mounting.

Reverberation time before and after acoustic treatment in the interior space in relation to frequency

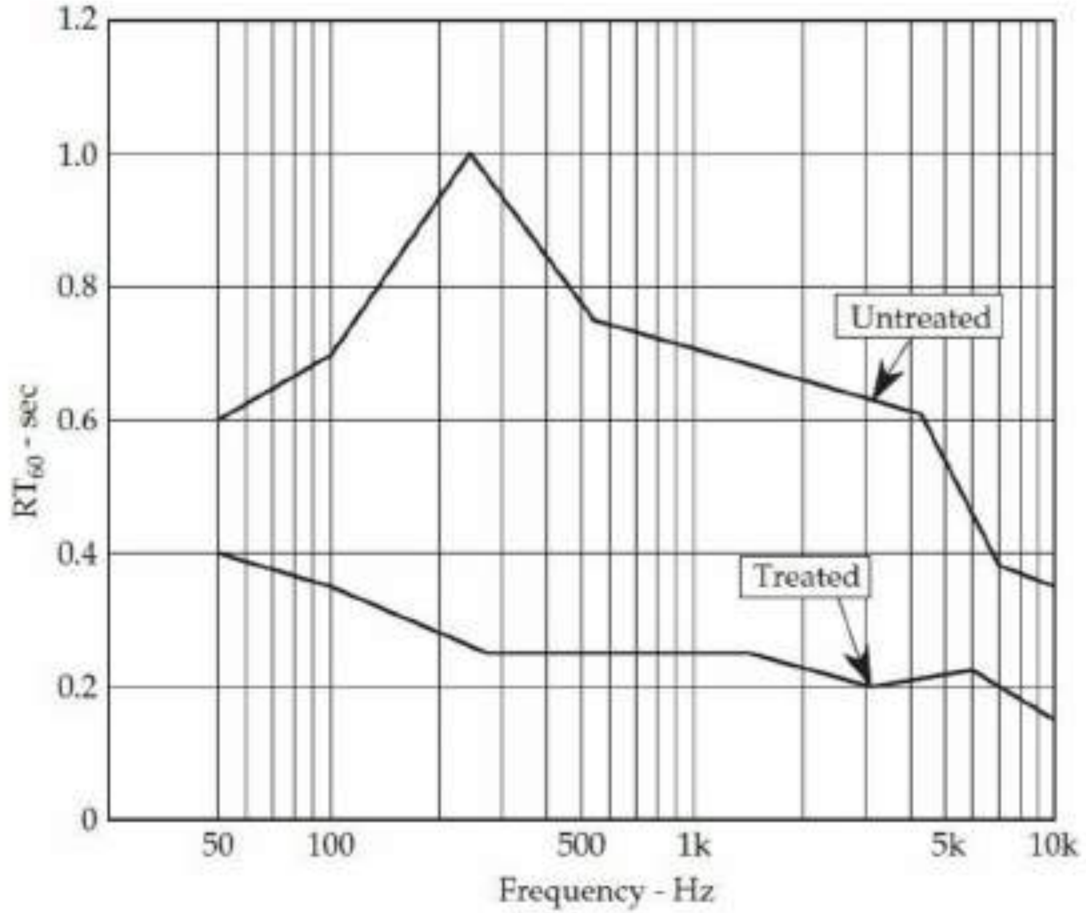


FIGURE 11-10 An example of a room's reverberation characteristic before and after room treatment. A significant rise in reverberation time in the upper bass and lower midrange is changed to a flatter characteristic with a moderate increase in reverberation time at low frequencies.

ARTIE - računalniški program za analizo akustike notranjega prostora

Naš računalniški program za analizo akustike notranjega prostora
ARTIE (**A**nalysis of **R**everberation **T**ime in **I**ndoor **E**nvironments)

pokriva računalniško simulacijo odmevnega hrupa notranjega prostora (ne pa gradbene akustike – torej prehoda zvoka zaradi zvoka v zraku ali udarnega zvoka, komunalnega hrupa…)

Acoustical Analysis and Adaptation of a Playroom

Prototypical Acoustic Elements

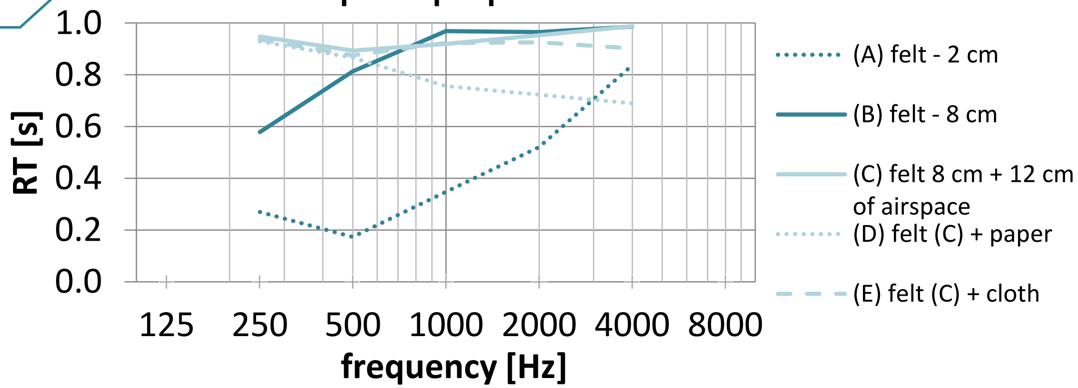
Hanging Wall Element
- Felt: 2 + 2 cm
- airspace between layers and behind the element

Ceiling Elements
- Rock wool: 5 cm
- airspace behind the element
- covered with paper

Temporary Elements
- Felt: 2 cm
- airspace behind the element or freely hung
- partly coloured

Floor Element
- Felt: 2 + 2 +2 +2 cm
- covered with textile

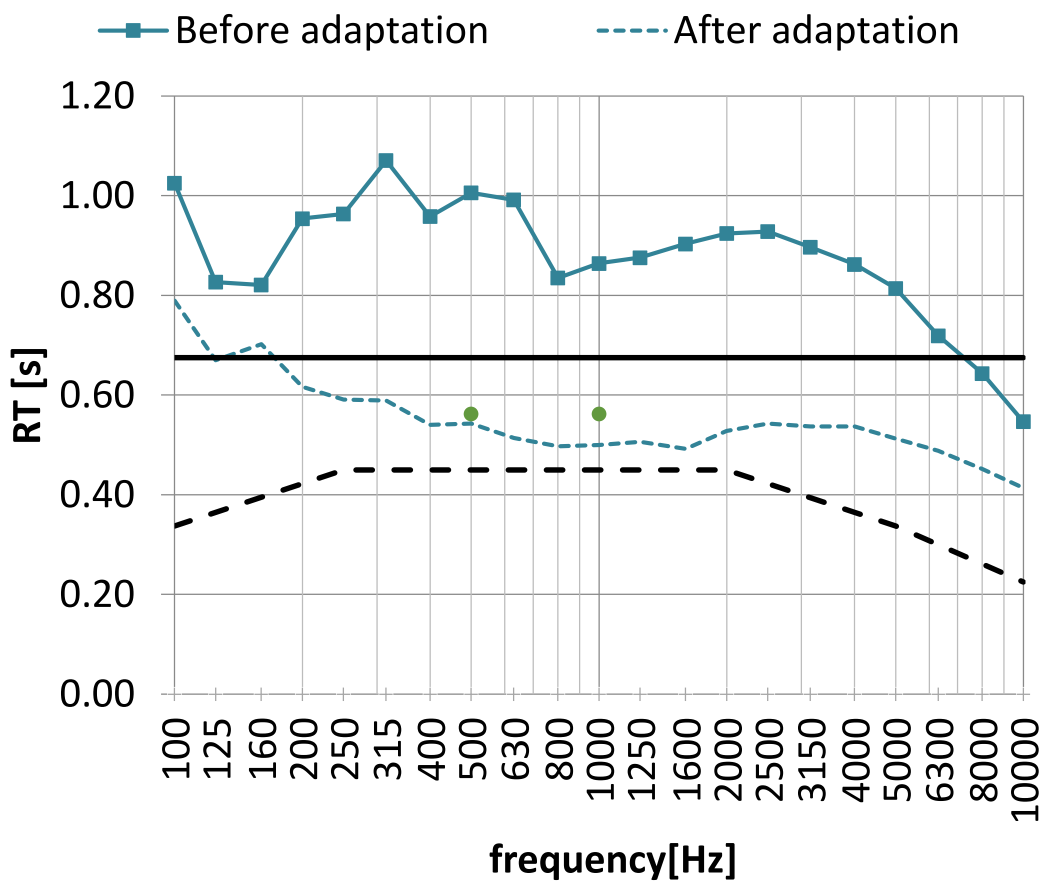
Sound absorption properties of different felts



Acoustical Analysis and Adaptation of a Playroom

Reverberation Time Measurements

- Results:
  - Aprox. 20 m² of acoustic elements
  - Overall drop of 0,31 s (> 35 %)
  - 500 Hz – 4000 Hz: drop of 0,38 s (> 42 %)
  - L_{eq} dops for 2,5 dB
  - Satisfaction of users
  - Low cost
  - Child friendly



Advanced insulation materials and systems in buildings, and energy savings

Many thanks !

Any questions?

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