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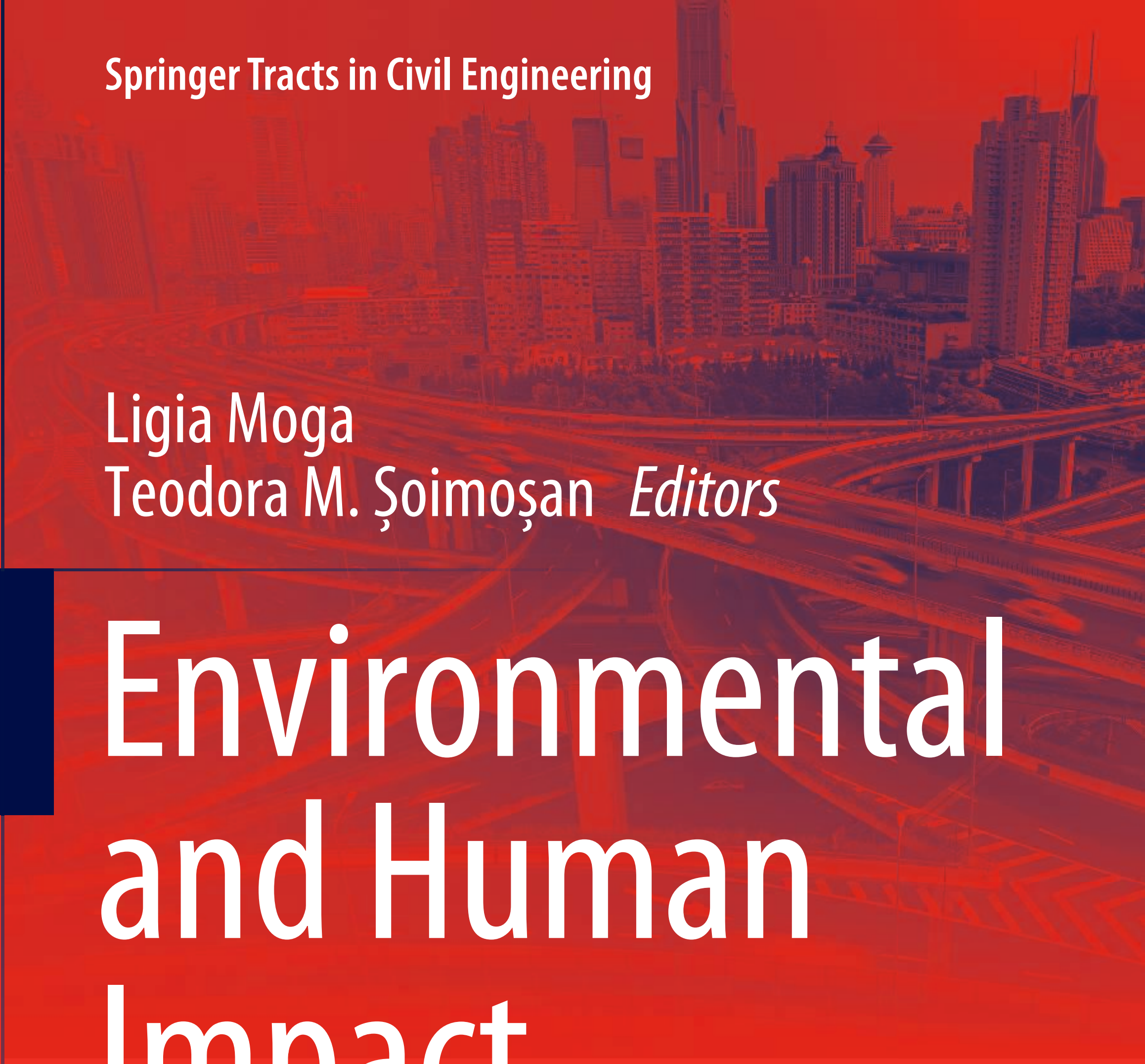

Ligia Moga
Teodora M. Șoimoșan *Editors*

Environmental and Human Impact of Buildings

An Energetics Perspective

Springer

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Contents

Chapter 1
Current Practices in Energy Retrofit of Buildings

Ligia Mihaela Moga, Adrian Bucur, and Ionuţ Iancu

Abstract The chapter presents a state-of-the-art both for main thermal insulation materials used on the market and prefabricated insulation panels, which constitutes a deep retrofit solution for buildings. There are presented certain advantages compared to traditional rehabilitation measures and its setbacks, which can be solved in most of the situations. The panels design is based on several general principles, after which there are developed different approaches, as the practical experiences presented in the chapter show. The presented solutions constitute a review of several research projects. An analysis regarding the application opportunity of these solutions at existing Romanian building stock is also presented, considering a fast mass retrofitting strategy.

Keywords Thermal insulation materials · Thermal conductivity · Thermal rehabilitation · Prefabricated insulation system · Modularity · Integrated retrofitting · Building stock

1.1 The Situation of Existing Buildings Fund Across Europe

1.1.1 Introduction

European and global regulations are increasingly focusing on reducing energy and resource consumption. Thus, there is an increasing need for energy efficiency in all areas (i.e. construction, cars, industry, etc.). The human beings through their activities affect the global climate, leading to effects such as global warming, increasing concentrations of harmful gases in the atmosphere and other negative impacts on the environment. For these reasons, an action at global level to replace harmful, polluting materials, both through the manufacturing process and through the operation mode,

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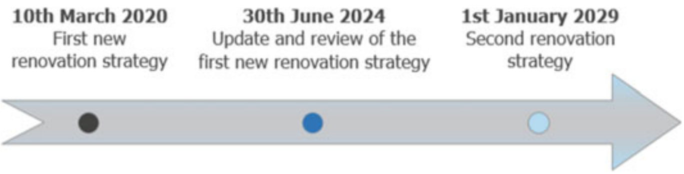


Fig. 1.1 Requirements timeline for new renovation strategies adapted from [20]

with environmentally friendly, renewable materials, with a low impact on the environment and implicitly on human health, as well as through implementing modern technologies that use a smaller amount of energy in operation, has to be pursued.

Construction industry is a sector that, by its nature, has a major impact on the environment. On a global level, the cumulative impact of construction processes has increased exponentially due to the accelerated development of the built environment. It is reported that the exploitation of buildings (i.e. heating, cooling, maintenance, occupancy) contributes to one third of global greenhouse gas emissions and more than 40% of the use of energy resources globally [41]. The growth of the population and the migration phenomenon to and from urbanized areas, constitutes the premise of the need to develop new housing units with complementary functions, shopping centers, industrial buildings, etc.

At present, the main source of greenhouse gas emissions from buildings is its energy consumption. Thus, the construction sector has the greatest potential to provide long-term effects in reducing gas emissions. Through the implementation of high-performance technologies, as well as through an energy management system, energy consumption can be reduced between 30–80% [41], both in existing buildings and in new buildings. Therefore, a clear direction is now being set for the complete decarbonisation of the EU building stock by 2050 [19, 38]. The revised EU Directive (European Parliament & Council of the European Union, Directive 2018/844/EU amending Directive 2010/31/EU on the energy performance of buildings and Directive 2012/27/EU on energy efficiency, 2018) which contains certain energy efficiency measures to be implemented by each member state, was published in the Journal of the European Union on June 19, 2018. In addition, the Energy and Climate Action Governance Regulation (Regulation (EU) 2018/1999 of the European Parliament and of the Council) has established new requirements in terms of planning and reporting of national renovation strategies as part of the National Energy and Climate Plans [20] (Fig. 1.1).

1.1.2 *Statistical Analysis of Buildings Fund Across Europe*

According to buildingradar.com, the construction output of buildings (i.e. residential and non-residential) is estimated to be 78% of the total construction sector in the EU and the 22% remaining for civil engineering works (i.e. other sectors of construction: dams, roads, railways etc.) [29].

The graph from Fig. 1.2 shows the extent of the building development before de 2008 crisis, the drop after the crisis and the slow recovery to be followed. Building across the EU number in the range of millions, as it can be seen in statistics (see Figs. 1.3, 1.4, 1.5 and 1.6) for both residential and nonresidential. Thus, a conclusion can be drawn, that the building sector indeed has a major role in the total energy consumption and greenhouse gas emissions, and that there is an increased need of more energy programs to be implemented in this sector, that will yield proper results on a long term.

For comparison, according to European database [14], the accounted number of dwellings in 2014 in Belgium was 2.576.330, in Germany 41.185.160, France 33.894.000, Romania 8.840.600 and the rest can be seen in the next graphs containing statistical data for the years 2011–2014 (2015). The average energy consumption for residential buildings, per square meter, in Belgium, was 243.34 kWh/m^2 in 2011, 254.35 kWh/m^2 in 2012, 271.65 kWh/m^2 in 2013 and 223.34 kWh/m^2 in 2014. In Germany, the average energy consumption was recorded as it follows: 191.81 kWh/m^2 in 2011, 197.99 kWh/m^2 in 2012, 201.59 kWh/m^2 in 2013 and 171.52 kWh/m^2 in 2014. In Romania, the average energy consumption was: 307.06 kWh/m^2 in 2011, 312.99 kWh/m^2 in 2012, 296.65 kWh/m^2 in 2013 and 281.56 kWh/m^2 in 2014. From all the mentioned values, one can identify a descending trend in the energy consumptions levels of buildings. Nevertheless, the non-performing building stock is very large (European [19] and significant investments need to be done in order to obtain the nearly Zero Energy Buildings levels imposed by the Energy Performance of Buildings Directive [17].

Fig. 1.2 Total construction: number of newly executed constructions/year, buildings, and civil engineering work between 2005 and 2016 [29]

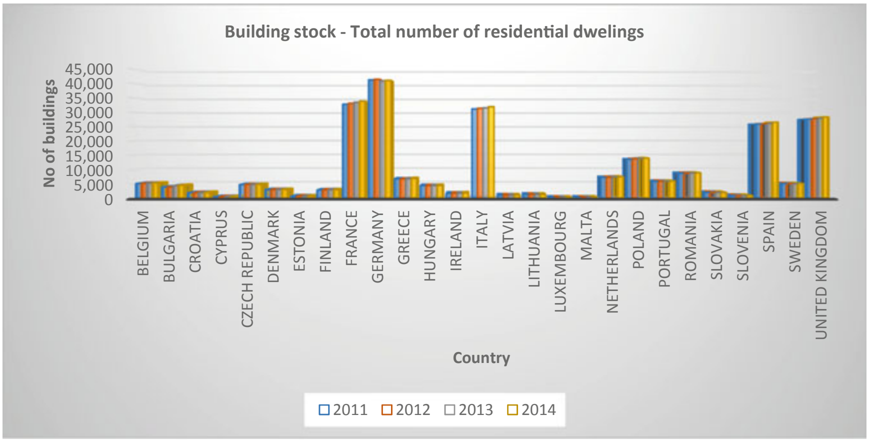


Fig. 1.3 Building stock—total number of residential dwellings [14]

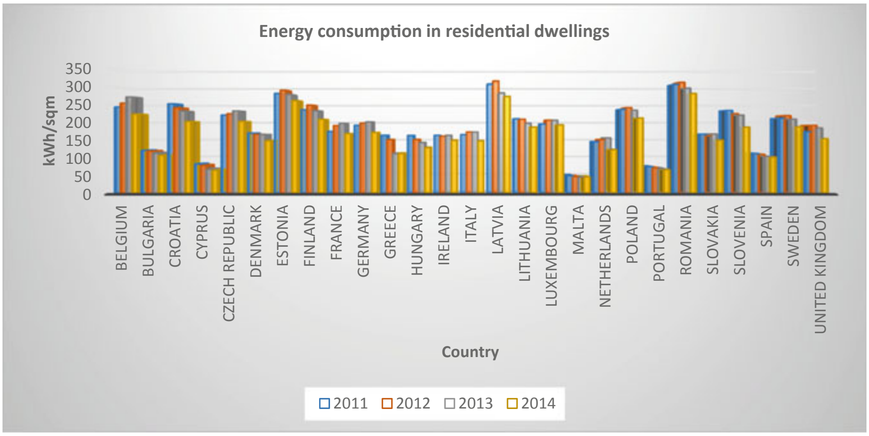


Fig. 1.4 Energy consumption in residential buildings [14]

1.2 Classical Solutions for Thermal Retrofit

1.2.1 Traditional Thermal Insulation Materials

The quickest and most efficient way in improving a building's thermal efficiency is by doing a thermal retrofit using constructive solutions (i.e. thermal insulating systems) available on the market. These solutions can be classical ones or newly developed, based on either local materials or nano-insulating materials. The classical solutions rely on traditional insulation materials such as: mineral wool (i.e. rock wool, fibred

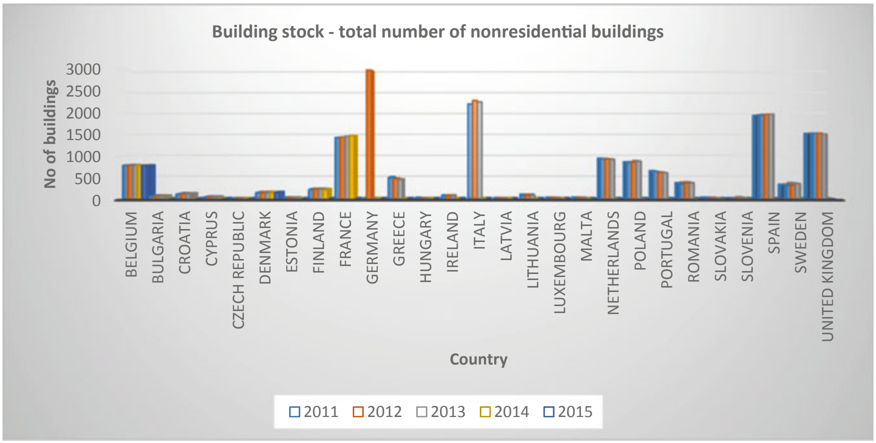


Fig. 1.5 Building stock—total number of nonresidential dwellings [14]

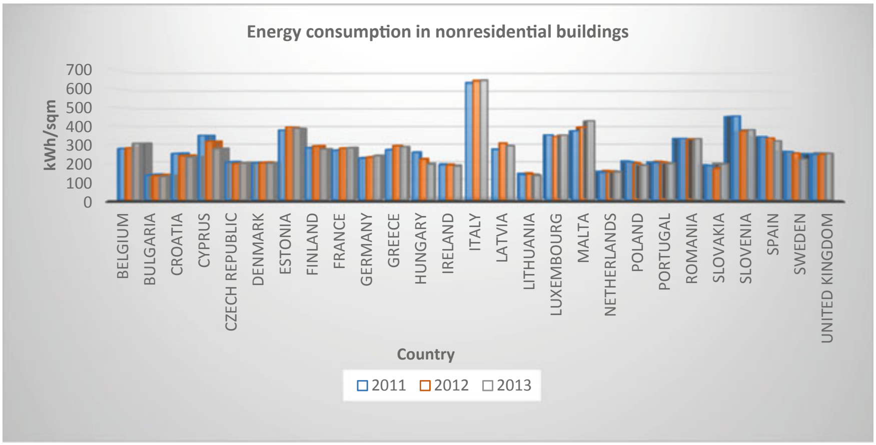


Fig. 1.6 Energy consumption in nonresidential buildings [14]

glass), expanded and/or extruded polystyrene (i.e. EPS, XPS), polyurethane foam (i.e. PUR), cellulose, cork. These are commonly used in current practice, being integrated in available systems for thermal rehabilitation of buildings.

Modern insulation solutions, some of the state of the art solutions are: vacuum insulation panels, gas-filled panels, aerogels and phase change materials as mentioned by Jelle [1]. These types of materials are characterized by superior thermal characteristics compared to traditional ones, but some of them by lower mechanical resistance and significantly higher costs.

Considering that the market is dominated, due to several advantages, by traditional materials, the authors focus on available materials and systems on the construction market, with a focus on the Romanian case.

1. Polystyrene is a waterproof thermoplastic foam which has excellent sound and temperature insulation properties. It comes in two forms, expanded (EPS) and extruded (XPS), which is also known as Styrofoam. The two types differ in performance ratings, mechanical properties and cost. Polystyrene insulation has a smooth surface which makes it easier to apply any kind of coating on top of it. Polystyrene is flammable as well, and acts as a vapor barrier which can cause an increase in humidity inside the living space [2]. Both EPS and XPS can be found as boards or continuous lengths.
2. Fiberglass, along with EPS, is one of the common insulation materials used in our times. Its composition is obtained by weaving fine strands of glass into an insulation material which confers the ability to minimize heat transfer. Another positive aspect is that the fiberglass is non-flammable. But, the downside of fiberglass is due to the workmanship. Fiberglass is made out of silicon; thus glass powder and tiny shards of glass appear. In order not to cause injuries to the ones handling it, proper safety equipment must be used [2].
3. Mineral wool can be found in different types of insulation materials, i.e. glass wool, rock wool and slag wool. The glass wool is manufactured from recycled glass (i.e. the fiberglass), while the rock wool is made from basalt. The slag wool is made from slag from steel mills. [2] It has a low thermal conductivity, similar to polystyrene. It can be used as a filler material, or in the shape of mats and boards (Fig. 1.7).
4. Cellulose is considered to be an ecological and also eco-friendly thermal insulation due to the fact that is obtained from wood fiber mass or recycled paper. Beside its good thermal behavior, it can be considered as a better fire-retardant compared to fiberglass insulation. One negative aspect is that cellulose dust may give allergies to people, thus skilled and experienced workers are needed [2]. Cellulose can be used as a filling material or may come in boards and mats.
5. Polyurethane foams (PUR) are used but not as much as the previously mentioned materials due to their negative aspects regarding health concern. Although that its producers are trying to reduce the negative impact of PUR, there are still ongoing discussions on the toxicity of PUR combustion products. The thermal conductivity is significantly lower compared to other mentioned thermal insulations, several producers giving values around an average 0.030 W/(m·K). The PUR thermal insulation is produced with a continuous length or as boards, but it can also be used as a filling material on the site.
6. Cork is obtained from the cork oak without damaging the tree. On the construction market is found as insulation boards, mats or it can be used as filler (Table 1.1).

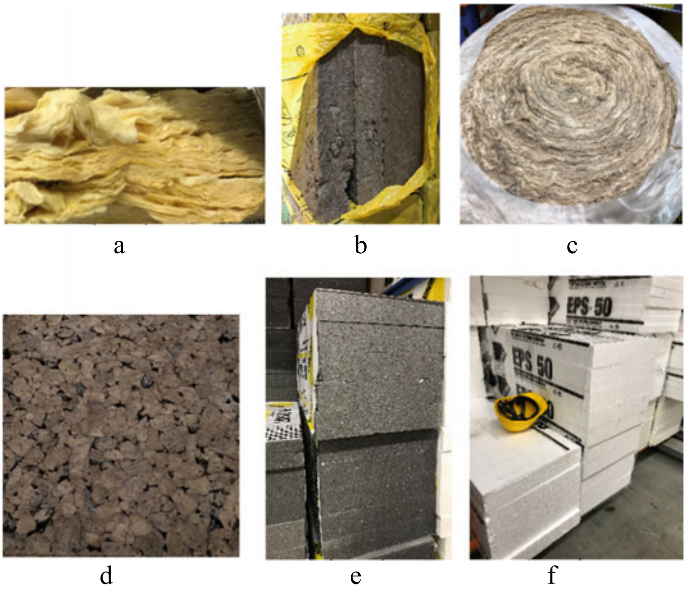


Fig. 1.7 **a** Glass wool, **b** Mineral wool mats, **c** Mineral Wool roll, **d** Cork, **e** Gray polystyrene, **f** White polystyrene

Table 1.1 Thermal characteristics of insulation materials [8]

Insulation Material	Apparent Density ρ [kg/m^3]	Thermal conductivity λ [W/(m·K)]	Thermal assimilation coefficient s [W/(m^2·K)]	Vapor permeability resistance 1/k$_D$
Polystyrene (EPS)	20	0.044	0.3	30
Fiberglass	80	0.036	0.42	1.1
Mineral wool	60	0.042	0.37	1.1
Cellulose	220	0.084	2.08	2.7
Polyurethane foam	30	0.042	0.36	30
Cork*	~ 220	~ 0.045	-	~ 15

*average values from literature

1.2.2 Thermal Insulation Systems Available on the Market

Leading companies on the construction market offer a whole variety of solutions (i.e. thermal insulating systems-and others) for the thermal rehabilitation of buildings (i.e.

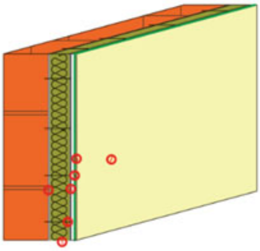
energy retrofit process). Some of the top producers found on the market are Rockwool, Baumit, Knauf, Isover, Termocel, Sto, Ursa, Caparol, Fibran, Austrotherm, Woodwool, and others. On the Romanian market, the most used systems are the following: Rockwool-uses mineral wool as insulation material, Baumit-offers insulation systems based on EPS and mineral wool, Knauf-uses products made out of gypsum and perlite-for its thermal insulation and Isover- products made of mineral wool. Part of the existing solutions on the Romanian market, are further presented:

Rockwool Group [36]: Rockwool Group was founded in Denmark in the year 1937 when they first produced mineral wool out of rock. Since then, it developed into a multinational company with centers and activities all over the world. As mentioned before, the company's products are from mineral wool, which was classified in 2001 by the International Cancer Research Agency as belonging to Group 3: *cannot be classified as cancer causing agent for humans.*

Rockwool applications:

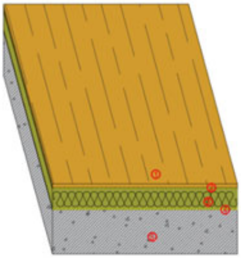
- Facades (external walls)—rockwool offers facade systems in which aesthetic aspects are accompanied by fire protection, acoustic performance and thermal comfort. The rockwool basaltic wool is water resistant and vapor-permeable, which helps the building to control possible damage caused by moisture.
- Roof insulation—used for improving thermal, acoustic and fire protection performance. Rockwool offers several solutions, several product variants, both for new and renovated roofs and for attic conversions and different types of construction
- Interior walls—solutions, which provide thermal, sound and fire protection. They have a very good acoustic performance, reducing the noise level in the interior environment and prevent the outside noise from entering, due to the spaces between the fibers and the open porous structure of the material (Fig. 1.8).

- Floors—the company offers solutions for all types of constructions, including floors, base floors and dividing floors. The basic floor insulation offers thermal performance inside the building, air noise reduction and maintenance of a comfortable living environment. The insulation of the floors and the separation floors provides protection against noise and is frequently used for acoustic benefits. Being made of basaltic wool, rockwool insulation is also non-combustible, which means it will prevent the spread of fire (Fig. 1.9).



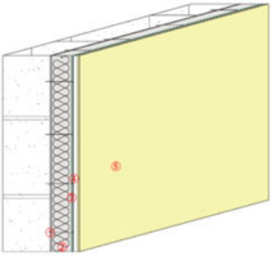
1. Basaltic mineral wool
2. Mechanical fastening with dowels
3. Adhesive
4. Adhesive (adhesive and filler board)
5. Reinforcement mesh
6. Primer for decorative plastering
7. Silicone decorative plaster

Fig. 1.8 Example of facade insulation



1. Parquet
2. Backing made of wood-based panels
3. Mineral wool boards
4. 100 mm fibreboard belt
5. Ceiling

Fig. 1.9 Example of floor insulation



Anchors with adhesive

1. Insulation panels made of white or gray EPS, with reflective layer /mineral wool insulation panels with longitudinal or vertical fibers
2. Premium glass fiber mesh
3. Adhesive and primer
4. Decorative plaster

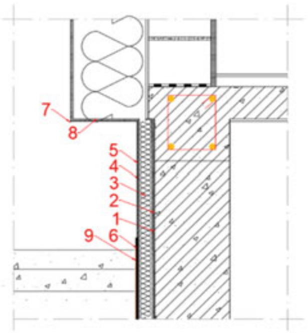
Fig. 1.10 Baumit Star System for exterior walls (EPS) (adapted from [7])

Baumit [7]*:* The company was founded in 1988 in Austria and manufactures finishes and thermal insulation systems. Baumit has three complete sets of solutions for thermal performance, as it follows:

- Baumit Star. On new masonry or original base, the system consists of the following layers (from the wall outward) (Fig. 1.10):

- Baumit Pro: On new masonry or original base, the system consists of the following layers (from the wall outward): base (new masonry or original base), adhesive, mineral wool insulation panels with longitudinal or vertical fibers, anchors, adhesive and shoulder, fiberglass net, primer, decorative plaster.
- Baumit Open: On new masonry or original base, the system consists of the following layers (from the wall outward): base, anchors, adhesive and filler, insulation panels, premium glass fiber mesh, primer, decorative plaster.
- Thermal insulation of the base (Fig. 1.11)
- Protection foil

Knauf [28]: Knauf Westdeutsche Gipswerke was founded in 1932 in Germany, being one of the main producers of construction materials in Europe. Some of their products are:



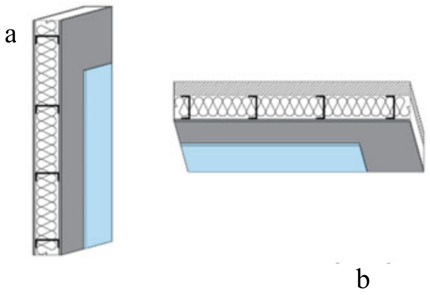
1.Substrate: In many cases, the substrate consists of bitumen insulation
2.Bonding layer
3.Insulating material
4.Consolidation layer: plaster with adhesive
5.Facade plaster
6.Additional protection against water
7.Baumit molding fastened to the pin profile
8.Insulation tape or flexible cement with possibility of removal

9.Protection foil

Fig. 1.11 Baumit base insulation (adapted from [7])

- Interior walls made of gypsum boards that offer great protection against fire, sound insulation, great mechanic resistance and in some cases thermal insulation (Fig. 1.12);

- Ceiling systems—the range of products for ceiling systems is very wide, starting from smooth gypsum board, various perforated boards and slots, or prefabricated elements such as curved elements, convex or concave curved profiles etc. Self-supporting ceilings plated underneath and above with cardboard gypsum boards, metal support frame and mineral wool.
- Indoor thermal insulation system consists of TecTem plate system based on pearlite, a flame-retardant material, with a very good thermal insulation capacity and a capillarity that allows the rapid migration of water vapor to the inside or outside of the building, depending on the need (active capillarity).
- Exterior thermal insulation made of rock mineral wool, used for both thermal and acoustic performance in ETICS (External Thermal Insulation Composite Systems).



Layers from front to back:
Knauf fireboard (optional),
Knauf gypsum board,
thermal insulation, closing
Knauf gypsum board;
metallic structure for
fixing the panels

Fig. 1.12 Knauf **a** interior walls and **b** ceiling systems (adapted from [28])

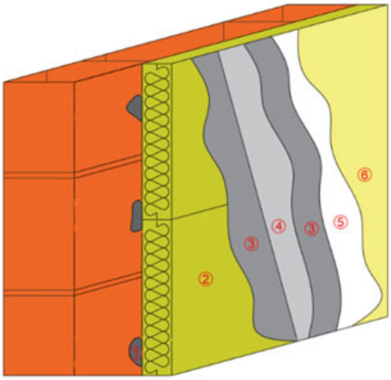
Isover (Isover [27]: Founded in 1937, Saint -Gobain Isover is the world leader on the insulation materials market, offering a wide range of products in the following categories: mineral glass wool, basaltic mineral wool and vapor barrier membranes. Isover offers complete solutions for both new and renovated buildings and creates efficient thermal and acoustic insulation solutions. It has a great variety of solutions and applications for attics and roofs, lofts, compartment walls, ceilings and soffits, floors, roof terrace, exterior walls, ventilated facades, wooden houses, metal halls, industrial equipment protection, pipe work insulation and naval industry.

External thermal insulation composite systems for walls consist of the following layers (from the wall outward) (Fig. 1.13):

Roof terrace with gravel layer (Fig. 1.14):

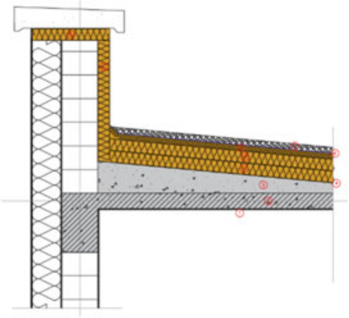
Another solution is for the attic roof- reinforced concrete floor or the case of a roof: Isover Rio—compressed and rolled mattresses, made of mineral wool, obtained by melting in the furnace the mineral raw materials, the fibrillation of the melt, spray application of a binder and the addition of mineral oils; Vapor barrier membrane—modified polyamide film with variable permeability; Various binders and tapes for better sealing.

Termocel [40] Termocel Ecotec is a company that offers professional cellulose insulation services. The process consists of injecting/spraying cellulose fibers made from wood/recycled paper with a professional pump, thus covering the entire space between panels and effectively sealing all the joints. The solution is simple to use and very efficient in terms of thermal and sound proofing qualities.



1. Adhesive mortar for bonding the thermal insulation plates of basaltic mineral wool;
2. Isover Profi Fassade - panels made of basalt mineral wool. These plates are obtained by melting in an electric furnace the mineral raw materials, at a temperature of 1520 ° C, the fibrillation of the melt, spray application of a binder and the addition of mineral oils for protection against dust penetration and for hydrophobization. The resulting mineral fibers are processed on the production line in the form of panels;
3. Adhesive mortar for splitting the insulation plates made of basalt mineral wool;
4. Reinforcement layer with fiberglass mesh;
5. Primer;
6. Silicate decorative plaster.

Fig. 1.13 External thermal insulation composite system



S – Section:
1. Interior plaster
2. Reinforced concrete floor
3. Perlito-concrete for the slope
4. Vapor barrier membrane
5. Basaltic mineral wool
6. Waterproofing membrane
7. Gravel layer.

Fig. 1.14 Attic roof

1.3 Modern Solutions: Prefabricated Insulation Panels

1.3.1 Introduction

The growing rate of the European residential buildings is of only 1% per year. Therefore, in order improve all the existing building stock from the point of view of energy consumption, emissions and thermal comfort, a large attention should be given to the existing buildings which are 50–100 years old, or even older. These types of buildings exist in a large number, and in order to obtain a significant mass thermal rehabilitation rate (i.e. energy retrofit) in a short period of time, a different approach to the traditional renovation activity, has to be applied [9]. Other similar issues that must be adjusted through a deep thermal retrofit process, are found at most existing buildings: high energy consumption, insufficient ventilation, overheating and inadequate thermal comfort.

For the value retention of the building, minimal works are required after 10–15 years of use. A partial renovation may be required after 20–25 years of use, in which all the interiors and parts of the building envelope are refurbished. A deep renovation is usually required after 45–50 years of use, in which apart from the interior refurbishment, a new building envelope and building technologies are required. The building replacement with a new one can be avoided in most of the cases because the deep renovation is more feasible [23].

There can be defined four distinct façade renovation systems [23]:

- External composite insulation system (ETICS)—traditional measure, in which insulation panels are mounted manually on site and are covered with plaster.
- Rear ventilated façade system—a manually procedure done on site consisting of insulation brought up between laths and fixed with a mounting system, being covered with different claddings.
- Partly prefabricated façade system—a prefabricated substructure with blown in insulation with an exterior cladding which is also prefabricated or is installed on site.

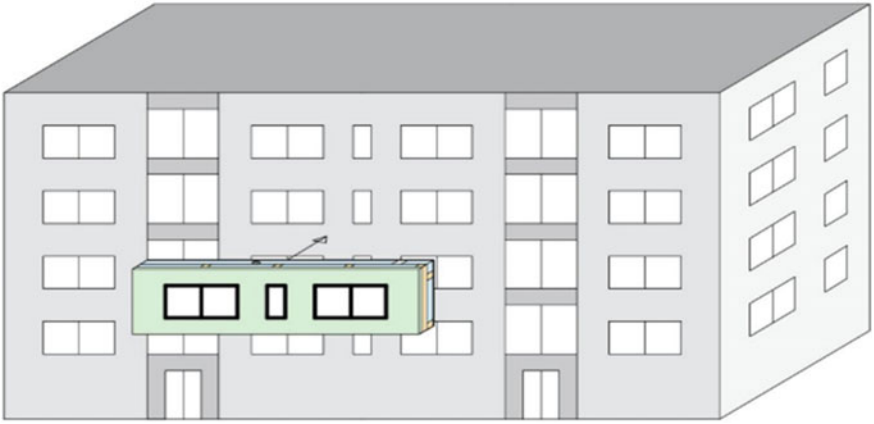


Fig. 1.15 Prefabricated insulation panel concept

- Prefabricated module system—fully prefabricated panels, assembled in a factory, transported and mounted on site.

The prefabrication can be described as the off-site industrial production of the building elements, in order to reduce the on-site works to the minimum possible level. Compared to the traditional "on site" works, the industrialized prefabrication can increase the productivity up to 50–60%. [3]. The prefabricated insulation panels are a viable option to deep retrofitting (which includes partial demolition, services replacement, and new aesthetics) and also to total demolition of the building and construction of a new one. If the building renovation objectives require only a light measure such as the application of a thermal insulation and the replacement of the windows, an alternative such as the modular insulation may prove too expensive and unnecessary [21].

As any other insulation system, one of the main challenges for the prefabricated panels is to obtain a retrofitted building which has an energy performance as close as that of a new building, even if the original one was not constructed based on energy efficiency principles [9]. The solutions must be cost effective and must have a low environmental impact on all their life cycle: from the production stage to the end of life. Also, they must be as durable as possible (e.g. 50 years) and have to be protected against any exterior hazards: air humidity, rain, frost, biological hazards (insects, plants, and mushrooms), fire, wind, intensive sun exposure etc. [32] (Fig. 1.15).

1.3.2 Advantages

Traditional renovation is not future oriented, it requires technical compromises and too many workers which are poor coordinated on site, resulting in a low-quality execution in a relatively long time. The use of prefabricated insulation for renovation integrates the building as a whole, which eliminates the technical compromise, requiring fewer parts involved which are better coordinated ensuring a high-quality execution in a faster time [25]. The common rehabilitation solutions require a relatively large execution time and may create discomfort due to overheating, poor ventilation or even space reduction, requiring the use of ventilation and heat recovery systems. One of the most time-consuming processes is the installation of the heat recovery ventilation system, which disturbs the building users and also presents difficulties in coordination [21]. Compared to common insulation solutions, prefabricated panels reduce the disturbance and impact over the building users and the neighborhood by the large time reduction of the in-site works. Therefore, the users can remain in the building during these works. When the building space is rented, the users' temporal relocation is not a comfortable solution for them and is not an economical solution for the owner as well.

An advantage of the modularity is the possibility to extend its functions and systems. Therefore, given the structure of the prefabricated panels, in some situations they may also be used to extend locally the existing buildings: e.g. balconies, corridors, etc. The water pipes, heating equipment and devices, sewage systems and electric conduits in the old buildings need to be replaced. Additionally, most of them don't have a mechanical ventilation system, which is compulsory for the current requirements regarding the airtight envelopes. In traditional renovation practices, these must be installed inside the existing buildings, a difficult solution in most of the cases. Therefore, from the costs point of view, by integrating these installations in the retrofit panels, the total value of the retrofit solution is increased because of its multifunctionality [21]. Using the modules with the additional services, the building owner can obtain 80% energy savings, 90% CO_2 reduction and added values such as rooms extension or attic apartments[25].

At the same time, if a collective dwelling (i.e. block of flats) has open balconies, they can be closed with panels, increasing in this way the useful area of the apartments [37]. When the building façade doesn't have a structural role, bearing only their own weight and the wind load, the retrofitting process may allow the full replacement of the respective façade with a prefabricated insulated panel. By using the prefabricated panels as a retrofit solution, the property value of the residential buildings can be increased not only from the internal comfort point of view but also from the aesthetic one. This idea is more valid for the Eastern European countries and former Soviet countries which have a large number of blocks of flats from the Communist era. These buildings were designed more from the functional point of view and less from the thermal performance approach, although prefabricated panels used thermal insulating materials. The use of prefabricated panels reduces the time required to work at height and the corresponding danger. The execution time shortening is given not only by the panel structure itself, but also by the additional elements: preinstalled windows, mold drips, flashings, etc. [37]. The quality control and finishing are in general superior to the common insulation solutions. Compared to other solutions, the renovation works are nearly independent on weather, which is a significant advantage [23].

Prefabricated panels can be used for new buildings too, as an integrated solution which may prove faster and more cost effective compared to the common practice [21]. There is a slightly increasing interest for the prefabricated solutions for new buildings which will reduce their costs in time [3].

1.3.3 Setbacks

There are several setbacks for this solution which are presented in the following paragraphs.

First of all, the total weight of the panels may represent a problem for the existing walls and foundations, requiring its own new foundation. Frequently, the surface of the construction element has irregularities which creates a discontinuous contact with the panel [9]. This is solved usually using a foam insulation, which has to be carefully chosen in order to avoid moisture accumulation and which also won't guarantee the perfect contact. In case of mass production, it creates a generic appearance for different buildings, regardless of their location, which may not be in accordance with the local architecture and the building type [9].

Design requirements in case of heritage building limits at the moment the use of prefabricated panels not only from the technical point of view but also from the costs point of view. With the technology development, it is possible that in the future, the modules design will preserve the façades of these buildings, while a 3D simulation on the exterior may simulate then the original façades. These panels must be easily mounted and dismounted and mustn't have an impact on the building.

A possible problem would represent the fact that the use of prefabricated panels with planned dimensions is not a common practice for some countries, which produce transportation and installation difficulties. Therefore, it would be necessary a training for all the people involved in a prefabricated insulation panels project. The use of large prefabricated panels can be advantageous if the façade length is no longer than 12 m (i.e. the maximum transport length of a trailer truck). For larger lengths it requires specific approvals from the authorities for special transport (only during the night and with an escort), which is not feasible from logistical point of view [24].

Even the execution time and labor are reduced, these systems are still more expensive than common insulation solutions. A larger market is required to develop a mass production for this insulation solution [32]. The building industry is very conservative and new renovation concepts such this one will require some time to be applied at larger scales. Also, the planning and implementation can present a risk from the planners and investors points of view, because even a three-dimensional survey of the building is made, unexpected situations appear in the process, their resolution being time consuming and increasing the final costs [21]. Lastly, in the social housing sector, where low rents are involved, this kind of solution may not be economically feasible [24].

1.3.4 Design Specifications and Requirements

The prefabricated retrofit systems are standardized in construction layers and joints, flexible in architecture, form and cladding and can be combined with each other or with conventional renovation systems [24]. In the development of this solution, besides the thermal design, one must consider other aspects such as: structural engineering, architecture, building physics, material science, Life Cycle Analysis and Life Cycle Cost. Therefore, the specialists involved in the panels design are the thermal specialist, the building physicist, the architect, the HVAC engineer, the structural engineer and the contractor.

1.3.4.1 Design Strategy

It is important to establish from the start how long the building proposed for renovation can continue to operate in its current state. At the same time, all the available data should be gathered in order to decide the opportunity of partial renovation, deep renovation or building replacement. If the data is not available, a survey is compulsory. Furthermore, the number of heated stories of the building influence the retrofit strategies. Then, the decision is based on local regulations and owner criteria as well [23] (Fig. 1.16).

Two modular insulation retrofitting strategies are competitive to the common renovation ones, in terms of costs: those applied on simple and repetitive façades and roofs and those applied with extensive changes such as window sizes, room extensions, new apartments on the roof top [25]. Then, the main retrofitting approach for the prefabricated panels is the identification of the similar buildings (façades, structures, etc.) and make their rehabilitation a priority. Therefore, for buildings having standardized layouts (e.g. blocks of flats) there can be applied a mass production modularity. In this case, the façades and roofs are divided in several main panels which are then installed on all the buildings of the same type. In this way, the renovation process at a large scale is less time consuming.

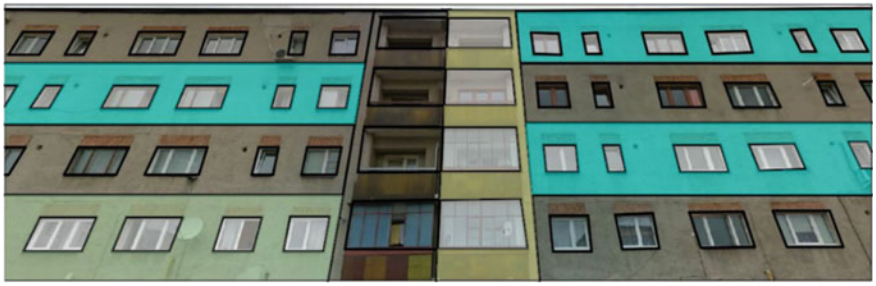


Fig. 1.16 The segmentation of the façade into similar panels

Regarding the location, it is important to check if an exterior insulation system can be brought up (local regulations) and the site free areas allow the delivering and the mounting of large prefabricated panels which usually involves the use of cranes [23]. For every project the focus should not be only on the energy optimization of the building, but also on the increased value for the client: investor, owner and user of the building [25].

1.3.4.2 Building Inspection

Specific targets have to be defined in initial phases in order to ensure a better quality for construction works and after completion. A first step in the renovation is given by the tachometric and constructive survey on the building. A three-dimensional laser scanning of its envelope is always useful in order to obtain a real image about the exterior walls and roof surface (i.e. roughness, unevenness) and the openings position. The layers of the building elements are determined through a partially destructive survey. Based on this data, a three-dimensional model of the building is generated with its constructive elements, precise geometry and position. In this way, the panels can be designed and dimensioned to overlap on the existing envelope, resulting in a smooth exterior surface and the perfect integration of the window openings. Additionally, the usual problems raised in the mounting stage, related to connections limitation, the partial cover of the openings and others, can be avoided [33, 37].

At the same time, before renovation it is important to determine the weak points within the airtight envelope (e.g. with a “Blower Door” test). It has to be checked if these weak points can be eliminated by renovation and if not, compensation measures have to be taken, glazing area decrease or increase, balconies integration, new barrier-free infrastructure (e.g. elevators, staircases, and corridors) and loft conversion or extension. All these can be obtained by the use of prefabricated panels [23].

1.3.4.3 Structure of the Panels

The fundamentals for the structural concept of the panels and their fixings have to be established depending on the walls and roofs type, structure (from technical documents or local inspection) and unevenness (with a 3D laser scanning) [23]. The modular concept of the prefabricated panels derives in most cases from the framed structural walls. The standard layering of the prefabricated panels is: equalizing layer to the existing façade, load bearing structure with insulation, ducts and wires (if a HVAC system is included), second insulation layer (with shading system), cladding [24]. This varies from a project to another depending on the thermal performance required and on other characteristics of the building. It also evolves in time, as experience is gained from multiple pilot projects.

Depending on the building, the modules can be developed in large or small sizes, usually on timber or metallic framing and most of them are designed for the external walls or for the roofs. For the walls, the panels can be oriented horizontally or vertically, and they usually have the height of one building level. There can be developed multiple modular panels for certain façade elements: building base, façades and gables and for pitched or terrace roofs (with or without skylights). The systems can be completely prefabricated on a façade or can be with local modularity: e.g. special modules for glazing areas [24]. The position of the staircase inside or outside the building may influence the panels' distribution as well. For each situation, there should be studied in which conditions the prefabricated panels are feasible for the buildings with masonry, concrete, steel, aluminum or timber structure.

The use of timber frames is in accordance with sustainability and productivity objectives in the building sector, wood being a carbon neutral and renewable resource with increased prefabrication capabilities. One must keep in mind that the current design codes limit the application of this material within the façade to buildings up to 4 levels. For taller buildings, special timber solutions (e.g. cross laminated timber), aluminum or steel for the panel frame structure must be used [24]. The depth of the timber frame depends on the ducts size, if a ventilation system is used. At the same time, fire safety requirements impose that the timber uprights adjacent to windows must be at least 80 mm wide [24]. Any exterior finishing can be used. In general, most of the panels integrate triple glazed windows.

Fire behavior and resistance of each layer of the panel must be considered. Fire protection measures must be taken to avoid the fire growth within the façade area and along pipes and cables integrated within façade. The panel insulation against outdoor sound, within the building and from the installations must be evaluated [23]. If a ventilation system is used, the insulation layer between the timber frames may be moulded after its ducts sections which will be installed in it. In this way, the pipe mounting is easier, since it doesn't require brackets to put them in place or to fill the empty gaps. For sound insulation in the frame space, the chosen insulation has to have an increased density or else sound attenuators may be required between the ducts [24].

For the roofing, the panels can integrate its structural elements (i.e. rafters) or can be placed on top of the existing rafters. The second option is preferable because it has fewer problems regarding the positioning and design [24]. The panels must be designed in order to adjust the visual appearance with technical and physical aspects. At the same time, attention should be paid on the integration of the service installations kit into the modular system. The panel must meet the continental and national product standards [23].

1.3.4.4 Hygrothermal Design

From the building physics point of view, the thermal performance is the primary objective. But the panels require careful design against moisture and for air tightness as well. Therefore, another key factor is to determine by hygrothermal measurements the possible joints and cracks, allowing a free moisture flow in the existing structure. The modular insulation panels may increase the moisture accumulation in the wall and the mold growth risk and therefore an appropriate vapor barrier should be chosen. As the duration of the moisture dry out is longer, the hygrothermal condition of the building is worsening. This vapor barrier should consider both the moisture dry out after the mounting (requiring a certain degree of permeability), and the tightness for the long-term use in order to prevent the moisture penetration into the walls from the exterior. It was demonstrated through computations that for an initial moisture content of $w \leq 110\ \text{kg/m}^3$, a vapor barrier with changing tightness (with Sd between 0.2 m and 5 m) should be used. For a $w \leq 75\ \text{kg/m}^3$, a 2.2 cm OSB vapor control layer can be used and for $w \leq 55\ \text{kg/m}^3$ a PE foil is a suitable solution [34].

To minimize the thermal bridges and air leakage, foam insulation is used at critical joints and sealants at the fixings. In order to minimize convection, the joints between the panels are filled with foam insulation (e.g. expansive polyurethane foam and mineral wool) and sealed on site with an exterior waterproof layer (e.g. plywood). The joints between the roof and wall elements must be filled as well (e.g. adhesive belt and mineral wool) [37].

Windows can be mounted either on the exterior, on the center or on the interior of the insulated wall and have to be provided with shadings in order to avoid the overheating by passive measures [23]. If the existing wall has a lower thermal conductivity, the windows should be placed closer to it, at the same time remaining within the insulation layer [24]. At the same time, the window openings and the panel joints must be airtight. A special attention should be paid at the balconies and chimneys joints [37]. Balconies integration into the new thermal envelope with prefabricated panels contribute in reduction of the local thermal bridges [25].

If a ventilation system is integrated, its ducts have to be installed in such a way that they are protected against the exterior conditions in order to reduce the long thermal bridges. This is ensured by their wrapping in thermal insulation and their placement as far as possible from the exterior [24]. The shading given by any new balconies or roof hangings have to be considered in design, because it may reduce the solar heat gains [24].

1.3.4.5 HVAC Design

In order to reduce the retrofitting time, the modules must integrate the HVAC ducts, heat distribution piping, wiring (electricity, internet, sensors, TV, etc.) and renewable energy systems, if applicable. It is important that the HVAC ducts to be placed very precisely and to be properly fastened in the structure because their position define the one in which the modules are mounted [37] (Fig. 1.17).

Regarding the services installations, there are different approaches for each project. It is recommended that a mono-functional building (e.g. block of flats) to have a unique system for HVAC and other services with all the piping and wiring involved and not a separate one for each apartment. In this way, the piping and wiring can be integrated more easily in the prefabricated panels. For multipurpose buildings, with different HVAC and services requirements for each space, this will require separate piping and wiring systems which complicate the panels' structure.

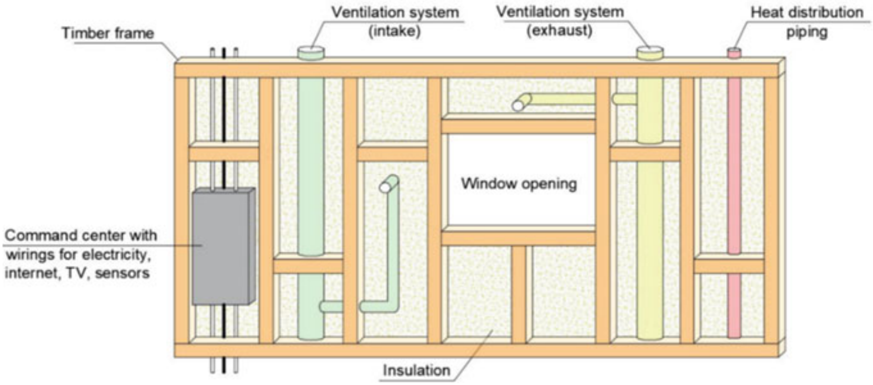


Fig. 1.17 Framing structure of a prefabricated panel with different services included

At the same time, another approach can be applied: e.g. only the ventilation piping to be installed in the panels, while the rest of the services remain in their original position, into the building. When the prefabricated panels are equipped with different services, a technical room which controls all these services must be established. This is usually placed in the basement or in the attic of the building. If is not possible, then the building may require an annex or an extra floor on top for this purpose.

For hot climates, the use of prefabricated panels can slightly increase the energy demand for cooling, since the building requires a longer time to cool down. However, this will not significantly increase the total energy demand, since the heating is the largest energy consumer which is drastically lowered, by the use of these solutions [24].

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The water pipes integration presents a risk because possible leakages may occur which damage the panel layers. Pipe in pipe solutions may represent a safer solution in this case. Façades south oriented may have integrated solar collectors for active energy generation [24].

1.3.4.6 Mounting System

The loads from the prefabricated panels can or cannot be undertaken by the existing walls and foundations and this must be considered in the design of the fixing system. Different bearing systems can be designed depending on the continuity of the bearing system and if it is suspended or standing [23]. Furthermore, the anchoring systems must be adapted to the wall type (i.e. masonry, concrete, or others).

The installation can be done on fixed module systems or by single module systems. Compared to single module systems, fixed module ones are assembled quickly, offering good sealing and waterproofing, but they don't allow the access to intermediate space between new and old façade and if modules are damaged there is a limited intermountability. Fixed module system is a standing or hanging construction system with tongue and groove joints or rabbet. For single fixed modules, only the hanging construction system is possible having open joints with cover profiles or rabbet with slide-in technique [23] (Fig. 1.18).

For each wall panel there can be provided self-supporting systems (i.e. hot-tip galvanized steel corner brackets) attached directly to the wall, which allow mounting adjustment in all three directions. In this way, the panel in-place position can be adapted based on the envelope real surface [37]. The suspension of the panels only at the bottom of the façade is not recommended because modules may present vertical deflections and settlements in time [24]. The space between the supporting brackets can be filled with light foam insulation [25]. Another way to compensate the surface obliquity is the use of a filling layer, consisting in a light material (e.g. mineral wool) of 1…5 cm placed on the inner side of the panel [37].

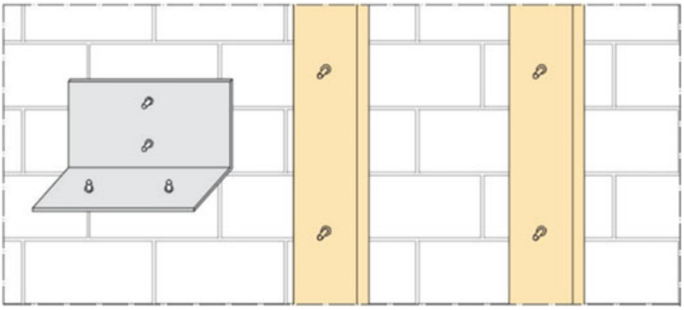

Fig. 1.18 Anchoring systems: angle bearings and lathings

The panels can also be installed on a levelling lathing system attached to the wall. Between the timber laths, the heat ducts (supply lines and heat distribution system) are inserted in a layer of rigid thermal insulation (e.g. extruded polystyrene panels). In this way, the wall surfaces are warmed from outside [24]. The connection between the panels can be done by tongue and groove system, while the horizontal joints are covered with rain sealing. The fixing and junction of the modules must be done with as low weak points and thermal bridges as possible [24].

1.3.4.7 Production

The next step is the frame design based on all this data, the result being then used by the production factory to develop the panel. The internal insulation, external and internal cladding are provided as well [33]. For logistical purposes, the producers prefer the large prefabricated panels. The prefabrication accuracy is ± 1 mm. Two important aspects in this matter are given by the tolerances for the supports and for the space between the panels and the building [25].

1.3.4.8 Installation

It is recommended that the production entity to have a specialized mounting team as well, in order to take full responsibility of all the process [32]. Whenever possible, the prefabricated panels have to be transported with usual transport means without special requirements [37]. This means that the large-scale modules have a maximum length of 12 m and 3 m high, their transport to the construction site being made by a low loader [24].

The mounting process consists of: installation of the anchoring system (e.g. steel angle bearings, levelling lathing system with the thermal insulation in between etc.), removing the old windows from inside (if applicable), mounting of the façade modules and closing the vapor barriers [24]. The panels can be installed either with pulleys by workers or lifted with crane to the installation place. Most of the prefabricated insulation systems require a fixed scaffolding for installation. However, alternatives may be found: for example, in the project Reliable Models for Deep Renovation (4RinEU) an alternative solution was used, given by a mobile construction platform [3]. For extensive changes, the site may require the moving out of the building inhabitants during the works [25]. For the minimum disturbance of the building users, it is recommended that the existing windows are removed shortly before the panels mounting and ventilation inlets drilling. Then, the ventilation pipes telescopic section is inserted just before the panels are fully lowered and put in position [25].

For the mounting phase it is very important that the panels are hanged vertically and in balance. Prior to the placement of an upper panel, the integrated ventilation ducts from it should be connected with those from the lower panel [24]. It should be noted that a roof overhang will make the installation process more difficult [25]. Roof panels (flat or sloped) have to be mounted prior the wall panels in order to prevent the wall wetting from rain [37]. A special attention should be given to the connection between roof panels and façade panels and for the ventilation ducts junctions, if is the case [24]. Regardless the level of prefabrication of the panels, on-site manual work is still required at their junctions, in order to ensure their air and water tightness [3]. All junctions at corners, windows and attics are finished after the panels are mounted, paying a close attention to the vapor retarder enclosures [24].

1.3.4.9 Importance of Design

The prefabricated panels have to be put in place only after all the specific problems regarding the façade geometry related adjustments, mounting details and extra facilities are solved. For example, the panel openings dimensions and position must be always correlated with the façade windows and the panels have to be dimensioned in such way that no gaps will result between them after they are put in place. A special attention should be given to the utilities ducts integration, because this is a key aspect in the design. Furthermore, if possible, it is important that all the involved parties to work on the continous improvement in the design and manufacturing of a certain solution. In this way, the problems in the mounting phase can be limited or even eliminated [32].

1.3.5 Pilot Systems and Practical Experiences

Several European projects analyzed the prefabricated panels from different points of view: structure, location, mass production, integration with service installations. A detailed description of these projects is presented in the following pages.

1.3.5.1 Panels Adapted to the nZEB Requirements

MOdular REtrofitting and CONNECTions (or More-Connect) is a project involving university researchers from several European countries (i.e. Czech Republic, Denmark, Estonia, Latvia, Portugal and Netherlands) which evaluates the opportunity of building retrofit using prefabricated panels (for walls and roofs), reaching a thermal performance similar to the new nZEB ones. The nZEB is defined by the European Energy Performance legislation [18] and follows several directions: primary energy reduction to nearly zero levels and the use of locally produced renewable energy. This represents a challenge because the renovation costs must not be significantly higher than common retrofit solutions [37].

For the Estonian project, the building type chosen for rehabilitation consists of a five story block of flats (80 apartments) made of prefabricated concrete panels, specific for the 1960–1990 era in this country, 65% of its population living in this type of buildings. From the exterior to the interior, the layers of the prefabricated panels are: façade hardboard which acts against summer overheating and as a rainscreen as well (8 mm), ventilated airgap (25 mm) for the air pressure equalization and water vapor dry out, wind barrier from dense mineral wool (30 mm), timber frame / mineral wool (70 mm), timber frame / mineral wool (195 mm), air and vapor barrier (with Sd between 0.2 m and 5 m), light mineral wool layer for filling (10…50 mm) which is attached to the existent envelope element. The total thickness of the module was 34…38 cm, depending on the surface flatness. In the larger timber frame/mineral wool layer, the ventilation ducts were mounted. The panels were installed on the existing walls and roof without structural elements demolishing. At the same time, by using this system, the panels don't require a specific foundation. The renovated walls have a thermal performance of $U = 11\ W/m^{2}\cdot K$ and the roofs $U = 10\ W/m^{2}\cdot K$. The airtightness of the retrofitted envelope is $q < 2\ m^3/h\ m^2$ [37].

The pilot building has a simple rectangular shape (i.e. approximately 4300 m^2 total area) and required the following time periods in order to finish the project: on site 3D scanning with 10 scanning stations—6 h, point cloud processing and 3D building model—20 h, architectural project and detailing—4 months, panels installation on site—3 weeks (Fig. 1.19).

For similar buildings with a less complicated design (i.e. blocks of flats with multiple floors), the duration of all the renovation process can be similar. If the building is smaller (e.g. a single or multi-family dwelling with up to 2 floors) the duration time can be reduced (steps 1, 2 and 4), but only if the details are not in large number because the key step in this matter is the architectural project. Then, for larger and more complicated building designs, the project duration will increase significantly [37].

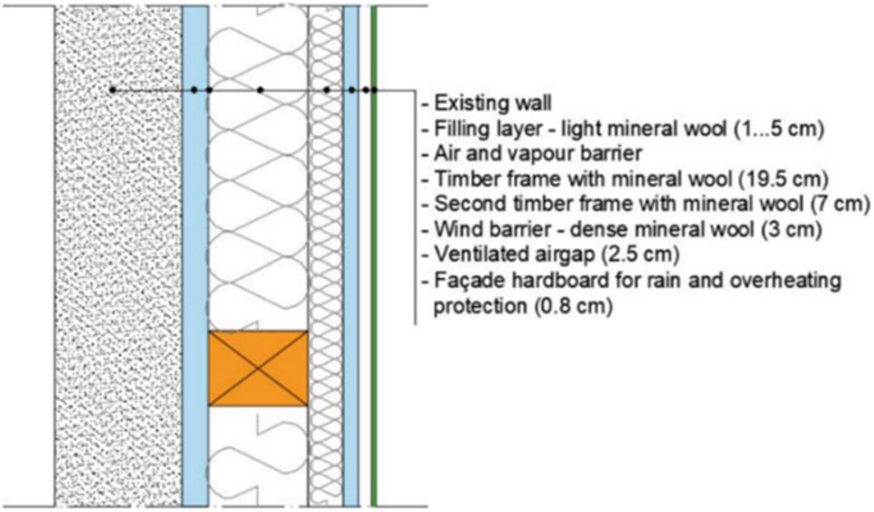

Fig. 1.19 Prefabricated insulation panel model which meet the nZEB requirements

The Latvian pilot building represented a two story multi apartment building from 1960s with silicate brick walls. It has a net area of 200 m^2 and a simple rectangular shape with a two-sloped roof. In this case the prefabricated insulation panels system chosen for renovation is very similar to that used in the Estonian project. Similarly, all the steps needed for the building renovation, from 3D scanning to the mounting were followed. This project required 5 days for the panels' installation, including the on-site problems solving, which were not foreseen in the project. The authors estimate that if all the mounting aspects are well known from the design phase, the panels can be installed on a similar building in 3 days [37].

A three-story post World War II building with brick masonry walls was chosen as a pilot building for the Czech project. It has a rectangular shape with lateral gables and a two sloped roof. The panels used in this project consist of a timber frame filled with thermal insulation and covered with fire resistant boards with a plaster finishing. A layer of soft mineral wool is placed on the core's back side, which integrates the ventilation ducts, wirings and piping. Panels are hanged and there is no need for additional foundation. The panels integrate several building services such as: HVAC with monitoring and control system (temperature, humidity, CO_2 levels, and individual room control), DC, data hubs. The target U values were: 0.08–0.21 $W/m^{2\cdot}K$ for façades, 0.6–1 $W/m^{2\cdot}K$ for windows (triple glazed with shading devices), 0.11 $W/m^{2\cdot}K$ for roofs (with the need of eaves extension). In this project, there were defined three levels of renovation, depending on their costs. A Real-Life Learning Lab (RLLL) was used in order to evaluate the panels' performance and make the possible enhancements. The RLLL simulates a single-family house with reduced dimensions. Therefore, the modules were installed on it in a single day. After that, the panels were installed on the pilot building [37].

For the Portuguese project, the building chosen for rehabilitation consists of a multifamily three floors block of flats built in the 1990s, which is specific for 40% of the residential buildings in this country. The panels used in this project consist of a 10 cm timber frame with polyurethane foam filling and 1 cm claddings on both faces made of a recycled material. A wood frame was chosen even if the aluminum is very used in the construction sector in this country, because the thermal bridges between the panels are lower. The cladding material is made of Kraft and cellulose paper, polyurethane foam, fabrics and fiberglass with certain advantages such as: durability, water and fire proofing, thermal performance and allowance of any possible exterior finishing. The panels are installed with metallic connections. In order to even the possible surface irregularities of the walls, a thin layer of light mineral wool was used between the panels and the walls. As a renovation measure, prefabricated insulated panels for walls ensure a reduction of primary energy of only 25% in this case. Therefore, other measures have to be taken for this project: e.g. insulation of the roof and cellar, new hot water and ventilation systems etc. [37].

Most residential dwellings from Netherlands consist of row houses with tilted or flat roofs (i.e. about 4 million, built between 1950s–1980s). Therefore, because they present a repetitive design, a renovation approach at an industrial scale can be applied. For the Netherlands project the front and back walls of the pilot building were fully removed with prefabricated insulated wall panels. These panels have a timber structure with mineral wool closed gypsum plates and OSB and an external expanded polystyrene layer finished with putz or brick cladding. The modules are fully finished and they require only to be fixed in place. The prefabricated walls are mounted on the existing foundations and then on top of each other. They are also connected with the existing walls to withstand the wind load. All the connections and openings are sealed with special foils and tapes [37].

1.3.5.2 Panels for Very Low Energy Consumption

iNSPIRe was a European Commission funded project in which were developed several prefabricated insulation panel kits in order to reduce the primary energy consumption of the existing residential and office buildings to values lower than 50 kWh/(m^{2}·yr). Furthermore, they are adapted for various European climates integrating energy generation and distribution systems as well [33].

Three renovation kits were proposed. The first kit integrates a compact unit for mechanical ventilation with heat recovery and air heating. The ducts for fresh air are installed under the windows, while the ones for the air extraction are installed above the windows. All the connection ducts through the walls are sealed with airtight tape and are equipped with silencers to avoid the propagation of the sound of the air flow. The second kit consist of a prefabricated vertical shaft with timber structure which integrates the water and sewage pipes and electrical conduits, replacing in this way the existing main distribution systems. The cables and pipes (for heating supply lines and dissipation) are installed on the existing façade before the panels are mounted. The penetration of the internal space is made in several points, where is needed. The shaft connects all the building floors and is used for the fast connection of the main distribution lines to the technical room. Additionally, it is provided with thermal and fire insulations and it has reduced thermal bridges. The third kit integrates an in-roof solar thermal collector at a large scale. This approach is different from standard solar collectors which are usually mounted on the building roof and not integrated in it. The timber structure has reduced thickness for this kit in order to level it with the rest of the roof. By using these three retrofitting kits combined, the result is a viable alternative to demolishing the existing building and building a new one [33].

The panels have the following layers: external cladding 22 mm, battens 30/60 mm, orthogonal battens 30/60 mm, soft timber layer 35 mm, timber frame 60/300 mm with cellulose insulation 300 mm, OSB layer 15 mm, cellulose insulation 60 mm, plaster layer 15 mm, insulation system 45 mm, interior timber cladding 20 mm. The panels include windows with sun shading as well. They are designed to undertake the gravitational and wind loads. The installation is made through steel supports which are chemically anchored on the existing structure with stud bolts [33].

A multifamily two story building from Germany was used as a pilot in this project. One aim of the project is to reach the Passive House Retrofitting standard objectives. Because there were some in-site obstacles, for the pilot building this target was not reached: 30 kWh/(m^{2}·yr) compared to 25 kWh/(m^{2}.yr), the maximum value imposed by the standard. The renovation process lasted 7 weeks, but the target for the future projects is 30 days [33].

In the following paragraphs, there are presented several case studies from another projects, where low thermal transmittance values for the rehabilitated walls were obtained. The use of prefabricated panels was only a part of these projects, which included the integration of HVAC systems and renewable energy sources as well. Therefore, the total energy savings were about 90% in all the situations.

A three floors brick building from Switzerland built in the 1950s was renovated using prefabricated panels. The layers of these panels are: equalizing layer of cellulose (20 mm), cellulose insulation layer in timber framing (180 mm), timber fiber board (40 mm), exterior rendering (10 mm). At the same time, the inlet ducts from the centralized ventilation system are integrated in the prefabricated panels and are mounted above the windows. The field U-value of this system mounted on the existing brick wall (32 cm) is 0.18 $W/(m^2 \cdot K)$ [25].

Then, another building from Switzerland was insulated and several service systems were installed. Additional value was added to the building by the construction of an extra annex and of an attic made of prefabricated insulated elements [25]. In this way, the renovation project costs could be partially sustained by selling those added areas. Therefore, this kind of approach is recommended in similar circumstances. Another example of prefabrication panels use is given by a Swiss school renovation project (built in 1969, with two floors), in which the modules have the following layers: ductile sheep wool insulation 20…40 mm for the equalizing layer in contact with the existing façade, medium dense fiber board 15 mm, timber frame 60 / 280 mm with sheep wool insulation 280 mm, medium dense fiber board 15 mm, ventilated space 27 mm and wood cladding 21 mm. The field U-value of this system mounted on the existing brick wall (30 cm) is 0.12 $W/(m^2 \cdot K)$. In two days, all the 24 façade modules (of which 2 are gable) from the two floors of the building were mounted [25].

1.3.5.3 Adaptive Heat Changer Panels

Prefabricated panels can be designed as an element which adapts to the exterior conditions in order to regulate the interior one. This means that they act as a heat exchanger. In this manner, the auxiliary heating or cooling demand are reduced to a minimum [13].

Adaptiwall is a European Community funded project which targets the renovation of the low rise single and multi-family buildings mainly built before 1990 and which are from different climate types [6]. The solution used is represented by heat exchanger prefabricated panels composed of an adaptive insulation layer, a buffer layer made of lightweight concrete, an integrated ventilation and a total heat exchanger [13].

In order to store the heat from solar gains or cold from the exterior, the buffer layer has to have an increased heat capacity at reduced density. The storage has to be maintained until the thermal load is required at the building interior. The buffer layer

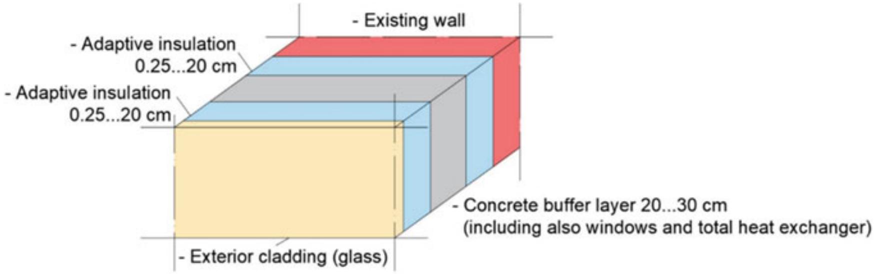

Fig. 1.20 Adaptive insulation system layers

has also a structural load bearing role, fire safety and sound insulation properties. Another important aspect referring to the buffer is that all its exterior edges and all its windows and doors openings edges are insulated in order to reduce the leaking of the stored energy to the exterior. The optimum buffer thickness ranges between 25 to 30 cm. Smaller sizes present a reduced buffer capacity and larger ones cannot load at their full capacity. At the same time, there is no optimum density, however it should range around 2000 kg/m^3. Regarding the thermal properties, the buffer has to have a thermal conductivity of minimum 2 W/(m·K). All these values correspond for the maximum reduction of the heating demand, as it was expressed by computations [13]. The buffer structural role implies that it must undertake all the panel loads. The structural engineering requires that this layer to be reinforced with steel bars [6] (Fig. 1.20).

An adaptive insulation layer is mounted on both sides of the buffer. It has to be able to switch thermal properties, by transferring to or from the buffer the heat or cold load. The thickness of the outer insulations influences the solar heating storage in the buffer. This influence is more prominent for the insulations with a thermal resistance in the range 2.5 to 10 m^2·K/W. At the same time, the inner insulation has to have a thermal resistance as low as possible (i.e. 0.12 m^2·K/W), in order to allow the buffer to transfer the thermal load effectively to the interior of the building, when it is required [13]. The adaptive insulation is provided with a switching system made of actuators and sensors to control the device, which are located within the panel [6].

The heat exchanger is mounted beside the buffer layer with an anchorage system. In order to function in good condition, the heat exchanger has to be placed in thermally stable conditions. This cannot be ensured by adaptive insulation and therefore its margins should be covered with static insulation and the internal and external claddings must be provided with air inlets and outlets. Furthermore, for its regular maintenance, the heat exchanger should be accessible from the interior. Other small buffer points are introduced locally and in the same segment with the heat exchanger system. The rest of the segment is filled with edge insulations around the windows, doors and heat exchanger. Therefore, all these elements will have the thickness of the heat exchanger [6].

Cladding layers must be linked to the buffer before concrete casting and at the same time the anchorage must consider the prevention of the local thermal unloading of the buffer. Cladding permeability and anchors are also important as they may affect the performance of the adaptive insulation layer. For the interior cladding, the existing wall is provided with a plasterboard layer. Windows are linked to the buffer through an anchoring system too [6]. The installations provided by this solution ensure a ventilation with heat recovery and a humidity regulation. These systems may require an extra layer to be added, which affect the thermal transfer in the panel. Another approach is their integration into the buffer layer [13].

Several simulations of this system were done for a one-room model in certain locations: Netherlands, Poland, France and Spain, each being adjusted to the local thermal performance requirements [6]. The results show a 70% reduction of the heating demand compared to a usual retrofit solution. Depending on the retrofit extent, the total heating and cooling demand can be reduced between 20–90%, by varying the thermal properties of the opaque façade elements [13].

Some common elements of a façade are not key aspects in the Adaptiwall design, even if they influence its performance: the windows and the exterior finishing. However, they must be as thermal performant as possible. Therefore, the computations analyzed different exterior cladding types for the Adaptiwall: none, brick, glass and metal. It was demonstrated that the solar gains in the buffer can be maximized by the use of a glass cladding. In the other versions, the heat could not reach the buffer layer [13].

The concept of climate adaptive panels is not yet mature, requiring improvements in order to raise its cost–benefit ratio. However, by regulating the interior condition based on the exterior ones, it reduces the need of HVAC installations, which partially compensate the initial costs. For these systems it is important to notice that the optimum values from the energy savings point of view may not coincide with those from the structural and costs points of view [13].

1.3.5.4 Solar Façades

Two retrofitting projects in Austria for residential buildings built in 1950s–1960s consist of the use of prefabricated insulation modules with the following layers: OSB board (19 mm), timber frame and rockwool (120 mm), OSB board (15 mm), MDF board (19 mm), cellulose solar comb (30 mm), rear ventilation free space (29 mm), safety glass (6 mm). This is called a solar façade in which the sunlight passes the glass layer leading to an increased temperature in the free space and in the solar comb. In this way, the difference between inside and outside temperatures is lowered in the cold season, reducing the heat losses and resulting an improved effective thermal transmittance. Additionally, the modules integrate windows with shadings (between glass panels of the windows), ducts for decentralized ventilation devices with heat recovery and heating pipes (needed for a centralized heating system based on solar collectors and groundwater heat pump). Decentralized ventilation systems are mounted near the windows and are covered with opaque façade elements. The ventilation system inlet and outlet are located in the rear free space. The bottom panels were mounted on a steel angle bearing and after that all the following modules are mounted on the previous ones. Using this system, passive house standard requirements were achieved [25].

1.3.5.5 Interior Prefabricated Panels

There are situations in which the exterior modular insulation panels have limited application: heritage buildings or any building with complex façades, which are intended to be preserved by the owner. In these cases, a prefabricated insulation panel solution can be used on the inside of the building. This has the main disadvantage of space reduction and possible mold developing, but the exterior aesthetics is maintained.

A solution of internal prefabricated panels is proposed by [39]. It has a total thickness of 20…40 mm and it consists of a structural layer made of dispersed fiberglass reinforced plaster plate with profiles on its edges and an insulation layer made of graphite expanded polystyrene. The panel is attached on the wall through the structural layer and on the insulation layer an exterior finishing is applied. The panels are fitted with tongue and groove joints in order to reduce the local thermal bridges. The panel is mounted on the masonry wall with adhesive in such way that no free space remains between them and by the use of plastic anchors (6 pieces/m^2). The permeability is a key factor in this case. If the supporting walls are made of concrete, the panels are installed on a timber slats system with free space in-between and at the floor and ceiling in order to ensure the natural ventilation of the wall, allowing in this way the vapor dry out [39]. The internal modular insulation system can be improved by the use of rigid mineral wool panels instead of expanded polystyrene in order to increase the solution permeability and reduce the risk of mold growth. Another possible improvement is given by the use of thicker insulation layers, considering at the same time the maximum allowable internal area reduction and the load bearing strength of the structural layer of the panel.

1.3.5.6 Standardized Panels

The International Energy Agency—Energy Conservation in Buildings and Community Systems Programme—Annex 50 refers to the Prefabricated Systems for Low Energy Renovation of Residential Buildings. In order to make this design guide, several case studies were analyzed for dwellings from Austria, Czech Republic, France, Netherlands, Portugal, Sweden and Switzerland, in which different approaches for the prefabricated panels were adopted. These case studies included not only the use of prefabricated panels as renovation solution but also the replacement of the old heating, hot water and energy systems and the integration of different HVAC systems based on current technologies (e.g. controlled ventilation, photovoltaic systems, heat pumps, etc.). In this way, the total primary energy consumption is reduced in large proportions.

The system proposed by the Swiss team for the International Energy Agency Guide focus on standardized detailed modules for the windows areas, while the rest of the opaque façade can be insulated with any solution. This kind of approach resulted from the inconveniencies related to the large panel errors given by the façade dimensions, tolerances and angles. If possible, the modules should be designed in order to be applied to entire windows façade vertical strips and for as many openings as possible. The layers used for this system are: ductile glass wool for the equalizing layer (3 cm), gypsum fiber board (1.5 cm), timber frame with mineral wool (14 cm)—including the ducts and wires, gypsum fiber board (1.5 cm), timber frame with vacuum insulation panels (2 cm) and glass wool or rock wool (10 cm), external finishing of any kind. The system is directly connected to the wall and a layer of air sealing and vapor barrier is provided around the window frame from the prefabrication stage. The windows have sun shading systems as well. Each panel is suspended with steel or aluminum flats (10 mm thick and 60 mm wide) with anchoring details which vary depending on the wall structure and pull-out forces (wind load or exceptional forces such as seismic loads, if is the case). The use of vacuum insulation panels requires a special attention because any frame screwing should avoid perforating this layer, in order to maintain its thermal performances. It is used to reduce the impact of the linear thermal bridges between the ducts and the exterior. The system has a thermal transmittance with values ranging from 0.09 to 0.13 W/($m^2 \cdot K$) [24].

In France, 44% of the total residential buildings are collective dwellings and 65% of them are built before 1974, when the first thermal regulations were imposed. These buildings have very high energy consumptions, this being the segment which is of the greatest interest for renovation [24].

The France team system consists of a metallic frame with horizontal and vertical uprights (with a distance between them of maximum 60 cm) in which glass wool is inserted, the framing having a thickness of 20 cm. The modules height is equivalent of two stories and a width of 2.7 m in order to be easily transported. They are provided with an interior smart vapor retarder and a weather protection membrane as well. The window edges are provided with 5 cm glass wool insulation and a frame is pre-installed to ensure the fast mounting of windows on site. Before the panels' installation, a first layer of glass wool insulation (> 10 cm) is added on the existing façade in a common manner. The panels are then mounted on brackets fixed on the walls and their exterior cladding is mounted on site as well. For this kind of systems, the main concern regards their thermal bridges. Large thermal bridges were computed, many of them with values $\Psi > 0.1$ W/($m \cdot K$). Considering the metallic framing and composite thermal break fasteners, the façade module has a thermal transmittance of 0.22 W/($m^2 \cdot K$), for a total insulation thickness of 30 cm. From the simulations, humidity does not represent a problem for this system, however the metallic studs may be covered with anti-corrosion paint, for safety. The ventilation inlet and outlet systems are integrated in the framing system, if the windows position allows. This prefabricated solution requires a separate foundation.

The retrofitting system developed by the Portugal team for the International Energy Agency Guide concentrates around small modules, using local materials and with a simple mounting system. In this case, the modules consist of: smart vapor barrier, extruded polystyrene (120 mm), steel U profiles (1.5 mm), agglomerated black cork insulation (60 mm) and aluminum exterior finishing (6 mm). The aluminum finishing lodges the cork layer and is glued to the steel U-profile. The cork is very widespread across Portugal and is 100% recyclable, while the extruded polystyrene has a very competitive price and it allows the moulding and cavities creation for the ducts. Aluminum finishing is 100% recycled, easy to manipulate and is available in various templates. The vapor retarder eliminates the risk of interstitial condensation. The panels have small dimensions: 1 m × 1 m and a weight of 12 kg/m^2 in order to ease their transport and manipulation. There are designed different module types: simple, for corners, with mould ducts and with cavities for ducts and cables. The mounting system is based on two steel U-profiles attached on each vertical side of the panel and linear support structures which are bolted to the existing walls. In this way, the panels are very simply mounted or withdrawn, having an increased recycling potential. Therefore, the mounting in this case has two phases: the installation of the support structure and then the fitting of the modules into the support structure. In order to reduce the thermal bridges, the connection zone is covered with the exterior layer of black cork. The system mounted on existing walls (concrete masonry units) has an effective thermal transmittance of 0.23 $W/(m^2 \cdot K)$ [24].

1.3.5.7 Mass Production

MEEFS (Multifunctional Energy Efficient Façade System) was a European Union funded project which developed a prefabricated retrofit system for mass production. The system is modular, and it adapts to the specific requirements of each building. In the project it was made an analysis regarding different strategies for rehabilitation in relation to the climate in which the building is located. In this way, one may identify the most suitable solution from an early stage of the project, avoiding the feasibility uncertainties. These strategies include color, glazing, insulation, shading and ventilation. Based on these strategies, the panels' concepts can be determined. For example, ventilation is compulsory regardless the climate type. The shading and color are more important for the southern climates in order to avoid overheating, while the insulation and glazing are more important for the central and northern climates [9].

A massive retrofit project with prefabricated panels for more than 100 social houses (120 m^2 heated area) from Netherlands was implemented from 2010 to 2011. The panels had a 35 cm timber frame with cellulose insulation. The dwellings façades had repetitive designs which allowed the renovation of 4 houses per week, considering that the producing factory was at 250 km from site and all the elements for one house could get on site with a single truck transport. There was only one day in which the tenants of a house were deprived of windows and roof. Additionally, it should be considered that in this case, the houses structure couldn't undertake the panels load and therefore, the modules required a separate foundation. Regarding the costs, this solution turned out to be slightly cheaper than a traditional renovation with 20 cm EPS of another houses from the same area and with same geometry [25].

1.4 Prefabricated Panels Used in Romania. An Analysis

1.4.1 Introduction

To the best of the authors' knowledge, there is no single private or public building from Romania which adopted the prefabricated insulation panels as a retrofit solution. Additionally, the use of timber or metallic framed panels with insulation material in between as a structural solution for walls is a niche in the construction industry in Romania, where masonry and concrete are widely used for the new residential and public buildings. However, in the recent years, there is a slight increase in demand for these solutions, especially for the single-family houses. Under these circumstances, the following paragraphs will analyze the opportunity of using the prefabricated insulation panels solution for residential, public and other types of buildings from Romania.

1.4.2 Residential Buildings

The residential buildings from Romania consist of single family and multi-family residential buildings. There are about 9 million dwellings (houses and apartments), from which about 5 million in the urban area and 98% are private owned, according to a recent Housing Report from the Romanian National Statistics Institute (2018). Therefore, for large retrofit projects the private owned residential buildings are a priority. At the same time, most of the rural dwellings consist of single level houses and their retrofit with prefabricated insulation panels is not a viable option. Frequently, they have a poor structural condition, which requires rather a demolition and a full reconstruction. Following this idea, the prefabricated insulation solution is more feasible for the buildings from the Romanian towns and cities.

Most of the Romanian population (96%) live in owner-occupied dwellings, in the largest proportion across the European Union, according to the Eurostat's Housing Statistics. This may be both advantageous and disadvantageous. It may be advantageous because in the case of full rented dwellings, when the owner invests into the building retrofit with prefabricated panels, a rent increase may be necessary in order to recover the expenses in time. In the case of individual home ownership, this does not apply. However, for the collective buildings with individual ownership, the decision of full building retrofit will be taken harder, because all the users have to agree and to have the financial possibility. This decision may be easier, if some external funds are involved.

As was presented in the last subchapter, a key priority for the mass application of prefabricated insulation panels is the identification of buildings with repetitive façade and roof designs. There are more than 5 million single family houses and a reduced number of row and duplex type dwellings in Romania, according to the last Romanian census (2011). Because most of these buildings are owner-occupied, they are based on individual projects, having different façade and roof designs. This is the same reason for which there is a lack of housing neighborhoods for rentals, with buildings with repetitive designs similar to those from the Western Europe and United States of America. Therefore, the retrofit of low-rise residential buildings from Romania with prefabricated insulation panels is not advantageous from the mass production a point of view.

At the same time, there are around 100.000 blocks of flats, most of them with 4 up to 10 levels, of which more than 90% are in urban areas. Around 75–80% of these buildings were built in 1960–1990. All this data is given by the last Romanian census (2011). In this period, one national policy was the massive building program of dwellings for the factory workers. Entire neighborhoods of blocks of flats were built, based on a reduced number of design project typologies. Therefore, they present repetitive façade and roofs designs. This is the category of buildings which have the largest compatibility with the prefabricated panels for a large scale retrofit. Besides, they are fewer, older and newer blocks of flats built based on individual projects, which would not allow a fast retrofit at a large scale. Furthermore, the older buildings may require a deep retrofit, including structural rehabilitation, while the newer ones are built after the recent energy performance regulations and for both situations the use of prefabricated panels is not feasible from the costs point of view (Fig. 1.21).

From the blocks of flats built in 1960–1990, more than 35% have the walls made of prefabricated concrete elements, 35% made of reinforced concrete, 20% made of masonry and the rest are made of another materials, according to the last census (2011). Their roofs are usually made of reinforced concrete slabs or, in fewer cases, they have a timber sloped roof. Most of these configurations correspond to some of those presented in the last subchapter. A large number of these buildings require pipes and wirings replacements and they don’t have a mechanical ventilation system, while the apartments are heated either locally or from a neighborhood centralized heating system. Therefore, the integration of a HVAC system in the prefabricated panels for these blocks of flats may be advantageous. A special attention is required for the buildings made of reinforced concrete frames, because the masonry which is filled in-between doesn’t have a bearing role and therefore the mounting system has to be adapted to this situation.

Then, it is worth to study further if the expertise from another European projects presented in this chapter can be applied to the Romanian collective dwellings. A special interest should be given to those applied in the countries with similar building typologies (i.e. Eastern European countries).

Fig. 1.21 **a** Blocks of flats **b** Hospital **c** Blocks of flats in need of deep retrofit in Romania

1.4.3 Public Buildings

In Romania, most public buildings are in the following domains: administration, culture, education, health, religion and sports. Most of the urban public administration from Romania operate either in heritage buildings or in buildings which were built between 1950–1990. The application of prefabricated panels on the exterior of the heritage buildings is limited by the façade conservation regulations, but interior solutions may be studied for each situation, if the useful area allows this kind of approach. This applies on the most cultural buildings as well: theaters, museums, operas, etc. At the same time, most of the urban administration buildings which were built in 1950–1990 are compatible with the prefabricated panel solutions, their structure being made either of prefabricated concrete, masonry or reinforced concrete. For each building of this kind, it is worth to study further if the application of prefabricated panels with or without an integrated HVAC system may represent a viable solution. The rural public administration operates in buildings similar to low-rise single-family houses and each one is based on different projects, so the application of prefabricated panels may not be feasible.

In Romania, there are several thousands of public pre-college education institutions: kindergardens, primary schools and high schools, with 1 up to 3 levels. A part of the high schools operates in heritage buildings, but the rest of these buildings have simple repetitive façade designs with the walls made of prefabricated concrete, masonry or reinforced concrete. Therefore, for these buildings, apart from the heritage protected ones, the prefabricated panel solution with or without integrated HVAC systems may represent a retrofit solution. The large majority of the public colleges operates also in heritage buildings and this type of approach is not well suited for them. Their dorms however are compatible with this solution, considering that each campus have its buildings based on a few project designs with repetitive façade designs.

There are 375 public hospitals in Romania built mostly in the twentieth century and most of them require deep retrofitting. Therefore, the prefabricated panels may represent an option in their rehabilitation, especially for those which operate in high-rise buildings with repetitive façade design. Furthermore, since they don't have a mechanical ventilation system and most of their other services are obsolete, an integrated HVAC system may be considered. The private hospitals were built only in the recent years in Romania, based on the recent energy performance regulations and therefore their retrofit with prefabricated panels may not be economically feasible even in the future. Additionally, some of them have at least one façade made of curtain walls, which are not compatible with this insulation solution and which may require a full replacement with the prefabricated panels in case of retrofitting.

The religious buildings such as churches and monasteries are in large number in Romania, but their thermal retrofit is not a common practice, some of them being also heritage protected. However, because of their shape (towers, curved corners, etc.), the use of prefabricated panels for their retrofit is not a viable solution.

Most of the sports buildings in Romania are in the public sector. First of all, only the closed buildings of this type are of interest: basins, ice rinks etc. Thus, this type of buildings may be rehabilitated with prefabricated insulation panels, but each project requires different panel distribution because their façades are not similar. Additionally, their walls structure must be analyzed because it may be different from one project to another. Therefore, in their situation, a deep cost benefit analysis may be required.

Consequently, for the public buildings sector, a special interest may be given to the use of prefabricated insulation panels with integrated HVAC systems in case of several public administration buildings, for the primary schools, and a part of the high schools buildings, for college dorms, for public hospitals and for sports buildings, if is required. One needs to note also, that some of these buildings were thermally rehabilitated in the recent years with different ETICS systems and in their case, the use of prefabricated panels, may not be feasible from the costs point of view.

1.4.4 Other Private Buildings

Apart from the residential buildings, most of the touristic, office, commercial, agricultural, industrial and entertaining buildings from Romania are in the private sector.

The touristic buildings in Romania consist of hotels, pensions, hostels, motels, villas, pensions and cabins. Aside from the hotels, the rest of the buildings have a reduced number of levels and are based on different project designs. Therefore, in their case, the same principle as for the low-rise buildings applies, in which a mass retrofit cannot be applied, which may prove not economically feasible. At the same time, the hotels operate either in heritage buildings, buildings from 1950–1990 or more recent buildings. For the heritage protected ones, there should be studied the possibility of interior panels use, which may require a reconfiguration of its useful areas as well. The hotels which were built recently will have the possibility to be retrofitted to higher energy performance standards in the future, if their façades don't have curtain walls. If that is the case, a façade replacement with the panels may be required. The hotels from 1950–1990 and especially those which were built from the 1970–1990 are compatible with the prefabricated insulation panels solution. Most of them are located in the seaside resorts, mountain resorts and spa resorts across the country. These buildings have a structure similar to that of blocks of flats built in that time period and even that these are not based on similar projects, they have similar designs and repetitive elements. By the use of prefabricated panels, their functionality and exterior layout can be greatly improved. Also, a part of them are closed even though their structure is in good condition. In their case, a deep retrofit using prefabricated panels can be a fresh restart.

The number of office buildings from Romania is rather reduced and most of them were built in the recent years following the energy performance regulations. Furthermore, they frequently have curtain walls which are not compatible with the prefabricated panel solution. Therefore, in their case, this solution is not applicable not even in the future. The commercial buildings in Romania are divided in farmers markets, supermarkets, hypermarkets, malls and in a reduced proportion of robust commercial buildings which were built in 1950–1990. Most of the farmers markets are either in open space or in a light framing construction, while the supermarkets, hypermarkets and even malls have their own structural framings with the façades consisting of sandwich panels. For all these buildings, the prefabricated panel solution may not represent a retrofit solution. However, there can be an exception, if the retrofit decision may consider the full replacement of the existing façade systems with prefabricated panels. For the commercial buildings which were built before 1990, there should be studied in each case the viability of this solution. For agricultural and industrial buildings, there are well established insulation systems and services and the use of prefabricated panels for their retrofit may not represent a solution both from technical and economical point of view. At the same time, entertaining spaces such as pubs, clubs etc. operate in buildings with reduced sizes and usually, a large-scale rehabilitation is not feasible for them.

Therefore, from the private buildings sector, apart from the residential buildings, a special interest may be given to the hotels and commercial buildings, which were built between 1950 and 1990.

1.5 Conclusions

The use of prefabricated insulation panels is the most feasible measure for deep retrofit of buildings with repetitive façade and roof design. Apart from thermal insulation, this solution may provide the integration of heating, cooling, sewage, electricity and internet systems and most importantly, its design frequently includes ventilation systems, which are lacking in most of the older buildings. Regarding the panels structure, different approaches can be developed for the thermal, sound and moisture insulation, flexibility and improvement possibility being their strongest points. However, for heritage buildings or for those with non-repetitive façade designs, it may not prove appropriate from the costs-benefit point of view. In those cases, a solution of prefabricated panels on the interior may be used, with the mention that they don't have all the attributes of the exterior ones and they must be studied further in order to be improved.

The solution of prefabricated insulation panels is rather new, and it will require time to be taken into consideration by the building industry, which is known to be a conservative one. At the moment when this kind of solution will be used at a larger scale in developed economies, it will later become more attractive from the costs point of view in developing countries, as well as in Romania. Therefore, in order to be used as a large-scale solution, the buildings with repetitive façades and which have similar problems (e.g. insufficient thermal insulation, lack of ventilation) must be identified. These buildings are the greatest priority for any massive retrofit program and in case of Romania, they are represented by the blocks of flats built in the second part of the twentieth century, the primary schools and part of the high school buildings, most of the public hospitals, a part of the public administration buildings and also the hotels built before 2000.

1.6 Key Terms and Definitions

Adaptive insulation:	An insulation which is able to switch the thermal properties, by transferring to or from an element or space the heat or the cold load.
HVAC (Heating, ventilation, and air conditioning system):	A system of multiple services and technologies with the purpose of ensuring the indoor environmental comfort.
Prefabrication:	The off-site industrial production of the building elements, in order to reduce the on-site works to the minimum possible level.
Modularity:	The degree to which a system's components may be separated and recombined, often with the benefit of flexibility and variety in use.

nZEB (nearly Zero Energy Building):	A building with a very high energy performance, for which most of the energy required is covered from renewable sources, including renewable energy produced on-site or nearby.
Three-dimensional scanning:	The process of analyzing a building to collect data on its shape and its appearance (e.g. colour), based on which there is developed a three dimensional digital model representation.

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Chapter 2
Concepts of Energy-Efficient Buildings

Sebastian George Maxineasa, Dorina Nicolina Isopescu,
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Abstract The present consumption rates of natural resources and the level of greenhouse gases emissions are currently endangering future generations' chance of development. Our daily activities imply a significant negative environmental impact, which translates to an accelerated altering of the traditional climatic conditions. Therefore, different solutions need to be developed and implemented at the global scale with the goal of reducing humans' present ecological footprint. The construction industry is responsible for a tremendous negative environmental impact, and it is justified to consider that the built environment is a key factor in reducing the global ecological footprint. A way of improving the environmental performances of the construction sector is to reduce the amount of nonrenewable energy consumed during the operation stage from the life cycle of a building for providing a proper level of indoor conditions. In order to do so, it is first needed to fully come to grips with the general concepts surrounding energy-efficient buildings.

Keywords Greenhouse gases · Environmental impact · Ecological footprint · Built environment · Nonrenewable energy · Life cycle · Indoor conditions · Nearly zero-energy building · Passive house · Multi-comfort buildings

2.1 Introduction. The Present State of the Natural Environment

At present, we are witnessing a series of alarming consequences related to the climate change phenomena that is, in turn, a direct effect of daily human activities that have a heavy negative impact over the natural environment. The distressing rates of temperature anomalies registered each year, the alarming rates of melting ice caps, the rising sea levels, the increasing frequency of heavy rains, as well as the magnitude and the increasing number of registered droughts represent serious and real global events that

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will jeopardize the existence of the human race. Moreover, considering the present volume of natural resources consumed yearly, which is completely unsustainable, it is justified to argue that the future generations' chance at development is seriously threatened.

As a direct consequence of the above, the last decades have seen an increasing level of awareness regarding the massive negative influence human activities exert on the Earth's ecosystem, an influence that is significantly increasing year after year. Two of the most important environmental issues are the alarming consumption rates of natural resources and the tremendous volume of greenhouse gases emitted into the atmosphere. It is well-known that nowadays, consumption habits are satisfied by using a volume of raw materials that highly surpasses the Earth's capacity of renewing the natural resources stock. At the present moment, in order to maintain our well-being standards, we are consuming more natural resources than the Earth's stock renewing capacity, which is an important environmental issue that will negatively affect the development of the human race [11, 13, 30, 31, 47, 54]. The Global Footprint Network has disclosed that at the present moment, the human race is consuming a volume of natural resources that is 75% higher than the Earth's capacity of renewing the stock of ecological resources in one year. The same organization has reported that in 2019, the Earth Overshoot Day (i.e. the day of the year when the human race has depleted the natural resources that the Earth can regenerate in that year) was registered on the 29th of July [12]. Thus, it can be stated that the present natural resources consumption rates are unsustainable and will have a major negative influence at the global scale in the near future if different mitigation solutions are not developed and applied as soon as possible.

At the same time, as mentioned above, another significant environmental problem is represented by the volume of greenhouse gases emissions into the atmosphere. The present values are reaching alarming levels and are exerting a highly notable negative load over the state of the natural environment. It is well-known that the level of emitted pollutants into the atmosphere is significantly influenced by the human race; the negative emissions result from all the activities that we complete on a daily basis. The volume of greenhouse gases emissions has been increasing constantly since the European industrial revolution in the beginning of the 18th century. In Fig. 2.1, it can be observed that according to the Climate Change 2014: Synthesis Report published by Intergovernmental Panel on Climate Change, the levels of primary greenhouse gases registered at the beginning of the 21th century are significantly higher than those from the middle of the 18th century. The reported values at the start of the present millennium are 40% higher in the case of carbon dioxide (CO_2), 150% in the case of methane (CH_4), and 20% in the case of nitrous oxide (N_2O) than those registered in 1750 [19]. Figure 2.2 displays the last measurement made by the National Aeronautics and Space Administration in October 2019, which shows that the level of CO_2 reached 412 ppm [35].

The most important negative effect resulted from reaching the above-mentioned alarming values regarding greenhouse gases emissions is reflected by the global warming phenomena, which represents the primary reason for the current alteration of traditional climatic conditions. The data provided by the National Aeronautics and

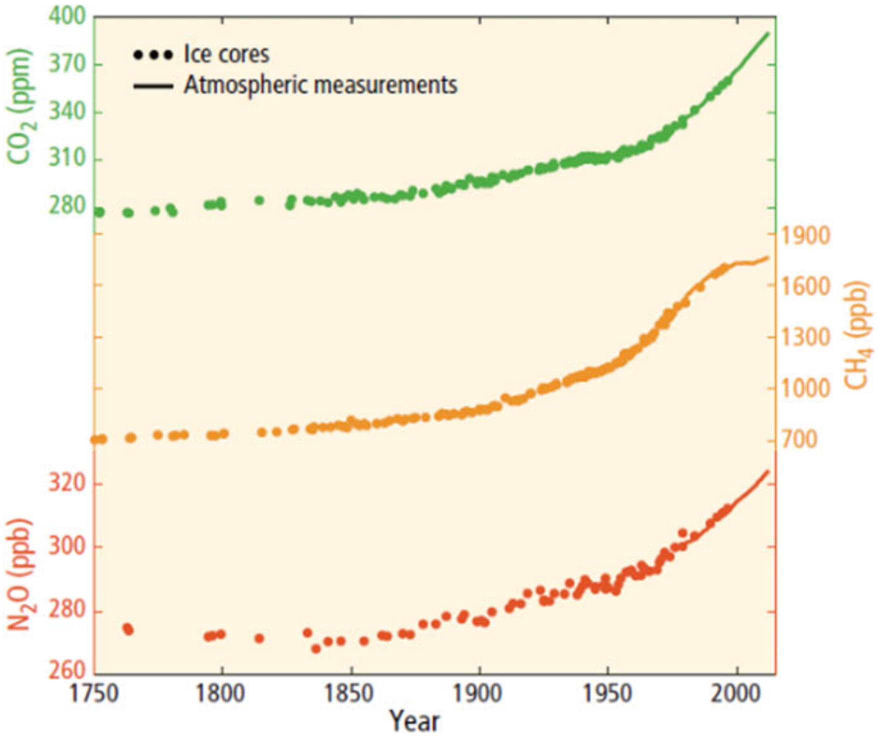

Fig. 2.1 Registered greenhouse gases emissions levels [19] (Fig. 1.3 from IPCC 2014: Climate Change 2014: Synthesis Report. Contribution of Working Groups I,II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, Pachauri, R.K. and Meyer, L. (eds.)]. IPCC, Geneva, Switzerland)

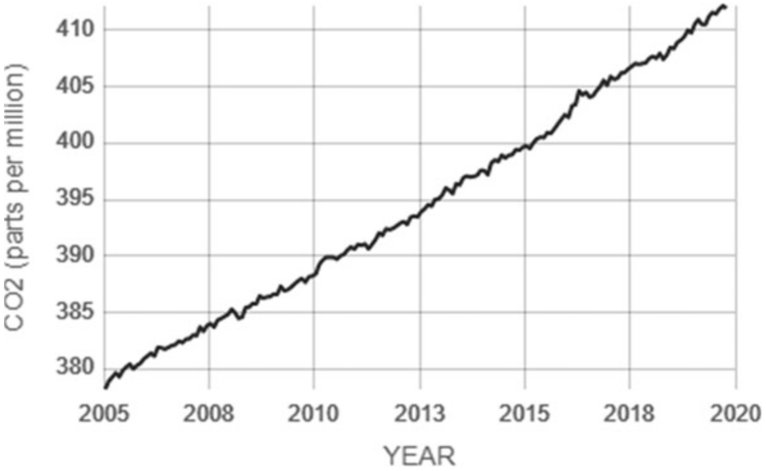

Fig. 2.2 Amount of CO_2 emissions registered in the last 15 years [35] *Source* climate.nasa.gov

Space Administration regarding the emissions of carbon dioxide and the registered temperature anomalies can be correlated to show that along the years, the values of the average global temperatures rise as the concentration of CO_2 into the atmosphere increases, which can be observed by analyzing Figs. 2.2 and 2.3. Also, Fig. 2.3 shows that the years 2015, 2016, 2017 and 2018 were the warmest years on record. The highest value regarding the global temperature anomaly was registered in 2016, when the measured data was with 1.02 °C higher than the normal worldwide average value. At the moment, the latest data regarding the annual average temperature anomaly recorded that in 2018, this value was 0.85 °C, which makes 2018 the fourth warmest year since 1880.

The continuous increase of the global average temperature has many negative effects over the human race as well as a significant influence over our daily activities. One of the most important negative environmental impact resulted from the rising of greenhouse gases into the atmosphere and the global value of the temperature anomaly is reflected by the reduction of the Artic sea ice surface and the melting of the ice sheets from Antarctica and Greenland [35]. In Fig. 2.4, it can be observed that at the present moment, the Artic sea ice has a surface of approximately 4.30 million km^2, which is the third lowest value ever registered. The available data shows that the declining rate of the Artic sea ice is 12.85% per decade, compared with the 1981–2010 average [35]. The same problem can also be found in the case of ice sheets. Figures 2.5 and 2.6 show that Antarctica and Greenland ice sheets are continuously losing mass in an alert way since 2002. At the moment, Antarctica is losing around 127 Gigatonnes of ice each year, and in the case of the Greenland ice sheet, the registered value is approximately 286 Gigatonnes [35].

The reduction of the Artic sea ice and the rapid loss of ice mass from the Antarctica and Greenland ice sheets are pressing problems caused by the global warming

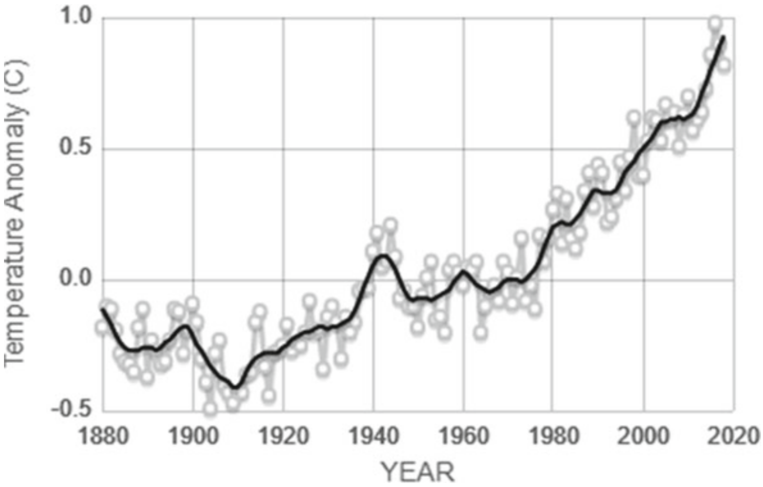

Fig. 2.3 Global land-ocean temperature index [35] *Source* climate.nasa.gov

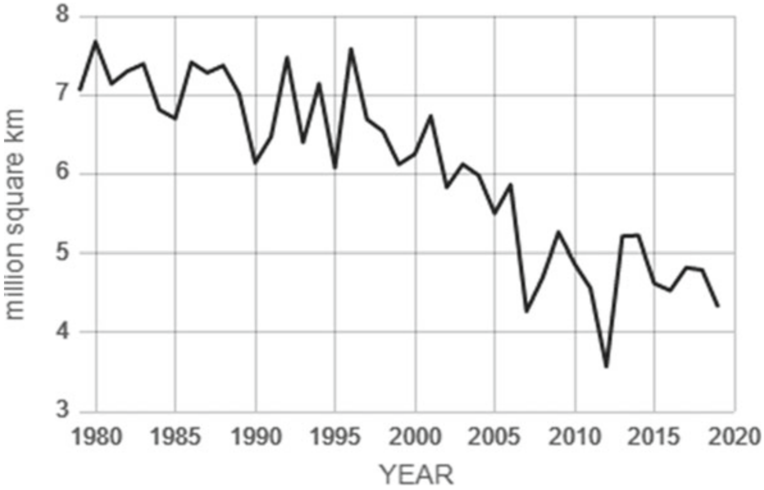

Fig. 2.4 Artic sea ice surface [35] *Source* climate.nasa.gov

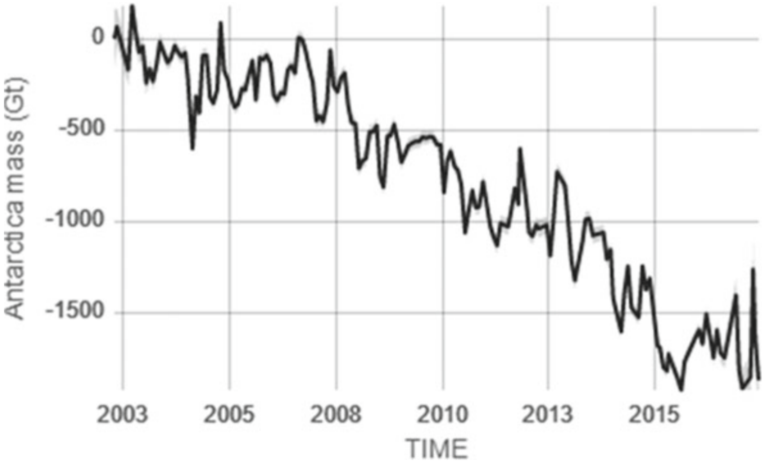

Fig. 2.5 Ice mass variation in Antarctica [35] *Source* climate.nasa.gov

phenomena, and are provoking a significant environmental issue for the human race—the increase of the global sea level. In Fig. 2.7, it can be observed that the sea level has increased with approximately 95 mm since 1993. In the last decade, this has started to be considered one of the most consequential environmental issues that will significantly affect the human race in the near future The data provided by National Aeronautics and Space Administration [35] shows that the present rate of rising sea height reaches the value of 3.3 mm per year. It is estimated that by 2050, the global sea level will increase with approximately 30 cm. This will endanger approximately

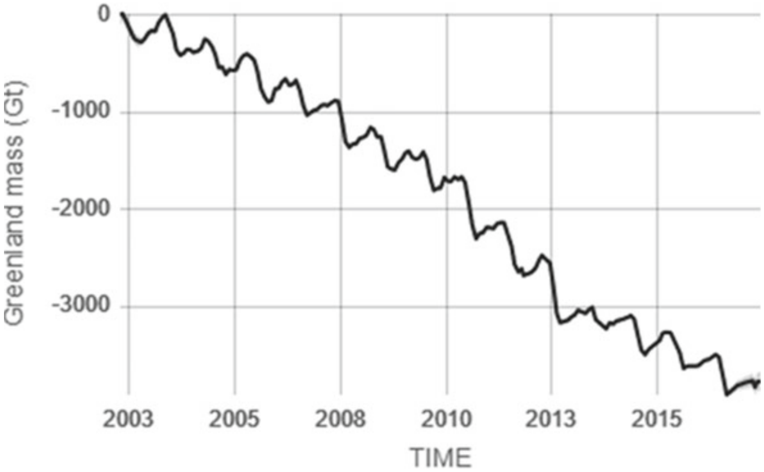

Fig. 2.6 Ice mass variation in Greenland [35] *Source* climate.nasa.gov

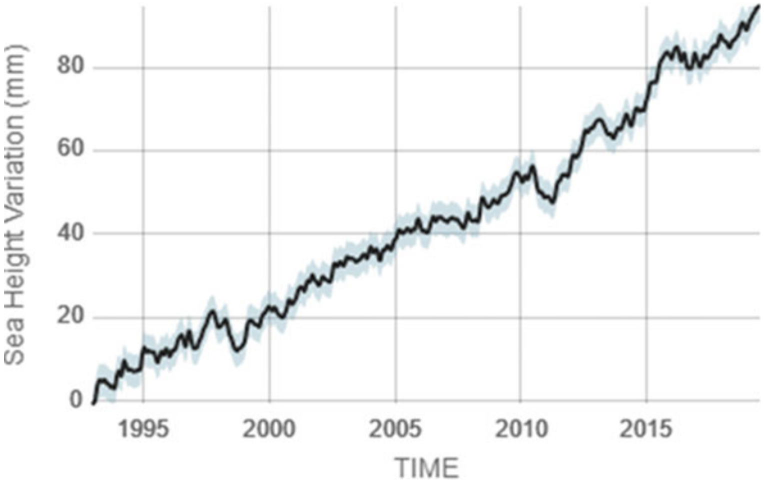

Fig. 2.7 The change of the sea level since 1993 [35] *Source* climate.nasa.gov

170 million people, seeing as the land on which they live will be below the sea water level. There are different scenarios that reveal that even if the greenhouse gases emissions are seriously reduced, the sea level could still increase with another 0.5 m [25].

The information presented above describes the present situation of the Earth's ecosystem, which is continuously negatively affected by our daily activities. All these negative environmental effects will definitely jeopardize the very existence of future generations. Therefore, different mitigation solutions should be developed at the global scale in order to rapidly reduce the impact of people over the natural environment. There are various documents and acts that have been ratified worldwide that specify the efforts the signatory states will make in order to reduce the level of greenhouse gases emissions, with the goal of minimizing the effects of the global warming phenomena. Probably the best known document recognized worldwide is the Paris Agreement, presented on the 12th of December 2015 at the end of the 2015 United Nations Climate Change Conference COP21 in Paris. Article 2 of the Agreement specifies that all parties should "hold the increase in the global average temperature to well below 2 °C above pre-industrial levels and pursue efforts to limit the temperature increase to 1.5 °C above pre-industrial levels, recognizing that this would significantly reduce the risks and impacts of climate change" [51]. At the present moment, 194 states and the European Union signed the Paris Agreement, and 186 states and the European Union have ratified, accepted or approved the document [53]. The Intergovernmental Panel on Climate Change Special report from 2018 offers a high volume of data that shows that reaching the limit of 1.5 °C temperature increase beyond pre-industrial levels will have a significant negative impact over the world population, one that will be extremely difficult to reduce [20]. This document rises an alarming sign regarding the global level of greenhouse gases emissions, which needs to rapidly reduce in order to bring the global temperature average value under control. Another crucial document that advocates for urgent action regarding the global warming phenomena is "Transforming our world: the 2030 Agenda for Sustainable Development", adopted in 2015 during a special United Nations summit [52].

Worldwide, different solutions for reducing the emissions of pollutants into the atmosphere have been implemented. For example, at the level of the European Union, due to the adopted legislation, the volume of greenhouse gases emitted is lower by approximately 23% than the value registered in 1990. Therefore, the Union is on track in satisfying the 2030 climate and energy framework, whose primary target is to cut the domestic greenhouse gases emissions by 40% by 2030. It is expected that if all frameworks regarding the climate change issues are applied, the European Union member states could reduce the greenhouse gases emissions by approximately 45% until 2030 [8]. While this is an encouraging example, there is still a lot of work to be done in order to reduce the load over the Earth's ecosystem. Globally, in order to reduce our negative impact over the natural environment, we first need to completely understand the activities that have the most negative ecological effects in order to develop and implement the best mitigation solutions. All the actions that must be taken should have the target of bringing us closer to satisfying the primary dimensions of sustainable development (i.e. environmental dimension, economic dimension, social dimension).

2.2 The Need for Energy-Efficient Buildings in the Present Global Sustainable Development Context

One of the most important economic activities that has a significant economic global effect as well as a tremendous environmental footprint is represented by the construction industry. One of the most significant ecological negative effects is represented by the fact that from the total volume of greenhouse gases emitted worldwide, the construction sector accounts for almost 40%. Furthermore, the built environment is responsible for consuming approximately 50% of all raw materials that are extracted and processed globally, and for producing more than 25% of the overall volume of worldwide waste. At the same time, the construction industry utilizes approximately 40% of the overall energy that is consumed worldwide [17, 26–28, 30, 38]. Inside the European Union's borders, the built environment is responsible every year for depleting more than 40% of the entire energy consumed by the member states, approximately 40% of the entire amount of materials, having at the same time an influence of about 40% over the total volume of waste. Another important aspect related to the negative environmental influence of the construction sector at the European Union level is reflected by the fact that this industry is also responsible for around 36% of the total carbon dioxide emissions [9, 10, 27, 30].

By analyzing the information presented above, it is extremely justified to state that the built environment is sustained by a series of economic activities that have a significant negative ecological impact. Adding the fact that this industry also possesses a notable influence in every national economy as well as a tremendous social effect, it is clear that the construction sector represents one of the most important factors in achieving global sustainability [2, 5, 29, 30, 39, 55]. The high volume of negative effects exerted by the construction industry over the Earth's ecosystem is expected to significantly rise in the near future and reach new record values. This situation is directly linked to the increasing need of a new expansion of the built environment due to the higher global population. Bearing this in mind, the environmental impact of the construction sector should be clearly divided between the impact resulted from reusing the existing building stock, and the negative ecological effects of constructing new structures in order to satisfy the need for new built surfaces.

For example, at the level of the European Union, the present state of the existing construction stock has a considerable influence over the overall environmental impact. In order to reduce these negative effects, it is needed to develop and apply a series of innovative solutions. A technical report presented by the Joint Research Center states that approximately 80% of the existing building stock in the European Union was built before the '90s. At the same time, almost 40% of the old constructions are being used since before the '60s [22]. Solving this problem involves choosing between two solutions: demolishing the old buildings and replacing them with new ones, or retrofitting and reusing the existing building stock. Each of the two options implies a significant level of environmental burdens, and in order to choose the most suitable one, civil engineering specialists must fully understand the life cycle of a construction. Only after analyzing the negative environmental effects of all life

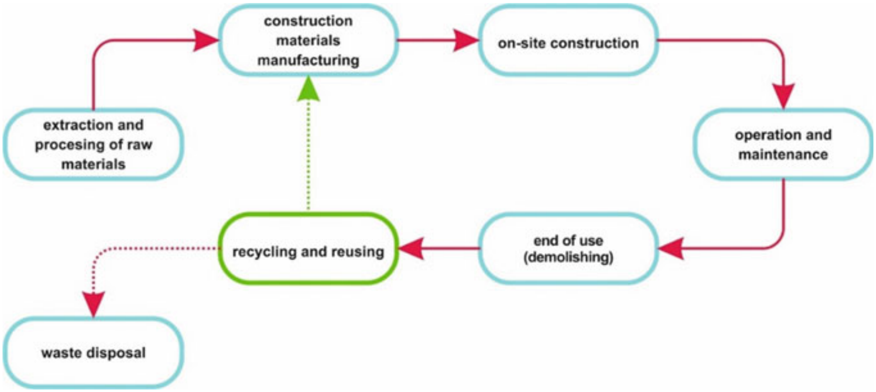

Fig. 2.8 Complete life cycle of a building [28, 30]

cycle phases, it is possible to optimize and improve the ecological performances of a structure.

Therefore, it is needed to clearly identify and split the environmental impact of a building by taking into account all the phases that define a complete life cycle of a considered construction product. Different studies show that from the entire life cycle of a building (presented in Fig. 2.8), the pre-operation phase is responsible for between 8 and 20% of the total ecological impact, while the post-operation phase accounts for 2–5% of the entire volume of environmental burdens emitted during the entire life cycle of the building. The operation phase is considered to have the highest influence over the final negative impact of a construction over the natural environment. All operations, activities, and materials that are used during the utilization phase are responsible for 80–90% of the total life cycle impact [1, 18, 24, 36, 37]. Thus, in order to reduce the overall environmental impact of the construction sector, the level of negative burdens resulted during the operation stage of buildings must be reduced as much as possible.

The utilization phase has the highest environmental footprint due to the amount of energy consumed during a significant number of years (i.e. the life span of a building) for satisfying the users' indoor climatic conditions. This situation is met in both residential and non-residential buildings, even if the interior conditions are different for these two types of constructions. It is estimated that heating, ventilation, and air conditioning technologies are responsible for more than 50% of a building's energy consumption [23, 43]. Thus, the most important part of the environmental impact of a building is mainly influenced by the heating and cooling needs for the interior space. At the present moment, the most consequential issue regarding the environmental issues resulted during the operation phase of a construction is reflected by the fact that tremendous amounts of energy from non-renewable resources are consumed, emitting into the atmosphere a significant volume of greenhouse gases, which, as has been mentioned before, is actively influencing the global warming phenomena. For example, in Romania, burning methane or solid wood for the heating of the indoor space is currently still the most used solution. Apart from the serious environmental issues, the use of a high volume of non-renewable energy can also pose a serious economic problem due to the availability of the required natural resources.

The consumption of a high volume of non-renewable energy for creating the proper indoor conditions is recognized worldwide as one of the most important environmental problems that must be tackled at the beginning of the 21st century in order to satisfy the sustainable development conditions. Therefore, the energy consumption values needed for heating and cooling the buildings' interior spaces must be reduced by creating new highly energy-efficient buildings and also by retrofitting the existing stock in order to significantly improve the thermal performances of existing constructions. Over the years, different concepts, standards, directives, and legislative acts have been developed and promoted at the global scale with the goal of building new high energy-efficient constructions, as well as improving the thermal performances of the existing building stock. For instance, at the European Union level, in order to significantly increase the energy performances of new and existing buildings, two directives have been adopted: the Energy performance of buildings directive [48] and the Energy efficiency directive [49], both part of the Clean energy for all Europeans package.

Therefore, we need to implement more solutions regarding energy-efficient buildings for new constructions, but also for existing ones, so as to reduce the energy consumption of the construction sector. In order to achieve this objective, it is crucial that all involved actors, from materials' manufacturers to the buildings' users, fully understand the characteristics of a construction that requires a low level of energy consumption for creating and maintaining an ideal level of indoor climate conditions. At first glance, this type of building requires a thick layer of thermal insulation material, which is characterized by a low thermal conductivity, in order to achieve a reduced value of thermal transmittance for the overall construction's envelope. In reality, achieving an energy-efficient building is a more complex problem, one that implies the right level of involvement from all parties working in the processes of designing and building or rehabilitating a new or existing structure. Creating indoor spaces using the most suitable structural system, designing the best construction details for the elements that form the building envelope, applying performant heating, cooling and ventilation systems, all represent important stages in the designing phases and are meant to result in an energy-efficient building that satisfies the user's requests regarding indoor climatic conditions. In the last years, besides reducing the energy consumption for heating and cooling, another important step is beginning to be considered as mandatory in order to build efficient constructions. This is represented by the implementation of different systems that produce energy from renewable sources at the building site or nearby, energy that can be used to perform daily basic indoor activities. Similarly, analyzing the construction phase of a building is also a key step for achieving a high performant building that requires a low energy consumption. Therefore, fully understanding the main characteristics of an energy-efficient building is a must in order to correctly implement the various concepts related to this issue.

Due to the fact that an energy-efficient building implies a highly significant reduction in the energy it consumes during the operation phase for heating and cooling the indoor spaces, and adding that non-renewable energy is considered to have a significant impact over the environment, this type of construction is often considered to be sustainable. This assumption is partially correct, seeing as the way in which the low level of energy consumption during the operation stage of the building is attained is crucial—that could be achieved by solutions that imply the use of materials with a significant environmental impact, or the use of structural systems with a low level of recovering and reusing or recycling of the materials that have been considered in the building processes. This issue is another important argument towards the high level of knowledge needed for building energy-efficient or energy-saving buildings.

2.3 Principles of Energy-Efficient Buildings

As stated above, in order to build a construction with a reduced consumption of energy needed for heating and cooling during the operation phase from its life cycle, it is necessary that all parties are involved. Also, it is required that that a series of basic practices be known and respected during the designing and utilization stage. Thus, even if we are talking about new buildings or existing ones, it is needed to provide a construction that can constantly maintain, in a uniform way, the indoor thermal needs with a reduced consumption of energy [16]. There are various solutions and principles that can help civil engineers achieve an energy efficient standard for buildings, but it must be clearly understood that every construction is unique in its own way and that not all recommendations can be used for all structures. These solutions should be optimized from building to building in order to satisfy the conditions of having an energy-efficient construction. The following section presents some of the principles that should be considered in order to obtain a building that will require a low amount of energy for satisfying the users' indoor climate conditions.

The first step is considering and analyzing the construction site, as this will provide information that can have an important influence in the designing phase. Depending on the placement of the building, different microclimate boundary conditions will change in value. The most significant coefficient that is influenced by the location of the building is the design value of the exterior air temperature in the cold and hot seasons, as this information is used in different computations needed for determining the thermal performances of a building (e.g. the linear thermal transmittance that characterizes the linear thermal bridges; the thermal transmittance of the building's envelope elements). Other climatic values that are influenced by the location of the construction site are the sun radiation and humidity levels.

Another important aspect related to the location is represented by the buildings in the vicinity and their heights, as well as the distances between them. The natural surroundings, like hills and trees, must also be considered, seeing as these can influence the solar gains during winter or provide a natural shading of the building during high temperature days in the warmer season. For example, it is recommended to have trees on the east and west sides of the building because they can reduce the cooling load during summer. As for orientation, in the designing phase, the building must be properly oriented with respect to the cardinal direction. In order to reduce the heating needs during winter, a large surface of glazing must be considered on the exterior walls that face south.

At the same time, the south façade should be considered during the partitioning of the interior space. On this side of the building, during the architectural design, we must consider rooms that are used for a high period of time and that need a high operation temperature, and a certain level of natural light (e.g. living rooms or bedrooms). By taking this into consideration, as well as the principle regarding large windows facing south, we practically increase the solar gains during the cold season, while the need of energy for interior heating is reduced. Also, in order to reduce the risk of overheating during summer, the south glazing surface must have passive or active shading or blinds systems. Another aspect that must be considered during the architectural phase of designing an energy-efficient building is reflected by the shape of the construction. This is important, seeing as in order to reduce heat loss through the exterior walls, their surface must be reduced. For instance, an L-shaped building will consume more energy for heating than a cubic building.

The most important part of an energy-efficient building is reflected by the building's envelope. All construction elements that protect the indoor space from external climatic condition must be properly designed. It is well-known that the envelope of a building has the highest influence on the consumption of energy for creating and maintaining proper indoor conditions. Thus, it is needed to achieve low values for the thermal transmittance coefficient or high values for the thermal resistance for all the building's envelope elements. These values must respect the national legislations, or the recommendations required to be achieved by different energy-efficient buildings standards. In order to have high thermal performant envelope elements, quality construction materials must be used, mainly thermal insulating materials that have a low value for the thermal conductivity coefficient. It is common sense that very thick layers of insulating materials should be used in order to have a performant building envelope.

Another problem that needs to be properly managed is represented by the building's thermal bridges. This is a crucial issue that should be considered and resolved. One solution that can be adopted is the use of a continuous layer of thermal insulating layer, but in this case it is needed to take into consideration the structural behavior of the building, which can be highly influenced by insulating different parts of the structure. For example, in Romania, due to the fact that it is a seismic country, continuously insulating the foundation of the building by placing various insulating materials between the soil and the structure could have a damaging effect during an earthquake. Thus, the consideration of the thermal bridges will not only influence the thermal performance of the building, but also the structural one. The authors believe that the best way to reduce the negative influence of the thermal bridges, mostly of the linear ones, is to model each of them for every building that is designed in order to provide the best mitigation solutions. An important part of the building's envelope is represented by the exterior windows and doors. Firstly, very performant elements should be used in order to reduce the heating losses through the glazing surfaces and joineries. After that, it is needed to provide the correct construction detail for the mounting phase in order to reduce the linear thermal bridges that could appear as a result of a bad assembling. In order to reduce the influence of the thermal bridges resulted after installation, it is recommended that the windows be mounted as much as possible in the external wall insulation layer (e.g. in the case of a masonry wall, the window frames should be installed on the exterior surface of the wall, before the insulating material is assembled).

The modern design approach states that an extremely important phase that must be considered is moisture proofing. It is crucial to check the relative air humidity on the surfaces and the possibility that the humidity that is transferred from the interior of the building to the exterior through the envelope's elements will condense in the interior layers. There is a risk that the condensation will appear in the thermal insulating material, which will damage the thermal insulating properties of the layer. Thus, it is necessary to use some materials in order to limit the vapors transferring in the building's components. For example, in the case of masonry walls, applying a finishing mortar with a thickness of at least 1.5 cm that is disposed in two layers on the interior surface restricts mass transfer. At the same time, heat losses through air leakages have to be taken into consideration. Therefore, a certain level of airtightness must be provided by considering different construction details and materials (air barriers). As in the case of thermal transmittance and resistance, the value that characterizes the uncontrolled interior air changes per hour must respect the national requirements.

Taking into account the airtightness of the building, another important aspect of an energy-efficient building that is necessary for creating optimum living conditions is a mechanized ventilation system that should provide the possibility of recovering the heat from the extracted indoor air. Civil engineers need to design a proper airflow rate and also to specify the rooms from which the interior air is extracted, and the rooms that receive exterior fresh air. Normally, the extraction is made from the rooms that have a high moisture content and a temperature that in different parts of the day can by higher than in the other rooms (e.g. kitchens or bathrooms), and the new air is supplied in the living rooms and bedrooms.

In the last years, it has come to light that in order to reduce the environmental impact of the construction sector, it is needed to increase the use of renewable energy. This assumption is also applied to energy-efficient buildings. Therefore, technologies that can enable the building's users to use renewable sources of energy should be installed. The last important aspect in order to achieve an energy-efficient building is reflected by the way the construction is operated. The final users must completely understand how to correctly use the building in order to maintain the designed level of energy-efficiency. For example, during winter, it is not necessary to open the windows in order to have access to fresh air, because the building has a ventilation system that replaces the indoor air, and by opening the window we are practically removing the heat from the interior spaces without recovering it.

In order to achieve a high energy-efficient building, it is necessary to take into consideration the above-mentioned principles. The entire designing team should work alongside the final users of the building as well as with the contractors that are going to build the construction. This effort is necessary to satisfy the needs of the users by applying the right concepts with a minimum financial effort. In order to have a better understanding on some of the concepts related to buildings with a low level of energy consumption for heating and cooling, in the following section the authors will present brief descriptions and a series of requirements for different types of energy-efficient buildings.

2.4 Nearly Zero-Energy Buildings

The concept of nearly Zero-Energy Buildings (nZEB) started with the publishing of the recast of the Directive 2010/31/EU [48], also known as the Energy Performance of Buildings Directive (EPBD). The document was amended in 2018 by the Directive 2018/844, which modified and clarified a series of articles [50]. As a concept, nZEB emerged from the need to drastically reduce the greenhouse gases emissions at the level of the European Union. European environmental policies advocate for cutting the domestic emissions by 80–95% below the levels registered in1990 until 2050 in order to achieve a low-carbon economy [6]. According to the above mentioned directive, the nZEB building is 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". Article 9 of the document states that all European Union Member States will ensure that all new buildings will be nearly zero-energy by the 31st of December 2020, and starting the 31st of December 2018, all new buildings used by public authorities should satisfy the nZEB concept [48]. Another important definition presented by the Directive 2010/31/EU is represented by the energy performance of a building, which is "the calculated or the measured amount of energy needed to meet the energy demand associated with a typical use of the building, which includes, inter alia, energy used for heating, cooling, ventilation, hot water and lighting" [48].

Therefore, an nZEB building represents a high energy-efficient building that consumes a low amount of energy for creating and maintaining indoor conditions. Part of the used energy must also be attained by using renewable sources. The levels of the consumed energy used and the volume of energy covered from renewable sources is not imposed at the level of the European Union due to the fact that every Member State has its unique climatic conditions. However, the European Commission recommends a set of values that should be considered at the level of national legislations. These values are presented in the Commission Recommendation (EU) 2016/1318 and specify the following [7]:

- for the Mediterranean climatic zone: for offices—primary energy used should be between 80 and 90 kWh/m^{2}y and should be covered by 60 kWh/m^{2}y of on-site renewable sources; for new single family houses—primary energy used should be between 50 and 65 kWh/m^{2}y and should be covered by 50 kWh/m^{2}y of on-site renewable sources;

- for the Oceanic climatic zone: for offices—primary energy used should be between 85 and 100 kWh/m^{2}y and should be covered by 45 kWh/m^{2}y of on-site renewable sources; for new single family houses—primary energy used should be between 50 and 65 kWh/m^{2}y and should be covered by 35 kWh/m^{2}y of on-site renewable sources;
- for the Continental climatic zone: for offices—primary energy used should be between 85 and 100 kWh/m^{2}y and should be covered by 45 kWh/m^{2}y of on-site renewable sources; for new single family houses—primary energy used should be between 50 and 70 kWh/m^{2}y and should be covered by 30 kWh/m^{2}y of on-site renewable sources;
- for the Nordic climatic zone: for offices—primary energy used should be between 85 and 100 kWh/m^{2}y and should be covered by 30 kWh/m^{2}y of on-site renewable sources; for new single family houses—primary energy used should be between 65 and 90 kWh/m^{2}y and should be covered by 25 kWh/m^{2}y of on-site renewable sources.

Using the nZEB Directives allows for a rapid transition from the present low-energy buildings to new or renovated constructions that consume a low amount of energy during the operation stage from their life cycle. Thus, in order to achieve an nZEB building, the principles mentioned in the previous section must be taken into consideration. The nZEB does not only represent an energy-efficient building concept; this is actually going to be the official standard for new and existing buildings inside the European Union. The regulations contained in the above-mentioned directives are going to be transposed in national technical regulations in each country in the European Union. Therefore, civil engineering specialists from the Member States must define how to perfectly satisfy the nZEB standards at each national level by developing solutions that are characteristic to their climatic conditions and by imposing different thermal performances values that should be respected (e.g. thermal transmittance coefficient).

An important aspect regarding the correct application of the above mentioned Directives in all member states is reflected by the way in which each government will transpose and implement the European legislation in their national technical regulations and standards. For example, in Romania, at present time (February 2020), only four official national documents have been developed and approved with respect to the Energy Efficiency Directive recommendations. The first document, a National Plan for increasing the number of nearly zero-energy buildings in Romania, was published by the Ministry of Regional Development and Public Administration in 2014. This development plan offers information regarding the situation of the existing building stock with respect to energy efficiency, a series of values pertaining to energy consumption targeted to be achieved until the end of 2020 in order to satisfy the nZEB Directives, as well as some information regarding the economic performances of different types of buildings (offices and residential buildings) that are situated in different climatic zones [32].

In 2016, the Government of Romania issued the decree 13/2016, which modifies and completes the existing Romanian law 372/2005 regarding the energy efficiency of buildings. This official government document modifies a series of definitions used in the building sector regarding energy performances, and also, extremely important, this decree states that in Romania, the energy consumption of an nZEB construction (office and residential buildings) must be covered from at least 10% renewable resources [44]. If we compare this value with the one recommended by the Commission's Recommendation (EU) 2016/1318 for the Continental EU climatic zone, it can be observed that the current Romanian legislation does not comply with the EU recommended values. This decree also presents the definition of a nearly zero-energy building in Romania: "a building with an extremely high energy performance, with a very low or almost zero energy consumption, with a minimum 10% of this consumption covered by energy produced on-site or nearby by using renewable sources" [44].

Another important official document that has the goal of implementing the Energy Efficiency Directives in the Romanian construction sector is represented by the decree 386/2016, issued in 2016 by the Government of Romania [45]. This act modifies the national technical regulation C 107-2005 "Normative regarding the thermotechnical calculation of the construction elements of buildings" by presenting a new map of the climatic zones of Romania, as well as the levels of energy requirements and the admitted levels of carbon dioxide emissions for nZEB buildings, values that are influenced by the designated functions of the buildings and the climatic zones in which they are located. The forth national act that tackles the nZEB Directives is the National Annex for the European Standard EN 16798-1:2019, a document related to the ventilation of energy performant buildings. An important aspect of the National Annex is reflected by the fact that it recommends a set of values for optimal interior temperatures for office and residential buildings [4]. At the present moment, two important national technical regulations regarding the energy performances of buildings are currently under debate with regards to a series of major modifications on computations methods, energy consumption values, airtightness limits, and thermal transmittance coefficient for the building envelope's elements. Due to the fact that these alterations are unfortunately not valid officially, the authors have decided not to present these values in order to avoid creating any misunderstanding.

In the scientific literature, there are many studies that target the implementation of nZEB principles on existing or new buildings. Moga and Bucur [33] compiled a significant study regarding the way in which nano insulation materials can be used for the application of nZEB principles. The innovative materials mentioned in the study that can be used for achieving the nZEB regulations are vacuum insulation panels and aerogel. The paper published by Ascione et al. [3] presents a dynamic energy simulation completed with the goal of optimizing the building envelope's elements in four cities from the Mediterranean climate. Another study related to the energy renovation of an old apartment building from Estonia by achieving the nZEB targets is presented by Hamburg et al. [15]. Murano et al. [34] have published a paper with the main goal of determining the effect of the window-to-wall ratio over the energy need for nZEB residential buildings in different Italian climatic zones. Another important aspect related to the application of nZEB requirements is reflected by the issue of how the optimum thermal comfort parameters influence the overall energy demand; the paper published by Guillen-Lambea et al. [14] presents an interesting study regarding this matter. The above-mentioned papers represent just a small part of the published research studies regarding the nZEB principles; it can be stated that almost all issues related to this type of building have been clearly treated by the scientific community in order to develop the required solutions for correctly applying the European Directives that are related to highly energy efficient buildings.

2.5 Passive House

The passive house concept has been developed by the Passive House Institute in Darmstadt, Germany and represents a high energy-efficient building private standard. The goal of using this concept is to achieve buildings that are energy-efficient, comfortable and ecological. A passive house is defined as "a building, for which thermal comfort can be achieved solely by post-heating or post-cooling of the fresh air mass, which is required to achieve sufficient indoor air quality conditions—without the need for additional recirculation of air" [41]. In order for a new building to be certified as a passive house, the following certification criteria must be met [21, 40]:

- space heating demand $\leq$15 kWh/m^{2}y, or peak demand $\leq$10 W/m^2;
- space cooling demand $\leq$15 kWh/m^{2}y, (the value can be increased for dehumidification contribution);
- primary energy demand $\leq$120 kWh/m^{2}y (needed for heating, cooling, hot water, and domestic electricity) or renewable primary energy demand 60 kWh/m^{2}y;
- airtightness $\leq$0.6 h^{-1} air changes at a pressure of 50 Pascals;
- thermal comfort—no more than 10% of the hours over 25 °C for the interior temperature (must be fulfilled for all living areas).

The above-mentioned criteria must be met for the certification of a building as a passive house Classic, but there is the possibility of receiving the certification as a Plus or Premium passive house. The difference between Classic, Plus and Premium certification is that in the case of the last two, instead of the primary energy demand criteria, only the renewable primary energy demand is used (45 kWh/m^{2}y for Plus and 30 kWh/m^{2}y for Premium). Also, in order to receive the Plus and Premium certification, it is also needed to satisfy a supplementary request regarding renewable energy generation (60 kWh/m^{2}y for Plus and 120 kWh/m^{2}y for Premium) [40].

In the case of existing buildings, the EnerPHit certification can be used, which also has three classes—Classic, Plus and Premium. In order to certify an existing building, two computation methods can be used: the building component method and the energy demand method. In the case of the second method, the space heating demand should not go above the following values: 35 kWh/m^{2}y—for the Artic climate zone; 30 $\text{kWh/m}^2\text{y}$—for the cold climate zone; 25 $\text{kWh/m}^2\text{y}$—for the cool-temperate climate zone; 20 $\text{kWh/m}^2\text{y}$—for the warm-temperate climate zone; 15 $\text{kWh/m}^2\text{y}$ for the warm climate zone. The space cooling demand criteria remain the same as in the case of a classic passive house. The criteria regarding renewable energy generation for Plus and Premium EnerPHit certification remains the same as in the case of a passive house. As for the renewable energy demand criteria, the values from the passive house (all classes) can have a deviation of ± 15 $\text{kWh/m}^2\text{y}$ for the EnerPHit buildings. The main difference between a passive house and a retrofitted one is represented by the airtightness factor, which in the case of EnerPHit must be $\leq 1\ \text{h}^{-1}$ air changes at a pressure of 50 Pascals [40]. The Passive House Institute also has a standard for low energy buildings—in order for a new construction to be certified, it has to meet the following criteria: space heating demand ≤ 15 $\text{kWh/m}^2\text{y}$; space cooling demand $\leq$ passive house requirements $+15$ $\text{kWh/m}^2\text{y}$; airtightness $\leq 1\ \text{h}^{-1}$ air changes at a pressure of 50 Pascals; primary energy demand ≤ 120 kWh/y (needed for heating, cooling, hot water, and domestic electricity) or renewable primary energy demand 75 $\text{kWh/m}^2\text{y}$.

In order to achieve all standards mentioned above, it is necessary to take into consideration the following five principles: airtightness of the building; good and continuous thermal insulation; a thermal free bridge design; ventilation systems with heat recovery; quality windows and doors that are certified as passive components [21]. Taking into account the criteria that must be satisfied, the passive house standard is considered to be one of best that can be used in order to achieve a high energy-efficient building. This standard has been in use for many years; at present, more than 4900 buildings have been certified as passive houses around the globe. According to the Passive House Database, only eight buildings are certified in Romania at the moment of writing this chapter [42]. The database is a good example of the successful application of passive house principles in order to achieve high energy efficient buildings.

2.6 Multi-comfort House

The multi-comfort house concept has been developed by the Saint-Gobain company, and it is now used worldwide. The concept not only takes into consideration the energy-efficiency of a building, but also a host of other criteria that will significantly improve the interior comfort level of the building's end users. The supplementary specifications are related to the indoor and outdoor sound insulation as well as the daylight autonomy. For the cold and moderate climatic zones, a new house can be certified as multi-comfort if the following requirements are satisfied [46]:

- heating energy demand ≤ 15 $\text{kWh/m}^2\text{y}$;
- cooling energy demand ≤ 15 $\text{kWh/m}^2\text{y}$;
- airtightness $\leq 0.6\ \text{h}^{-1}$ air changes at a pressure of 50 Pascals;
- daylight autonomy 60%;

- summer comfort—overheating % of season 10%;
- acoustics—between dwellings—airborne noise $\geq$58 dB;
- acoustics—between dwellings—impact noise $\leq$45 dB;
- acoustics—between rooms of one dwelling—airborne noise $\geq$45 dB;
- acoustics—between rooms of one dwelling—impact noise $\leq$50 dB;
- acoustics—exterior noise—urban and rural zones 25 dB.

As can be observed, a multi-comfort house is a high energy-efficient building that uses a low amount of energy for heating and cooling. It can easily be noticed that the thermal performances of this type of house are highly based on the passive house concepts. Therefore, in order to achieve these values, it is necessary to take into consideration the principles for completing a passive house. A multi-comfort house can be considered more performant than an nZEB and a passive house, seeing as it implies supplementary requirements that will significantly improve the users' comfort level. Thus, during the designing phase, besides the thermal performances computations, involved parties should also take into consideration supplementary acoustic insulation solutions.

2.7 Conclusions

Considering all the negative ecological effects of the construction sector, it can be argued that the built environment has one of the most consequential influences over the present state of the Earth's ecosystem. The high levels of consumed non-renewable energy and greenhouse gases emitted into the atmosphere by activities specific to the construction sector are transforming this industry into a key factor in the journey towards achieving all environmental policies at the global scale. Therefore, in order to reduce its environmental impact, it is necessary for civil engineering specialists to understand the ecological influence of a building. From the life cycle of a construction, the operation phase has the highest influence over the overall environmental influence due to the consumption of energy for creating and maintaining an optimal level of indoor climatic conditions. It is thus needed to reduce the amount of non-renewable energy consumed in order to improve the environmental performances of the construction sector. To achieve this goal, various solutions for building new energy-efficient buildings and for energy retrofitting the existing building stock should be considered.

Taking into account the present state of the natural environment, the need of considering energy-efficient buildings is more and more pressing. A series of principles that need to be considered in order to achieve buildings with a reduced consumption of energy for heating and cooling must be applied in the designing phase. Solutions such as placing large windows on the south façade, taking into consideration a thermal bridges free design, or properly displacing the thermal insulating materials have a significant influence over the energy demand for heating and cooling. Besides these principles, the chapter also touches upon three of the most important energy-efficient building concepts that are currently being used globally and that take into account all the needed aspects for increasing the thermal performances of buildings. As a conclusion, the authors believe that it is extremely important to fully comprehend these concepts before being able to use them in order to reduce the consumption of energy and the level of greenhouse gases emissions of the built environment.

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Chapter 3
Indoor Environment from Wellbeing Perspectives

Cristina Liliana Vladoiu, Dorina Nicolina Isopescu, and Sebastian George Maxineasa

Abstract Wellbeing of occupants is a new concept in the design of high performance energy efficient buildings. From this point of view, the indoor comfort must be ensured taking into account first of all the wellbeing of the users of these buildings. The present modern architecture proposes innovative solutions for facades, roofs, joinery and other building envelope components, so that performances of the ecological and energy efficient buildings are ensured to a maximum extent. The indoor environment quality depends on a large variety of factors, which directly or indirectly influence the hygrothermal, visual, acoustic comfort and the quality of the indoor environment. These factors can be quantified by means of indoor climate parameters. These parameters must comply with the limits set by specific design norms and standards, so that the wellbeing of users is fully satisfied.

Keywords Wellbeing occupants · Indoor environment quality · Hygrothermal · Visual · Acoustic · Lighting comfort · Indoor air pollution · Ventilation rate · Ener-gy-efficient buildings

3.1 Introduction. The Concept of Wellbeing and Its Necessity

Over the years people have built a shelters with the aim of providing a safe indoor environment, regardless of the aggressions from the exterior environment. The expectations for modern buildings are in continuous change, determined by the dynamics of needs (i.e. from primary needs to luxurious conditions), the dynamics of environment, as well as knowledge dynamics in field.

Researches in this direction have been accentuated especially after the great global energy crisis of 1970s. It was the moment when people realized the need to maintain a balance between their consumptions, the available resources and negative

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consequences on the environment. In particular, it refers to the energy consumption which ensure the desired indoor environment, about the available resources, and obviously, about the consequences of the interventions on the external environment, to conform internal environment according to their needs.

Thus, a continuous increase of the human demands have been identified and researched (hygrothermal, visual, olfactory, acoustic comfort etc.). All the requirements are expressed in relation to the building in which people operate. As a result, more building concepts that respond to a set of requirements have been proposed (those were substantiated, designed and tested). With each new proposed concept, an increase in the performance criteria of buildings was also felt, and an adaptation of these characteristics to the present times [13]. At the same time, consideration was given to prioritizing performance needs, in relation to economic, energy, ecological, climatic and social context, respectively, [55].

Thus, it was proposed: the buildings with reduced energy demand and increase environmental performance (i.e. NZEB - near zero energy building, Green House, Passive House); social buildings (for poor populations), which provide minimum of human needs; buildings with high comfort requirements.

In each of these buildings types, it was sought to ensure the healthy indoor environment simultaneously with high energy performances. Yet, the requirements according to this criterion, are very different from one concept to another. Also, the obligation to consider all the determinant aspects, in ensuring and maintaining an adequate environment, is not present in all design standards.

Recently, in the European Community the concept of nearly Zero Energy Building (i.e. NZEB) was proposed. The specialists wanted to promote the buildings in which the interior environment is comfortable from all hygrothermal points of view, and this comfort is to be obtained with minimal energy efforts, fully clean and renewable resources. They, also, intend to ensure comfortable interior environment from sanitary point of view (i.e. air quality, space hygiene possibilities etc.).

Sick buildings syndrome, negative radon effect, volatile organic compounds, impact of formaldehyde from interior environment on humans, but also, the consequences on human health due to electromagnetic radiation, it led to reinvention of the old concept of a habitat, correlated with demands imposed on buildings as well as with design strategies, [44, 47].

Wellbeing of occupants is a new concept from modern design of high energy performance buildings. From this point of view, indoor comfort must be ensured taking into account, first of all, the wellbeing of users [39]. The present modern architecture proposes innovative solutions for facades, roofs and other building's elements, so that performances of and ecological and energy efficient building are ensured to a maximum extent.

Architectural modern solutions for facades, joinery, roofs and basements must a proper waterproofing level, so that water penetration and heat losses are significantly reduced. In the same time, all these building envelope elements must be permeable for mass transfer. Failure to comply to these characteristics leads to deterioration of the indoor comfort quality, respectively reduced wellbeing levels for the building's occupants [19, 50].

Indoor environment analysis must take into account the main directions for design, that will ensure high quality for all previously highlighted conditions: a healthy environment, an adequate indoor environmental quality and proper standard approaches, wellbeing and satisfaction of building's occupants, and the safety of the built environment, [15, 18, 50].

3.2 The Indoor Environment Quality

The indoor environment quality depends on a big variety of factors, which directly or indirectly influence hygrothermal, visual, acoustic comfort and the indoor environment quality [1]. These factors can be quantified by means of indoor climate parameters. These parameters must comply with limits set by the specific design norms or standards, so that wellbeing of users is fully satisfied [34].

The evaluation and the design of parameters that provide the indoor environment quality must aim to ensure energy saving, recovery of all forms of energy and their conversion into useful energy, storage of these energies for reuse. The main scope of these is in satisfying the wellbeing of occupants, so that, at the end, to obtain independent functioning, with respect to alternative/renewable energy sources of studied buildings [26].

The indoor environment must ensure optimal conditions for health and wellbeing of occupants, regardless of their activity, period of year or location of the building. The comfort and wellbeing of occupants of each room depends on very many factors, [2].

According to the specialized literature, we can list part of these factors: the indoor air temperature, the indoor surfaces temperature, the relative humidity of the indoor air, the air circulation speed, the smells and people respiration, the acoustic factors, the light, the objects color, the brightness surrounding surfaces, the specific solar factors, the touch sensations, the tactile factors, the buildings vibrations and oscillations, the safety factors, the durability factors, the economic factors, the unpredictable risk, the innovative conceptions, the design of buildings [42, 43, 57].

Factors that influence the indoor environment quality and its characteristic parameters, can be classified according to the contribution of each in satisfying one of types of comfort levels, that all together contribute to ensuring the wellbeing of the building's occupants, [56].

Indoor environment quality is a broad concept in the field of interior climate engineering, which includes the influence of all factors within indoor environment, [45]. These factors affect main human sensory systems. There are also number of parameters determined by personal, cultural and interior design preferences, which are analyzed separately and occasionally [3, 38].

In order to optimize the quality of interior environment, the creation and design process must follow number of principles [36].

- The insurance use of good quality design, execution, commissioning, operation and maintenance practices;

- The consideration of aesthetic aspects, including the importance of views and integration of natural materials and elements;
- The performing checks for specific parameters of thermal comfort for occupants, during the maintenance period of buildings;
- The ensuring adequate, necessary and quality ventilation levels;
- The preventing appearance of airborne bacteria, mold and other fungi through a design that correctly manages the moisture sources inside and outside building;
- The used of construction materials, especially for finishes, which do not emit pollutants;
- The used of sound-absorbing materials/ sound insulations to create optimum acoustic levels.

Another important direction which quality of indoor environment can be improved is the building management. In close connection with this, there are a number of ways in which indoor environment quality of existing buildings can be improved, including.

- The use of cleaning and hygiene products without fragrance and with low volatile organic compound (VOC) content;
- Carrying out audits of the products used in cleaning and hygiene, as well as elaborating plan of specific activities to replace chemicals with safer alternatives;
- Vacuuming regularly and use of vacuum with HEPA filters (High Efficiency Particulate Air Filters);
- Ensuring the HVAC (heating, ventilation and air conditioning) equipment, that must be well maintained and works optimally;
- Create a protocol for opening doors and windows to maintain sufficient airflow;
- Avoidance dust blowing equipment and other garbage;
- When using pesticides, fertilizers and lime applications, the weather conditions should be checked so that wind action is completely absent, or speed of air currents is low as possible;
- Keeping buildings, construction elements, finishes and furniture to high standards, thus reducing the need for renovation and remodeling;
- Ensuring the proper maintenance of filters in HVAC (heating, ventilation and air conditioning) systems;
- Optimization of natural lighting, as well as fixtures for artificial lighting.

3.3 The Hygrothermal Comfort

According to present standards and norms from field, the hygrothermal comfort depends on following factors and their specific parameters: indoor air temperature, boundary surfaces temperature, resulting temperature, difference between indoor air temperature and temperature of building elements surfaces, relative indoor air humidity, indoor air movement speed, (in special) the global PMV (Predictive Mean

Vote) indicator and the global PPD (Predicted Percentage of Dissatisfied) indicator [10, 30, 34].

The hygrothermal comfort parameters can be controlled through cooling and air conditioning systems. In principle, many of technologies that control hygrothermal comfort are technologies with considerable reaction times, which leads to fact that their adaptation to present requirements (new air temperature and climate change) can take longer time.

3.3.1 Challenges in Context of Climate Change

Previous information focused on indoor environment quality as part of a construction system and highlighted the important role of occupants. But a holistic vision must also include external environmental factors, considered globally. It is expected that the major and continuous climate change will lead to periods of much higher, more frequent and severe temperatures, as well as precipitation in quantities much higher than usual, in many parts of the world. These phenomena will affect buildings and their interior environments. The consequences will have direct and indirect influence on the health, wellbeing and performance of occupants, but also on the indoor environment quality [49].

Direct exposure of people to heat or cold, is felt as a form of stress, whose negative health effects must be well studied. This situation is responsible for high mortality among exposed persons. For example, the high temperatures will indirectly affect outdoor air pollution levels due to increased emissions (pollen, dust, unpleasant odors, etc.), as well as chemical reaction rates increased, which lead to formation of the secondary pollutants.

The buildings occupants without the air conditioning and efficient filters for air purification, may feel the direct exposure to high temperatures during summer time. Also, people will feel the higher levels of outdoor air pollution, when the windows are used incorrectly, to mitigate the consequences of high temperatures. Exposure of people to outdoor air pollution has various negative health effects. In particular, outdoor air pollution, due to multiple particles contained in its composition, is classified as main cause for different types of cancer or diseases with high mortality risk [40].

In addition, high indoor temperatures will result in increased emissions of organic substances from the building materials, and higher concentrations of the gaseous pollutants. These pollutants can react with gases and particles existing in the indoor air. Then, resulting substances can be available for following reactions, which will have as reaction products another secondary pollutants, both form of suspended particles and gases. Due to higher temperatures, both amount of chemicals available for the indoor air reactions and the rate of these reactions will increase significantly. In present, these phenomena are more and more frequent in the indoor environments, which are strongly influenced by chemical composition of indoor air. The benefit is that at the moment, the subject receives increased attention, due to the great concern about their effects on human health.

3.3.2 Role of Hygrothermal Comfort

The indoor temperatures correlate with outdoor air temperature changes, especially at buildings that are commonly used. However, the indoor air temperature can vary significantly compared to outdoor temperatures, being up to 50% higher than the external air temperatures. The literature reviews indicate that relationship between outdoor and indoor temperatures, in the buildings that are not air conditioned, is complex. The connection between the two parameters is depending on: interaction between the natural phenomena and technical systems, design of buildings, passive cooling through achievement of appropriate tire elements (such as solar shading), the individual behavior of beneficiaries, adoption of specific programs the social systems [48].

The hygrothermal comfort is very important for wellbeing of the occupants of buildings. Usually it is considered to be much more important than visual and acoustic comfort, or good air quality. Hygrothermal comfort does not depend solely on temperature. The thermal balance of the human body and thermal comfort are influenced by: the climatic factors (i.e. air temperature, humidity, air speed and radiation), the personal factors, the intensity of physical activity (i.e. production of metabolic heat), the isolation of clothing, the preferences and personal experience each person, also and their exposure in past at different indoor environments.

The human thermal comfort is given by the mental expression, which shows the satisfaction state at indoor environment of buildings. This expression is not related to particular point of view or reference range but is determined by several factors. Adjusting indoor air temperature at the fixed time interval may not be the optimal solution from the point of view of occupants or perspective of energy consumption. At the constant air temperature, any change in other climatic factors will influence hygrothermal comfort. For example, the exposure to solar radiation through large windows during the day and additional loss of heat at night, cause large changes in indoor air temperature [40].

Because the main purpose of using heating or cooling equipment for the internal environment is to create hygrothermal comfort, all factors which directly or indirectly influence the level of hygrothermal comfort, should be considered, studied and regulated by norms and standards.

3.3.3 The Hygrothermal Comfort Analysis

Probably, hygrothermal comfort is the most important and necessary parameter for indoor environment quality satisfaction. The occupants must perform activities to their full capacity. Therefore, their workspace must be comfortable from several points of view, but especially hygrothermal. However, hygrothermal comfort is based on adaptation of each occupant to ambient temperature, which is directly related to number of factors, such as geographical location and climatic area, time of year, human race, age, health, etc.

The human body permanently maintains a temperature of about 37ºC, through its own metabolism. The temperature is ensured by a heat exchange between the human body and the indoor environment, through convection, radiation and evaporation. The hygrothermal comfort has direct impact on the energy consumption of building, because any feeling of discomfort to occupants leads to automatic adjustment of the functioning of equipment to ensure new non-optimal levels [54].

According to Ashare 55 (2010), [10] and ISO 7730 (1994), [30], thermal comfort is defined as “the state of mind that expresses satisfaction consistent the thermal environment in which it is located". These standards are used by specialists from construction field around the world. The legal provisions in these are the main criteria in correct design of buildings, so that quality of indoor environment and wellbeing of occupants are ensured.

The concept of passive building design has evolved over the last fifteen years. Therefore, achieving passive standards in the climate of Northern Europe is totally different from the one in the Middle East, where mechanically cooling systems is necessary to reach optimum level for indoor air conditioning parameters and the occupant comfort.

Thus, in tropical climate, buildings are naturally ventilated, and their operation faces higher energy consumption. This is necessary to fulfill desire of occupants to feel very close and connected with nature. Hygrothermal comfort proves to be well maintained, using methods and equipment that can used less energy, such as being local air conditioning and/ or environmental conditioning.

Perception of internal comfort differs from one climate zone to another and is also influenced by human culture. Possibility of the thermal adaptation of an occupant in certain indoor environment and his perception of comfort are defined by three main factors: behavioral adjustment, physiological adaptation and psychological habit or the expectation, that are described in specialty literature.

There are many previous researches, which have the purpose of defining the temperature variation in the built environment or the ideal temperature limits for the indoor environment in buildings. There are also well established methods for measuring and quantifying hygrothermal comfort. Thus, in metric system, PMV and PPD indicators are quite commonly used by specialists on a global level [24].

The PMV model is widely used in buildings with modern heating, ventilation and air conditioning systems, located in areas with lower temperatures winter and warmer climate summer. However, it can be applied in buildings that have not HVAC systems, in a predominantly warm climatic area, using an expectation factor. The physical adaptation to environment and the design of buildings, to ensure the necessary thermal comfort, must be taken into account at actual stage of design and dimensioning. That is mandatory due to the fact that change of constructive solutions after the execution of buildings is inefficient, difficult to achieve and expensive.

3.3.4 Indoor Environmental Parameters for Design

The first step in design of the indoor environment is represented by classification of building in one of categories recommended by actual standards.

The reference categories are presented in Table 3.1, with brief presentation, necessary to identify corresponding category [10].

These categories can be used in different practical ways. Firstly, they can be used to establish the different levels for design criteria of buildings and their systems. The design specialists use these categories to agree on a performance level design. The presented categories can be used to describe yearly the indoor environment quality of building by showing distribution of parameters in different ranges.

In EN 16798 standard, [22], the criteria for the hygrothermal environment in heated and/ or cooled buildings is based on thermal comfort indices PMV—PPD with assumed levels of activity and typical values thermal insulation for clothing (of winter and summer).

As describe in EN ISO 7730 standard, [30], and assuming the different criteria for the PPD—PMV, the different categories of indoor environment are established needed for wellbeing of the occupants. Recommended PPD ranges are given in Table 3.2. The PMV—PPD indices values take into account the influence of all the six thermal parameters (clothing, the activity of occupants, the air temperature and the mean radiant temperature, velocity and humidity).

In Table 3.3, met is the unit measure for the metabolic rate, the human body heat or the power production. The metabolic rate of relaxed seated person is 1.0 met, where

Table 3.1 Description of applicability for the categories used

Category	Explanation
I	High level of expectation and also recommended for spaces occupied by very sensitive and fragile persons with special requirements like some disability, very sick, very young children and elderly persons, to increase accessibility
II	Normal level of expectation, which should be used for new buildings and renovations
III	An acceptable, moderate level of expectation, which may be used for existing buildings
IV	Value outside the criteria for above categories. This category should only be accepted for limited part of the year

Table 3.2 The PMV—PPD indices values for buildings design EN 16798 (2014)

Category	Thermal state of the body as whole	
	PPD [%]	PMV (Predicted Mean Vote)
I	<6	$-0.2 < \text{PMV} < = +0.2$
II	<10	$-0.5 < \text{PMV} < = +0.5$
III	<15	$-0.7 < \text{PMV} < = +0.7$
IV	<25	$-1.0 < \text{PMV} < = +1.0$

Table 3.3 The design values of indoor operative temperature in winter and summer for buildings with mechanical cooling systems EN 16798 (2014)

Type of building/space	Category	Operative temperature [ºC]	
		Minimum for heating (winter season), ~1.0 clothing level	Maximum for cooling (summer season), ~0.5 clothing level
Residential buildings: living spaces (bedrooms, drawing room, kitchen etc.) Sedentary ~1.2 met	I	21.0	25.5
	II	20.0	26.0
	III	18.0	27.0
	IV	16.0	28.0
Residential buildings: other spaces (storages, halls etc.) Standing—walking ~1.6 met	I	18.0	24.0
	II	16.0	25.0
	III	14.0	26.0
Single office (cellular office) Sedentary ~1.2 met	I	21.0	25.5
	II	20.0	26.0
	III	19.0	27.0
	IV	17.0	28.0
Landscaped office (open plan office) Sedentary ~1.2 met	I	21.0	25.5
	II	20.0	26.0
	III	19.0	27.0
Conference room Sedentary ~1.2 met	I	21.0	25.5
	II	20.0	26.0
	III	19.0	27.0
	IV	17.0	28.0
Auditorium Sedentary ~1.2 met	I	21.0	25.5
	II	20.0	26.0
	III	19.0	27.0
Cafeteria/ Restaurant Sedentary ~1.2 met	I	21.0	25.5
	II	20.0	26.0
	III	19.0	27.0
	IV	17.0	28.0
Classroom Sedentary ~1.2 met	I	21.0	25.0
	II	20.0	26.0
	III	19.0	27.0
	IV	17.0	28.0
Kindergarten: standing/ walking ~1.4 met should this be 1.2 like other sedentary	I	19.0	24.5
	II	17.5	25.5
	III	16.5	26.0
Department store Standing—walking ~1.6 met	I	17.5	24.0
	II	16.0	25.0

(continued)

Table 3.3 (continued)

Type of building/space	Category	Operative temperature [ºC]	
		Minimum for heating (winter season), ~1.0 clothing level	Maximum for cooling (summer season), ~0.5 clothing level
	III	15.0	26.0

one meet is equal 58 W/m^2. Another definition can be the 1.0 met is the equivalent energy for burning approximately 1 kcal, per kg body weight, per hour.

For design buildings and dimensioning of room conditioning systems, the criteria of thermal comfort (the minimum room temperature in winter and the maximum room temperature in summer, Table 3.3) are used as inputs for calculating heating load (EN 12831) and cooling load (EN 15255). These will ensure that the maximum/minimum room temperature can be achieved in the external design conditions and internal design tasks. The ventilation rates used for sizing the equipment must be specified in the design (EN 13779, EN 15241, EN 15242).

The criteria are used as input values, for HVAC systems dimensioning, as well as for buildings design (facades, orientation, solar shading, etc.). The use of a higher references category for the buildings, will lead to higher capacity systems, but not necessarily with higher energy consumption. In building design, normally, it will be using the average external temperature for heating and standardized reference day (including solar charge) for cooling.

3.4 Visual Comfort

The visual comfort in the different rooms, according to EN 12665, is defined as a subjective human condition vis-à-vis the visual wellbeing of occupants satisfied by visual environment. This definition implies that is a psychological dimension to the visual comfort. However, several physical properties of visual environment are defined and used to evaluate its visual quality in objective way [6]. The visual conditions are characterized by following parameters: the luminance distribution, uniformity of light, the brightness, color of light, the color rendering, the glare rate and amount of daylight. The visual comfort is correlated with standard requirements for lighting and natural lighting, necessary to satisfy the wellbeing of users, and is influenced by following factors: the natural light, lighting of interior spaces, the exposure to sunlight, glare of the objects, the color perception, the light source color, the light source, the visual intensity and destination of room [12, 27].

The visual comfort is very important, at same time, for wellbeing and productivity of occupants the buildings. The specialists in field have carried out several previous studies, through which they analyzed the effect of visual comfort on productivity and performance the work, on comfort and satisfaction of the people, which are the direct beneficiaries of the buildings. In the specialty literature, the need for windows and visual therapeutic impact of natural environment is well established [16]. Thus, the glass surface of windows must be at least 10% of the useful surface of the room, for which the window is dimensioned. It is a mandatory design condition to ensure the proper natural lighting during the day. Windows are highly favored construction elements in building envelope, due to light of day that they deliver and for ensuring the visual contact with external environment. Therefore, for safety in exploitation, it is very important to ensure the necessary surfaces of windows with own safety systems, so as not to cause visual or thermal discomfort or loss of privacy [6].

The lighting conditions (quantity, intensity, clarity, color, warm/ cool white, etc.) and views from workspace, determine visual comfort quality. Light is a necessary part of human health and wellbeing. Light affects people's mood, the emotion and mental alertness. It can also support and adjust circadian rhythms and influence the physiological and psychological state of people, when they are inside the buildings [51]. For wellbeing of occupants and energy economy, in most cases, daylight is preferred. Insufficient natural light or increased brightness reduces the ability to see and clearly and correct perceive the objects or details, [4]. Architectural design of buildings has important and direct impact on office lighting. And the lighting of workspaces has direct and major impact on wellbeing and productivity people. Both natural and artificial lighting are essential to ensure wellbeing of occupants. Artificial lighting becomes just as important in areas where natural lighting is lacking or when natural light fades or disappears completely: in the evening, during the night and the early morning [27].

Visual comfort from workplace has significant impact on the comfort and wellbeing of the people and after work schedule. Over the years, there have been several studies that analyzed the impact of visual comfort on the quality of sleep at home, outside the work program. These studies documented the differences of impact according to several parameters (sex, age, season, etc.), on the general levels of discomfort but also on the health status of people. Some features of visual comfort from buildings have a significant impact on the physical and psychological health of occupants. These characteristics can be specified: the type of view, quality of the visualization, the social density. For example, offices with high density and open plan design have a negative influence on visual comfort. In long term, this negative effect influences the wellbeing of occupants. Orientation towards the cardinal points and dimensions of windows, photometry of surrounding surfaces, glazed surface of facade gaps, and others, all have a major impact on the lighting levels from a work area. Providing visual comfort plays a very important role in the productivity, comfort and overall wellbeing of occupants. For this reason, excessive use of artificial lighting in buildings should be avoided as much as possible. Nevertheless, it (still) retains a certain level of optimal normality [5].

The lighting system must provide adequate illumination to ensure safety and enable movement of humans, contribute to visual comfort and satisfy visual performance and normal and real color perception. The main analyzed parameters include the quantitative physical measures of luminous environment (illumination, luminance, natural light and glare) and qualitative aspects of vision (distribution, uniformity, color rendering, spectral composition of radiation). A significant part of illumination of spaces must be provided by natural light through the glazed area of facades and roofs, which facilitates view to outside of buildings and it ensures necessary relationship between a human being and the environment, contributing to wellbeing of occupants [29].

The degree of visibility and visual comfort have great variation depending on the type of activities inside buildings, as well as duration of lighting time intervals required in different workplaces (EN 12464-1, EN 12193). For the activities from buildings and workplaces or recreation areas, which require certain visual conditions, the necessary lighting criteria are presented in Table 3.4. According to EN 12464-1:2011, the main lighting requirements are determined by satisfying three basic human needs: visual comfort, human performance and visual safety.

Glare is measured with luminance meters or luminance cameras, both of which can determine luminance of objects within small solid angles. The International Commission on Illumination (CIE) so defines glare: visual conditions in which there is excessive contrast or appropriate distribution of light sources that not disturbs observer or not limits the ability to distinguish details and objects. The CIE recommends the unified glare rating (UGR) as quantitative measure of glare in given environment.

Table 3.4 Examples of design illumination levels for some building and spaces from EN 12464 (2011)

Nr. crt	Type of building	Space	E_m [lx]	UGR [−]	R_a [−]	Remark (m)
1	Office buildings	Single office	500	19	80	at 0.8
		Open plan office	500	19	80	at 0.8
		Conference rooms	500	19	80	at 0.8
2	Educational buildings	Classrooms	300	19	80	at 0.8
		Classrooms for adult education	500	19	80	at 0.8
		Lecture hall	500	19	80	at 0.8
3	Hospitals	General ward lighting	100	19	80	at 0.8
		Simple examination	300	19	80	at 0.8
		Examination and treatment	1000	19	80	at 0.8
4	Hotels and restaurant	Restaurant, dining rooms	–	–	80	at 0.8
5	Sport facilities	Sport halls	300	22	80	at 0.1
6	Wholesale and retail premises	Sales area	300	22	80	at 0.8
		Till area	500	19	80	at 0.8
7	Circulation areas	Corridor	100	28	40	at 0.1
		Stairs	150	25	40	at 0.1

Where E_m—maintained luminance at working areas, [lx]; UGR—Unified Glare Rating limit, [−]; R_a—color rendering index, [−]

Unified Glare Rating (UGR) is an indicative rating for glare, based on prescribed set circumstances in lit environment. Glare sources within typical field of vision on lit environment can be numerous, including daylight from windows and internal lighting. The UGR value is calculated using a complex equation that includes the luminance value of luminaire, value of background luminance, the solid angle of luminaire as seen by viewer and several other values.

The color rendering index (Ra) defines ability of light source to identify colors and is measured on scale of 1–100. On this scale rendering of 1 is monochromatic light and rendering of 100 is natural sunlight. So, it may think of this scale as measure of quality the light produced by certain source.

In each room of buildings, the necessary lighting criterion can be met if daylight is allowed to provide full or partial illumination of space in question. For time of day, when daylight is lacking, it is necessary to provide sufficient light through artificial lighting. The classification of availability for natural lighting is detailed as function the daylight factor, in specific standards, [21, 23].

The windows with reduced glass surface area provide a small amount of light. This leads to dissatisfaction for occupants due to visual discomfort and concomitant use of artificial lighting, which will lead to additional energy consumption. At the same time, windows that have too large glass surfaces and that are not protected by specific shading systems, can lead to overheating. This is another disadvantage, which will create discomfort to users and will result in additional energy consumption.

In residential, social-cultural and other buildings, daylight can enter in the indoor environment through the windows or skylights located on the roof or a combination of both. The contribution of daylight will vary depending on illumination level, direction and spectral composition. Variation in time, respectively moment of day from sunrise to sunset, offers variable models of modeling and luminance. This aspect is perceived as beneficial for the health and wellbeing of people from the indoor environment. A good daylight distribution depends on the illuminated area size due to daylight, compared to the area that is not illuminated by daylight.

3.5 Indoor Environment Quality

Indoor air quality (IAQ) is an important issue in the field of construction, which should concern both designers and specialists in charge of building maintenance, [58]. The indoor air quality problem has major impact, both on short and long term, on health and wellbeing of occupants, [44, 56]. Currently, there are two common strategies in building design that are used to secure indoor air quality in new or existing buildings. The first strategy refers to improvement of indoor air quality by increasing the speed of ventilation, which has a first effect of reducing pollutants from the indoor environment [7]. The second strategy aims to reduce sources of pollution inside and outside building. Reducing pollution from outside of buildings will reduce introduction of pollutants into the indoor air [14].

Recently, research shows that an increased rate of natural ventilation, namely outdoor air supply in protected environment, improves indoor air quality and reduces air pollutant concentration. The rate at which air is supplied from outside the building must be proportionate to pollutants in the interior environment. The amount of pollutants in buildings varies directly in proportion to occupancy of the spaces and number of occupants. Therefore, the old or new buildings must be equipped with automated mechanism that accurately assesses the concentration of indoor pollutants. Accordingly, it must have the ability to vary the inlet rate of the outside air, according to internal requirements, [8, 9].

The significant sources of internal pollutants are due to the use of certain construction materials, operation of different equipment, but also due to occupants. Presently, the new tendencies in developing ecological constructions are focused on several directions. The most important ones are use of environmentally friendly building materials, which have low level of pollution, and the efficient management of indoor air quality through appropriate air handling systems [24, 25].

Ensuring indoor air quality leads to an important field of research in the context of major climate change and irreversible depletion of non-renewable energy resources. Therefore, changing the paradigm of thinking in the field has opened up wide research area of specialty literature, which aims to use natural ventilation to ensure the indoor comfort. Natural ventilation system must be appropriate for the built environment which it serves. If the modern buildings are properly designed, these systems can have the potential to deliver considerable energy savings, precisely from reducing the need for cooling or ventilation of the indoor air. Nowaday, there exist statistical databases that indicate as that occupants of naturally ventilated buildings have less symptoms specific to sick buildings syndrome, compared to people that live and/or use buildings equipped with indoor air conditioning systems.

There are situations when the natural ventilation can have harmful effects on human health. This can happen in large cities with significant urban sprawl, where outdoor air pollution levels are high. Exposure of people to particulate matter (PM) and ozone has major negative impact on wellbeing and health of the occupants [11]. Unlike the natural ventilation, in the mechanically ventilated buildings there is in composition of air conditioning units, in general, the multiple filtration mechanism, before outside air enters the indoor environment. Because the naturally ventilated buildings don't have these mechanisms of filtering the outside air before it is admitted in the indoor environment, uncontrollable concentrations PM and ozone may be reached. In the indoor environment, the ozone concentration depends on several parameters: ozone concentration from outside air, the air exchange rates, the indoor emissions, size of surface that ensures air exchange rates and the chemical reactions from indoor air.

The investigation of the general quality of the indoor air implies good knowledge of biology, chemistry and physics. In literature, different methodologies are presented, which are recommended for assessment of the indoor air quality [46].

These methodologies, presented by the two authors, are based on multiple experiments that include the study of bio markers, study of specimens and individuals, laboratory studies in which tested individuals are exposed to controlled environmental conditions.

At present, there are not enough studies related to the direct or indirect influence of indoor air quality to occupants of buildings. What is missing from the most analyzes already carried out, are the studies on physiological state of occupants, impact of indoor air quality to occupants, as well as the reaction human body to indoor air quality. This leads to development different types questionnaires regarding the satisfaction of occupants. All the information and data thus collected are analyzed together with indoor air quality parameters [59].

The indoor air quality is ensured by the ventilation rates, the relative humidity of indoor air and exposure limits at pollutants from interior air, (CO_2 content, other gases, airborne particles and smells). Establishment of indoor air quality are based first of all on indirect measuring the intensity of ventilation and number of indoor air exchanges per hour (ventilation rate). When the standard requirements for the ventilation rates are reached, measurements for specific pollutants can be made, so that specifications of the current standards and norms are met, [20].

3.5.1 The Design of Ventilation Rates in Buildings

The design calculated ventilation rates have two components (a) the ventilation for pollution produced by occupants (bio effluents) and (b) the ventilation for pollution from building and systems. For each category, the ventilation is sum of these two components as illustrated in follow Eq. (3.1), [22].

$$q_{tot} = n \cdot q_p + A \cdot q_B, \tag{3.1}$$

where

q_{tot} = total ventilation rate from room, [l/s]; n = design value for number persons in room, [−]; q_p = ventilation rate for occupancy per person [l/s/person]; A = room floor area, [m^2]; q_B = ventilation rate for emissions from building, [l/(s·m^2)].

According to EN 16798 (2017), [22], ventilation rates for occupants (q_p), [l/s/person], are listed in Table 3.5, and ventilation rates (q_B), [l/(s·m2)]; for emissions from building are presented in Table 3.6.

There is no single common standard for all requirements that ensure the indoor air quality. Indoor air quality can be expressed either as required level from ventilation of building spaces, or as permissible limits of CO_2 concentration.

There is a general concept which accepts that indoor air quality is directly influenced by several factors: emissions from people (heat, odor, humidity, CO_2), correlated with their activities, vapors and odor from construction materials and furniture,

Table 3.5 Ventilation rates for occupants (q_p), [l/s/person] EN 16798 (2017)

Category	Expected/ percentage of dissatisfied	Airflow per non-adapted person, [l/s/person]	Airflow per adapted person [l/s/person]
I	15	10	3.5
II	20	7	2.5
III	30	4	1.5
IV	40	2,5	1.0

Table 3.6 Ventilation rates for emissions from buildings (q_B), [l/(s·m^2)] EN 16798 (2017)

Category	Very low polluting building	Low polluting building	Non low-polluting building
I	0.5 [l/(s·m^2)]	1.0 [l/(s·m^2)]	2.0 [l/(s·m^2)]
II	0.35 [l/(s·m^2)]	0.7 [l/(s·m^2)]	1.4 [l/(s·m^2)]
III	0.2 [l/(s·m^2)]	0.4 [l/(s·m^2)]	0.8 [l/(s·m^2)]
IV	0.15 [l/(s·m^2)]	0.3 [l/(s·m^2)]	0.6 [l/(s·m^2)]
Minimum total ventilation rate for health	4 [l/s/person]	4 [l/s/person]	4 [l/s/person]

from the HVAC system itself. Usually, the last two sources specified are called building components.

Ventilation rate required in different spaces is based on health and comfort criteria occupants. In most cases, correlation between the interior environment quality with health criterion will also be fulfilled by a necessary ventilation that ensure the indoor comfort level. Some effects on occupants' health and wellbeing may be attributed to the specific emission components. Thus, if the concentration of one source may be reduced, then by default, concentration of other sources will be reduced. Otherwise, these will determine a certain level of discomfort. Indoor air quality is also linked to perception indoor air quality. In some situations, different emission sources may have an odor component that adds at the total odor level of a building. However, there is no general agreement on how to quantify different emission sources.

3.6 Acoustic Comfort

Acoustic comfort is ensured when there is an acceptable level of noise in buildings. The perception of sound is complex issue that depends on sound intensity and its temporal and spectral features, but also activity of person, state of mind and her personal expectation [28]. The noise is defined (DIN 1320) as "the sound occurring the frequency range of the human hearing and which disturbs silence or intended sound perception, that can result in annoyance or endangers health". The sound is defined as wave move from sound transmitter and varies according to frequency and pressure.

According to specialized literature, acoustic comfort is ensured when all individual requirements of participants, imposed and required at certain auditory event, are met. Other authors have defined acoustic satisfaction as state of contentment under different conditions of exposure to airborne or impact noise, including the personal annoyance, the internal noise and distraction, [37].

Currently, there is no standard definition for acoustic quality or acoustic satisfaction. Isolation of unwanted sounds and the presence of pleasant sounds are the main criteria that ensure good acoustic environment [31–33].

The acoustic quality from buildings is multidimensional and includes several types of different variables, which are influenced as follows [17, 45].

- Physically of size and intensity of the sound field,
- Psychologically from level of auditory evaluation and
- Psycho-acoustically aware of auditory perception.

The acoustic quality of buildings can be influenced and achieved by appropriate sound insulation and absorption. Reduction of unwanted exterior noise (i.e. especially from road, rail and air traffic) is ensured by efficient sound insulation measures for facades, roofs and windows. This insulation is important in terms of interior protection of the building and for ensuring acoustic comfort in the indoor environment. Also, interior and impact noise can be reduced by proper sound insulation of floors, partitions walls and doors. The main and important sources from the buildings interior, which should not be neglected, are the presence of neighbors, the indoor air conditioning systems and the different appliances or devices.

The sound produced inside a space can be amplified due multiple reflections. The amplified sound level causes deterioration of speech intelligibility and presence of unacceptable noise levels from internal sources. For this reason, shape, quality and total quantity of absorption play decisive role [52, 53].

Any source of noise can cause the attention to disappear, can stress or upset, which leads to fatigue, and—in some cases—can even damage human hearing. It is known that single high-level sound event, such as 130 dB, it may favor hearing loss at least for one person. Then, continuous exposure to sound levels greater than 85 dB can lead to gradual hearing loss. At the same time, significantly lower sound levels can affect human health. Any person exposed to inappropriate sound levels for a long period of time, will suffer both from health and wellbeing perspective. Nevertheless, even very low noise level of 35 dB can affect human health, causing some metabolic changes. If these noises occur during periods of silence, then insomnia may occur, which will cause serious sleep disturbances. Recent studies show that guilty of these effects is not just the difference in sound pressure level. The frequency characteristics of harmful sounds affect degree of annoyance resulting, which leads to emotional discomfort [35, 41].

In the past, noise's negative effects were only associated with impaired hearing. But nowadays, it was also established that prolonged exposure to noise can cause wide range of health problems. These include hearing impairments, cardiovascular problems, psychological problems, stress, sleep disorders and distress. At the same time, exposure to noise can also have negative effects on wellbeing of occupants, their cognitive performance and attention.

3.7 Conclusion

In the present chapter are described minimum performance requirements for quality of the indoor environment defined in current design standards and norms. These are the basic conditions for wellbeing of the occupants. The most important principles of buildings design must considered all this, so that it results in an energy efficient building and a healthy indoor environment for occupants. In the same time, the health and wellbeing of occupants is a priority, and it must be insured from all points of view.

Design principles, initiatives and tools that encourage energy efficiency culture and active involvement of occupants should be increasingly used. Otherwise, the potential of innovative built environment remains largely untapped.

Main purpose of high performance energy efficient buildings is to increase the sustainability of the built environment, while ensuring long term wellbeing of occupants. Unknown requirements for wellbeing of occupants can lead to failure in adopting the performance levels. Thus, the disinterest and disappointment of occupants of buildings may occur.

The future of residential and non-residential buildings design, lies in the ability of the built environment to adapt at performance requirements of indoor environment and also to the external environmental conditions. This is a real challenge for future standardization and paradigms changes in this field.

The need to direct designers' attention from the measurable physical parameters which are used to evaluate the performance of indoor environment quality (thermal, visual and acoustic comfort, the indoor air quality) to performance parameters of users' wellbeing, has a greater impact on the overall satisfaction of occupants from the built environment.

3.8 Key Terms and Definitions

Acoustic comfort: is very important for human existence and for human activities, therefore must be correlated with the hearing needs of each occupant.

Energy-efficient buildings: buildings that are designed to require small amounts of energy for operation and which are capable (as by their own operation) to provide some of the necessary energy, and the rest to be obtained from renewable or free sources energy.

Hygrothermal comfort: is ensured by the appropriate values of parameters that define optimum comfort conditions, such as: indoor air temperature, the surface temperature of surrounding surfaces of a space, the indoor air relative humidity, the speed of air currents.

Indoor air pollution: the health status of occupants is directly influenced by indoor air quality provided by accepted quantities of CO_2, odors, particles or the total absence of gases or microparticles responsible for the occurrence of certain diseases.

Indoor environment: is the environment delimited by various construction elements, which has the role of ensuring all human activities, care of animals and plants.

Indoor environmental quality: represents the fulfillment of all criteria and levels of performance, which must be ensured by any built environment, so that each occupant is safe and feels good.

Lighting Comfort: the quality, the quantity, the color of the light (natural or artificial) that contributes to a considerable extent for the satisfaction of the occupants.

Ventilation Rate: is the volume of fresh air, rich in O_2, which replaces the stale air from the spaces occupied by humans (naturally or mechanically ventilated), at optimum time intervals.

Visual comfort: ensures the wellbeing of people through the surrounding images, through the quality of finishes as well as through the permanent visual relation with environment.

Wellbeing of occupants: refers to occupants satisfaction, from all points of view of existence of the human genome, which exploits any environment constructed or arranged from a construction.

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Chapter 4
The Investigation of the Relationship Between Exposure to Nature and Emotional Well-Being. A Theoretical Review

Timea Buru, Éva Kállay, Maria Cantor, and Ionel Papuc

Abstract In many modern societies, urbanization, resource exploitation, and lifestyle changes have diminished humans' possibilities to get in contact with nature. Research on urban green areas and human well-being has based on landscape preference, and social scientists and public health researchers have been studying how various aspects of human health and well-being are affected by exposure to green spaces. Considering the role of the natural environment, and the relationship between people and plants, additional principles of social and therapeutic horticulture can be explored, as meaningful activities, within a social environment or context. The motivation of the review is to gather and analyze the work done in recent decades, highlighting the relationship between exposure to nature and emotional well-being.

Keywords Well-being · Urbanization · Horticulture therapy · Therapeutic horticulture

4.1 Introduction

In the twenty-first century urbanization has spread rapidly throughout the globe, and today more de 50% of the people are living in urban environments [10, 42]. Based on the total number of individuals living in cities in 1950 (0.75 billion), compared to 2018 (4.22 billion), humans became officially an urban species [81, 92]. Almost 30 years later, according to the World Urbanization Prospects, the proportion of Romanian population living in urban area was 56.9% [82]. This proportion is expected to exceed 68–70% [31, 91], and by 2050, 9 billion people around the globe (i.e., 75%) will live in cities in [45].

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In many societies, this uncommon migration from rural areas to urban areas was found to be associated with the reduction of the time spent in natural spaces [10, 14, 66]. The effect of urbanization brings changes at all levels of resource exploitation, lifestyle and access to maintain contact with nature [28]. Throughout the last 200 years, agriculture has acquired an important role in treatment, rehabilitation and/or residential care of individuals with disabilities. Observation conducted on people who were required to work outside (e.g., gardening), lead to the recognition that being occupied with responsibilities and tasks in open air facilitated rehabilitation and returning to the community [59]. According to this, in 1933 Dessa Hartwell wrote: "*Even workers in the field of occupational therapy have hardly begun to realize the therapeutic effects of working in or with the soil and its products*" (as cited in [59], p 315).

Similar studies evidence a relationship between environmental interventions made by design strategies and healthcare outcomes [13, 80]. The constructed environment must be recognized as a health-promoting and health-protecting asset that can extend life, improve its quality and increase overall well-being [91]. According to EPA—United States Environmental Protection Agency, 93% of Americans and 90% of Europeans spend between 22.32 to 21.6 h indoors in a day [41, 45]. High level of social cohesion, in which feeling emotionally safe is associated also with the lack of crime, violence and aggressive behavior, creates a link between access to green areas and contact with nature and health [28].

Further research indicates a link between access to nature and reduced depression [13, 21, 24, 26, 51, 69, 88, 90], increase in physical, social, emotional and cognitive functions [3, 20, 56, 78], reduce self-reported anger and fatigue [28], anxiety [28, 39, 43, 60, 70, 71], stress [26, 30, 39, 84], social isolation and loneliness [32].

This chapter reviews the connection between people-plant interaction in the field on mental health. The motivation of the review is to gather and analyze the work done in recent decades, highlighting the relationship between exposure to nature and emotional well-being. This paper has a two-fold purpose, firstly, to redefine the nature-based interventions in the urban areas, and secondly, to analyze the results obtained by the scientific literature using therapeutic horticulture activities in order to enhance mental health benefits. In Romania, the percentage of people living in urban areas is continuously increasing, and an urban development that facilitates well-being, mental and psychical health can have a positive effect on the inhabitants. In the case of indoor environments, the built space can generate a state of attachment and isolation, having a negative effect on people's social relationships. According to the existent research, the integration of the green environments can have a positive effect within the constructed cities, influencing people's health, behavior, and their psychological states. Considering the specific importance of this topic, it can be stated that the design of the built environment has important role for mental health, promoting well-being.

4.1.1 Exposure to Nature

Using nature to nurture good health is not a new idea [62], and several research studies have indicated that the urban landscape and human well-being have a specific layout pattern, as social and public health scientists proved a connection with human well-being and health influenced by the exposure to natural environments in urban areas [5, 37, 50, 76]. Spending time outside in nature, and in case of cities in urban green spaces has a beneficial effect on people health different conditions [17]. Nature, in most of the contexts, can be defined as an environment created by nonhuman processes, like a natural forest and national park with a specific flora and fauna. Also, the anthropic action in the environment made natural areas or green zones [28], designed as parks, community gardens, urban forests and botanical gardens where people can have a connection with vegetation. Evidence of the positive relationship between exposure to nature (incorporating a variety of outdoor settings, from the open countryside, fields and forests, to street trees, allotments and gardens) influence individual's health [62].

Viewing and admiring the natural landscape through a window [77], using a significant area of green space in the constructed landscape [49], obtaining access to a proximate green space as a public garden and park [12] are aspects which may be associated with different aspects of health [17]. A study conducted by Ekkel and de Vries [17] has evidenced the existence of a relationship between metrics evaluation, proximate green space in urban planning and human health. Analyzing this study, it can be noticed that the type of landscape architecture, proportion, distance and quality of green spaces are relevant in terms of well-being in the urban areas. Several research studies evidence that, natural environment and urban green areas, presented that people who have access to some forms of nature inside built environments have had reduced levels of cortisol [85], plants may play a relevant role in frustration tolerance, evincing a higher frustration tolerance during the experimental studies on roadside vegetation [11], a better access to green space is associated with lower depression incidence [12, 24, 26].

Urban green areas can also have a positive effect on sensory stimulation and experience, increasing the use of sight, hearing, touch, smell and taste [17] and the health benefits of contact with nature are evidence-based [28].

Most people feel good in nature, and the time spent outside in green environments improves mood, gives energy and vitality, refreshes and facilitates recovery [40, 45]. In accordance with this, Erich Fromm [19], social psychologist defines the biological need to be in contact with nature as biophilia—the passionate love of life and all that is alive.

The term forest-bathing, or *Shinrin-yoku* (taking the atmosphere from the forest) [36] in Japanese, was coined for the first time in 1982 by Tomohide Akiyama, the director of The Ministry of Agriculture, Forestry and Fisheries, in Japan. He admitted that people from Japan need the help of healing given by nature [45]. *Shinrin-yoku* is a relaxing activity in which the recreation is achieved by visiting a nearby forest, field [47] and the benefits of practicing *shinrin-yoku* even in urban forests are:

- relaxation, relief and recreation [47]
- lowers blood pressure [45] and blood glucose [47, 54]
- reduces the concentration of cortisol in saliva [42, 47, 72, 75, 89]
- improves the cardiovascular and metabolic health
- improves the concentration and memory
- helps in weight loss
- increases the energy level [45]
- the human immune system (NK cells), identifying an increased anti-cancer proteins activity [46, 47]
- decreases anxiety, stress, anger and depression levels [45, 79]

Another evidence-based method is the exposure to nature, in which human-plant interaction is accomplished by practice as *horticulture therapy*, a comparatively young profession, but dating from ancient times [65]. More recent studies indicate that contemplating nature can positively affect social and psychological well-being, having a stress-reducing effect and restorative benefits for humans [80].

Scientific research illustrates a correlation within several markers of well-being and connection with nature, concluding positive effect in recent studies regarding these benefits [28]. The evidence-based results conclude that the benefits of nature-based activities like gardening, having a positive impact on physical, social, emotional and cognitive development on people. Having considered the role of the natural environment, and the contact between people and plants, horticulture activities are well integrated in the social and therapeutic horticulture interventions.

According to Sempik in his report Green Care: A conceptual Framework, green care can be integrated in different therapy programs. Landscapes in the urban areas are places in which approaches as *horticulture therapy* (HT) and passive connection with nature can increase health and well-being in the natural environments Fig. 4.1 [36, 62].

Gardening, the active therapeutic potential of nature, is an attractive activity in the United States. According to the statistics which analyze the most frequent leisure

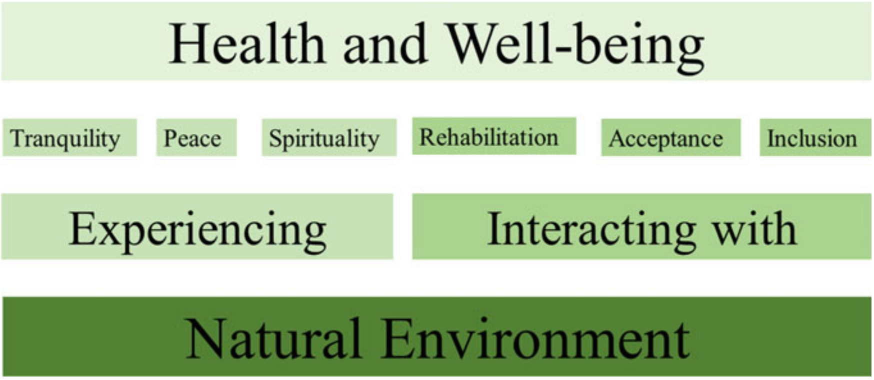

Fig. 4.1 Principles of Social and Therapeutic Horticulture—THRIVE (Reproduced from: [62])

time exercise in case of the people aged 65 years and older, gardening is the second most frequent activity succeeding walking [68]. The natural areas can influence the health of the people [28] and can be a unique therapeutic intervention within nature to well-being [36]. The active or passive *therapeutic horticulture* intervention can have a restorative effect on long-term physical conditions and mental health [44]. Interactive activities (active horticulture therapy) refer to the activities which we can do in nature where the activity itself involves shaping that nature. The landscape architecture design of therapeutic gardens tends to promote interactive contact with nature [25].

Today, *horticultural therapy* has followed trends within health and social care—moves towards person-centered and evidence-based approaches Table 4.1.

Scientific journals also evidence results regarding the restorative effect of nature, research conducted more intensely starting with 2004, concluded that results indicated reductions in self-reported anger, fatigue, anxiety, and sadness and an increase in feelings of energy [28, 67]. Also, original data yielded that, during the experimental research it was intended to decrease the level of depression for the participants involved in therapeutic horticulture activities. Measurements were made considering psychological aspects using Beck Depression Inventory and physiological conditions by assessing the changes in the contribution of biological biomarkers. Over the effect of *therapeutic horticulture* (TH) activities during ten sessions, changes in tryptophan biomarkers contribution and decreased depression level was observed [33].

The abbreviations contained in the table: (AFI) Attentional Function Index, (BDI) Beck Depression Inventory, (BDNF) Brain-derived neurotrophic factor levels, (DASS21) Depression Anxiety Stress Scale, (DCM) Dementia Care Mapping, (DHS) Dispositional Hope Scale, (K-MMES) Mini Mental State Examination, (KYN) kynurenine, (KYNA) kynurenic acid, (LRI-R) Life Regard Index—Revised version, (LSIA) Life Satisfaction Inventory A, (MMSE) Mini-mental Status Exam score, (PANAS) Positive and Negative Affect Schedule, (PDGF) platelet-derived growth factor, (POMS) Profile of Mood States, (PRS) Perceived Restorativeness Scale, (PWBS) Psychological Well-being Scale, (PWI-C) Personal Wellbeing Index, (SOC13) Sense of Coherence Scale, (SQUASH) Short Questionnaire to Asses Health, (TMD) Total mood disturbance, (TR) tryptophan, (VEGF) vascular endothelial growth factor, (WBA) Work Behavior Assessment.

Analyzing the relationship between exposure to nature, the proximity of urban green spaces, the frequency visits in nature, the duration of stay, longevity, risk of mental illness and level of self-reported stress experienced are corelated [1, 15, 27, 52, 74].

In the analysis made by researcher Hartig can be observed the interaction between how natural environment can influence people health. Based on this, four of the mentioned pathways interact with nature and natural environments, and other two evidence air quality and tress factors, in accordance that the mentioned pathways may affect health conditions. Also, a relationship between natural environment and contact with nature can be demonstrated, because of a bidirectional relationship. An interconnection between the following aspects: stress, social contacts, physical activity and air quality, and related pathways, seem to influence each other [28].

Table 4.1 Data base analysis—research design active HT/TH practice—Health outcome

Study	N participants	Female %	Mean age	Study data on the duration/season	Tests
[60]	6 experimental subjects 10 control subjects 16	100.0	84.7	150 min	indoor classroom positive/negative mood, anxiety, salivary cortisol
[22]	19—initially 14	45.8	80.0	9 weeks 3 times/week 27 sessions 30 min	(DCM) (MMSE)
[23]	48	–	83.0	9 weeks 2 times/week 18 sessions 30 min	(DCM)
[86]	220 experimental subjects 223 control subjects 402 (443—initially)	72.8	–	4 months, July–October	(LSIA)
[88]	59 experimental subjects 48 control subjects 107	39.3	–	60-min	mood state and heart rate (POMS), (TMD)
[24]	18 experimental subjects (22—initially)	88.3	49.7	12 weeks 2 times/week 24 sessions 90 min	(BDI), (AFI)
[25]	21 experimental subjects (28—initially)	100.0	44.1	12 weeks 2 times/week 24 sessions 90 min	(BDI) (AFI) (PRS) and Brooding
[39]	12 experimental subjects 10 control subjects 22 (24—initially)	29.2	44.3	2 weeks 2 times/week 10 sessions 60 min	(DASS21) (PWI-C) (WBA)
[68]	156 experimental subjects 103 control subjects 261 (298—initially)	59.8	Over 50	1 quality-of-life survey and	(LSIA)

(continued)

Table 4.1 (continued)

Study	N participants	Female %	Mean age	Study data on the duration/season	Tests
[84]	121 experimental subjects 63 control subjects 184	51.1	59.6	end of July—beginning of September	(SQUASH)
[26]	Study 1 16 (18—initially)	88.3	49.7	12 weeks 2 times/week 24 sessions 90 min	(BDI) (LRI-R)
	Study 2 25 (28—initial)	–	44.1	12 weeks 2 times/week 24 sessions 90 min	(BDI) (SOC13)
[61, 83]	30 subjects	73.3	57.6	30 min 2 weeks April–May	Salivary cortisol self-reported mood (PANAS)
[51]	45	100.0	35–55 years old	12 weeks 2 times/week 24 sessions 90 min	(PWBS) (DHS)
[21]	25 experimental subjects 25 control subjects 50	100.0	20.6	2 months 3 times/week 60 min	(BDI)
[90]	136 experimental subjects 133 control subjects 269	43.5	55.6	7 days 30 min Spring–summer	Self-esteem, mood and general health
[32]	8 experimental subjects (24—initially)	87.5	21.1	2 weeks 10 sessions 60 min	(BDI), urinary (KYN) and (KYNA)
[55]	20 experimental subjects 20 control subjects 40	65.0	73.85	12 weeks 24 sessions 60 min	(K-MMES), (VEGF), (PDGF) (BDNF) serum lactic acid, serotonine, (TR) and (KYN)

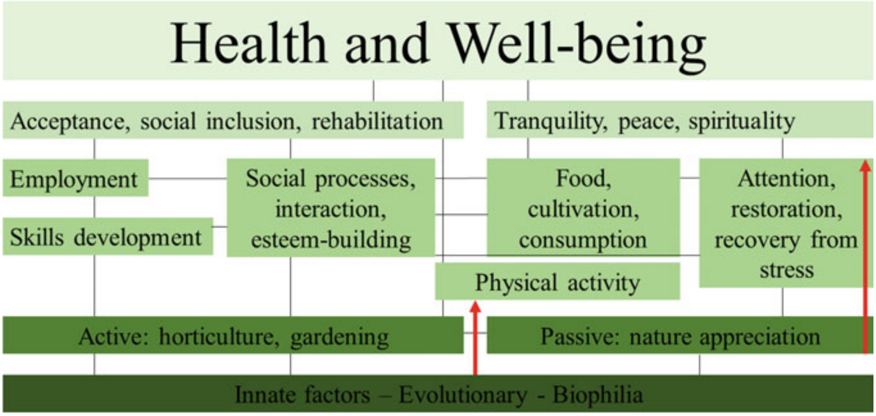

Fig. 4.2 Social and therapeutic horticulture: evidence and messages from research. (Reproduced from: [63])

4.1.2 Well-Being

Psychological well-being regards the ways in which people perceive their lives based on the interaction between their activities and psychological resources [35]. Well-being is associated with health, job and family-related benefits, and maybe that's why people with a high level of it, are considered more productive at work and add more value and attention to their communities [2]. True well-being Fig. 4.2 is related to the empowerment of individuals based on autonomy and feeling of well-being. Green care provides many possibilities to exert control over events and situations and offers opportunities for free choice and development of skills [62].

The notion of well-being is corelated with the characteristics of a good life, and was studied as a two-faceted phenomenon, being composed of the: hedonic (related to positive mood, happiness and satisfaction) and eudaimonic well-being (reflecting the human potential) [38]. Although, recent approaches consider that happiness may be elicited from the attainment of different goals and outcomes in different life domains [16].

4.2 Main Focus of the Chapter

Until the middle of the twentieth century, with all the progress made by developing the industry, Romania remained a country with a predominantly rural structure, with a low level of urbanization (23.4% in 1948), and the geographical form of the territory, as well as the history influence of the eastern part of the Europe, made the Romanian society maintain its generally rural features. Regarding to the gradual process industrialization in Romania between World War I and World War II, the number of Romanian cities increased from 119 cities in 1912, to 152 in 1945. Between 1950–1989, Romania's development model, as in the case of the other Central European communist countries, was based on extensive industrialization, and as a result, by 1986 more than half of the country's population was already living in cities [53]. According to the actual date, today in 2020 Romania has 320 cities and over 10,507,365.00 people are living in urban areas [93].

Population growth and urbanization add to the challenge of protecting people from its harmful effects [91]; the population in urban areas regarding Romania evidence an increased percentage during 1950 and 2050 Table 4.2, which highlights the need to develop a national strategy to support public health, natural environments and well-being.

4.3 Solutions and Recommendations

Dr. Benjamin Rush is often credited as being the father of modern therapeutic horticulture as a result of his observations of the benefits of farm and field work in American asylums [6] in one of his writings, we find the words: "*digging the soil has a curative effect on troubled souls*" (as cited in [61], p 226). In addition, using horticulture as an intervention has shown a reduction in depression, an increase in wellbeing and self-esteem [18], a relief in negative emotions and expressed frustration [58], and a strengthening in self-concept [57].

The natural environments are free sources of restoration, recreation and healing for people [91]. According to the listed research studied mentioned in Table 4.2, the next one Table 4.3 summarize the evidence-based effect, using HT and TH, as a tool to achieve nature exposure, people-plant interaction and well-being.

Green Prescriptions—a doses of nature, evidence the role of human connection to nature, in case of which people with good access to natural environments are more likely to have better mental well-being; an average increase of 69% in self-reported well-being during the 10–12 weeks program [7].

Several studies indicate a link between a frequency of accessing nature, duration, spending time surrounded by vegetation and health conditions in case of the urban population [64], and according to the green prescriptions results obtained by experimental studies [7] or nature-dose, nature pill, can be concluded:

- 30 min or more during a week (in case of: depression, high blood pressure) [64];
- 20 min—reduces stress hormone cortisol [34];
- 5 to 6 h each week—improving mental health [4];
- 120 min each week—associated with good health and wellbeing [87].

Table 4.2 Urban population and percentage urban—Romania (Reproduced from: [31] and [93]—Romania)

Country	Percentage of population in urban areas												
Romania	1950	1955	1960	1965	1970	1975	1980	1985	1990	1995	2000	2020	2050
	Percentage urban (%)												
	25.6	30.6	34.2	37.7	40.3	42.8	46.1	49.6	53.2	53.8	53.0	54.6	64.7

Table 4.3 Data base analysis—research design active HT/TH practice—summary of results

Study	Results
[60]	Analyzing the results achieved by the experimental group and control group during, it can be highlighted an improvement in cortisol levels in case of those how have gardening
[23]	The current study demonstrates the value of integrating many types of activities into HT programs as cooking and craft HT activities engendered responses equally as positive as planting HT activities. The use of planting activities in dementia-care programs enhances program diversity and the match between activities and participant abilities and interests
[22]	Observations were taken of HT and traditional activities, we frequently found that the scheduled traditional activities did not take place. Mini-Mental Status Exam (MMSE) was positively associated with affect expressed during HT, as participants possessing higher MMSE scores demonstrated more positive affect, on average, during HT
[86]	During gardening activities, this practice also used as a hobby enables people to spend time outside in nature, to grow different vegetables as food, meets the primary physiological needs of the human needs pyramid evidenced by Maslow
[88]	The results obtained by this experimental research study indicates that horticulture therapy sessions (HT) improves mood state and reduce stress states. According to the data which indicates that stress contributes to coronary heart disease, HT sessions can have a positive effect on cardiac rehabilitation
[24]	During therapeutic horticulture sessions, result of the research study indicate that decrease levels of depression and increase attentional capacity can be obtained by this practice
[25]	Where recruited adults with major depression, dysthymia, or depressive phase of bipolar II disorder. In case of clinical depression, during therapeutic horticulture activities, being away and fascination are influenced. Therapeutic horticulture (TH) in mental health care and further illustrates the potential utility of attention restoration theory for the design and assessment of nature-based interventions
[39]	During this research study, anxiety, depression and stress levels of those how were involved in horticultural therapy sessions had changed. But, in case of work behavior and quality of life, further study needs to be done. The result of the interviews suggests horticulture activities have a positive impact on the persons with psychiatric disabilities. It also reflected how horticultural activities could serve to achieve the goals of enhancing occupational performance and promote emotion health and social performance
[68]	Following the obtained research data, gardening activities are good alternative to gain life satisfaction and physical activity levels in case of adults aged 50 years or older, which are predisposed to lose mobility and/or exercise less
[84]	The impacts of allotment gardening on health and well-being were moderated by age. Allotment gardeners of 62 years and older scored significantly or marginally better on all measures of health and well-being than neighbors in the same age category. Health and well-being of younger allotment gardeners did not differ from younger neighbors

(continued)

Table 4.3 (continued)

Study	Results
[26]	Study 1: Recruitment targeted adults with major depression, BDI declined significantly over the course of the intervention and remained significantly lower at 3-month follow-up, as a significant indicator of a long-term health impact. This was not, however, matched by significant increase in life regard, and may have lacked sensitivity to change, or it may have treated existential issues more like trait-like phenomena than state-like phenomena Study 2: Recruitment targeted adults with bipolar II disorder with most recent episode depressive. Depression score (BDI) drop after attending TH sessions, and according to the 3-month follow-up, the obtained score remains in low measurements. The main finding in each of the two studies was that no significant change in existential issues took place, despite significant decline in depression severity during and after a 12-week TH intervention for clinical depression. There were, however, moderate positive correlations between improvements in existential issues and decline in depression severity during the TH intervention
[83]	Gardening activities had a positive effect on mood, based on the findings that HT sessions influence restoration from stress. Spending time outside in nature by gardening, after 30 min the salivary cortisol levels and self-reported positive mood were in normal parameters
[51]	Horticulture therapy indicates helpful psychological effects, on the point of interest in natural environments, improving mental health, social confidence and positive thinking. In case to this research study, result indicate increased well-being and hope reported in rural women how garden. Statistical analyses evidence that the life quality of participants was improved by gardening in a rural community setting
[21]	The results showed a significant recovery after intervention in case group based on the depression scores during therapeutic horticulture. According to this study, it seems that using purposeful activity of gardening has positive effects on decreasing depression in depressed female students. The results showed that the experimental group, depression has improved after the intervention
[90]	Well-being and mental health can be influenced by allotment gardening activities like a preventive health measure. Results evidenced that reports on self-esteem and mood were significant upgrade during gardening sessions
[33]	Regarding to the experimental study, analyzing by subjective and objective measurements, results indicate that therapeutic horticulture interventions may influence in a significant decreased level of depression and changes in the kynurenine pathway after TH. Therapeutic Horticulture activities can be a possible alternative therapy to increase people health and well-being measured by a non-invasive method
[55]	According to the research design, the gardening program was developed as a low to moderate intensity physical activity for the elderly. The results show that, in case of the gardening group, brain-derived neurotrophic factor and kynurenine levels were increased after the gardening program

4.4 Conclusion

This chapter presented a theoretical review of relationship between exposure to nature and emotional well-being. Research indicates that green urban areas may have a positive influence one human health; spending time outside in natural environments can improve the cardiovascular and metabolic health, improving concentration and memory, reducing the concentration of cortisol, improving the cardiovascular and metabolic health, decreasing anxiety, stress, anger and depression levels. *Therapeutic Horticulture* is a possible alternative form of therapy that may increase human well-being.

The present theoretical analysis reviews the fact that evidence-based research demonstrates correlations between well-being and nature (e.g. green care, natural environments) [36]; green spaces in the urban areas are promote access to nature, with an important role for public health in accordance with urbanization [64]. For future research directions, Richard Louv's who wrote the book 'Last child in the woods: Saving our children from nature-deficit disorder' [48], states that 'more high-tech we become, the more nature we need'. The value of the built environment, open space and urban landscape has been confirming by science, and not only, but the positive outcomes by people connecting with nature to achieve well-being in more recent.

The most common health/well-being outcome was some measure of an individual's emotions. Impacts on physiological variables were usually investigated on cardiovascular outcomes (e.g., blood pressure or pulse), or hormone levels, which included salivary or urinary cortisol, amylase and adrenaline [8]. Additional reading, knowledge is going to add value to the future developments in science, and assuming the implication of the built environment to people health in real, new opportunities can be identified to achieve and increase well-being [73].

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Chapter 5
Impact of Thermal Bridges in Low Energy Buildings

Mirel Florin Delia

Abstract Implementation of the European environmental directives (i,e. Directives 2010/31, 244/2012, 27/2012, 844/2018, 786/2019), as well as the national legislation (i.e. Law 372/2005 with subsequent additions and updates, MDRAP MO 386/2016, Law 184/2018) regarding the reduction of energy consumption during the use phase of buildings and CO_2 emissions, have led to the adoption of significant thicknesses for the thermal insulation of the opaque building envelope. urrently high-performance software and computing equipment is available. Yet often the modelling of the constructive details is done by "replacing" the effects of millimetre-sized metal profiles with equivalent coefficients for thermal transfer. The analyses carried out, in which the modelling of the constructive details is in accordance with the constructive solution, show that even when an important thickness of performant insulating materials is used, the thermo-energetic effect of the thermal bridges is non-negligible.

5.1 Introduction

5.1.1 The Issue of Thermal Bridges

In Romania there have been concerns since the 1980s in the development of thermal calculation programs that can model thermal bridges in 2D or 3D. Among the pioneering activities were noted Prof. Ioan MOGA [17] from the University of Cluj Napoca and Prof. Dan Preda STEFANESCU from the U.T.I. "GHEORGHE ASACHI" Iasi.

Among the programs developed by Prof. Ioan MOGA we should mention "CAMP", with the first versions running on Independent computers. For the analysis of the temperature fields, the author used the Finite Differences Method.

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Among the programs developed by Prof. Dan Preda ȘTEFĂNESCU we should mention “LAURA”. For the analysis of the temperature fields, the author used the Boundary Element Method [25].

During this period, a series of papers and books were published. Among the authors, it is noticeable the activity of Prof. Ioan MOGA as co-author of the technical norms C107, Mc001—Annex K “Catalogue of thermal bridges” [18].

Among the university publications we mention “Thermo-energetic optimization of glass elements” written by Assoc. Prof. L. MOGA from the U.T. Cluj Napoca [19, 20].

It can be considered that the analyses carried out during this period in Romania were based on modelling using equivalent coefficients for the composite materials.

In the foreign literature, the analyses focused on modelling that use equivalent coefficients for composite materials.

5.1.2 *The Modelling Program Used*

The numerical analyses are performed using the RDM 6 software (created at I.U.T. Le Mans—G.M.P. Department). The software allows analysis in the stationary thermal regime, in 2D, using the Finite Element Method FEM.

For modelling the structure, it uses isotropic plate elements.

The thermal excitation can be modelled as:

- imposed temperatures at nodes;
- heat sources;
- imposed thermal flow;
- thermal exchange through convection phenomena (convection-radiation).

In the presented analyses, the thermal excitation modelling was based on the thermal exchange through convection-radiation phenomena.

For discretization, the program can use several types of elements:

- straight quadrilateral with 4 nodes;
- curved quadrilateral with 8 nodes;
- straight triangular with 3 nodes;
- curved triangular with 6 nodes.

The main range of results offered by RDM6 are:

- the temperature field;
- the thermal flux density field;
- the value of the thermal flux on a surface;

5.1.3 *Materials and Modelling Conditions Considered in the Analyses*

For the analysed materials, the following values of the thermal permeability coefficients were considered:

- $\lambda_{\text{steel}} = 50$ W (mK);
- $\lambda_{\text{concrete}} = 1.60$ W (mK);
- $\lambda_{\text{reinforced concrete}} = 1.74$ W (mK);
- $\lambda_{\text{full bricks}} = 0.80$ W (mK);
- $\lambda_{\text{AAC bricks}} = 0.40$ W (mK);
- $\lambda_{\text{EPS}} = 0.04$ W (mK);
- $\lambda_{\text{MW}} = 0.04$ W (mK);
- $\lambda_{\text{cold flooring}} = 1.60$ W (mK).

Although some of the details presented are specific to the 1980s, and are no longer used in practice [3], the values of the thermal permeability coefficients of the component materials were considered in the analyses as being similar for the new materials.

For all the analyses, the following values were considered for the conventional temperatures of the indoor and outdoor environments:

- $\theta i = +20$ °C, specific to the main rooms of residential, offices or administrative buildings [21];
- $\theta e = -15$ °C, specific to climate zone II in Romania, during the cold season.

The reinforcement solutions of the reinforced concrete elements were considered to be those common in the 1980s, specific to the medium intensity Vrancean earthquakes, OB37 steel and diameters: 6, 10, 12 mm.

5.1.4 *Purpose*

Due to the complexities they generate (the need to use high performance computing programs, operator qualification, long modelling time of a detail, etc.) [11, 12], in most cases of thermal transfer, the details are modelled without describing the reinforcement in the case of reinforced concrete elements or thin metal profiles. Even if $\lambda_{\text{steel}} = 50$ W/(mK) and $\lambda_{\text{concrete}} = 1.60$ W (mK), it is often considered that metal parts can be neglected due to their small size, the equivalent value being used for the composite product $\lambda_{\text{reinforced concrete}} = 1.74$ W (mK).

In the last decade, the adoption of high-performance thermo-energy insulation [10] and with significant thicknesses, contributed to the "conservation" of the idea of using the equivalent permeability coefficients.

The applications analysed below aim to identify the differences of the results in the case of modelling using materials "with equivalent thermal permeability coefficients" and that of accurate modelling of the details.

5.2 Thermal Transfer Analyzes

A number of details considered to be representative from the point of view of the analyzed issue will be presented.

Among the results offered by the RDM6 program are presented the values of the following parameters:

- Φ = thermal flow; in (W);
- $\theta_{si,min}$ = inner surface temperature, minimum; in (°C).

5.2.1 *Field Areas*

5.2.1.1 Analysis Field Area 25 cm Thick Reinforced Concrete Wall

Without ETICS System

See Fig. 5.1.

The main results are presented in the following Table 5.1.

With ETICS System—10 cm EPS

See Fig. 5.2.

The main results are presented in the following Table 5.2.

5.2.1.2 Analysis Field Area 13 cm Thick Reinforced Concrete Slab, Below the Attic

Without Thermal Insulation

See Fig. 5.3.

The main results are presented in the following Table 5.3.

With 25 cm Mineral Wool Insulation

See Fig. 5.4.

The main results are presented in the following Table 5.4.

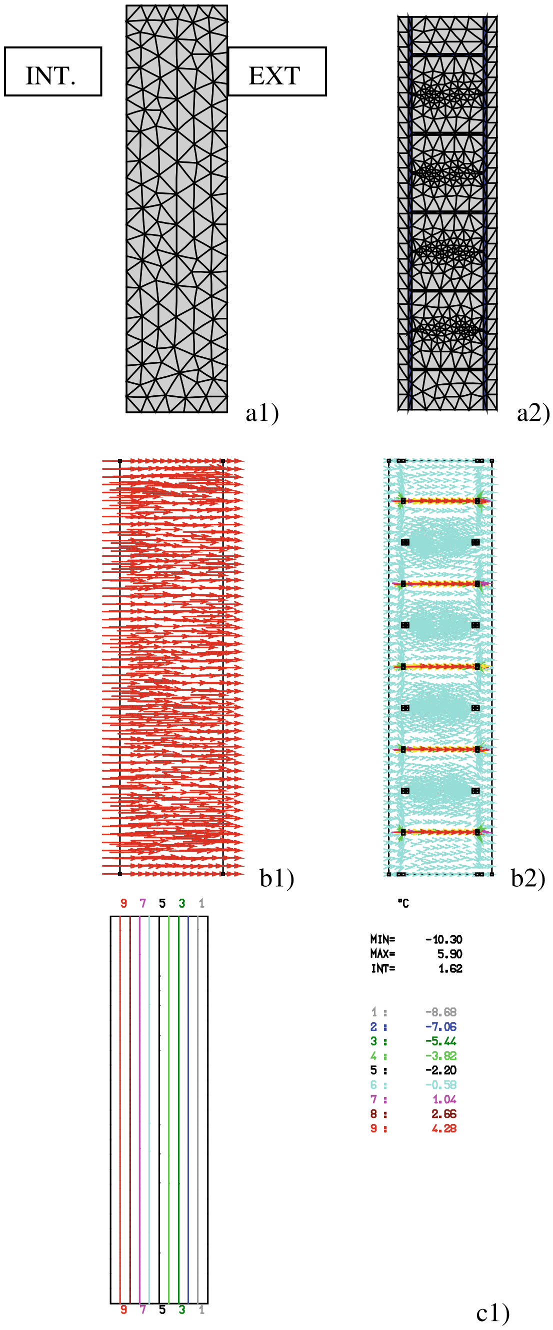


Fig. 5.1 Analysis field area 25 cm thick reinforced concrete wall, without ETICS system (1) solution without reinforcement; (2) solution with reinforcement; **a** finite element modelling; **b** heat flow direction; **c** isothermal field; **d** θ_{si} diagram

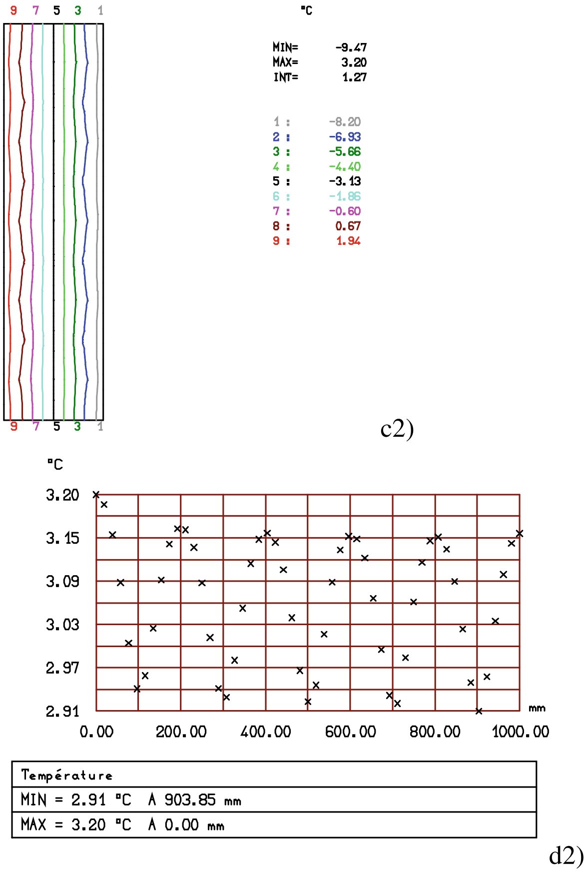


Fig. 5.1 (continued)

Table 5.1 Thermal analysis values

Modelling	Φ (W)	$\theta_{si,min}$ (°C)
Solution without reinforcement	112.78	5.90
Solution with reinforcement	132.60	2.92

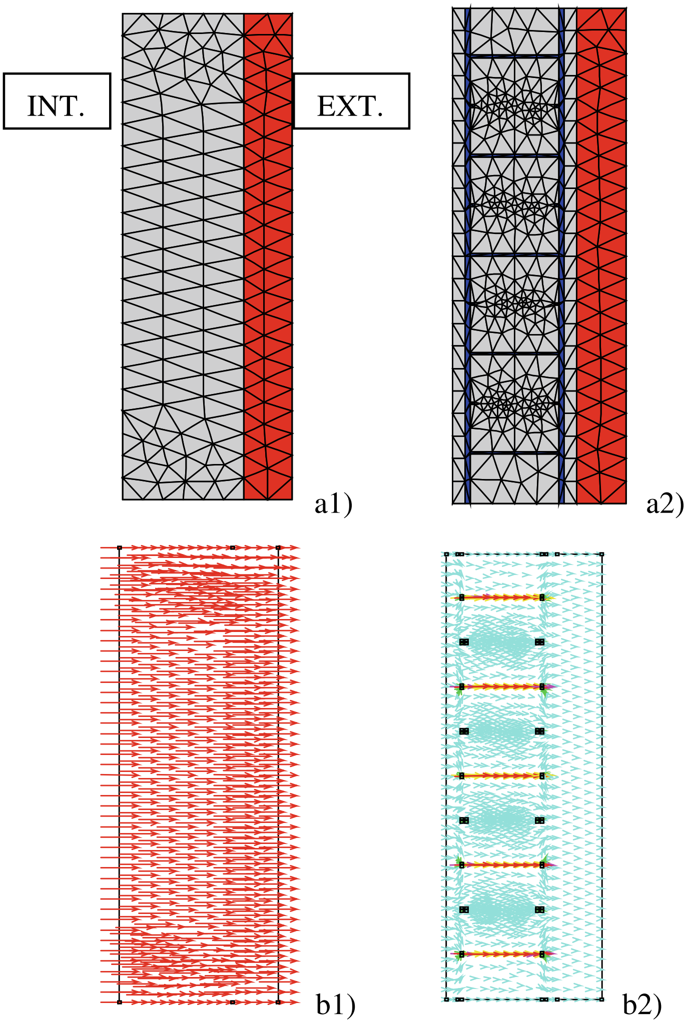


Fig. 5.2 Analysis field area 25 cm thick reinforced concrete wall, without ETICS system (1) solution without reinforcement; (2) solution with reinforcement; **a** finite element modelling; **b** heat flow direction; **c** isothermal field

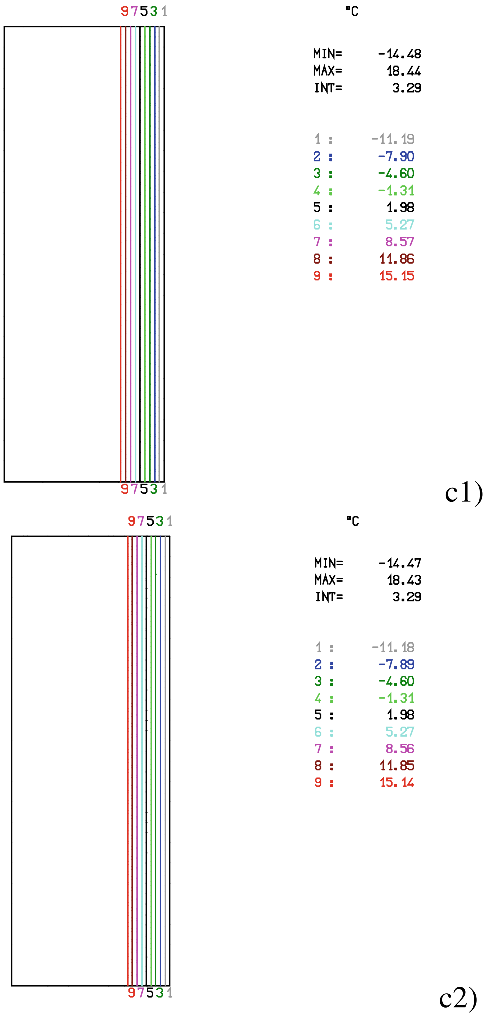
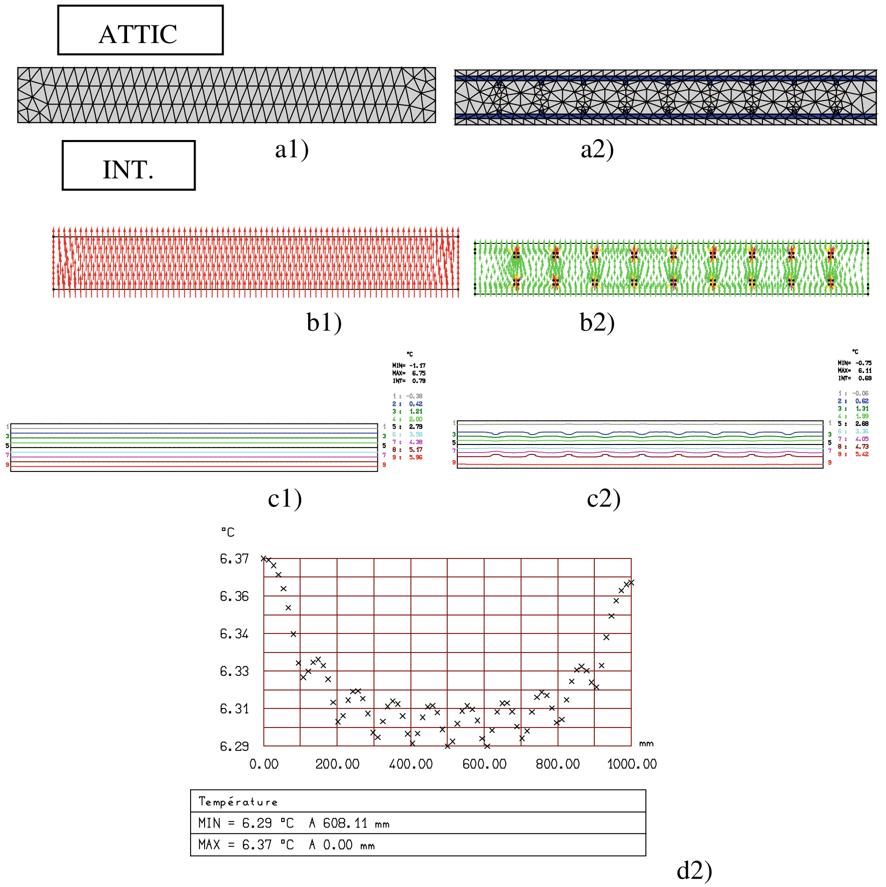


Fig. 5.2 (continued)

Table 5.2 Thermal analysis values

Modelling	Φ (W)	$\theta_{si,min}$ (°C)
Solution without reinforcement	12.45	18.44
Solution with reinforcement	12.66	18.40



a1) a2)

b1) b2)

c1) c2)

d2)

Fig. 5.3 Analysis field area 13 cm thick reinforced concrete slab, below the attic, without thermal insulation (1) solution without reinforcement; (2) solution with reinforcement; **a** finite element modelling; **b** heat flow direction; **c** isothermal field; **d** θ_{si} diagram

Table 5.3 Thermal analysis values

Modelling	Φ (W)	$\theta_{si,min}$ (°C)
Solution without reinforcement	105.99	6.75
Solution with reinforcement	109.45	6.03

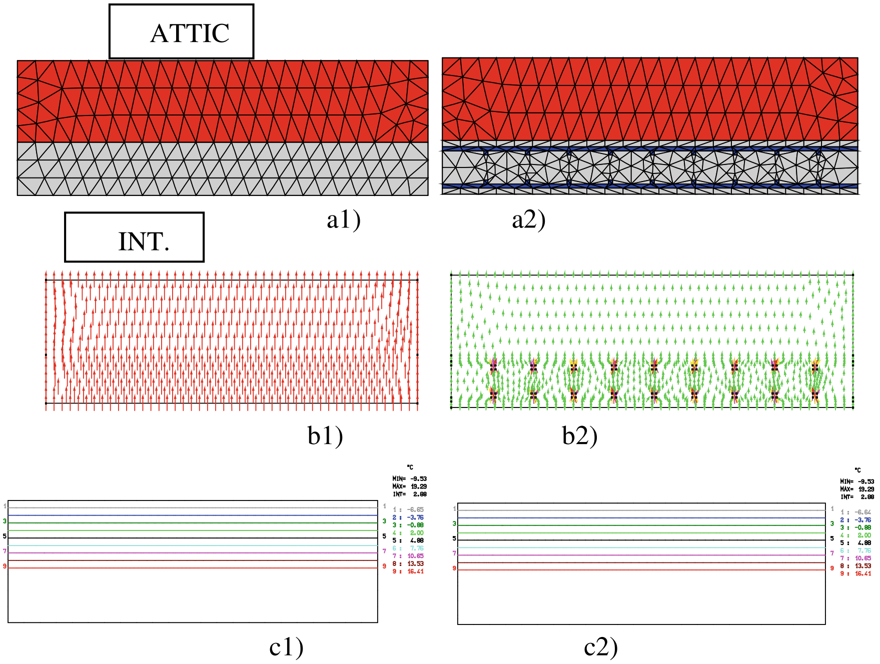


Fig. 5.4 Analysis field area 13 cm thick reinforced concrete slab, below the attic, with thermal insulation—25 cm MW (1) solution without reinforcement; (2) solution with reinforcement; **a** finite element modelling; **b** heat flow direction; **c** isothermal field

Table 5.4 Thermal analysis values

Modelling	Φ (W)	$\theta_{si,min}$ (°C)
Solution without reinforcement	5.68	19.29
Solution with reinforcement	5.69	19.29

5.2.1.3 Analysis of a 5 cm Wide Rib, Precast Facade Panel 25 cm Thick (120 mm R.C. + 50 mm EPS + 80 mm R.C.), with Ribs

Without ETICS

See Fig. 5.5.

The main results are presented in the following Table 5.5.

With ETICS—10 cm EPS

See Fig. 5.6.

The main results are presented in the following Table 5.6.

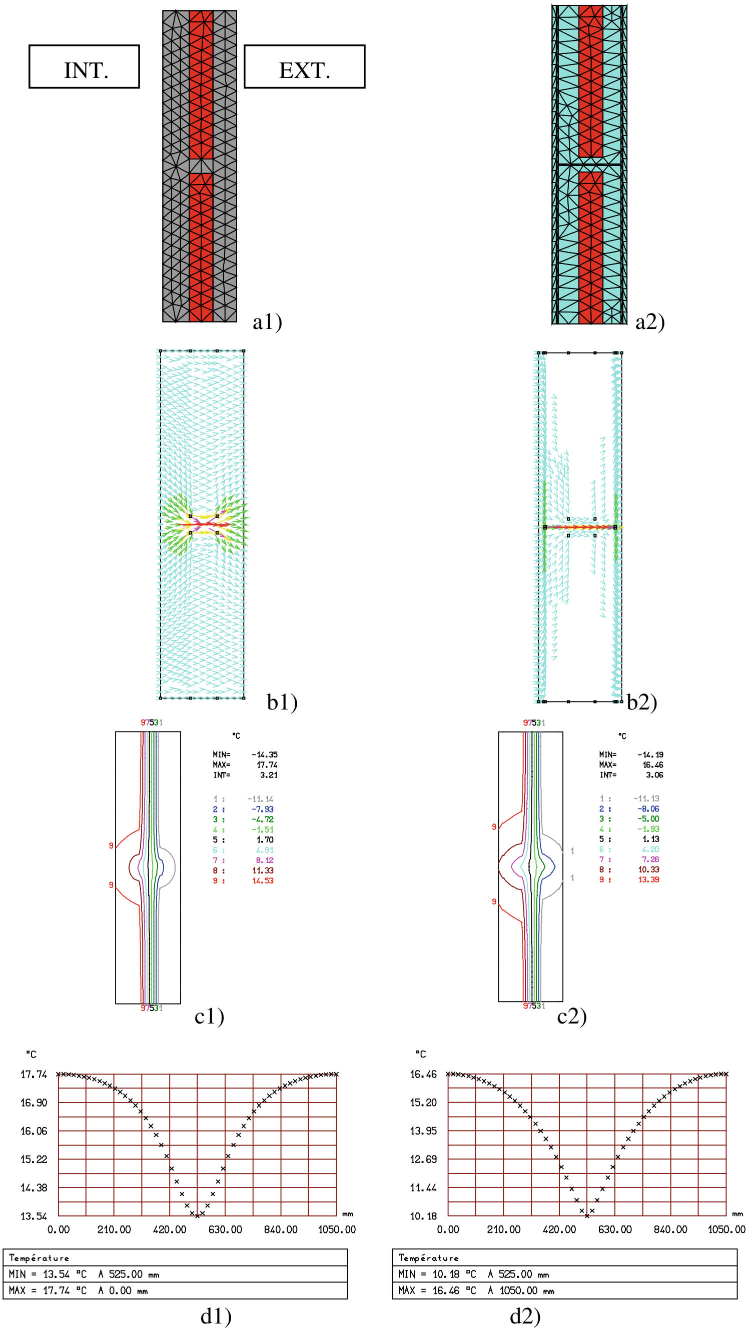


Fig. 5.5 Analysis of a 5 cm wide rib, precast facade panel 25 cm thick, without ETICS (1) solution without reinforcement; (2) solution with reinforcement; **a** finite element modelling; **b** heat flow direction; **c** isothermal field; **d** θ_{si} diagram

Table 5.5 Thermal analysis values

Modelling	Φ (W)	$\theta_{si,min}$ (°C)
Solution without reinforcement	29.59	13.54
Solution with reinforcement	46.94	10.18

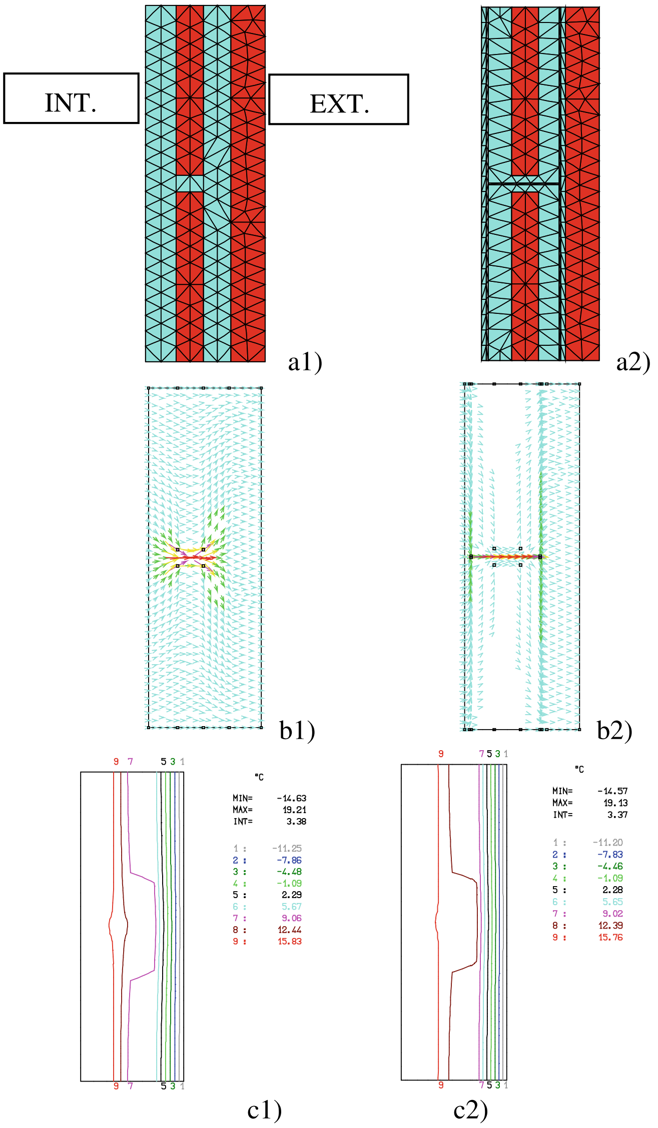


Fig. 5.6 Analysis of a 5 cm wide rib, precast facade panel 25 cm thick, with ETICS (1) solution without reinforcement; (2) solution with reinforcement; **a** finite element modelling; **b** heat flow direction; **c** isothermal field

Table 5.6 Thermal analysis values

Modelling	Φ (W)	$\theta_{si,min}$ (°C)
Solution without reinforcement	9.69	17.98
Solution with reinforcement	11.05	17.17

5.2.1.4 In-Field Analysis for a Precast Facade Panel 25 cm Thick (120 mm R.C. + 50 mm EPS + 80 mm R.C.), with Steel Connectors

Without ETICS

See Fig. 5.7.

The main results are presented in the following Table 5.7.

With ETICS—10 cm EPS

See Fig. 5.8.

The main results are presented in the following Table 5.8.

5.2.2 Wall Angles

5.2.2.1 Outer Angle Between 25 cm Thick Walls Made of Full Bricks

Without ETICS

See Fig. 5.9.

The main results are presented in the following Table 5.9.

With ETICS—10 cm EPS

See Fig. 5.10.

The main results are presented in the following Table 5.10.

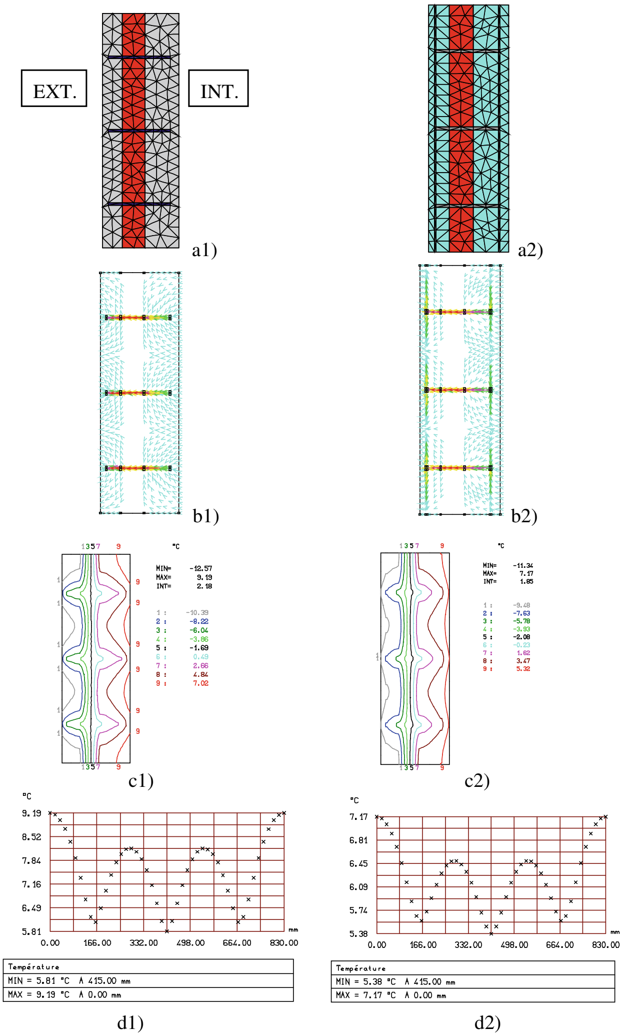


Fig. 5.7 In-field analysis for a precast facade panel 25 cm thick, with steel connectors without ETICS (1) solution without reinforcement; (2) solution with reinforcement; **a** finite element modelling; **b** heat flow direction; **c** isothermal field; **d** θ_{si} diagram

Table 5.7 Thermal analysis values

Modelling	Φ (W)	$\theta_{si,min}$ (°C)
Solution without reinforcement	82.10	5.81
Solution with reinforcement	91.41	5.38

5.2.3 Intersection Between Outer Wall and Interior Wall

5.2.3.1 Analysis of the Intersection Between an Outer and Inner 25 cm Brick Wall with a Reinforced Concrete Tie-Column in the Intersection

Without ETICS

See Fig. 5.11.

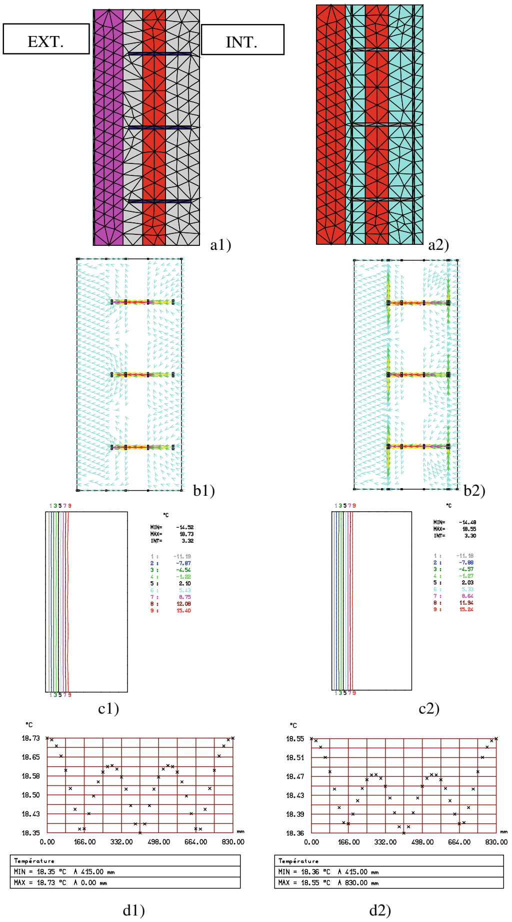


Fig. 5.8 In-field analysis for a precast facade panel 25 cm thick, with steel connectors with ETICS, (1) solution without reinforcement; (2) solution with reinforcement; **a** finite element modelling; **b** heat flow direction; **c** isothermal field; **d** θ_{si} diagram

Table 5.8 Thermal analysis values

Modelling	Φ (W)	$\theta_{si,min}$ (°C)
Solution without reinforcement	9.23	18.35
Solution with reinforcement	10.23	18.36

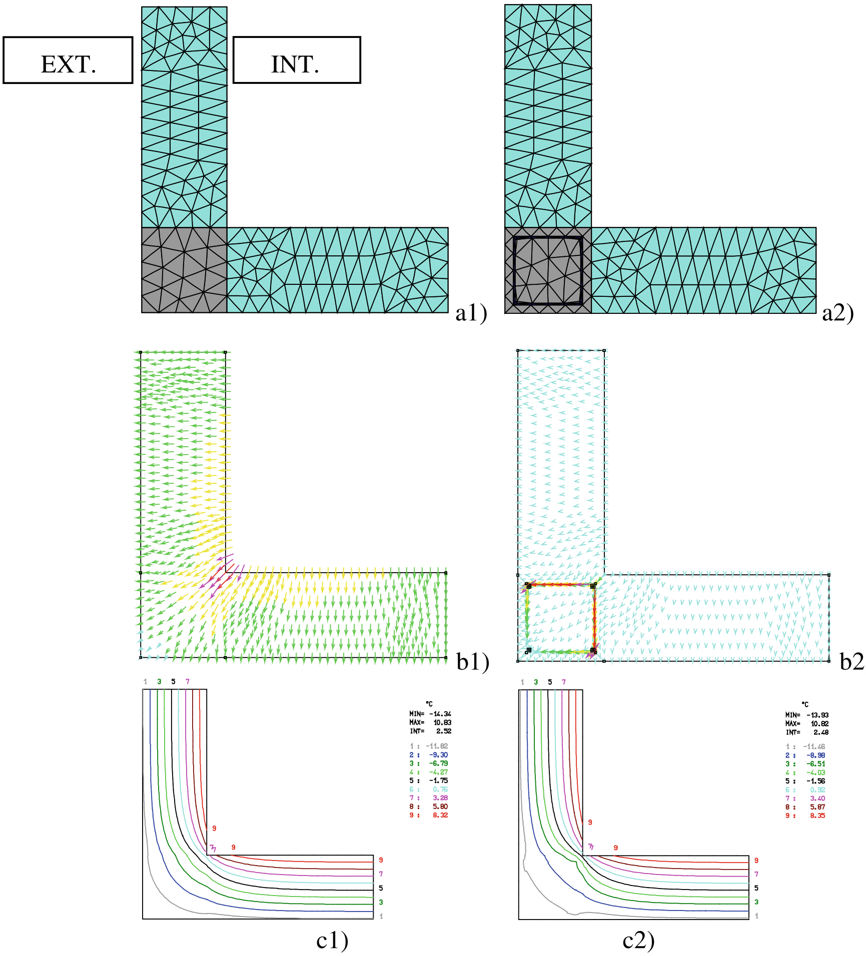


Fig. 5.9 Outer angle between 25 cm thick walls made of full bricks, without ETICS (1) solution without reinforcement; (2) solution with reinforcement; **a** finite element modelling; **b** heat flow direction; **c** isothermal field

Table 5.9 Thermal analysis values

Modelling	Φ (W)	$\theta_{si,min}$ (°C)
Solution without reinforcement	52.94	1.75
Solution with reinforcement	54.96	−0.52

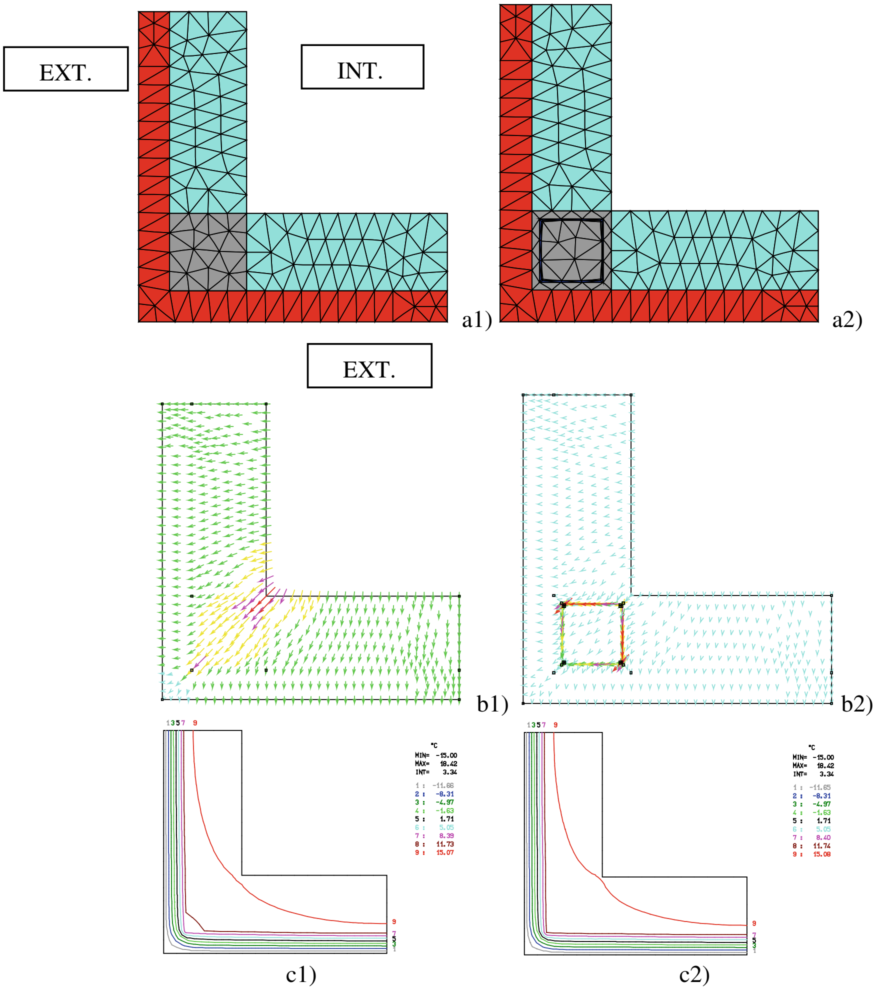


Fig. 5.10 Outer angle between 25 cm thick walls made of full bricks, with ETICS (1) solution without reinforcement; (2) solution with reinforcement; **a** finite element modelling; **b** heat flow direction; **c** isothermal field

Table 5.10 Thermal analysis values

Modelling	Φ (W)	$\theta_{si,min}$ (°C)
Solution without reinforcement	10.22	15.90
Solution with reinforcement	10.44	15.55

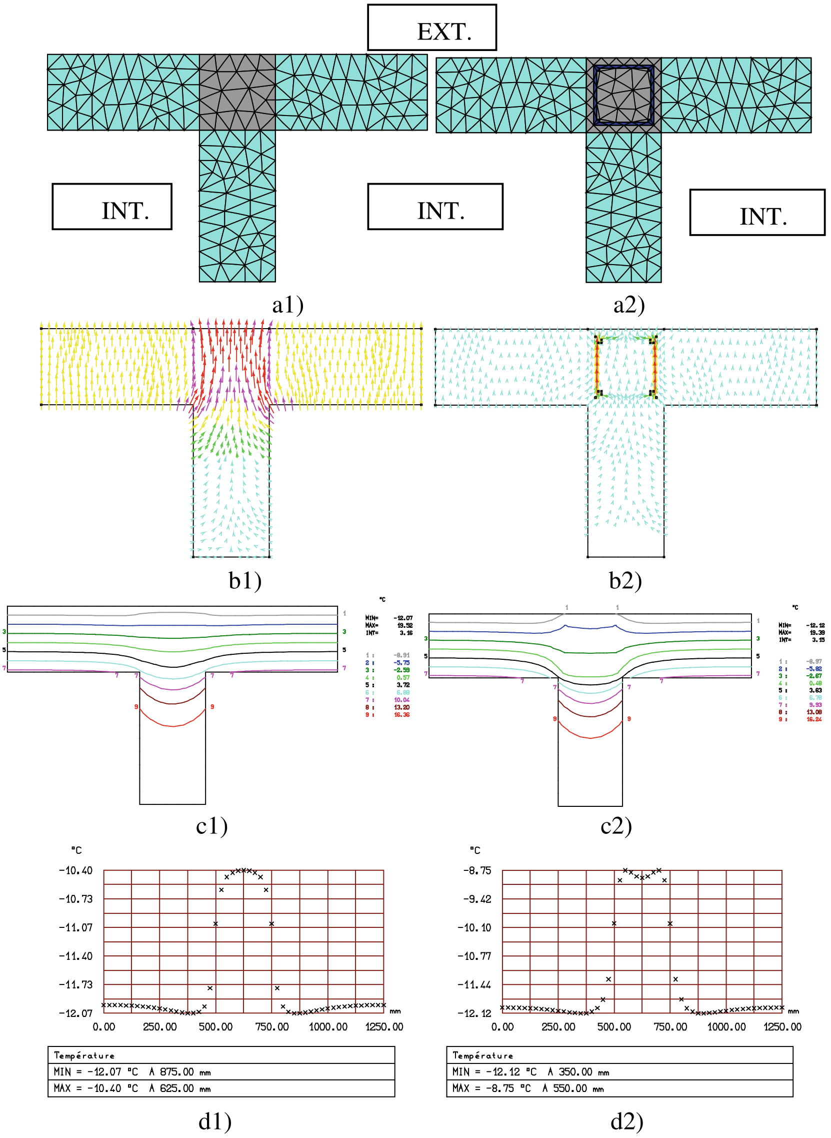


Fig. 5.11 Intersection between an outer and inner 25 cm brick wall with a reinforced concrete tie-column, without ETICS, (1) solution without reinforcement; (2) solution with reinforcement; **a** finite element modelling; **b** heat flow direction; **c** isothermal field; **d** θ_{se} diagram

Table 5.11 Thermal analysis values

Modelling	Φ (W)	$\theta_{si,min}$ (°C)
Solution without reinforcement	49.09	7.44
Solution with reinforcement	54.95	4.15

The main results are presented in the following Table 5.11.

With ETICS—10 cm EPS

See Fig. 5.12.

The main results are presented in the following Table 5.12.

5.2.3.2 Analysis of the Intersection Between a 30 cm AAC Exterior Wall and a 50 × 50 Reinforced Concrete Column

Without ETICS

See Fig. 5.13.

The main results are presented in the following Table 5.13.

With ETICS—10 cm EPS

See Fig. 5.14.

The main results are presented in the following Table 5.14.

5.2.3.3 Analysis of the Intersection Between an Exterior Precast “Sandwich” Wall Panel (27 cm Thick, 8.5 cm Mineral Wool Insulation) and a 14 cm Interior RC Precast Wall Panel

Without ETICS

See Fig. 5.15.

The main results are presented in the following Table 5.15.

With ETICS—10 cm EPS

See Fig. 5.16.

The main results are presented in the following Table 5.16.

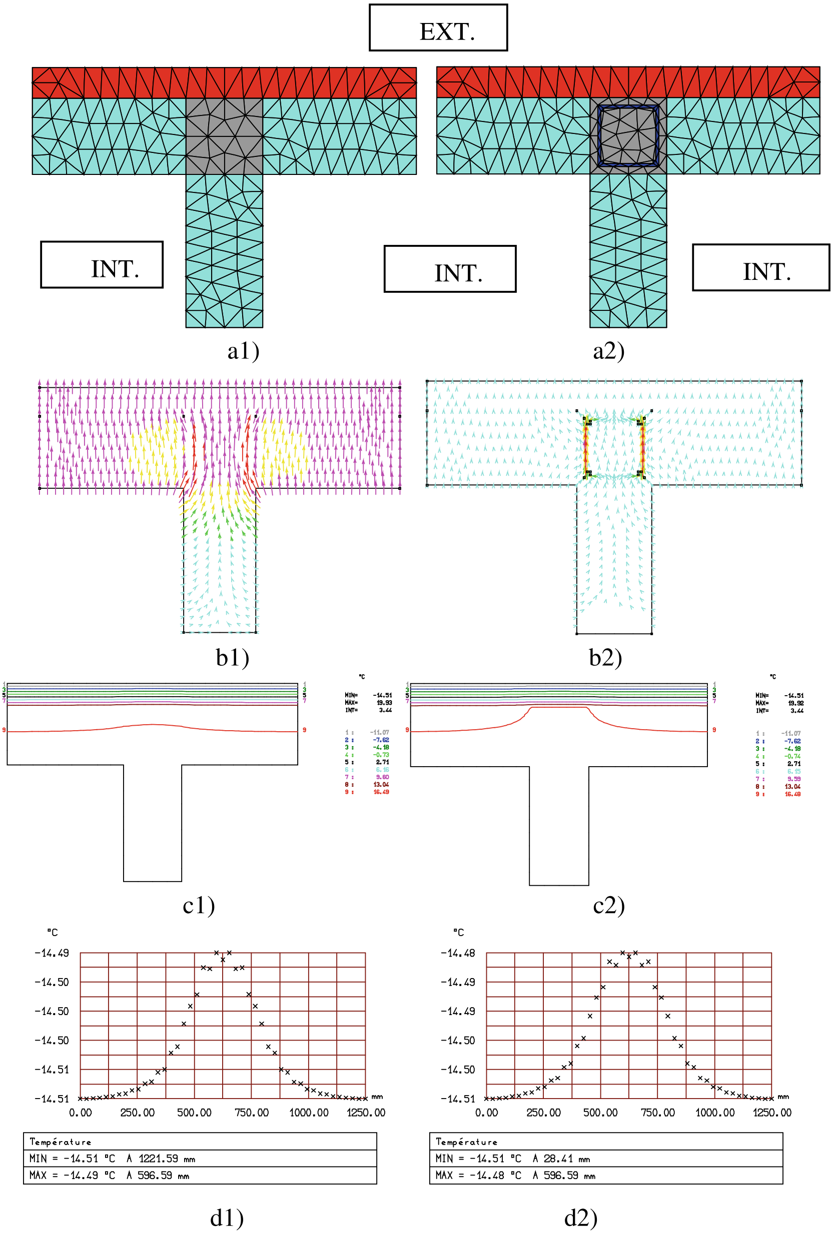


Fig. 5.12 Intersection between an outer and inner 25 cm brick wall with a reinforced concrete tie-column, with ETICS (1) solution without reinforcement; (2) solution with reinforcement; **a** finite element modelling; **b** heat flow direction; **c** isothermal field; **d** θ_{se} diagram

Table 5.12 Thermal analysis values

Modelling	Φ (W)	$\theta_{si,min}$ (°C)
Solution without reinforcement	7.35	18.22
Solution with reinforcement	7.58	18.05

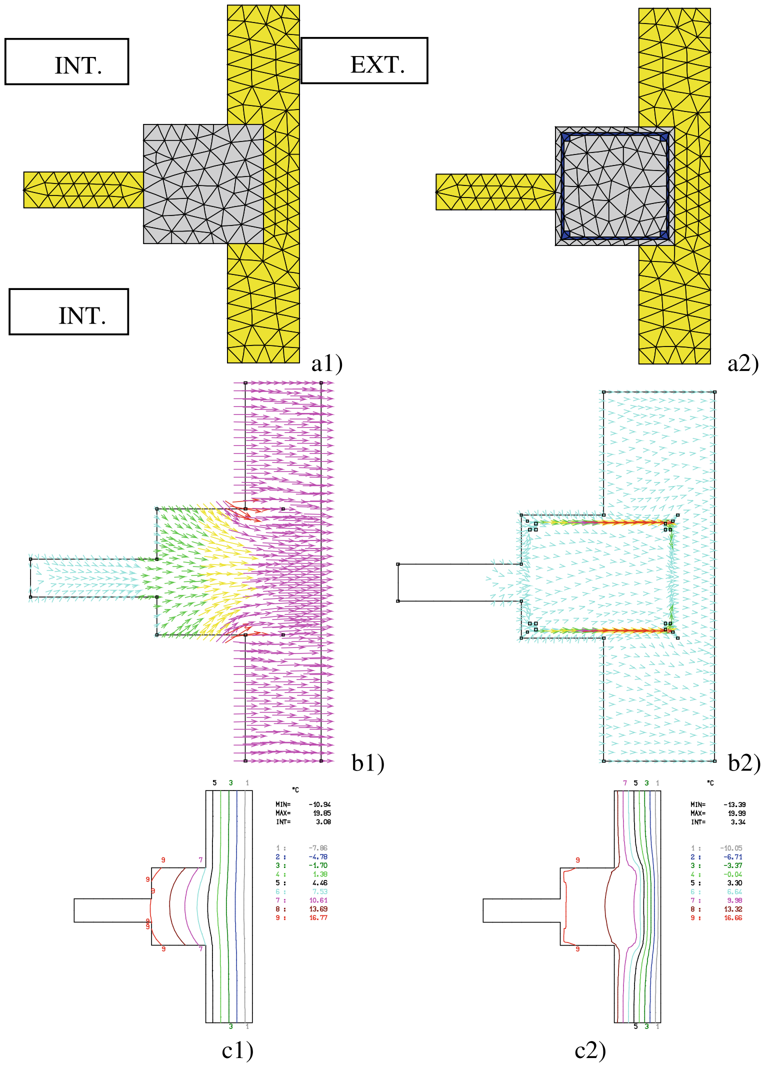


Fig. 5.13 Intersection between a 30 cm AAC exterior wall and a 50 × 50 RC column, without ETICS (1) solution without reinforcement; (2) solution with reinforcement; **a** finite element modelling; **b** heat flow direction; **c** isothermal field

Table 5.13 Thermal analysis values

Modelling	Φ (W)	$\theta_{si,min}$ (°C)
Solution without reinforcement	31.83	12.93
Solution with reinforcement	33.94	13.65

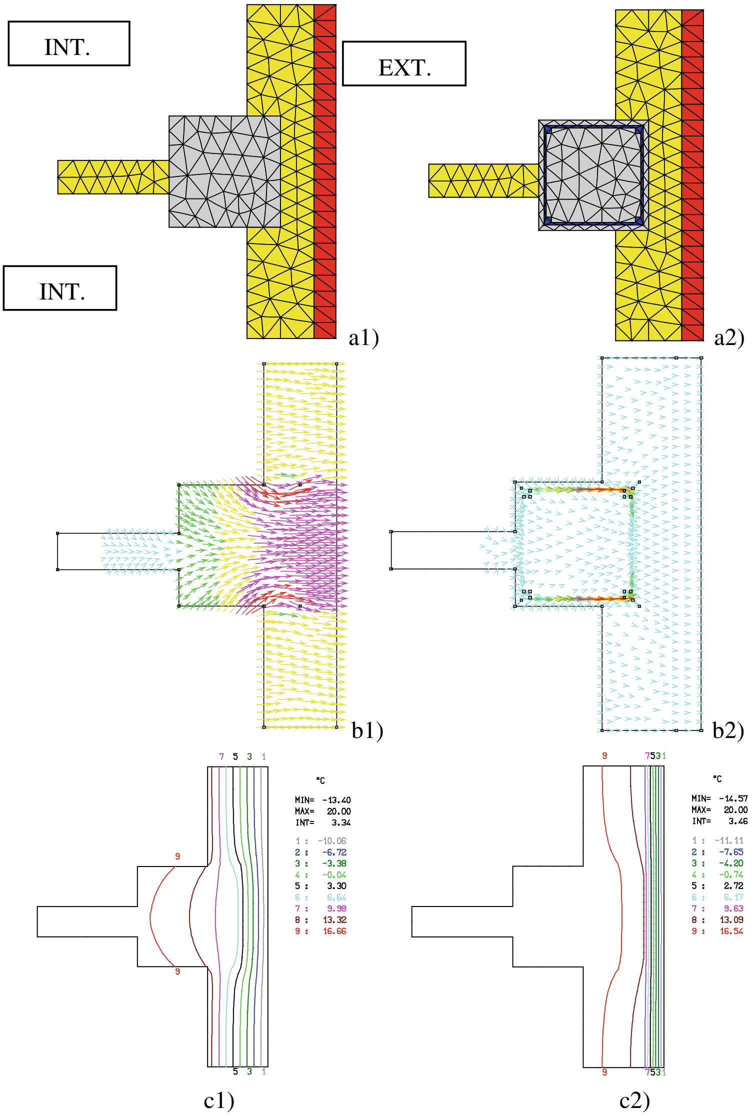


Fig. 5.14 Intersection between a 30 cm AAC exterior wall and a 50 × 50 RC column, with ETICS (1) solution without reinforcement; (2) solution with reinforcement; **a** finite element modelling; **b** heat flow direction; **c** isothermal field

Table 5.14 Thermal analysis values

Modelling	Φ (W)	$\theta_{si,min}$ (°C)
Solution without reinforcement	7.67	18.37
Solution with reinforcement	7.62	18.62

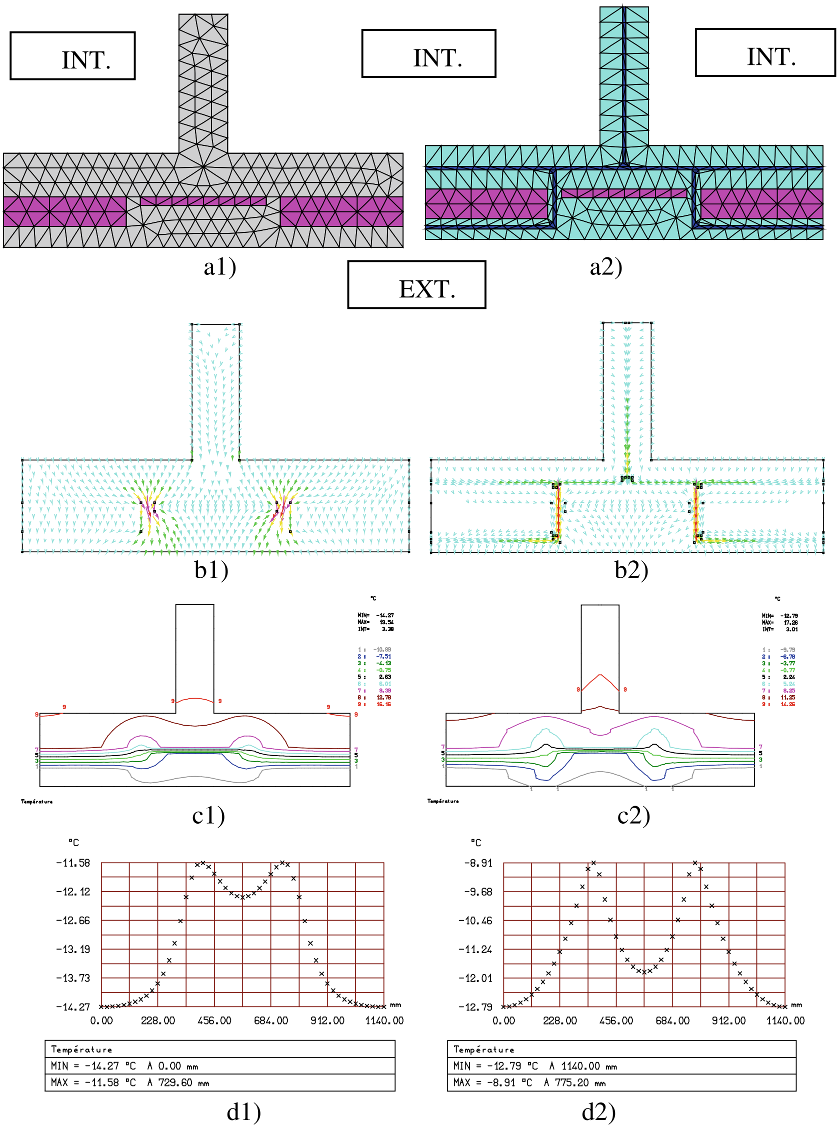


Fig. 5.15 Intersection between exterior and interior precast wall panels, without ETICS (1) solution without reinforcement; (2) solution with reinforcement; **a** finite element modelling; **b** heat flow direction; **c** isothermal field, **d** θ_{se} diagram

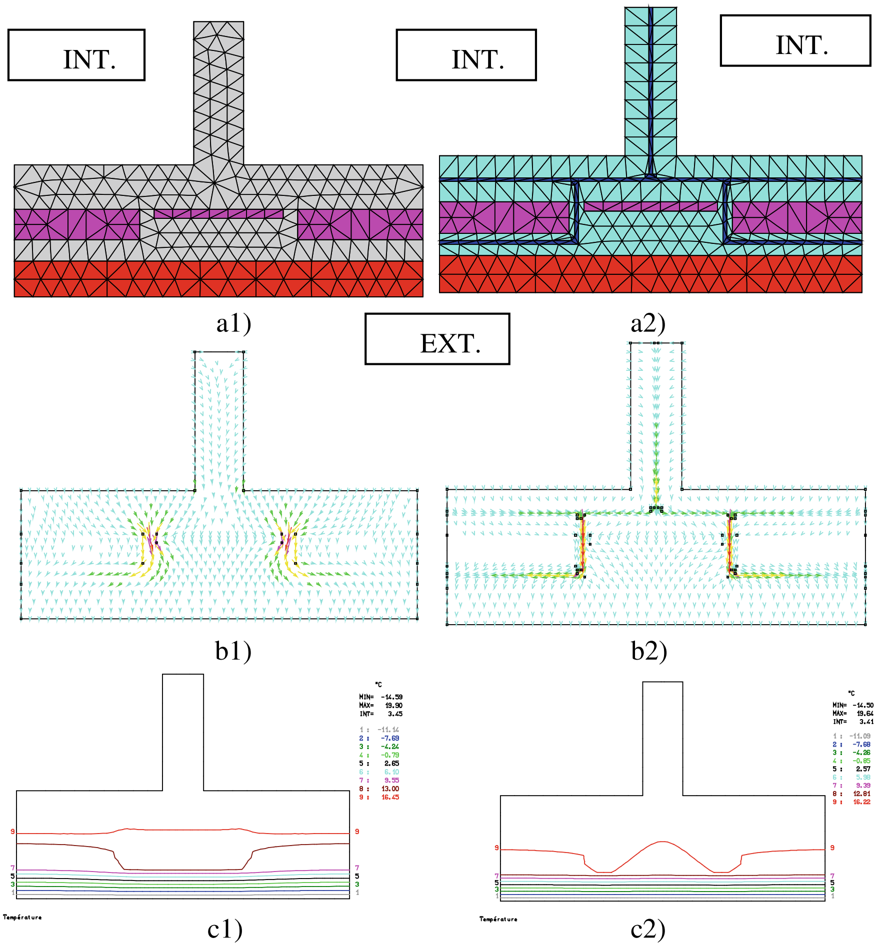
Table 5.15 Thermal analysis values

Modelling	Φ (W)	$\theta_{si,min}$ (°C)
Solution without reinforcement	26.24	13.11
Solution with reinforcement	40.74	12.59

5.2.4 Intersection Between Slabs and Outer Walls

5.2.4.1 Analysis of the Intersection Between a 13 cm Thick RC Slab and a 25 cm Exterior Full Brick Wall

Without ETICS



a1) a2)

b1) b2)

c1) c2)

Fig. 5.16 Intersection between exterior and interior precast wall panels, with ETICS, (1) solution without reinforcement; (2) solution with reinforcement; **a** finite element modelling; **b** heat flow direction; **c** isothermal field

Table 5.16 Thermal analysis values

Modelling	Φ (W)	$\theta_{si,min}$ (°C)
Solution without reinforcement	5.96	18.48
Solution with reinforcement	6.53	18.81

See Fig. 5.17.

The main results are presented in the following Table 5.17.

With ETICS—10 cm EPS

See Fig. 5.18.

The main results are presented in the following Table 5.18.

5.2.4.2 Analysis of the Intersection Between a 13 cm Thick RC Slab and Precast Façade "Sandwich" Panel, 27 cm Thick (with 8.5 cm Mineral Wool)

Without ETICS

See Fig. 5.19.

The main results are presented in the following Table 5.19.

With ETICS—10 cm EPS

See Fig. 5.20.

The main results are presented in the following Table 5.20.

5.2.5 Connection Infrastructure—Outer Wall, Building with Basement

5.2.5.1 Analysis of the Intersection Between 13 cm Thick RC Slab and 25 cm RC Outer Wall, When the Thermal Insulation of the Wall is Done with 20 cm AAC Blocks

Without ETICS

See Fig. 5.21.

The main results are presented in the following Table 5.21.

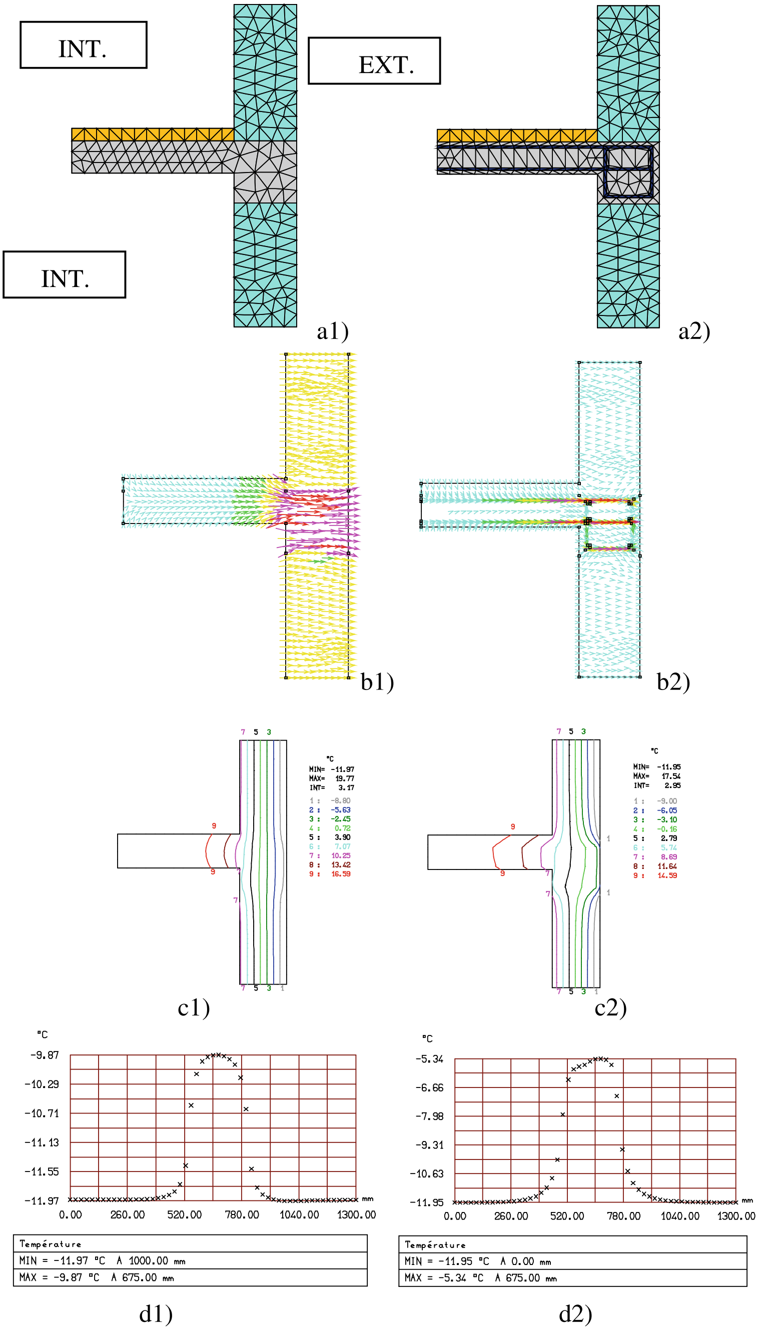


Fig. 5.17 Intersection between RC slab and a 25 cm exterior full brick wall, without ETICS. (1) solution without reinforcement; (2) solution with reinforcement; **a** finite element modelling; **b** heat flow direction; **c** isothermal field; **d** θ_{se} diagram

Table 5.17 Thermal analysis values

Modelling	Floor		Ceiling	
	Φ_{floor} (W)	$\theta_{si,min}$ (°C)	$\Phi_{ceiling}$ (W)	$\theta_{si,min}$ (°C)
Solution without reinforcement	47.08	1.79	61.5	7.68
Solution with reinforcement	60.91	9.53	79	5.80

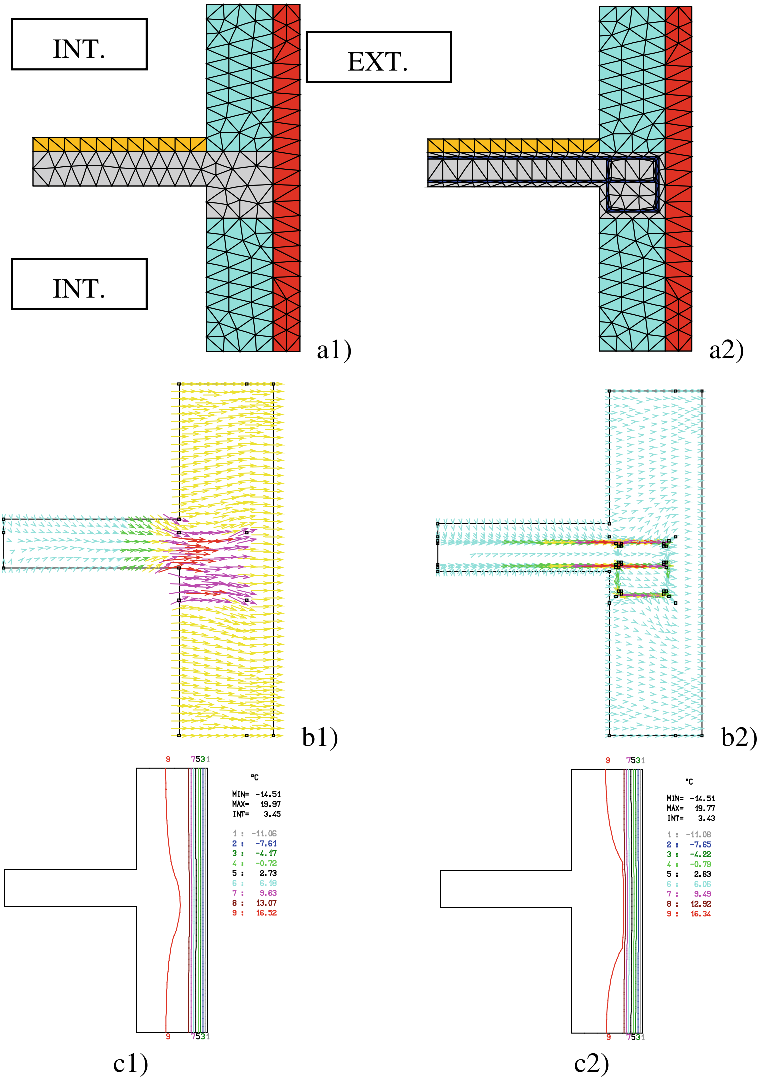


Fig. 5.18 Intersection between RC slab and a 25 cm exterior full brick wall, with ETICS, (1) solution without reinforcement; (2) solution with reinforcement; **a** finite element modelling; **b** heat flow direction; **c** isothermal field

Table 5.18 Thermal analysis values

Modelling	Floor		Ceiling	
	Φ_{floor} (W)	$\theta_{si,min}$ (°C)	$\Phi_{ceiling}$ (W)	$\theta_{si,min}$ (°C)
Solution without reinforcement	6.9	18.58	8.6	18.37
Solution with reinforcement	7.11	18.98	8.62	18.77

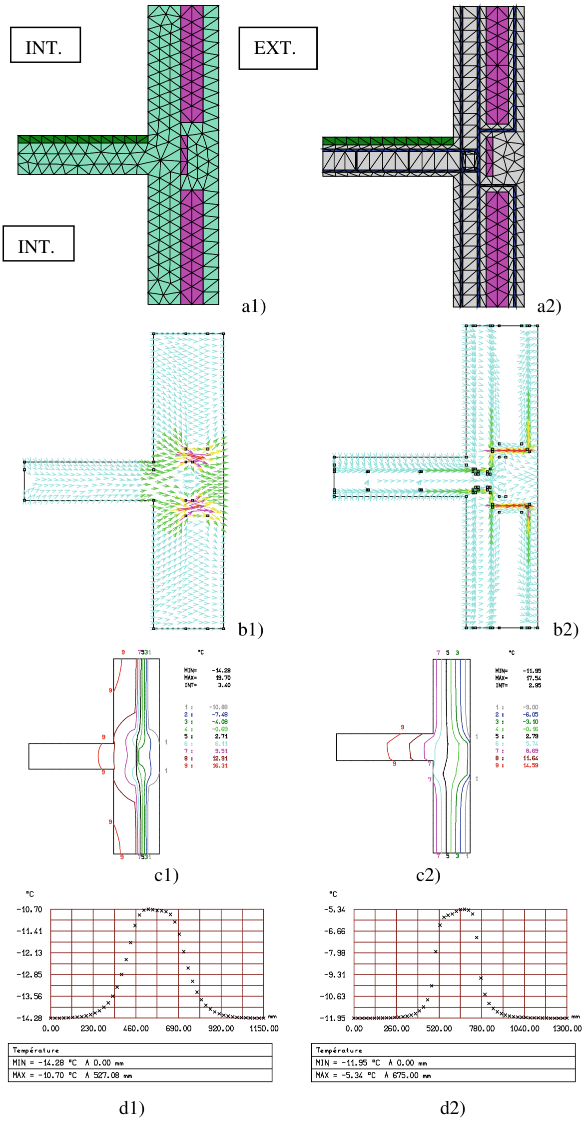


Fig. 5.19 Intersection RC slab—Sandwich precast façade panel, without ETICS (1) solution without reinforcement; (2) solution with reinforcement; **a** finite element modelling; **b** heat flow direction; **c** isothermal field; **d** θ_{se} diagram

Table 5.19 Thermal analysis values

Modelling	Floor		Ceiling	
	Φ_{floor} (W)	$\theta_{si,min}$ (°C)	$\Phi_{ceiling}$ (W)	$\theta_{si,min}$ (°C)
Solution without reinforcement	25.21	13.18	25.98	13.10
Solution with reinforcement	40.74	12.07	42.36	11.85

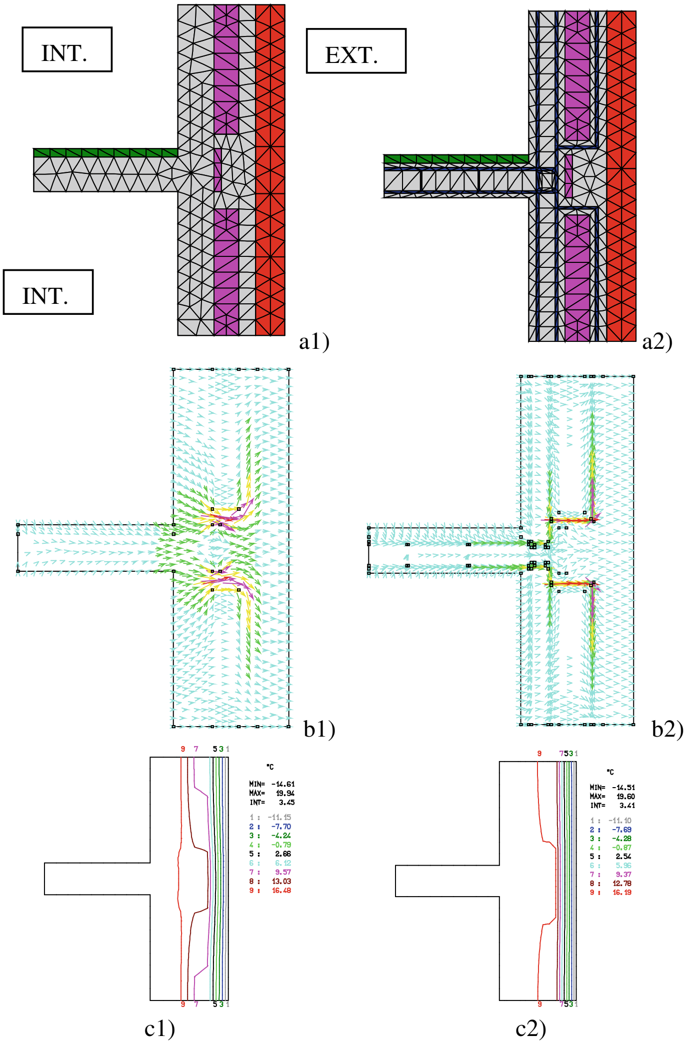


Fig. 5.20 Intersection RC slab—Sandwich precast façade panel, with ETICS (1) solution without reinforcement; (2) solution with reinforcement; **a** finite element modelling; **b** heat flow direction; **c** isothermal field

Table 5.20 Thermal analysis values

Modelling	Floor		Ceiling	
	Φ_{floor} (W)	$\theta_{si,min}$ (°C)	$\Phi_{ceiling}$ (W)	$\theta_{si,min}$ (°C)
Solution without reinforcement	5.83	18.52	5.93	18.50
Solution with reinforcement	6.49	18.70	6.69	18.72

With ETICS—10 cm EPS

See Fig. 5.22.

The main results are presented in the following Table 5.22.

5.2.6 *Connection Between Exterior Walls and "Last" Slab (Terrace Roof)*

5.2.6.1 Analysis of the Intersection Between 13 cm RC Terrace and 30 cm AAC Masonry Wall (for Post and Beam RC Structure)

Without ETICS

See Fig. 5.23.

The main results are presented in the following Table 5.23.

With ETICS—10 cm MW

See Fig. 5.24.

The main results are presented in the following Table 5.24.

5.2.7 *Influence of the Anchoring System of the Thermal Insulation on the Heat Transfer*

5.2.7.1 Analysis of the Intersection Between a 13 cm RC Slab and a 25 cm Façade Wall Made with Full Bricks

Case: dowel pin (metallic with PVC head and PVC jacket) ETICS, without contact with the reinforcement.

See Fig. 5.25.

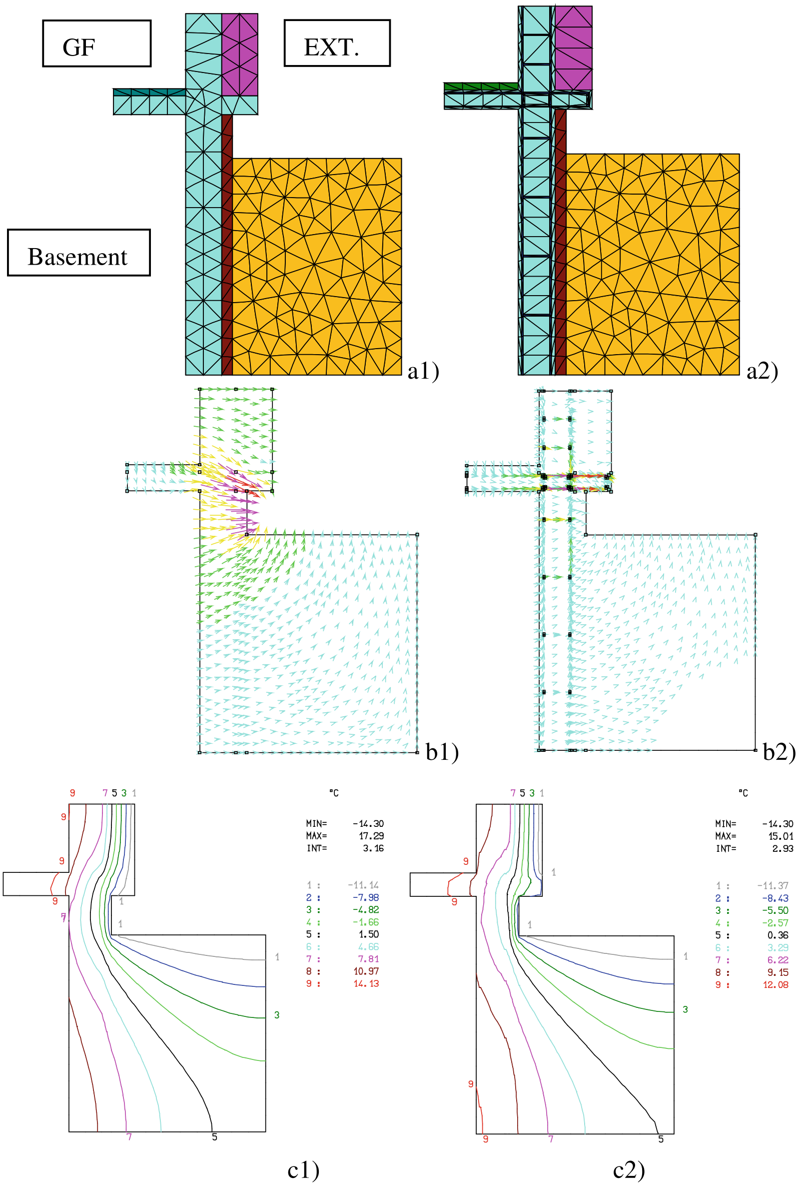


Fig. 5.21 Intersection RC slab −25 cm RC wall +20 cm AAC, without ETICS (1) solution without reinforcement; (2) solution with reinforcement; **a** finite element modelling; **b** heat flow direction; **c** isothermal field

Table 5.21 Thermal analysis values

Modelling	Slab		Wall	
	Φ_{slab} (W)	$\theta_{si,min}$ (°C)	Φ_{wall} (W)	$\theta_{si,min}$ (°C)
Solution without reinforcement	11.73	11.67	27.72	11.67
Solution with reinforcement	19.09	9.38	37.64	9.38

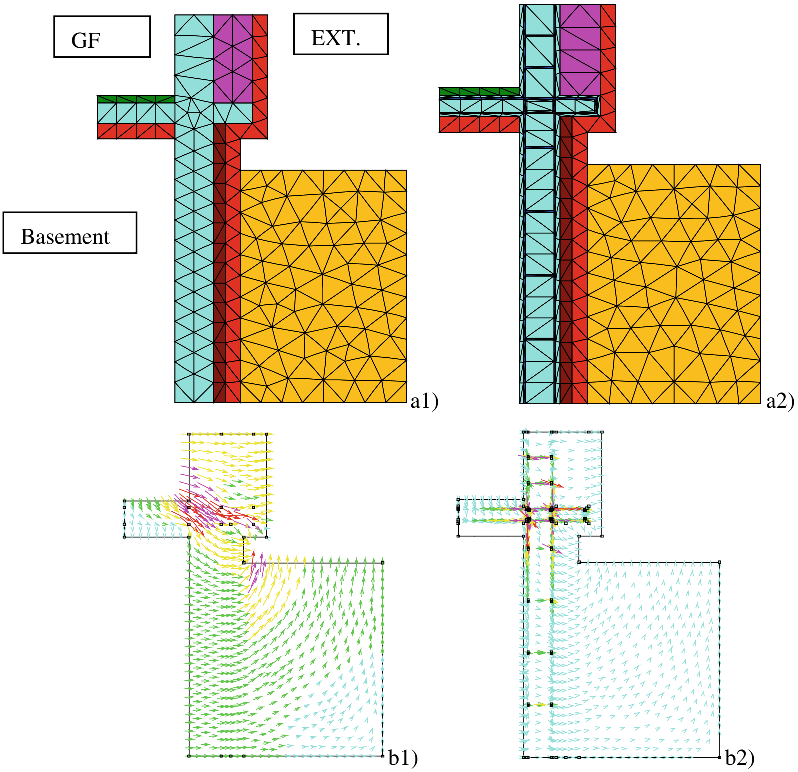


Fig. 5.22 Intersection RC slab −25 cm RC wall +20 cm AAC, with ETICS (1) solution without reinforcement; (2) solution with reinforcement; **a** finite element modelling; **b** heat flow direction; **c** isothermal field

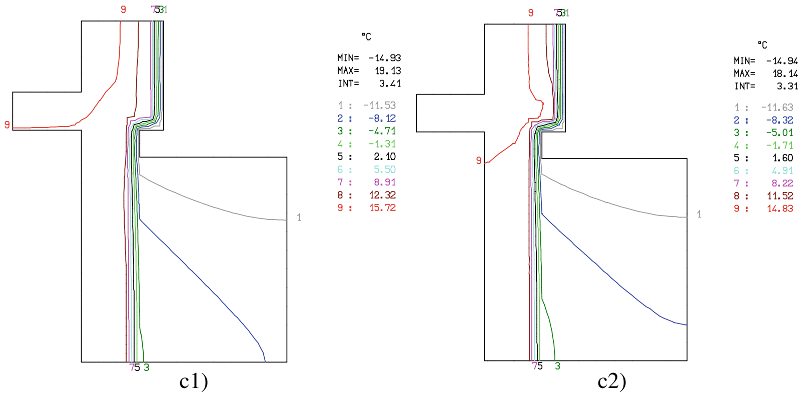


Fig. 5.22 (continued)

Table 5.22 Thermal analysis values

Modelling	Slab		Wall	
	Φ_{slab} (W)	$\theta_{si,min}$ (°C)	Φ_{wall} (W)	$\theta_{si,min}$ (°C)
Solution without reinforcement	4.08	17.37	7.96	17.37
Solution with reinforcement	6.39	17.07	9.71	17.07

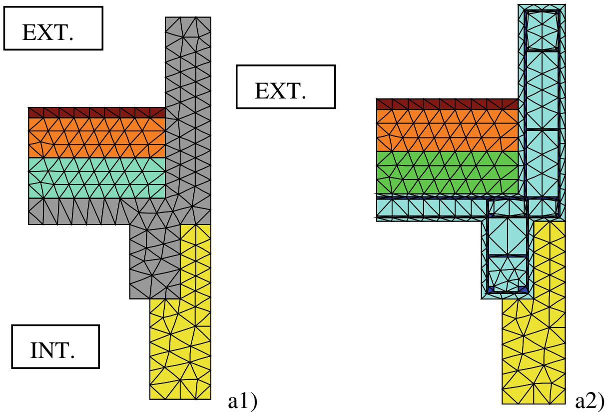
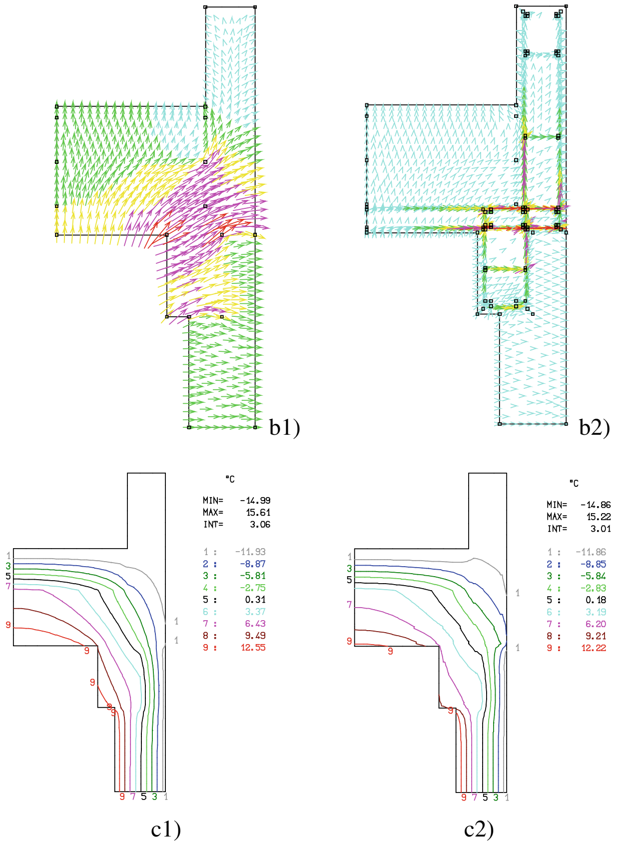


Fig. 5.23 Intersection between terrace slab and 30 cm AAC wall, without ETICS (1) solution without reinforcement; (2) solution with reinforcement; **a** finite element modelling; **b** heat flow direction; **c** isothermal field



b1) b2)

c1) c2)

Fig. 5.23 (continued)

Table 5.23 Thermal analysis values

Modelling	Slab		Wall	
	Φ_{slab} (W)	$\theta_{si,min}$ (°C)	Φ_{wall} (W)	$\theta_{si,min}$ (°C)
Solution without reinforcement	37.84	9.34	43.83	11.67
Solution with reinforcement	58.57	6.51	53.23	8.66

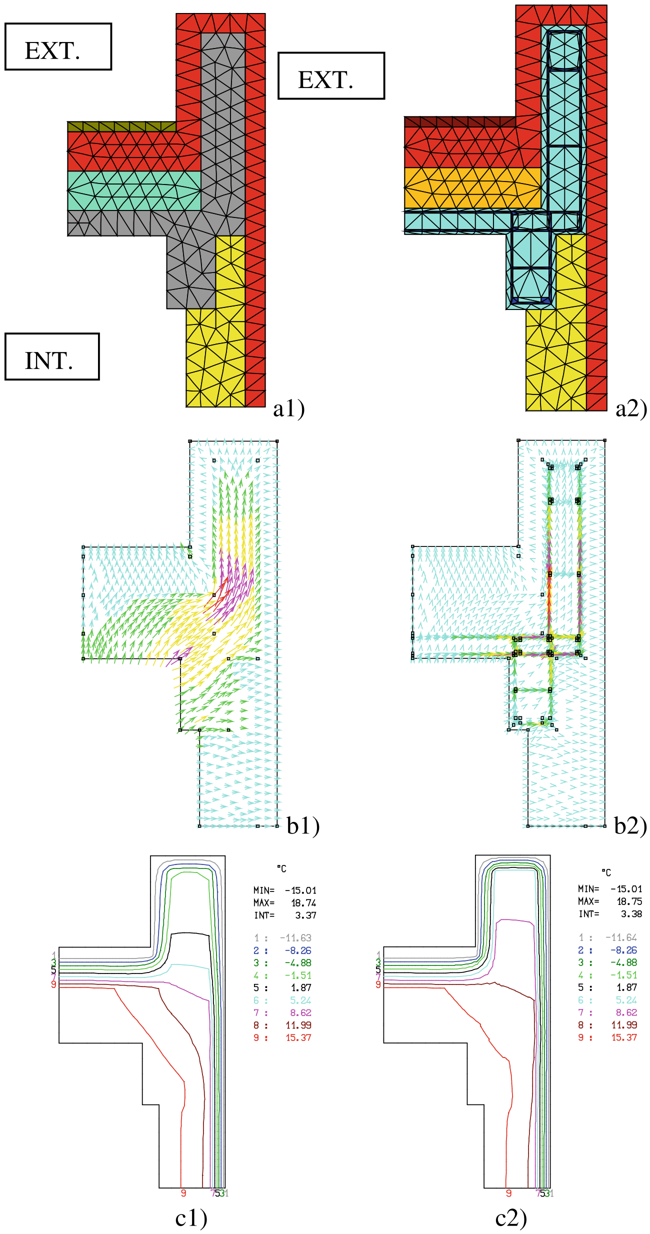


Fig. 5.24 Intersection between terrace slab and 30 cm AAC wall, with ETICS (1) solution without reinforcement; (2) solution with reinforcement; **a** finite element modelling; **b** heat flow direction; **c** isothermal field

Table 5.24 Thermal analysis values

Modelling	Slab		Wall	
	Φ_{slab} (W)	$\theta_{si,min}$ (°C)	Φ_{wall} (W)	$\theta_{si,min}$ (°C)
Solution without reinforcement	11.47	16.60	12.65	17.60
Solution with reinforcement	14.91	16.55	13.43	17.11

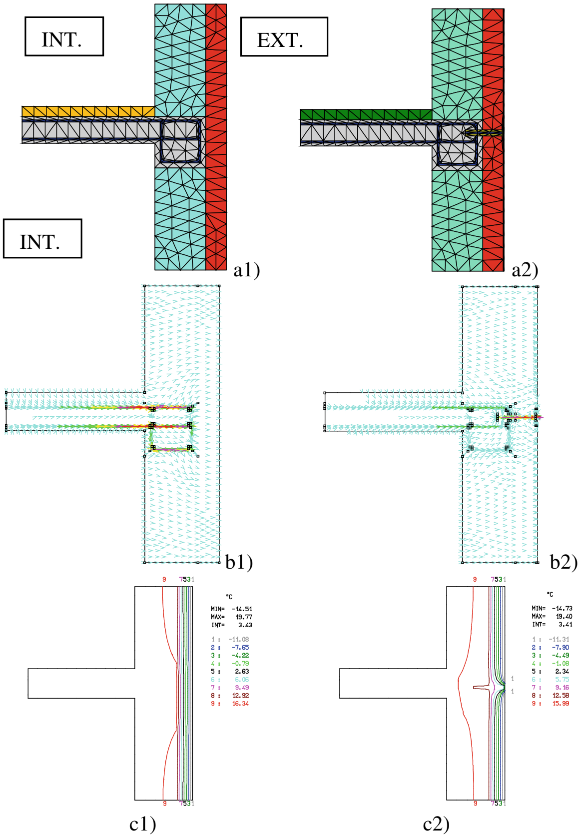
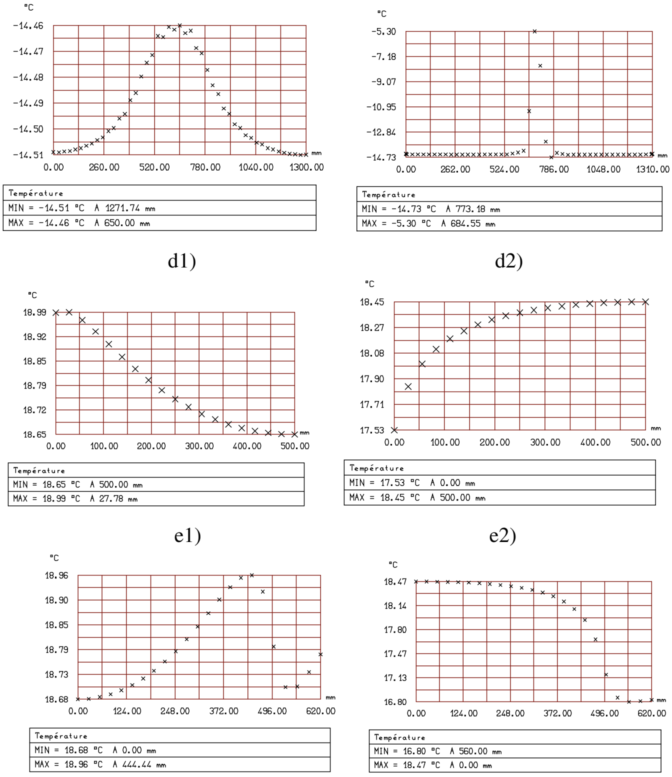


Fig. 5.25 Intersection slab −25 cm full brick façade wall, dowel pin, ETICS, without contact with the reinforcement, (1) solution without reinforcement; (2) solution with reinforcement; **a** finite element modelling; **b** heat flow direction; **c** isothermal field; **d** θ_{se} diagram; **e** $\theta_{si,min,skirting}$ diagram; **f** $\theta_{si,min,ceiling}$ diagram

The main results are presented in the following Table 5.25.



d1) d2)

e1) e2)

f1) f2)

Fig. 5.25 (continued)

Table 5.25 Thermal analysis values

Case	Skirting		Ceiling		$\theta_{se,min}$ (°C)
	$\Phi_{skirting}$ (W)	$\theta_{si,min,\ skirting}$ (°C)	$\Phi_{ceiling}$ (W)	$\theta_{si,min,\ ceiling}$ (°C)	
Without dowel pin	7.11	18.98	8.62	18.77	−14.46
With central pin	12.79	17.53	16.70	16.80	−5.30

Case: dowel pin, ETICS, in contact with the reinforcement

See Fig. 5.26.

The main results are presented in the following Table 5.26.

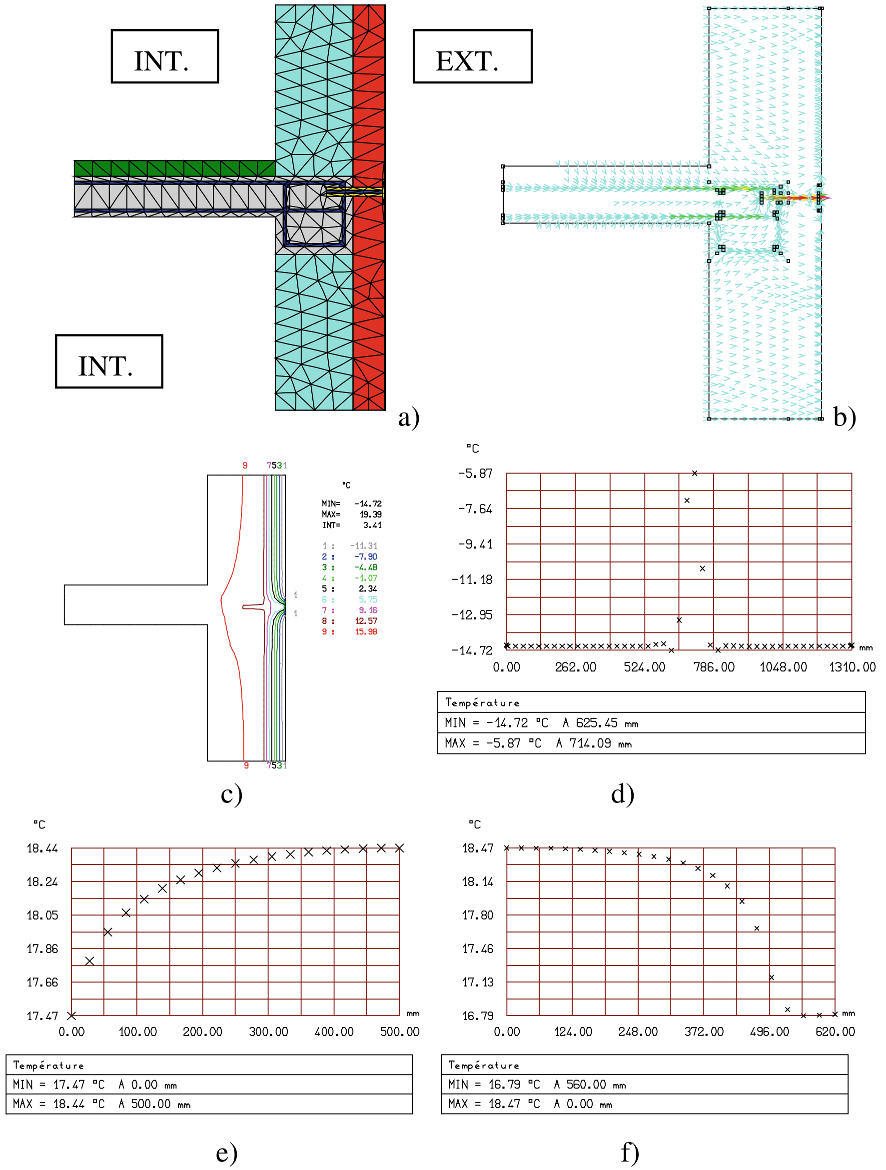


Fig. 5.26 Intersection slab −25 cm full brick façade wall, dowel pin, ETICS, with contact with the reinforcement **a** finite element modelling; **b** heat flow direction; **c** isothermal field; **d** θ_{se} diagram; **e** $\theta_{si,min,skirting}$ diagram; **f** $\theta_{si,min,ceiling}$ diagram

Table 5.26 Thermal analysis values

Case	Skirting		Ceiling		$\theta_{se,min}$ (°C)
	$\Phi_{skirting}$ (W)	$\theta_{si,min,\ skirting}$ (°C)	$\Phi_{ceiling}$ (W)	$\theta_{si,min,\ ceiling}$ (°C)	
Pin in contact with reinforcement	13.02	17.47	16.80	16.79	−5.87

5.3 Conclusions and Recommendations

In [9] an important number of details commonly encountered in buildings were analysed: field and corner areas, intersections between interior and exterior walls, intermediate floor intersections with exterior walls, detail of the intersection between the infrastructure and the exterior walls for buildings with basement, intersections between exterior walls and terrace roof.

Even if $\lambda_{metal} \approx 50$ W/(mK) and $\lambda_{concrete} = 1.60$ W (mK), relying on the fact that the metal parts are embedded in the reinforced concrete elements, for the practical "speed" equivalent characteristics of the composite material are often used: $\lambda_{reinforced\ concrete} \approx 1.74$ W/(mK). These give rise to local thermal bridges, often unfavourable.

Following the analyses carried out, the following conclusions were formulated:

- there are important differences (about 40 … 50%) in terms of thermal flows, between the analysed cases (without external thermal—system) with reinforcement on the outer face (prefabricated panels) and the modelling without considering the reinforcement;
- when we analyse the cases with external thermal system, we can see that there are no important differences in the level of the thermal flows (about 3–5%), between the cases with and those without reinforcement;
- between the models with and those without metal dowel anchoring of the external thermal system, there are significant differences (approx. 40%) in the thermal flow;
- if the metal anchor bolt of the thermal system is in contact with the reinforcement, the differences increase even more than in the previous case;
- the computed differences in terms of coefficients of thermal losses are extremely varied;
- differences in the internal temperature can reach up to 1 °C;

Consequently, it is appreciated that for a correct and complete thermo-energetic analysis of a constructive detail, it is necessary to use the calculation programs that allow the modelling of the details according to the real solution.

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Chapter 6
Movement Regimes and Determining the Main Parameters of Oscillating and Vibrating Conveyors

Dinu Ioan Stoicovici

Abstract The chapter refers, on the one hand, to the description of the construction and operation of conveyors, and on the other hand, to the establishment of the relations for the determination of the main parameters of the movements—the speed of the transport and the driving power—according to the dynamic evaluation of the conveyors, and determination of the optimal regimes of working of the oscillating and vibrating conveyors. Given the diversity and complexity of the functions performed by these machines in the industrial processes, the processes of designing and redesigning these machines are based on scientific and technological research, in order to be able to determine the working regimes and the main parameters both on the basis of some theoretical relationships depending on the main transport cases, as well as by using experimentally developed nomograms.

Keywords Oscillating machines · Vibrating mechanism · Nomograms

6.1 Introduction

The oscillating and vibrating conveyors are part of the group of technological equipment used in the construction materials, mining, chemical, and food industries.

The knowledge contained in the chapter is required for researchers, designers, and students in higher technical education, in order to have a design that ensures efficiency in their construction and use, to ensure low electricity consumption, minimum CO_2 emissions, during the production of the machines, and the operation of the machines of the works within the production lines, for a minimum impact on the environment.

Oscillating and vibrating conveyors are stationary machines, used for horizontal, inclined and vertical transport of bulk materials or individual parts, within a technological flow, with flow rates up to 300 t/h, and lengths up to 50 m for an operating group (with the possibility of assembling identical machines in flow for longer

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transport lengths in different technological processes where certain procedures are required).

Due to the widespread use of these machines in various industrial processes, the study of the design, construction and operation of these machines was substantiated and conducted starting with works such as [10].

In these studies, to increase the pace of design and introduction In the operation of the equipment, graphs and nomograms were widely used to correlate the values of various parameters, in order to obtain optimal operating regimes [7].

So far, recent studies have brought detailed improvements or customizations on specific areas of operation [3, 8], but the basic principles have remained broadly the same.

Finally, there have been applications of computer programs that increase the pace of design, facilitate and streamline work in the design of these machines [9, 14], supported at the level of enterprises by typing and standardization of the products.

These programs are based on the early design principles, and their knowledge is important to be able to work efficiently with modern computer design means.

The oscillating conveyors (Fig. 6.1), ensure the transport of the material by means of a gutter involved in a non-uniform periodic of forward–backward motion, produced by an external force provided by a motor mechanism. The gutter, as a transport organ, by its forward movement in the desired direction of movement of the material, drives the material to be transported in this movement due to the frictional force between it and the gutter. When returning to the initial position of the gutter, the material moves further, in the forward movement in the desired direction of movement, by sliding on the gutter, due to the forces of inertia, but without detaching from it. The material exerts a constant pressure on the gutter equal to its weight.

Vibrating conveyors (Fig. 6.2), provide material transport through a gutter driven in a harmonic oscillating motion, which repeatedly throws the material from the gutter to the desired direction of advancement. After each throw a jump follows, and when the component parts of the material return, it is in a position where a new throw follows. In this case, depending on the size of the normal component of the throwing

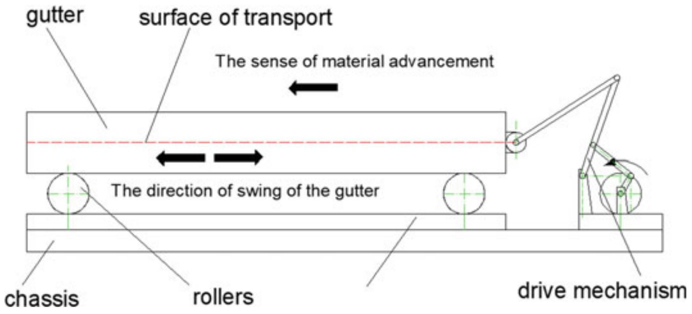


Fig. 6.1 Kinematic drive scheme in the case of the *oscillating conveyors*

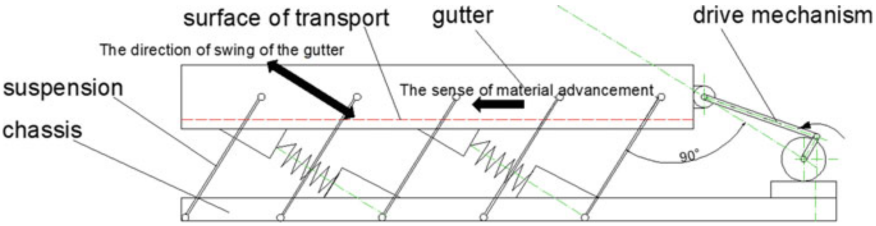


Fig. 6.2 Kinematic drive scheme in the case of the *vibrating conveyors*

force on the surface of the gutter, there may be cases of jumping or sliding on the displacement surface.

The Figs. 6.1 and 6.2 give examples of kinematic drive scheme in the two cases.

Oscillating conveyors are used mainly in the case of the technological transport of individual parts that need certain technological treatments during the movement on the gutter (for example, forged parts that need to cool down during transport).

Vibrant carriers have gained widespread coverage in almost all economic fields, due to their high efficiency and reliability.

The advantages are simple construction, the possibility of thermal and chemical sealing, resistance to mechanical and chemical wear, the possibility of integrating technological processes during the transport of the material, the possibility of control over the flow and dosage.

The disadvantages are flow limitations and transport lengths due to the intense noise and dynamic stress, the possibility of deterioration of the transported material. The decrease of the flow it is a necessity with the increase of the transport length and leads also to the necessity to connect several conveyors in the flow.

Vibrating machines generally have a relatively simple construct, but their operation depends on several factors that are harder to quantify in equations. Starting from the theoretical relationships for determining the speed of material advancement and for calculating power, the objective of this chapter is to highlight the possibilities of using nomograms to approximate the results of the theoretical calculations to the real evolution situation of these equipment.

6.2 Background

6.2.1 Oscillating Conveyors. Construction and Operation

The oscillating conveyors have been described from the point of view of the constructive and functional solutions [4, 10].

Oscillating conveyors are machines with a relatively simple construction. They consist of a chassis, on which is mounted a gutter. The gutter is a metallic structure in welded construction, which consists in a frame with a base of sheet (usually 4–5 mm steel profiled by stamping), a support system of this gutter that consists in a runway rails for the rollers and the spherical and/or cylindrical balls of the gutter, as well as a drive system consisting of the engine and a mechanical transmission. There is a wide range of technical construction solutions, mainly based on the driving system. The most common oscillating conveyors are with horizontal material transport. Oscillating conveyors can also have an inclination of up to 25°, in descending slope. In some cases, the use of oscillating conveyors in ascending slopes was also used.

The usual technical parameters of the oscillating carriers are:

Stroke: 100–300 mm;

Frequency: 100–40 strokes/min.;

Material speed on the gutter: 0.1–0.5 m/s;

Flow: max. 300 m^3/h;

Transport distance: max. 150 m.

The driving power of the oscillating conveyors usually came from linear hydraulic motors, one for the material feed stroke and the other for restoring the gutter to its original position. A case is represented by the oscillating slopes with a downward slope, which do not need a linear hydraulic motor for the forward direction of the material in the desired direction.

The main engine is mounted at the feed side of the gutter, and the return motor at its discharge end. The motors drive the gutter by means of rods provided with devices for adjusting the distance between the engine and the gutter.

The gutter is made of steel sheet by stamping. The running path is made of profiled elements, rigidized between them. The rolling system consists of rollers (balls), depending on the parameters of the transported (Fig. 6.1).

6.2.2 Vibrating Conveyors. Construction and Classification

The vibrating conveyors have been described from the point of view of the constructive and functional solutions [6, 12]. The vibrating conveyors operate on the principle of throwing the material to be transported.

A vibrating conveyor is composed of a conveyor path in the form of a gutter or tube, an oscillating suspension with a guiding role, an elastic suspension for vibrations reduction, and a vibrations generator (Fig. 6.2).

The suspension: It has the role of taking over the static efforts composed of the weight of the material to be transported and that of the gutter, as well as that of forming an oscillating system that drives the gutter so that the trajectory necessary to throw the material is formed.

At the same time, through the elastic support system, the main parameters of the vibration transmitted to the material are adjusted. From this point of view, the conveyors can be (Fig. 6.3):

- Guided oscillating system, in which the direction of vibration is given by the fixed suspension and the elastic dissipation of lamellar springs (Fig. 6.3a);

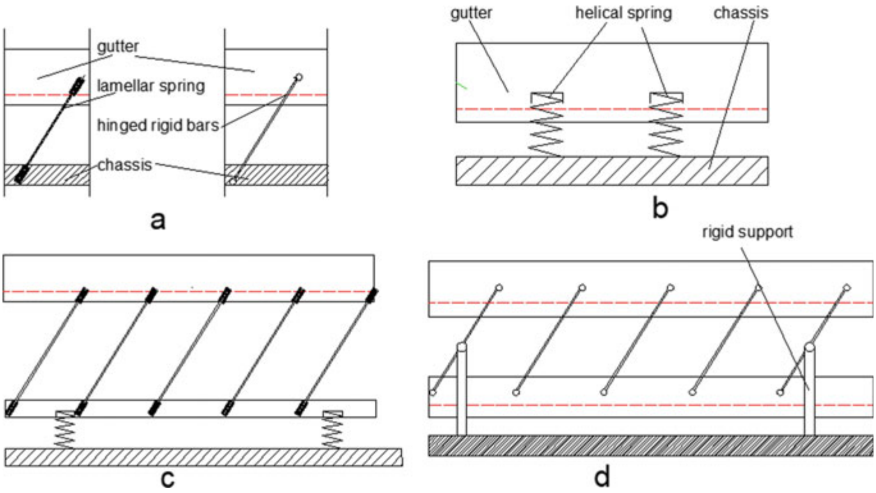


Fig. 6.3 Systems of support of the gutter

- Free vibrating system with a gutter supported on compression or stretch helical springs, in which the direction of oscillation is determined by the direction of vibrations (Fig. 6.3b);
- Vibrating system with two vibrating masses, the upper mass having the guided movement, and the lower one vibrating freely, with the aim of reducing the dynamic stress in the system (Fig. 6.3c);
- Vibrating system with two masses with rigid guidance for achieving the direct balancing of the two vibrating masses, the support being thus required only for static forces (Fig. 6.3d).

Each of these solutions has advantages and disadvantages. For example, certain solutions are not recommended in some cases due to the intense dynamic demands transmitted to the ground and throughout the vibrating system and because it can produce zero amplitude points which in turn produce material agglomerations, thus reducing the useful transport length. On the other hand, systems with two vibrating masses can offer solutions for high transport lengths with low energy consumption and low dynamic demands, but with more complicated constructions.

- **The vibrating mechanism**: It can work on rigid drive or elastic drive on the conveyor (Fig. 6.4).
- The rigid drive consists of a crank mechanism, having the amplitude equal to the radius of the eccentric (Fig. 6.4a).
- The elastic drive can be a crank drive with a spring zone, an inertia mechanism, or an electromagnetic jigger. There are also intermediate drives, at which the spring is included in the crank mechanism to attenuate the inertia forces of the carrier. The amplitude depends not only on the size of the mechanism, but also on the

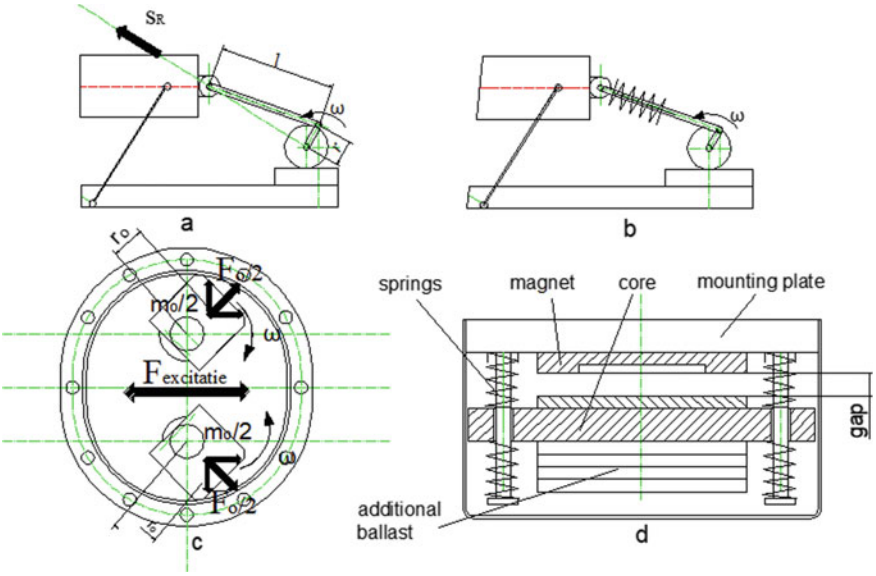


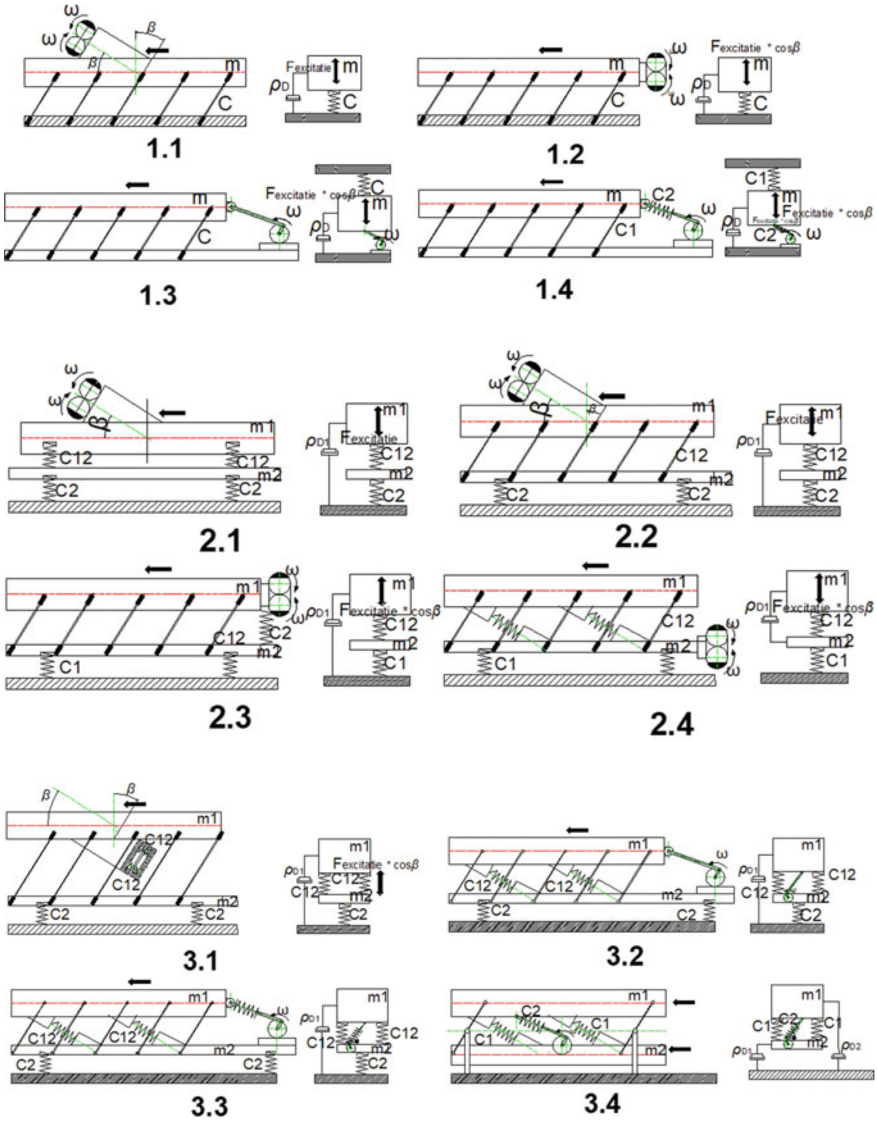
Fig. 6.4 Vibrating mechanisms

forces of inertia and friction in the joints. The frequencies used are between 5 and 15 Hz (Fig. 6.4b).

- In the case of vibrators with unidirectional, self-balancing movements the vibrations are produced by two counterweights. The two identical eccentric masses rotate synchronously in opposite directions, generating one-way vibrations. This is because the components of the centrifugal forces cancel out after a direction perpendicular to the direction of material throw and add up after the direction of throw. To synchronize the two eccentric masses, gears with a 1:1 ratio are used. The frequencies used are between 15 and 50 Hz (Fig. 6.4c).
- The electromagnetic vibrators used are of a reactive type, the operating principle being to attract some unbalance masses when the current intensity is maximum and to reject them when the current intensity is minimal, and the masses are pushed by the action of springs. The vibration frequency is equal to twice that of the supply current, so usually 100 Hz. However, if the 50 Hz frequency is desired, rectifiers are used to eliminate the alternation. In the case of DC power supply, switches are used to obtain the desired frequencies (Fig. 4d).

In Fig. 6.5, depending on these criteria, is a generic representation of the constructive solutions. The proper classification of vibrating conveyors is made according to the following criteria:

Number of vibrating masses: with a single vibrating mass (cases 1.1–1.4) or with two vibrating masses (2.1–2.4; 3.1–3.4);



1.1 1.2 1.3 1.4 2.1 2.2 2.3 2.4 3.1 3.2 3.3 3.4

Fig. 6.5 Constructive solutions of vibrating conveyors (principle diagrams and model)

Number of masses operated in the vibration movement: with a single drive vibrating mass (cases 1.1–1.4), with two masses but only one drive mass (2.1–2.4), with two driven masses (3.1–3.4);

Number of vibrating mechanisms: with one or two vibrating mechanisms;

Type of the vibrating mechanism: inertial vibrators; crank-crank mechanisms; electromagnetic vibrators;

Type of gutter suspension: helical compression springs, lamellar springs, rigid articulated bars;

Vibration generation mode: inertial vibrator with self-balancing coupled with helical springs or free inertial vibrator coupled with rigid articulated bars or lamellar springs.

6.3 Main Focus of the Chapter

6.3.1 Determination of Transport Parameters of Oscillating Conveyors

The oscillating conveyors operate on the principle of sliding the material on the surface of the gutter, the material exerting a constant pressure [7]. The movement of the gutter is a horizontal or quasi-horizontal, asymmetric, forward backward one.

In Fig. 6.6 are the forces that appear within the material-gutter system, when moving in the desired advance direction of the material.

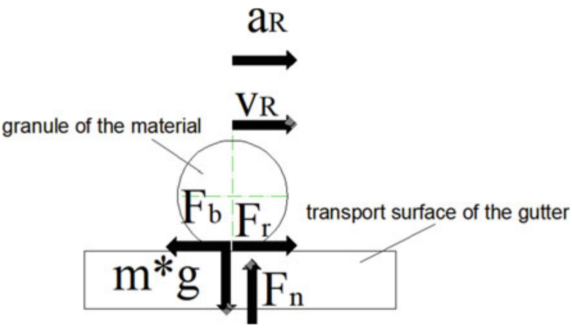
The condition for the material to be driven by the forward movement of the gutter is that the resistive force given by the frictional force between the gutter and material is greater than the driving force transmitted over the gutter, that is:

$$F_r \geq F_b \tag{6.1}$$

In which:

- Fr—the frictional force between the material and the gutter—$F_r = \mu_o \cdot m_G \cdot g$
- Fb—the force of driving the gutter transmitted over the material—$F_b = m_g \cdot a_R$
- Fn—normal reaction force
- v_R—movement speed of the gutter when moving in the desired direction of the material forward
- μ_o coefficient of friction between the transported material and the gutter;

Fig. 6.6 The forces that appear within the material-gutter system when moving a granule



- m_G the mass of the material transported on the gutter;
- a_R—acceleration of the gutter when moving in the desired direction of the material forward.

This results in the condition that the material is involved in the desired forward motion due to the frictional forces, without detachment of the gutter:

$$a_R \leq \mu_o \cdot g \tag{6.2}$$

The condition for advancement is that, at the dead end of the forward movement of the gutter, its acceleration must be chosen so that it is greater than the limit value, thereby producing a relative movement between the gutter and the material transported.

When changing the direction of movement of the gutter from "forward" to "backward", the gravitational forces will be balanced, and the material will slide on the transport organ due to its inertia, still in the desired forward direction, because the relationship exists:

$$|a_R| \geq \mu_o \cdot g \tag{6.3}$$

In Fig. 6.7 are represented the kinematic components involved in the process:

In which:

- S_R (t)—the trajectory of the trough oscillation;
- v_R (t)—movement speed of the gutter;
- a_R (t)—acceleration of the gutter;
- S—the total advance of the material during the considered period T;
- S_G (t)—material oscillation trajectory;
- v_G (t)—speed of movement of the material;
- a_G (t)—acceleration of the material.

The gutter and the material move together in the desired direction of material advancement until the acceleration of the gutter is less than the limit value $\mu_o \cdot g$. When the gutter is braked, and then its direction of movement is changed (in the opposite direction to the desired direction of material advancement) and is accelerated to a value that exceeds the limit value mode $\mu_o \cdot g$, the material continues its movement from its own inertia to the area of the discharge area on the gutter. The speed of the material decreases.

linearly from this moment of inversion of the movement of the gutter, according to the relation $v = v_R - \mu \cdot g \cdot t$.

When the acceleration of the gutter returns as sense of advancement to the desired one of the materials forwarding, and its value falls below the limit value $\mu_o \cdot g$, the material resumes its movement together with the gutter.

The distance traveled by material S is determined by the relation (the hatched area of Fig. 6.8):

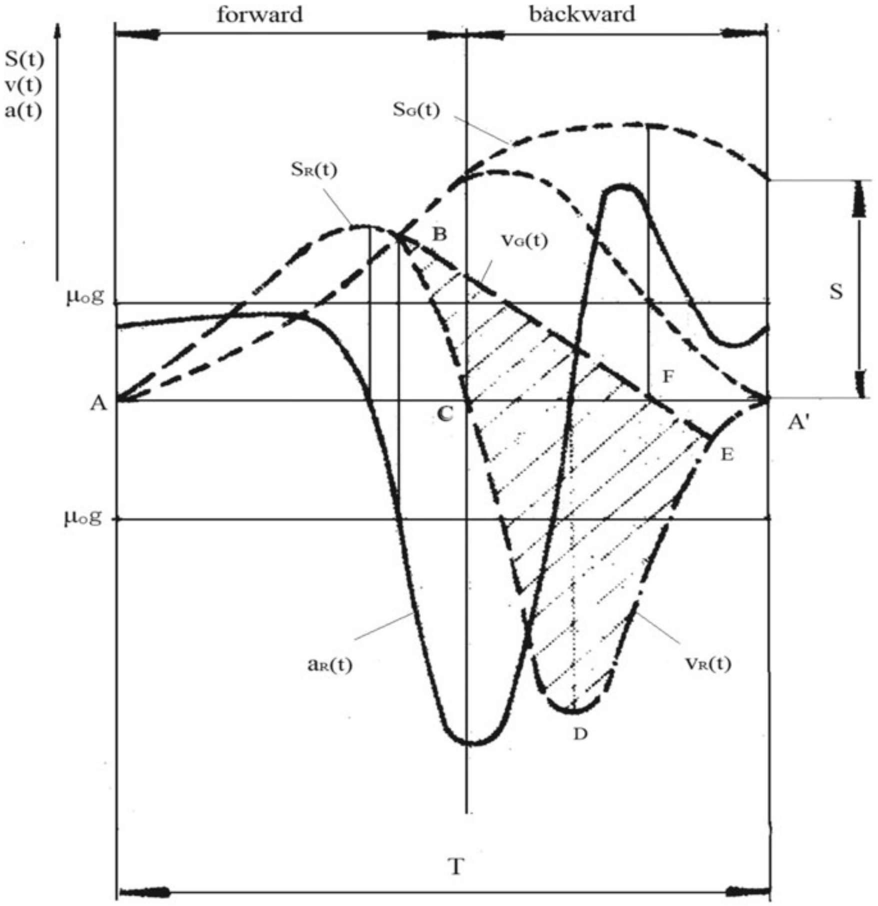


Fig. 6.7 The kinematic measurements involved in the transport process. (Reproduced from Marian [4])

$$S = \int_B^E (v_G - v_R)dt \tag{6.4}$$

- **The average speed** of material advancement is:

$$v_m = \frac{S \cdot n}{60} [\mathrm{m/s}] \tag{6.5}$$

- The carrier's flow is:

$$Q = 3600 \cdot A_{jg} \cdot \psi \cdot \gamma \cdot v_m \tag{6.6}$$

In which:

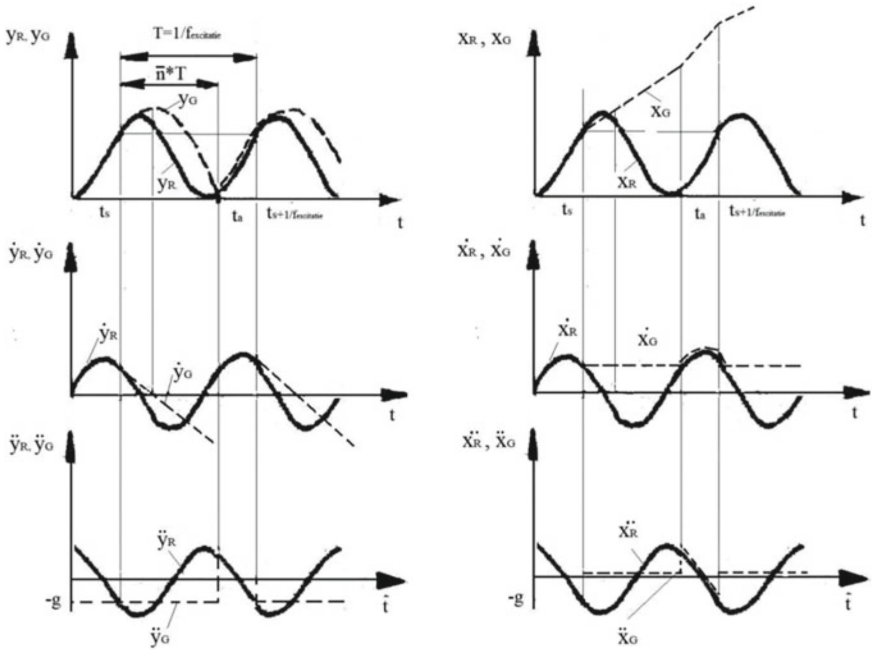


Fig. 6.8 The transport process by throwing the material into the sieve. (Reproduced from Nițescu [6])

- A_{jg}—the cross-sectional area of the gutter;
- ψ—the filling coefficient;
- γ—the volumetric weight of the material;
- v_m—average speed of the material

In the case of the flow, one can also use the formula:

$$Q = 3.6 \cdot q \cdot v_m \quad (6.7)$$

In which: q—the specific weight of the material per linear meter of gutter.

- **The driving power**:

Several theories have been elaborated regarding the way of carrying out the transport process, due to the existence of overlapping phenomena that are difficult to quantify [7]. In general, however, considerations are accepted by which the resistance forces during the transport process are static and dynamic ones. Static resistance forces, generated by gravitational force and friction, are:

1. **The resistance given by the gravitational force during the movement together of the gutter and the material:**

$$W_1 = \pm(G + G_o) \cdot sin\beta \quad (6.8)$$

In which:

- G = q L is the weight of the material on the gutter (L = the length of the gutter);
- G_o—the weight of the gutter;
- β—the slope angle of the direction of movement of the carrier.
- The "+ sign" is applied to the upward movement of the material, and the "– sign" to the downward movement.

2. **The resistance given by the gravitational force during the separate movement of the gutter**:

$$W_2 = \pm G_o \cdot sin\beta \tag{6.9}$$

3. **The resistance given by the friction force during the separate movement of the gutter**:

$$W_3 = \pm G \cdot f \cdot cos\beta \tag{6.10}$$

In which:

- f—the coefficient of friction in movement between the material and the gutter;
- the " + sign" is applied when the gutter and the material move in the same direction;
- the "– sign" is applied when the gutter and the material move in the same direction, but the gutter has a lower speed than the material.

4. **Internal resistance of the gutter support system:**

$$W_4 = (G + G_o) \cdot w' \cdot \cos\beta \, [daN] \tag{6.11}$$

In which: w′—the specific internal resistance to movement of the gutter support system.

Depending on the moment of the movement, we have the following cases of composing these resistances:

Case One: the gutter moves along with the material in the desired forwarding direction:

$$R_1 = W_1 + W_4 \tag{6.12}$$

Case Two: the gutter moves separately from the material, but also in the desired forwarding direction:

$$R_2 = W_2 + W_3 + W_4 \tag{6.13}$$

Case Three: the gutter moves in the opposite direction from the desired one of the materials forwarding, separated by the material:

$$R_3 = W_3 + W_4 - W_2 \tag{6.14}$$

Case four: the gutter and the material move together in the opposite direction to the desired one for the material forwarding:

$$R_4 = W_4 - W_1 \tag{6.15}$$

The dynamic resistances are determined by the relations:

- in the case of joint movement of the gutter and the material:

$$R_1' = \pm G_o \cdot \frac{a}{g}[daN] \tag{6.16}$$

- in the case of separate movement:

$$R_2' = \pm G_o \cdot \frac{a}{g}[daN] \tag{6.17}$$

In which: a—acceleration of the gutter.

The power required for the engine at different times of the work cycle is determined by the expression:

$$P = \frac{R_i \cdot v_i}{102 \cdot \eta_{tr}} \tag{6.18}$$

In which:

- R_i—the instant value of the static and dynamic forcing resistors;
- v_i—the instant value of the gutter speed;
- η_{tr}—efficiency of mechanical transmission from motor to gutter.

6.3.2 Determination of Transport Parameters of Vibrating Conveyors

- **Determining the speed of transport**

Because the factors that influence the actual transport process of the material are very difficult to establish analytically, the formula of the transport speed of the vibrating conveyors is established by building a model of the movement of the material on the transport pathway.

This model is based on the following simplifying hypothesis which are considered [5, 6, 11]:

Hypothesis One: The movement of a single granule of the material, of spherical shape, is identical for all granules;

Hypothesis Two: Phenomena such as internal friction and clashes between material components, air resistance, other properties such as loosening, humidity, elasticity, etc. are neglected;

Hypothesis Three: The bumps between the granules and the gutter are perfectly plastic;

Hypothesis Four: The vibrating machine is a completely centered system, all the perturbing, elastic and dissipative forces pass through the mass center of the system;

Hypothesis Five: The stationary machine is operated at a constant angular velocity; the electric drive motor has a power sufficiently high for the engine-machine interaction to be negligible;

Hypothesis Six: The vibrating machine is considered a vibrating system with constant parameters, the working member is considered a rigid one, the effect of the mass of the elastic elements is neglected;

Hypothesis Seven: It is considered that all the elastic elements of the vibrating machine component have similar characteristics, the elastic elements are considered perfectly linear;

Hypothesis Eight: The effect of weight and displacement of the environment in the interaction with the working body is neglected. the weight of the material being much smaller than the weight of the working member;

Hypothesis Nine: The movement takes place around the stable equilibrium position;

Hypothesis Ten: The dissipative forces are proportional to the speed of the working body.

Under these conditions, the harmonic excitation generated by the vibrator transmit to the transport gutter a movement parallel to itself under the angle of throw β.

The maximum acceleration in the vertical direction appears at the lifting stroke in the center of rotation [6]:

$$\ddot{y}_{min} = -4 \cdot \pi \cdot f_{driving}^2 \cdot A \cdot sin\beta \tag{6.19}$$

In which:

- A—amplitude [mm];
- $f_{driving}$—driving frequency [Hz] or [s^{-1}];

The angular velocity of the exciter is represented by the angular velocity $\boldsymbol{\omega}$ of the vector A, while the frequency of the excitation $\mathbf{f_{driving}}$ is the number of vibrations per second, between the two frequencies the relation exists:

$$\omega = 2 \cdot \pi \cdot f_{driving} \tag{6.20}$$

When there is equality $\ddot{y}_{min}$, the material breaks off the gutter and continues its movement according to the laws of vacuum throwing. At the end of the jump, the material is considered to hit the gutter and immediately continues its movement with the speed of the gutter, without slipping. This simplifying hypothesis is valid if the jump duration is more than 40% of the duration of a complete oscillation.

Figure 6.8 shows the transport main characteristics by throwing the material from the gutter.

The equations of motion of the material transport device are [2]:

$$\begin{aligned} &s_R(t) = A \cdot (1 - \cos \omega t) x_R(t) = s(t) \cdot \cos \beta \quad y_R(t) = s(t) \cdot \sin \beta \\ &\dot{s}_R(t) = A \cdot \omega \cdot \sin \omega t \dot{x}_R(t) = \dot{s}(t) \cdot \cos \beta \quad \dot{y}_R(t) = \dot{s}(t) \cdot \sin \beta \\ &\ddot{s}_R(t) = A \cdot \omega^2 \cdot \cos \omega t \ddot{x}_R(t) = \ddot{s}(t) \cdot \cos \beta \quad \ddot{y}_R(t) = \ddot{s}(t) \cdot \sin \beta \end{aligned} \tag{6.21}$$

At the exact moment t_s, the material jumps off the gutter and the expression results:

$$\ddot{y}_R(t_s) = A \cdot \omega^2 \cdot cos\omega t \cdot sin\beta = -g \tag{6.22}$$

From the relation (6.22) results the relation determining the moment of detachment:

$$t_s = \frac{1}{\omega} \cdot arccos\left(-\frac{g}{A \cdot \omega^2 \cdot sin\beta}\right) \tag{6.23}$$

As noted, the moment of detachment depends on the parameters of the conveyor, such as the frequency of the vibration, the amplitude of the movement and the angle of throw.

At the same time, one can define the *throw coefficient*—Γ as a dimensionless ratio between the maximum acceleration after the vertical direction of the carrier and the gravitational acceleration, a ratio that determines the working regime by jumping the material on the gutter or by moving it through the slide:

$$\Gamma = \frac{\omega^2 \cdot A \cdot sin\beta}{g} \tag{6.24}$$

There are three specific situations:

- $\Gamma = 1$—the limit of the throwing motion;
- $\Gamma > 1$—the material is transported by throwing;
- $\Gamma < 1$—the material transported by sliding.

The relationship (6.23) becomes:

$$t_s = \frac{1}{\omega} \cdot arccos\left(-\frac{1}{\Gamma}\right) \tag{6.25}$$

According to Fig. 6.8, the components according to the vertical direction of the material granule jump will be:

$$\begin{aligned} \ddot{y}_G(t) &= -g \\ \dot{y}_G(t) &= -g \cdot (t - t_S) + \dot{y}_G(t_S) \\ y_G(t) &= y_G(t_S) - \frac{g}{2} \cdot (t - t_S)^2 + \dot{y}_G(t_S) \cdot (t - t_S) \end{aligned} \tag{6.26}$$

The condition is that at the end of the throwing period, the vertical position of the gutter and that of the granule of material to be the same, namely:

$$y_R(t_A) = y_G(t_S) \tag{6.27}$$

The relationship results:

$$A \cdot sin\beta \cdot (1 - cos\omega t_A) = y_G(t_S) - \frac{g}{2} \cdot (t_A - t_S) + \dot{y}_G(t_S) \cdot (t_A - t_S) \tag{6.28}$$

The following substitutions are made:

$$\dot{y}_G(t_S) = \dot{y}_R(t_S) = A \cdot \omega \cdot sin\omega t_S \cdot sin\beta \tag{6.29}$$

$$y_G(t_S) = y_R(t_S) = A \cdot (1 - cos\omega t_S) \cdot sin\beta \tag{6.30}$$

The equation for determining the moment of impact follows:

$$0 = cos\omega t_S - \frac{\omega^2}{2 \cdot \Gamma} \cdot (t_A - t_S) + \omega \cdot \sqrt{1 - \frac{1}{\Gamma^2} \cdot (t_A - t_S)} \tag{6.31}$$

The term deduced in relation (6.25) is inserted in the (6.31) relation, as follows:

$$0 = \Gamma \cdot \cos \omega t_A - \frac{\omega^2}{2} \cdot t_A^2 + \left[\omega \cdot \sqrt{\Gamma^2 - 1} + \omega \cdot \arccos\left(-\frac{1}{\Gamma}\right)\right] t_A - \frac{1}{2} \cdot \arccos^2\left(-\frac{1}{\Gamma}\right) - \sqrt{\Gamma^2 - 1} \cdot \arccos\left(-\frac{1}{\Gamma}\right) + 1 \tag{6.32}$$

A *throw resistance factor*—$\overline{n}$ is also introduced, a dimensionless factor which has the significance of the quota-part of the jump phase during a complete oscillation throughout the period, as follows:

$$t_A = t_S + \frac{\overline{n}}{f_{excitatie}} = t_S + \frac{\overline{n}}{\omega} \cdot 2 \cdot \pi \tag{6.33}$$

The relations (6.25) and (6.33) are substituted in (6.32), resulting in:

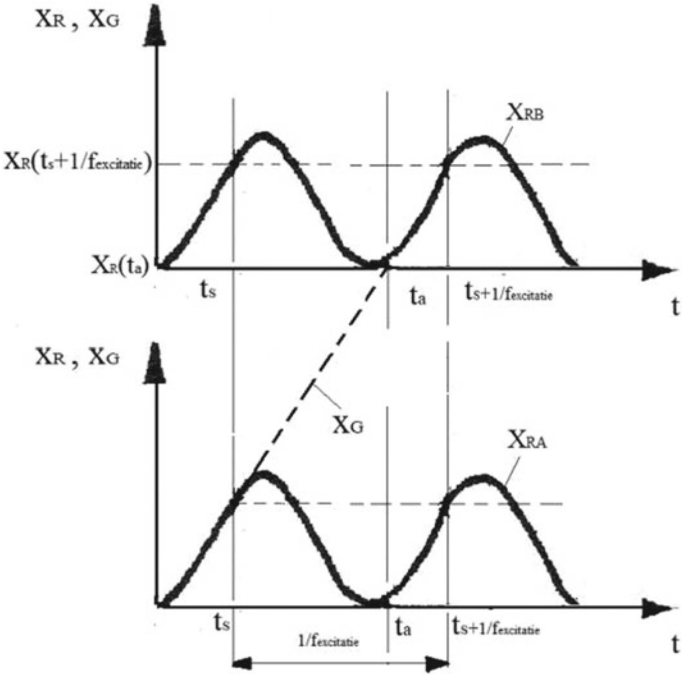


Fig. 6.9 The components of the average transport speed. (Reproduced from Posea and Takacs [7])

$$\Gamma = \sqrt{\left(\frac{\cos 2\cdot\pi\cdot\overline{n} + 2\cdot\pi^2\cdot\overline{n}^2 - 1}{2\cdot\pi\cdot\overline{n} - \sin 2\cdot\pi\cdot\overline{n}}\right)^2 + 1} \tag{6.34}$$

Figure 6.9 shows the two components of the average transport speed in the case of horizontal transport, when the frequency, amplitude and angle of throw are given, in which:

- v_{GA}—the component of the throwing speed during the jump period;
- v_{GI}—the component of the synchronization period;
- A—the launch point
- B—the impact point.

During the throwing period, the horizontal speed remains constant, according to the launch laws and has the form:

$$v_{GA} = \dot{x}_R(t_A)\cdot\frac{t_A - t_S}{\frac{1}{f_{driving}}} \tag{6.35}$$

During the synchronization period, the stated hypothesis is used that there is no slip between the gutter and the material. It turns out that during the period $t_S + \frac{1}{f_{driving}} - t_A$, a space is covered:

$$x_R \cdot \left(t_S + \frac{1}{f_{driving}}\right) - x_R(t_S) \tag{6.36}$$

Thus, the speed component during the synchronization period is:

$$v_{GI} = \frac{x_R \cdot \left(t_S + \frac{1}{f_{driving}}\right) - x_R \cdot (t_A)}{t_S + \frac{1}{f_{driving}} - t_A} \cdot \frac{t_S + \frac{1}{f_{driving}} - t_A}{\frac{1}{f_{driving}}} \tag{6.37}$$

$$v_{GI} = A \cdot f_{driving} \cdot \left(cos\omega t_A + \frac{1}{\Gamma}\right) \cdot cos\beta \tag{6.38}$$

The average speed is given by the sum of the two determined components:

$$v_{tr\_or} = 2 \cdot \pi \cdot f_{driving}^2 \cdot A \cdot \sqrt{1 - \frac{1}{\Gamma^2}} \cdot (t_A - t_S) \cdot cos\beta + A \cdot f_{driving} \cdot \left(cos\omega t_A + \frac{1}{\Gamma}\right) \cdot cos\beta \tag{6.39}$$

Using the expression value $cos\omega t_A$ from Eqs. (6.31) and (6.33) in the above expression, we obtain the final form of the theoretical speed of material transport:

$$v_{tr\_or} = \frac{g \cdot \overline{n}}{2 \cdot f_{driving}} \cdot ctg\beta; \quad (0 \le \overline{n} \le 1) \tag{6.40}$$

- **Determining the driving power**

It is considered that, after the throwing phase, the transported material returns to the gutter by plastic collision. At this moment a new impulse for throwing the granule of material takes place. If the velocity components of the material granule are noted with v_{Gx} and v_{Gy} and with v_{Rx} and v_{Ry} the gutter components at the exact moment of collision, then the value of energy loss at impact is calculated by the expression:

$$W = \frac{m_G}{\frac{m_G}{m_R} + 1} \cdot \frac{(v_{Gx} - v_{Rx})^2 + (v_{Gy} - v_{Ry})^2}{2 \cdot 9,81} [\text{daNm}] \tag{6.41}$$

The components of the gutter speed are given by the relationships (6.21) that can be extended to the components of the speed of the material to be transported:

$$v_{Rx} = \dot{x}_R(t_A) = 2 \cdot \pi \cdot f_{driving} \cdot A \cdot sin(2 \cdot \pi \cdot f_{driving} \cdot t_A)cos\beta \tag{6.42}$$

$$v_{Ry} = \dot{y}_R(t_A) = 2 \cdot \pi \cdot f_{driving} \cdot A \cdot sin(2 \cdot \pi \cdot f_{driving} \cdot t_A)sin\beta \tag{6.43}$$

$$v_{Gx} = \dot{x}_G(t_A) = \dot{x}_R(t_S) = 2 \cdot \pi \cdot f_{driving} \cdot A \cdot \sin(2 \cdot \pi \cdot f_{driving} \cdot t_S) \cos\beta \tag{6.44}$$

$$v_{Gy} = \dot{y}_G(t_A) = \dot{y}_G(t_S) - g \cdot (t_A - t_S) = \dot{y}_R(t_S) - g \cdot \frac{g \cdot \overline{n}}{f_{driving}} \tag{6.45}$$

By introducing into the relation (6.41) these components of the grain and the gutter speeds, one can obtain:

$$W = \frac{m_G}{2 \cdot 9,81\left(\frac{m_G}{m_R} + 1\right)} \cdot \left[\omega^2 \cdot A^2 \cdot f(\overline{n})^2 - 4 \cdot \pi \cdot A \cdot \overline{n} \cdot g \cdot \sin\beta \cdot f(\overline{n}) + \left(\frac{g \cdot \overline{n}}{f_{driving}}\right)^2\right] \tag{6.46}$$

In which:

- A—amplitude;
- $f(\overline{n}) = \sin\omega t_S - \sin\omega t_A$ function of the jump resistance coefficient, which is determined from the graph in Fig. 6.10.

The power output is given by the product between the energy loss value and the excitation frequency $\left(f_{driving} = \frac{\omega}{2 \cdot \pi}\right)$:

$$P = W \cdot \frac{\omega}{2 \cdot \pi} \tag{6.47}$$

Substituting in the above expression (6.47) the previous relations (6.46), (6.41), (6.24), one will obtain:

$$P = \frac{m_G \cdot g^2}{9,81\left(\frac{m_G}{m_R} + 1\right) \cdot \omega} \cdot \left[\frac{K^2}{4 \cdot \pi} \cdot f(\overline{n})^2 - \Gamma \cdot \overline{n} \cdot f(\overline{n}) + \overline{n}^2 \cdot \pi\right] \tag{6.48}$$

Since the mass of the gutter is much larger than that of the material at one point on the gutter, the ratio $m_G/m_R \rightarrow 0$ can be approximated.

In all cases of operation of vibrating conveyors, the variation of the loading of the gutter with material causes serious and rapid disturbances when these variations of the mass of material on the conveyor are comparable in order of size with the mass of the gutter. It is therefore recommended [12], from the practical experience, not to exceed the ratio of 25% between the mass of the gutter and the mass of the material.

So, the above relationship (6.48) becomes:

$$P = \frac{m_G \cdot g}{102 \cdot \omega} \cdot \left[\frac{K^2}{4 \cdot \pi} \cdot f(\overline{n})^2 - \Gamma \cdot \overline{n} \cdot f(\overline{n}) + \overline{n}^2 \cdot \pi\right] \ [\mathrm{kW}] \tag{6.49}$$

Relation (6.49) represents the power required to drive and depreciate the transported material. For the final dimensioning of the drive motor, the efficiency of the transmission, the efficiency of the electric motor and its overload coefficient must also be considered.

- **Dynamic analysis of vibrating conveyors**

For the dynamic analysis of the vibrating conveyors, a model is constructed for each system, in order to establish a differential equation that characterizes the evolution of the vibrators. By solving these differential equations one can determine the optimal amplitude and frequency.

Because the own vibrations of the system are rapidly damped due to the friction and the plastic collisions between the granules and the gutter, these vibrations are not considered to the differential equations.

To the value of the trough mass is added the mass of the material that is at one point in contact with the trough. In this respect, it is considered, from the practical experience of operating the vibrating conveyors, that only a certain percentage of this material is in permanent contact with the gutter. It is usually considered that only 20% of the material in the transport process at one point on the gutter is directly in contact with the gutter [11].

This defines a *coupling factor x*:

$$x = \frac{0,78}{\Gamma} - 0,18 \tag{6.50}$$

The *factor x* can be determined using the graph in Fig. 6.11 where curve 1 represents the values of the factor independent of the angle of throw β, and curve 2 expresses the coupling factor for the angle of $\beta = 30°$. For other angles, the value of the coupling factor is determined by multiplying the values on curve 2 with the value of the ratio $sin^2\beta/sin^2 30^o$.

The movements of the transported mass are decreased by springs and plastic collisions with the gutter. The dissipation given by the springs is basically negligible for the steel springs.

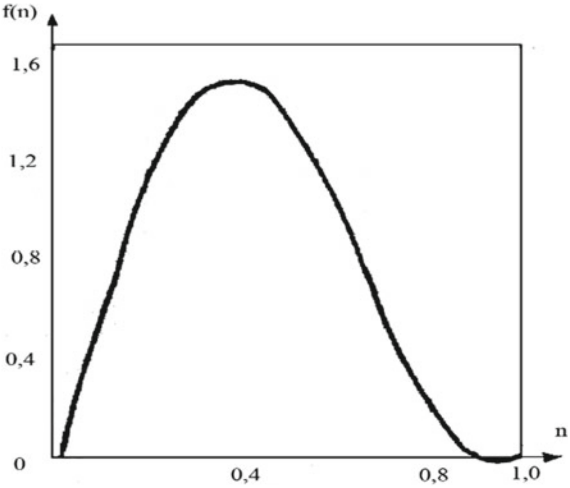


Fig. 6.10 Values of coupling factor ***X*** with the throw coefficient ***Γ***. (Reproduced from Posea and Takacs [7])

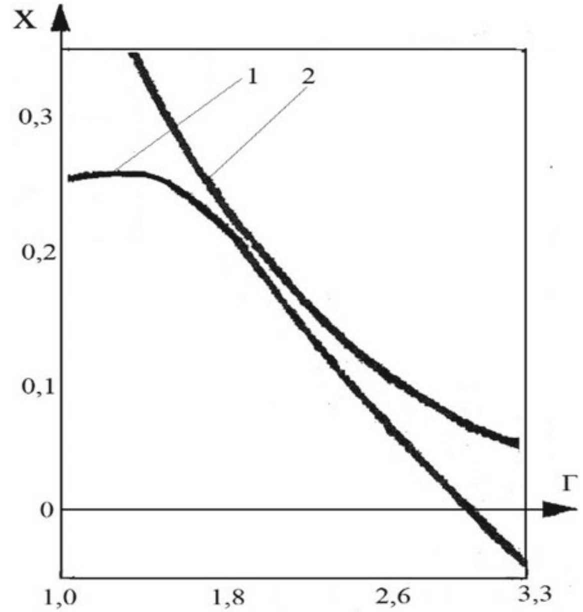


Fig. 6.11 Dependence of the function $f(\overline{n}) = \sin \omega t_S - \sin \omega t_A$ on the resistance factor of the throw. (Reproduced from Posea and Takacs [7])

For the rubber suspensions, the dissipation factor depends on the base material characteristics and is determined experimentally.

The damping given by the plastic collisions between the material and the gutter is equivalent to the energy lost by collision in (6.46). For a T period, the energy loss is:

$$W = 4 \cdot \int_0^{\frac{T}{4}} \rho_D \cdot \dot{S}_R^2 dt = 4 \cdot \rho_D \cdot A^2 \cdot \omega^2 \cdot \int_0^{\frac{}{2}} \sin^2 x dx = \rho_D \cdot A^2 \cdot \omega^2 \cdot \pi \tag{6.51}$$

The material is amortized at each period according to the relationship:

$$W = \frac{P \cdot 2 \cdot \pi}{\omega} \tag{6.52}$$

Equalizing the two relations, the depreciation factor can be extracted ρ_D:

$$\rho_D = \frac{2 \cdot P}{A^2 \cdot \omega^2} \cdot 9,81 \quad [kg/s] \tag{6.53}$$

In which:

- P—power consumed for depreciation [daNm/s];
- A—amplitude [m];
- ω frequency of oscillation [s^{-1}].

- **System with one vibrating table**

The differential equation for the system, characterizing the balance between the mass forces, the dissipation forces, force of spring, and the excitatory force, is:

$$m \cdot \ddot{s}_R + \rho_D \cdot \dot{s}_R + c \cdot s_R = F_o \cdot cos\omega t \tag{6.54}$$

The following notations are inserted:

– $\nu = \frac{\omega}{\omega_p}$ relative frequency;
– $\omega_p = \sqrt{\frac{c}{m}}$ the own pulsation of the elastic system;
– $c = \frac{\omega^2 \cdot m}{\nu^2}$ the spring constant;
– D—relative dissipation;
– $F_o = \omega^2 \cdot m_o \cdot r$ the maximum value of the driving force.

The general integral of the differential Eq. (6.38) has two terms: the first represents its own vibration which decreases very quickly, and the second represents the forced vibration.

The amplitude of the forced vibration is:

$$A = \frac{m_o \cdot r_o}{m} \cdot \frac{\nu^2}{\sqrt{\left(1 - \nu^2\right)^2 + 4 \cdot D^2 \cdot \nu^2}} = \frac{m_o \cdot r_o}{m} \cdot \nu^2 \cdot R \tag{6.55}$$

In which: R—resonance factor.

6.4 Solutions and Recommendations

- **The Throw Coefficient *Γ***

Regarding the *throw coefficient*, theoretical and practical considerations were considered [12] to determine the maximum reduction of the energy transmitted by the mechanism to the gutter and the reduction of the time in which the granule of material is jumping. This is because it consumes a lot of energy to throw the pellet too high, and during the jump the pellet cannot be accelerate for transport.

From the studies mentioned above of the dynamics of the jump, both theoretically and under real conditions, the following characteristic values were determined:

$\Gamma = 3.296$—the duration of the particle jump is equal to the duration of a complete oscillation of the gutter ($\Gamma \cong 3.3$);

$\Gamma = 6.362$—the duration of the particle jump is equal to the duration of two complete oscillations of the moving frame ($\Gamma \cong 6.4$).

In the practice of designing vibrating machines, values higher than $\Gamma = 7.5$ are not used because operating regimes with very high dynamic demands are obtained, which greatly reduce the durability of bearings, springs and lead to rapid cracks in the side walls of vibrating box.

Also, during vibration, a grinding of the material on the screen can be observed, which may be undesirable for certain industrial processes.

Equation (6.34) establishes the dependence between the throw coefficient and the resistances of the system to the material transport. The graph of evolution of Eq. (6.34) for $0 \le \overline{n} \le 5$ values is the one in Fig. 6.12. And in Fig. 6.13 is the dependence of the throw coefficient on the throw resistance for $0 \le \overline{n} \le 1$.

In this case, the final form of the theoretical speed of material transport:

$$v_{tr\_or} = \frac{g \cdot \overline{n}}{2 \cdot f_{driving}} \cdot ctg\beta;\ (0 \le \overline{n} \le 1) \tag{6.56}$$

Also, a *K coefficient of the machine* is defined, as the ratio of the acceleration component on the throwing direction and the gravitational acceleration component following the same direction:

$$K = \frac{\omega^2 \cdot A}{g} = \frac{\Gamma}{sin\beta} \tag{6.57}$$

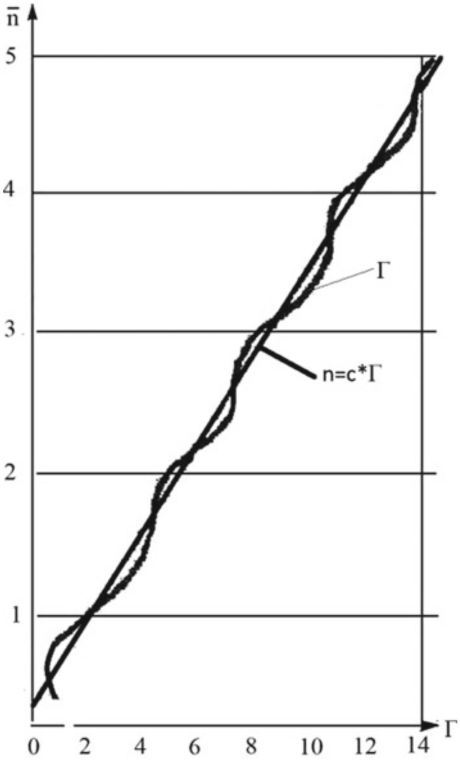
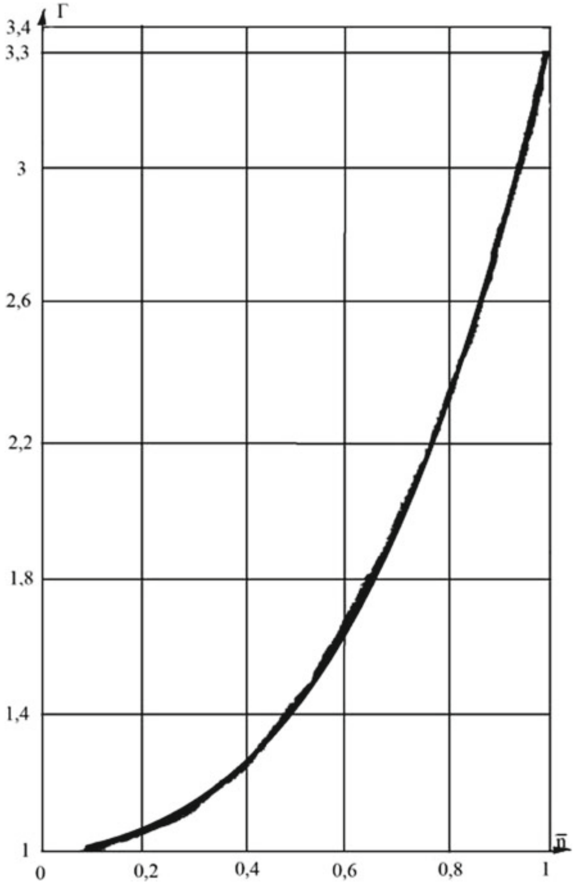


Fig. 6.12 Dependence of $\overline{n}$ on Γ. (Reproduced from Nițescu [6])

Fig. 6.13 Dependence of Γ on $\overline{n}$. (Reproduced from [6])



The usual values adopted for the coefficient of the machine K are 6 ≤ K ≤ 7.

By using the expression below (6.57) in Eq. (6.56), the theoretical transport speed can be expressed as a function of the *throw resistance* and the *coefficient of the machine K* (6.58):

$$f_{driving} = \frac{\omega}{2 \cdot \pi} \tag{6.58}$$

$$v_{tr\_or} = \sqrt{g} \cdot \frac{\overline{n}^2}{\sqrt{K}} \cdot ctg\beta \cdot \sqrt{A} \cdot \pi \tag{6.59}$$

The coordination between the values of the throw resistance and the coefficient of the machine K can be done by means of a nomogram according to Fig. 6.15:

How to use the nomogram, is as follows:

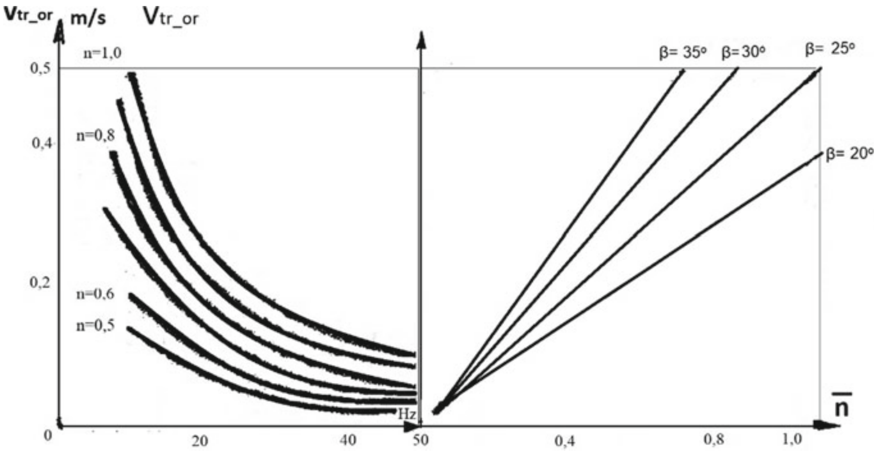


Fig. 6.14 Nomogram for determining the speed of transport. (Reproduced from Posea and Takacs [7])

Step 1: The throw resistances are the curves on the left side of the nomogram, for values $0 \leq \overline{n} \leq 1$;

Step 2: Choosing a value for K, reads on the left side of the nomogram for a certain angle of throw β, the transport speed v_{tr_or} for amplitude A = 1 mm;

Step 3: Next, on the right side of the nomogram, the definitive transport speed will be read, by intersecting with the right of the real amplitude.

Step 4: The amplitude A value is not a freely chosen but must be in accordance to the excitation frequency in Fig. 6.16, that is an evaluation of the Eq. (6.57).

Figure 6.14 shows a nomogram that can be used to determine the transport speed.

From the nomogram in Fig. 6.16, it is observed that for maximum speed values and maximum values for the coefficient of the machine K, give small angles of throw. To obtain high transport speeds for a given K and small amplitudes, one will have to choose the optimal angle of the throw.

In Fig. 6.17, the curve represented corresponds to the line of the maximum transport speed from Fig. 6.15.

Because the theoretical transport speeds do not correspond usual to the real actual speeds, correction coefficients are introduced which consider the properties of the transported material and the disruptive conditions:

$$v = v_{tr\_or} \cdot k_1 \cdot k_2 \cdot k_3 \cdot k_4 \tag{6.60}$$

- The value of the coefficient k_1 take into consideration the material to be transported for a thickness of the layer of several centimeters. The value is obtained experimentally only and comprises $k_1 = 0.85\ldots1.1$ for granular materials and in small pieces. The coefficient k_1 also depends on the throw coefficient, the maximum limit being related to the value $\Gamma = 3.3$, as already mentioned above.

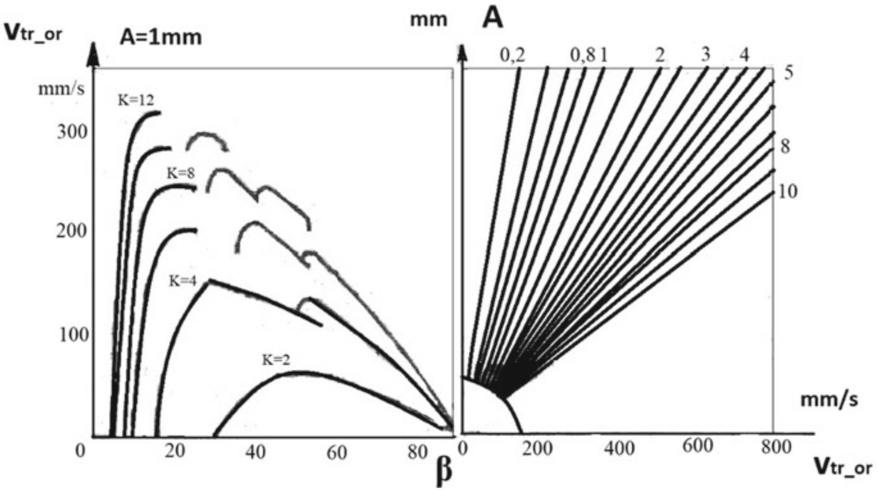


Fig. 6.15 Correlation nomogram between values $\overline{n}$ and K. (Reproduced from Posea and Takacs [7])

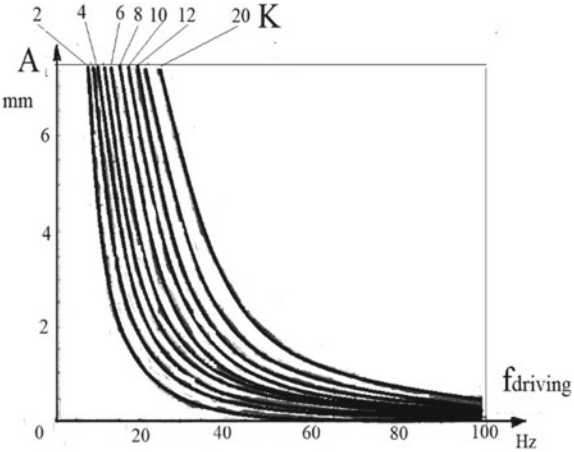


Fig. 6.16 Nomogram for determining the values of the amplitude A as a function on frequency $f_{driving}$ with constant parameter K values. (Reproduced from [13])

- Fig. 6.18 represents qualitatively the speed reduction by increasing the thickness of the transported material layer. For the material that are suitable for transporting on the vibrating conveyors—that is with a low percentage of fine granules—up to the thickness of the 200 mm layer, the speed reduction is quite small.
- Fig. 6.19 shows the dependence of the transport speed on the grain size. A major influence on the speed of transport is the structure of the material to be transported, especially an important presence of the fine granules. Especially the fine material -that is granules below 0.3 mm—reduces the transport accuracy, due to the occurrence of additional disruptive phenomena. Thus, by increasing the percentage of

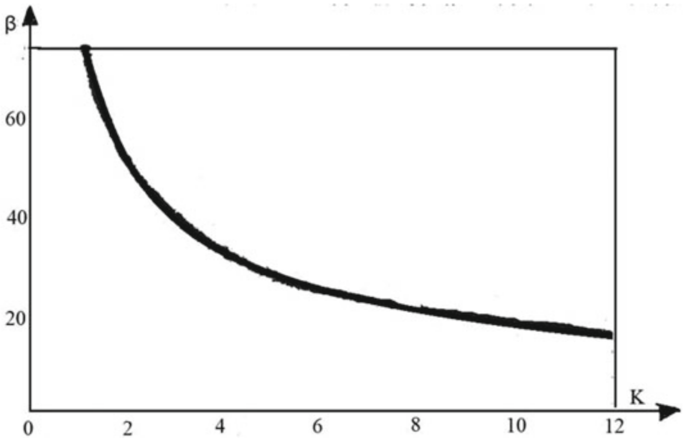
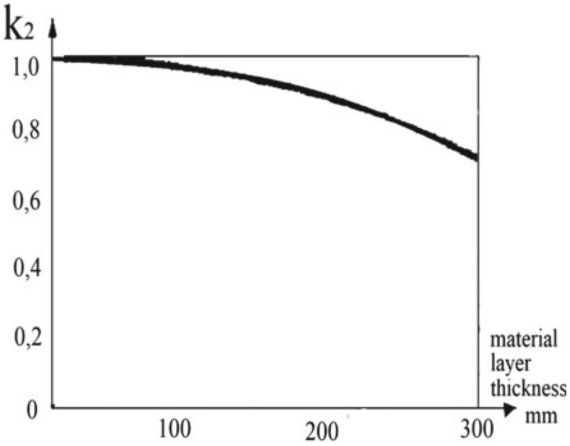


Fig. 6.17 The optimal angle of the throw depending on the coefficient K values. (Reproduced from Wehmeier [13])

Fig. 6.18 The coefficient k_2 of influence of the thickness of the material layer on the transport speed. (Reproduced from Posea and Takacs [7])



fine material, the gas permeability decreases. Due to the permanent movement of the material on the gutter, there is a continuous variation of the pressure in the layer, which must be balanced by the material layer with the atmospheric pressure. If this is not possible, air cushions are formed which impede the transmissibility of the impulses transmitted by the gutter on the material, and secondly, it causes a forced and abrupt balancing of the pressures, reaching eruptive triggers, which lead to the strong formation of dust.

- Fig. 6.20 the coefficient k_4 of influence of the slope of the gutter on the speed of transport. By tilting the gutter down, the speed of transport is increasing. The inclination should be limited to 10°–12°, because with its increase, the material slippage increases.

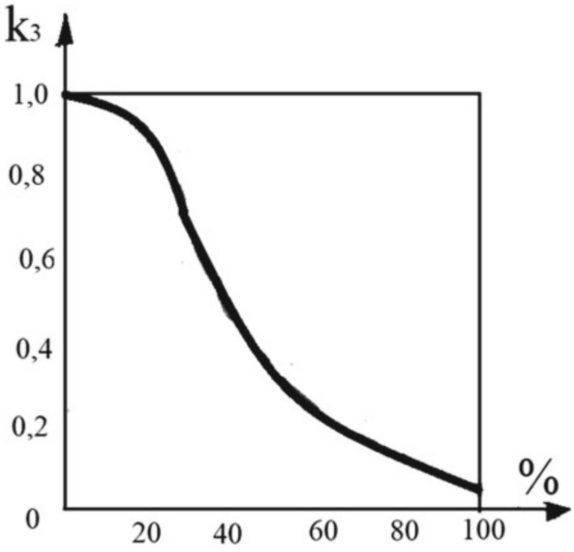


Fig. 6.19 The coefficient k_3 of influence of the percentage of fine material in the material on the speed of transport. (Reproduced from Posea and Takacs [7])

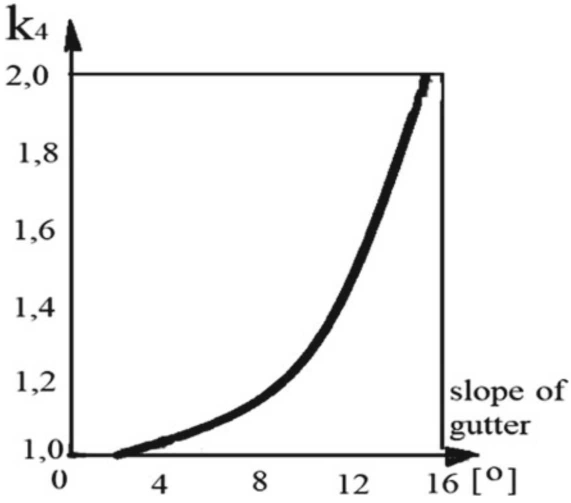


Fig. 6.20 The coefficient k_4 of influence of the slope of the gutter on the speed of transport. (Reproduced from Posea and Takacs [7])

As an example, for those mentioned above related to thickness of the material layer (k_3 coefficient), the Fig. 6.21 below give the experimental results of some measurements made for the transport of bulk cement, at the slight inclination of the gutter. Thus, it can be observed that at the same frequency of vibrations, a thicker layer greatly reduces the amplitude of the vibration. Also, there is a drastic reduction in the actual transport speed, as the thickness of the transported material layer increases (Fig. 6.22). All these examples show that one will always have to test these types of vibrating conveyors under real operating conditions.

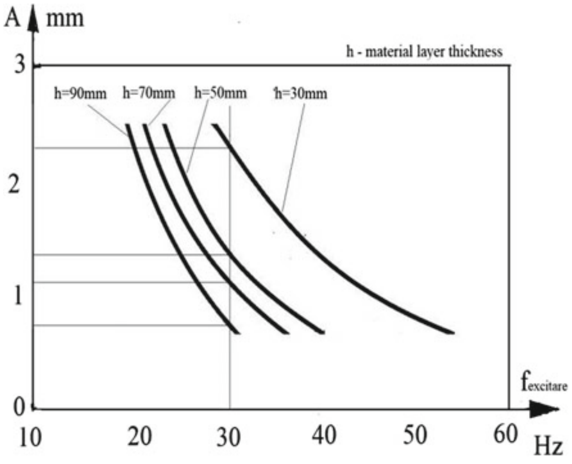


Fig. 6.21 Decrease in amplitude as the thickness of the material layer increases—at large thicknesses air cushions are produced. (Reproduced from Posea and Takacs [7])

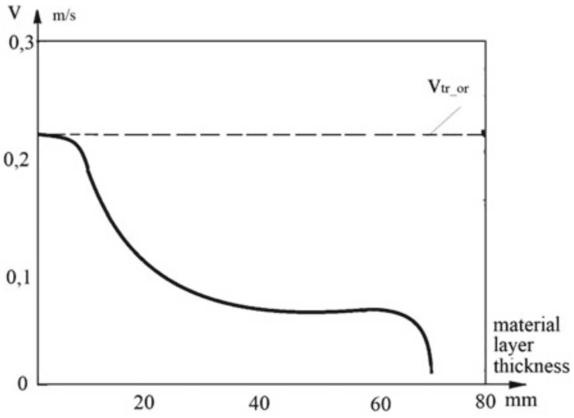


Fig. 6.22 The transport speed depending on the thickness of the layer for f = 18 Hz, A = 2.7 mm, β = 30°, Γ = 1.76. (Reproduced from Posea and Takacs [7])

- **The operating mode: pairs of amplitude / frequency parameters**

Not for any values of the amplitude and frequency parameters can be obtained optimal operating regimes, which allow energy savings, low values of dynamic solicitations and high transport efficiency. It has been proven that only for pairs of values in which small amplitudes are associated with high frequencies and respectively, high values of amplitudes are associated with low frequencies can be obtained optimal transport regimes. In the specialized literature there are nomograms for determining the amplitude/frequency pairs, in correlation with the other parameters of the technological process.

In order to establish a correct working regime, the frequency of resonance must also be considered. In Fig. 6.23 is presented the evolution of a carrier around the area of the resonant frequency for different values of the relative *damping factor D*.

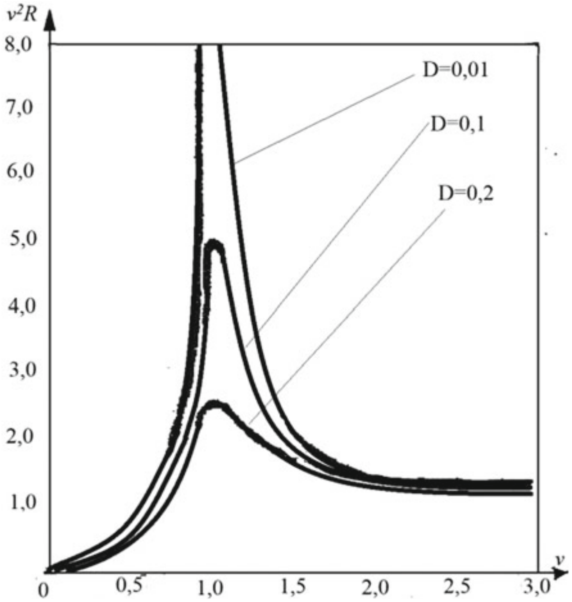


Fig. 6.23 The function ν^2R dependence of the frequency ν relative to an oscillator with a mass, having D as a parameter. (Reproduced from Munteanu [5])

This diagram shows the validity area of this type of vibrating conveyor. One can notice that it is possible for $\nu > 3$ to obtain a stable behavior of the conveyor that is not influenced by the frequency and relative dissipation variations.

It can be observed from Fig. 6.24 that, establishing the vibrational regime in the super-resonant field presents a net technological advantage: with the increase of the amount of material on the sieve which produces a temporary decrease in the frequency of vibrations, implicitly an increase of the amplitude of the vibrations; in turn, increasing the amplitude produces faster release of the material from the gutter; thus a continuous process of variations of the amplitude/frequency pair takes place around a relatively stable point of evolution of the process.

The rigidity of the suspension springs plays an important role in establishing the operating regime. The constant of the spring is determined from the equations above (6.38). Increasing the stiffness of the spring causes a decrease in relative speed, at constant angular velocities and masses. Steel lamellar springs produce bending forces and moments which are taken over by the foundation and which increase with increasing spring rigidity. For this reason, in general, the operation around the resonance zone is excluded for systems with a single vibrating mass ($\nu \approx 1$).

Some constructive solutions from those presented in Fig. 6.23 are better suited to transport over longer distances. Construction type 1.3 finds its use in long conveyors and it will be necessary to avoid that the excitation force has a vertical component at the longitudinal axis of the conveyor to avoid the possibility of bending demands. The disadvantage of this variant is that only the $F_{driving} \cdot cos\beta$ component is used, and the component requires lamellar springs.

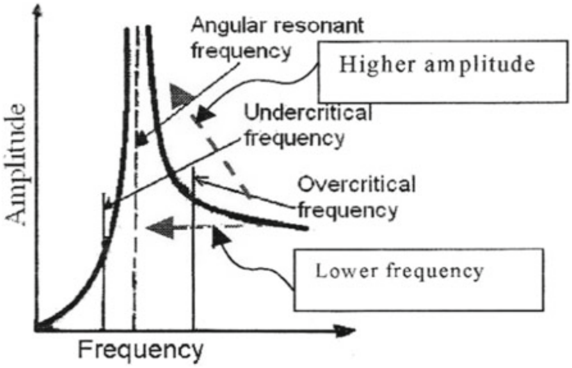


Fig. 6.24 The evolution of amplitude/frequency pair of values in the over-critical frequency zone. (Reproduced from Stoicovici [11])

- **Use of non-harmonic drive methods**

All the considerations studied are based on the harmonic action of the vibrating conveyors, because these types of excitation have been studied and applied. However, there is also the possibility of using non-harmonic operating methods.

There are two problems to study:

- The size of the transport speed while maintaining the constant *transport coefficient K;*
- Reducing the amplitude, maintaining the constant transport speed.

The speed of transport increases for large amplitudes, low frequencies and at the same time depends on the type of operation (Fig. 6.25) the theoretical law of oscillation can practically not be represented. However, the maximum speed limit at the operating frequency and the value of the accelerating acceleration were represented.

An approximation of the theoretical law is made for the interference of two harmonic oscillations, by the expression:

$$S_R = A_1 \cdot \left[cos\omega t + \frac{1}{i \cdot cos(k \cdot \omega t + \phi_k)} \right] \tag{6.60}$$

In which:

A1—amplitude of the basic oscillation;
AR—amplitude of (k − 1) oscillations;
i—amplitude ratio (i = A1 / Ak);
K—the ratio of frequencies to (k − 1) basic oscillation;
ϕ_k—the angle of adjustment of the phases (k − 1) oscillations with respect to the basic oscillation.

These results can be considered as new fields in the research direction of oscillating and vibrating conveyors.

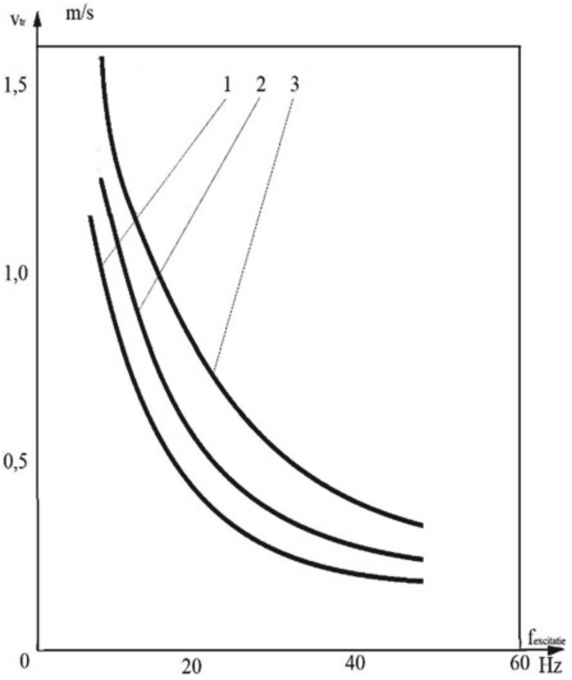


Fig. 6.25 Dependence of the theoretical transport speed vtr_or on the excitation frequency, for different excitation laws, for a period of oscillation (n = 1.0), in witch: incurve 1—harmonic drive (n = 1.0; k = 6.6; β = 30°); incurve 2—interference of two harmonic oscillations (k = 3; φ = 180°; I = 45; n = 1.0; k = 6.6) β = 23°); incurve 3—excitation limit function (n = 1.0; k = 6.6; β = 18°). (Reproduced from Posea and Takacs [7])

6.5 Conclusion

In this chapter, the main factors influencing the operation of oscillating and vibrating transporters were presented, such as: amplitude, frequency, throwing coefficient, damping coefficient, spring count.

Apart from these factors, there are factors such as the humidity of the material, its granulation, the internal adhesion forces, the natural slope angle of the material. There are also factors related to the specific features of the machine: the construction, the suspension, the vibrating mechanisms.

As can be seen, there are several factors that influence the operation of the carrier. Part of these factors cannot be quantified in formulas convenient to be technically usable.

At the same time, all these factors need to be coordinated with each other in order to obtain an optimal operating regime, which will allow energy saving and maintain the machine.

Therefore, it is recommended to use for the design of nomograms that combine the practical experience of exploitation and design in order to obtain the optimal operating regimes desired.

In general, the use of nomograms in the design of the machines represented, first, a substantial shortening of up to 50% of the time allotted for the calculations necessary to establish the optimum values for the main parameters specific to each type of machine. These parameters could be adopted in accordance with each other, thus obtaining optimal operating regimes, thus benefiting from the design experience of the respective unit.

At the same time, it can be estimated with sufficient accuracy that using these nomograms can achieve an energy saving of up to 10%, under the conditions of extending the life of the machine up to 30–50% due to the diminished dynamic demands to which the machine is subjected.

6.6 Glossary

Forward–Backward Motion: linear resultant motion of a constructive assembly produced by an external force provided by a motor mechanism, which executes in a direction parallel to the longitudinal axis of the constructive assembly, alternatively, in the sense forward, respectively, backward the assembly respectively.

Chassis: component part of a machine, usually in the form of a metallic construction, sometimes containing heavy materials of high density, obtained by welding, stamping, or removable screw-nut assemblies, intended to ensure the operating position of the respective machine within the technological flow of which it is part, as well as the transmission to the ground of the vibrations and stresses to which the machine is subjected.

Usual Technical Parameters: parameters by which values determine the operation mode of a machine, characteristics of each type of machine and which vary function of destination, construction and mode of operation.

Quasi-Horizontal Movement: movement of the moving part of a machine that is very close by its features to a horizontal plane-parallel motion itself.

Suspension: a component part of a machine, intended for transmitting vibrations, shocks and stresses to the ground to the respective machine, composed of elastic elements made of steel, rubber or other elements with similar behavior, with or without influence in the regime. of movement of the respective machine.

Vibrating Mechanism: a mechanism that by its construction produces a vibrating movement that is transmitted to the component of the machine on which it is mounted.

Eccentric Masses: masses so placed in a device that their center of gravity is not found on the mounting axis within the respective device, and thus, by rotating about this axis, creates a useful imbalance for the technological process of which the device is part.

Simplifying Hypotheses: assumptions that are adopted in the study of real phenomena whose unfolding implies a multitude of difficult parameters to quantify, by which the approach is simplified in order to obtain practically viable results and thus tends towards ideal phenomena.

Nomogram: one or more interconnected charts, comprising the evolution curves of two or more parameters, depending on which all the parameters competing for the proper functioning of a machine can be quickly determined

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Chapter 7
Energy Geostructures: An Innovative Renewable Energy Technology for Cooling and Heating of Buildings

Octavian Bujor, Iulia-Consuela Prodan, and Augustin Popa

Abstract Development of innovative technologies for alternative energy sources represents an important challenge of the twenty-first century. It is a given fact that sustainability and energy efficiency started to be in the past years two of the requirements that are more and more present in all sectors of development. Energy geostructures represent an innovative technology in the construction sector that has significant contribution to its development by providing sustainable energy efficiency and CO_2 emissions reduction. The concept behind this technology refers to the use of structural concrete elements of a building and give them a second role, that of energy exchanger between the building and the soil. This chapter represents an introduction into the concepts of this technology. Aspects related to the advantages of the system, principles, design and implementation considerations aspects are presented in the frame of thermal and thermo-mechanical behavior of the interacting soil and of the energy geostructures.

7.1 Introduction

The current accelerated speed of world development combined with climate change effects require a sustainable development of the energy sector with focus on renewable energy technologies. One of the most important advantages of renewable energies is their infinite resources. Within this frame, energy geostructures represent an innovative technology part of geothermal energy field that provides exceptional solutions in the construction sector in terms of energy efficiency and environmental protection. The basic concept behind energy geostructures is to take advantage of the thermal capacity of the soil by using any structure in connection with the soil and transport the renewable energy to the building for heating and cooling purposes. Soil is used as heat energy source during winter time and as a heat sink during summer. The key factor in the sustainability of such system is the use of the building elements that

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are usually required for structural reasons and exploit them as heat exchangers also, making so the system “green” and environmentally friendly. This chapter represents a general introduction and introspect within the general concepts of energy geostructures technology, highlighting its advantages and the specific aspects that need to be considered from site investigations to design and implementation stages.

7.2 Aspects Related to the Evolution of Energy Usage and Demands Worldwide

Managing energy resources is one of the most important global issues of our century. The environmental consequences of an overuse of energy from fossil sources it is proven to be problematic for many reasons. In addition, the CO_2 emissions in connection with climate change effects are problems that need to be addressed in the context of building a sustainable and environmentally friendly world for the future.

Current data regarding the energy sources usage show that renewable technologies popularity is in constant growth. However, compared to other energy resources their impact and contribution is still quite small. According to International Energy Agency (IEA) the average total primary energy sources will supply around 23 TW until 2030 (almost 320% higher than in 1970) based on current policies and political measures.

According to the same statistics (Fig. 7.1), until 2010 the increase considering the percentage share increase of renewable energy technologies usage from total was quite small. The statistics show that in the last years the increase is much higher, from 0.9% in 2010 to 1.8% in 2017. Despite the close percentage figures, it might

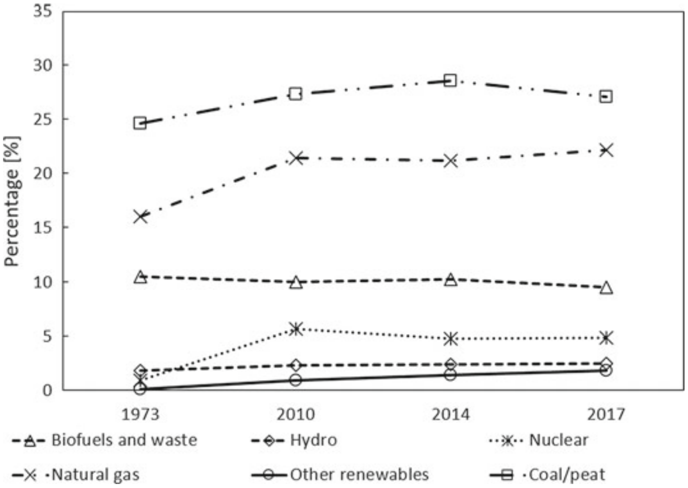

Fig. 7.1 Worldwide energy sources shares of Total Primary Energy Supply (TPES) according to IEA [1]

be relevant to be mentioned that 1.8% share from 13,972 MToe (Million Tons of Oil Equivalent produced by all sources in 2017) is about 251 MToe obtained from renewable sources compared to 6 MToe obtained in 1973, when all energy sources produced a total of 6,107 MToe.

Current available published data from European Environment Agency (EEA) regarding primary energy consumption shows that between 2005 and 2016, a decrease in energy consumption was about 10%, from 1,704 MToe to 1,526 MToe. According to EEA this was due to energy efficiency improvements, the economic recession and climate change mitigation. However, even if this type of fluctuations may always occur, looking at the situation on the long term, the total energy consumption is expected to increase especially due to industrial market development and increase of population. Therefore, the need for increase of the renewable energy sectors it is an undeniable aspect that is available worldwide no matter the continent.

The increasing trend regarding the production of renewable energies is significant higher in the last years as shown in Fig. 7.2. From 2010 to 2016 inside European Union the production of energy from renewable sources increased from 10.64% to 14.19%, an increase of 3.55%. Policy changes regarding energy efficiency and renewable energies that have been implemented across European countries had definitely an impact in this increase. Another important environmental aspect considered at the level of policy changes is related to CO_2 emissions. Reducing the CO_2 emissions is currently still one of the major challenges related to the environment especially since climate change started to be considered an actual real problem that needs to be addressed. However, real changes regarding renewable energy implementations and CO_2 emission reductions can be reached only with significant effort and measures sustained

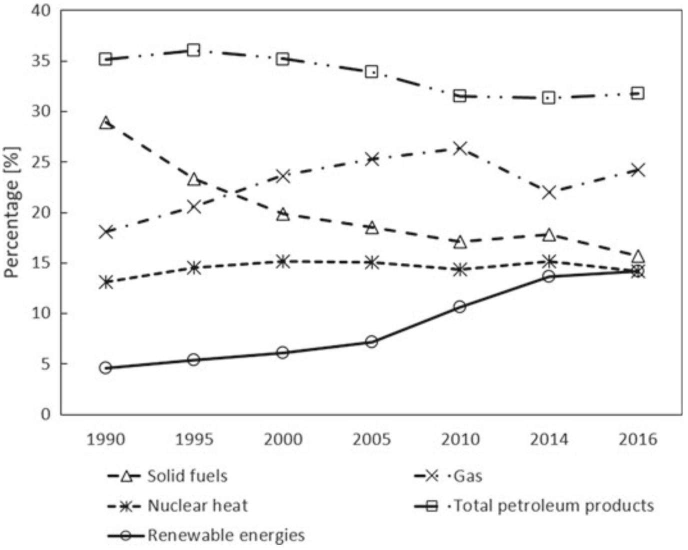

Fig. 7.2 European Union primary energy sources according to EEA, https://www.eea.europa.eu/

by political measures. In the European Union the Recast Directive 2010/31/EU on energy performance of buildings mentions on article 9 that “Member States shall ensure that by 31 December 2020 all new buildings are nearly zero-energy buildings; and after 31 December 2018, new buildings occupied and owned by public authorities are nearly zero-energy buildings”. Following this directive each state member has developed national plans for increasing the number of nearly zero energy buildings through measures that facilitate the implementation of renewable energy technologies. Due to this policies changes across Europe, an increase number of renewable energies implementations is to be expected in the following years. It is very important to specify that besides the increase in numbers the quality of what is implemented is very important also in order to ensure a sustainable and real change in terms of renewable energy usage and CO_2 emissions reduction. This applies especially to energy geostructures as this technology is a new technology compared to others existing renewables and its implementation can rise several challenges especially on new markets that do not have a tradition in the usage of geothermal heat pump systems.

Figure 7.3 shows that inside Europe Union (EU) the residential sector space heating and cooling consumes about 64.10% of the total energy consumption.

These consumption statistics are not specific only to countries inside EU. Other countries such as United States of America (USA), but not only, have very similar reports regarding energy consumption for commercial and residential buildings especially for heating and cooling [2]. Based on this, it can be assumed that new developments in terms of renewable energy usage in the heating and cooling sector with

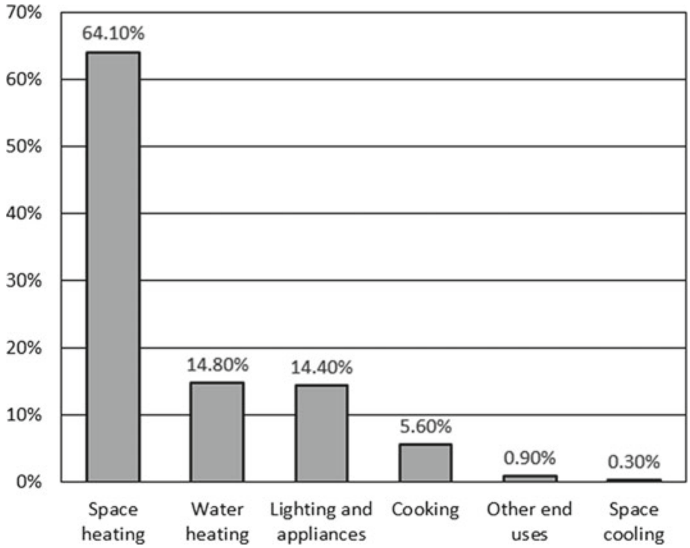

Fig. 7.3 Final energy consumption in the residential sector by use, EU-28, 2017 https://ec.europa.eu/eurostat

development of innovative and sustainable renewable energy systems could have a significant impact worldwide.

Geothermal energy is one of the most complex renewable energy domains with many various possible applications depending on the type of energy geothermal system and potential of the site. Among its various applications, heating and cooling is one of the most common with very successful results in terms of operational costs and long-term behavior. Depending on their depth, the geothermal energy systems can be classified into two major types: deep geothermal energy systems (deeper than 500 m) and shallow geothermal energy systems (less than 500 m). The key factor that makes these systems operational refers to the ground temperature. Starting with approximate 6 m and up to 100 m depth, the temperature distribution is constant no matter the season. This combined with the low thermal conductivity of the ground make the soil an optimum energy exchanger.

7.3 Energy Geostructures. Concept

7.3.1 Innovative Geothermal Energy System

Energy geostructures represent an innovative solution with important contribution to the environmental protection and providing at the same time important cost savings. As part of shallow geothermal energy systems, energy geostructures technology is a multidisciplinary domain that combines concepts from very different fields such as: geothermal energy, geotechnical and structural engineering, installations, etc. The innovative concept behind this technology is to use structural concrete elements of a building and give them two major roles: a structural one and an energy one. The structural role refers to ensure a mechanical equilibrium and resistance for the building. The energy role is to transform the concrete element into a massive absorber unit to exchange heat with the ground. A fluid circulating in pipes installed on the steel cages of such concrete elements can both extract heat during winter in order to heat the buildings and dissipate heat during summer, while cooling the building.

Compared to the classical geothermal systems (boreholes heat exchangers, horizontal loops, open loops, etc.) energy geostructures provide a series of advantages that makes this technology even more sustainable, Fig. 7.4. The most important advantage is given by the fact that in order to implement the renewable energy system there is no need for additional elements because the concrete elements used already for structural reasons are to be used for the energy purpose also. This automatically implies significant implementation cost reductions. The system does not require additional space on the site in order to be implemented as it is in the case of classical systems. As the energy system is embedded and protected in the concrete, a better long-time behavior and low maintenance costs are also ensured. If correctly designed and implemented the price of implementation is to be compensated in the very first years of exploitation.

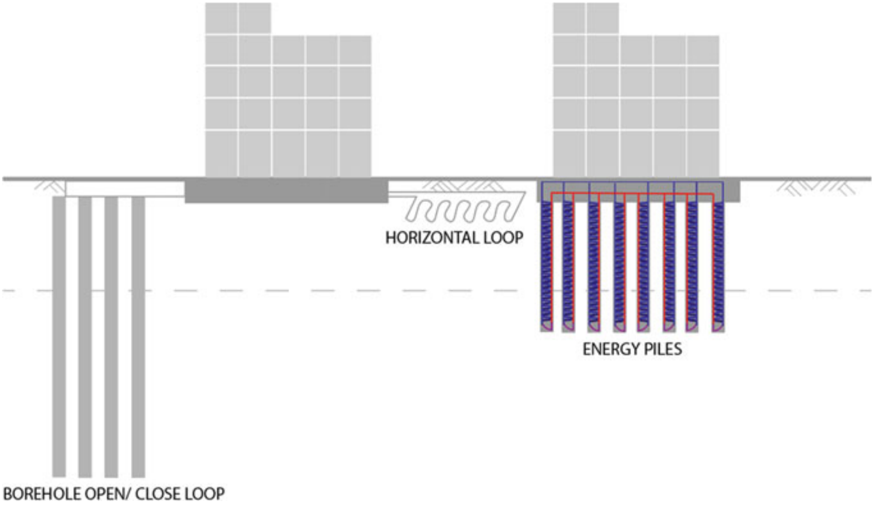

Fig. 7.4 Conventional geothermal system vs. energy geostructures

The energy geostructures system can be successfully implemented in different types of concrete structures, such as shown in Fig. 7.5:

- piles, as part of deep foundation systems or as part of retaining structures;
- diaphragm walls as part of underground level of residential buildings, underground parking or metro stations infrastructure;
- tunnels.

The most common utilization of the ground energy is related to heating and cooling of commercial and residential buildings. However, the captured energy can be used for other purposes also. Due to the high viability of the system, the ground energy

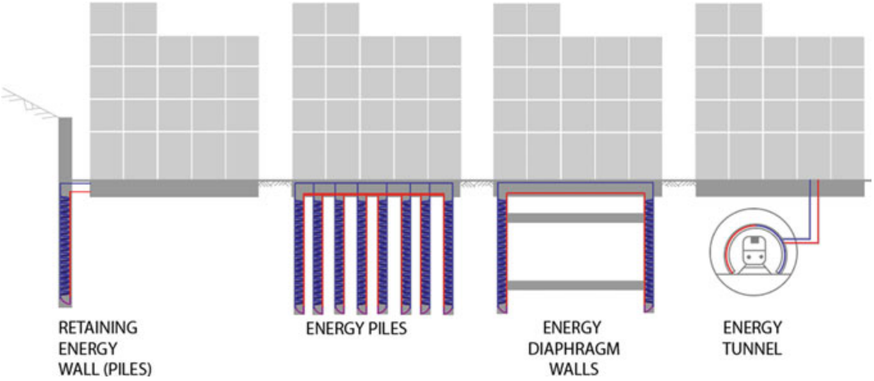

Fig. 7.5 Energy geostructures types

can be used in applications, such as: hot water supply, de-icing of open parking slabs, bridge decks, airport runways; in case of cooling the bridge decks reducing the temperature constraints, lifetime is increased and in the same time maintenance cost is decreased.

Among all the types of energy geostructures, energy piles cover most of the existing installations. However, the other types of energy geostructures have started to be implemented more and more also in the last few years. Tunnels especially are considered to have a very big potential within the frame of a sustainable urban development [3]. Their big advantage is represented by the fact that surface of the structure in contact with the ground is much higher than in the other above-mentioned structures. This favors the possibility to capture a bigger amount of energy that can be redirected to the buildings sustained by these energy foundations. Therefore, in case of energy tunnels the impact in terms of energy efficiency, sustainability and CO_2 emission reduction is significantly higher.

7.4 Energy Geostructures from Research to Practice

7.4.1 Geotechnical Considerations

The research related to energy geostructures has a very important geotechnical component. Due to their interaction with the soil, several aspects need to be taken into consideration in order to understand and predict the behavior of these geostructures from the geotechnical point of view. The entire system is subjected to cyclic temperature variations due to its seasonal operation. Therefore, these variations induce additional loads to the geostructures (concrete elements) which generates additional stresses and strains that need to be considered. This produces changes in the mechanical behavior of soil, mechanical behavior of the concrete element itself, and also on soil-concrete interface.

7.4.1.1 Soil Behavior Under Thermal and Thermo-Mechanical Loads

In energy geostructures the soil is used as source of energy and storage. There are three main mechanisms that govern the heat transfer processes in soils: heat conduction, heat convection and heat radiation. Heat conduction is a process where heat is transferred from one region of the medium to another, passing the energy from molecule to molecule. Heat convection refers to heat transport in a fluid by means of circulation flow. Radiation is the heat energy propagated as electromagnetic waves.

In case of energy geostructures clearly the most significant process in heat transfer is the conduction since the process governs both the heat transfer in reinforced concrete and soil, but is essential to verify the validity considering the factors that can affect thermal behavior such as: soil particle, saturation degree and the presence of ground water flow [4]. For example, if on site the existing lithology is saturated gravel, then convection in water is the main process which governs the heat transfer process.

Thermal behavior of soils

Thermal properties of the soils had been widely studied since 1948, when Kersten [5] published results for a range of soil types under different water content and dry unit weight conditions. The effect of water content on soil thermal properties had received more attention that other physical characteristics [6]. Summarizing these aspects: fine-grained soils have higher thermal resistivities compared to granular soils, increasing the degree of saturation, a bridge between soils particles is provided therefore an increase in thermal conductivity is an immediate effect; increase in the density involves an increase in thermal conductivity by improving contacts between soils particles.

Thermal characteristics of the soil are on high dependence of on-site specific conditions. Water flow and groundwater levels, scale effects, lithology heterogeneity, mineralogy are few of the influencing factors that affects the thermal behavior of soils. Considering this, in terms of investigation methods, in situ tests are considered more accurate than laboratory for thermal characteristics determination. However, since in situ tests are not always available laboratory methods are typically used also [7].

One of the most important parameters needed in the design of energy geostructures is the soil thermal conductivity. Several tests on different types of soils have been made in the last decades in very different areas across the globe and several correlations have been proposed. A summary of these correlations resulted from these studies can be observed in Table 7.1.

Table 7.1 shows that most of the correlations are valid for sandy soils in general. Less information regarding fine-grained soils is available.

As energy geostructures involves a more complex approach, different parameters such as undisturbed soil temperature, thermal expansion coefficient and ground heat exchanger's (GHE) thermal resistance are needed for research and real implementation also. While all these investigations could be carried out in the laboratory, the TRT (thermal response test) is preferred due to its ability to provide information directly from the site in the conditions where the real project is to be [10]. Extended research has been performed so far related to TRT testing and numerical simulations of the test also. However, additional research is needed in this area especially related to accurate execution and interpretation of TRT tests on large diameter piles and other types of energy geostructures. Even so, thermal response test provide accurately the ground thermal properties required for the design of energy geostructures [11]. At the same time, it was shown that 3D numerical simulation can provide a quite good simulation of TRT, providing a reliable thermal parameters estimation [10].

Thermo mechanical behavior of soils

During the heating and cooling cycles soils are affected by the temperature variations. Thermo-mechanical behavior of the soils refers to the following specific

Table 7.1 Correlations formulas for determination of thermal conductivity [18]

Author	Equation	Authors and literature observations
Kersten (1948)	Frozen sandy soils $\lambda = 0.011 \cdot (10)^{0.000812\rho_d} + 0.00462 \cdot (10)^{0.000911\rho_d} \cdot w$ Frozen loam and clay $\lambda = 0.00144 \cdot (10)^{0.00137\rho_d} + 0.0123 \cdot (10)^{0.000499\rho_d} \cdot w$ Unfrozen sandy soils $\lambda = \left[0.101 \cdot \log w + 0.0577\right] \cdot 10^{0.000624\rho_d}$ Unfrozen loam and clay $\lambda = \left[0.13 \cdot \log w - 0.0288\right] \cdot 10^{0.000624\rho_d}$	w is the water content in % and ρ_d is dry density of the soil in kg/m^3 It has been shown that Kersten's formula is suitable for sandy soils having a water content higher than 1, and in case of silty and clayey soils, greater than 7% [8]
Woodside and Messmer (1961)	$\lambda = (n - 0.03) \cdot \lambda_w + (1 - n + 0.03) \cdot [\frac{1-n}{\lambda_s \cdot (1-n+0.03)} + \frac{0.03}{\lambda_w \cdot (1-n+0.03)}]^{-1}$	Can be used in general for all type of soils
De Vries (1963)	$\lambda = \frac{x_w \lambda_w + F_a x_a \lambda_a + F_s x_s \lambda_s}{x_w + F_a x_a + F_s x_s}$	Suitable for all type of soils λ_a is the thermal conductivity of air. The thermal conductivity of air has a linear trend due to humidity which is in fact water x_w, x_a, x_s are the volume fractions of water, air and soils F_s and F_a are factors depending on the shape of the particles and a factor regarding the pores filled with air $F_s = \frac{1}{3} \cdot \{\frac{2}{1+[\left(\frac{\lambda_s}{\lambda_w}\right)-1] \cdot 0.125} + \frac{1}{1+[\left(\frac{\lambda_s}{\lambda_w}\right)-1] \cdot 0.75}\}$ $F_a = \frac{1}{3} \cdot \{\frac{2}{1+[\left(\frac{\lambda_a}{\lambda_w}\right)-1] \cdot g_a} + \frac{1}{1+[\left(\frac{\lambda_a}{\lambda_w}\right)-1] \cdot g_c}\}$ g_a and g_c are shape factors $g_c = 1 - 2g_a$ $g_a = 0.013 + 0.9444x_w$ for $0 < x_w < 0.09$ $g_a = 0.333 - (\frac{x_a}{n}) \cdot (0.333 - 0.035)$ for $0.09 < x_w < n$ $\lambda_a = 0.0615 + 1.96x_w$ in mcal/cm·s·°C

(continued)

Table 7.1 (continued)

Author	Equation	Authors and literature observations
Johansen (1977)	$\lambda = \left(\lambda_{sat} - \lambda_d\right) \cdot \lambda_e + \lambda_d$	Valid for general soils preferably with degree of saturation greater than 20% λ_{sat}, λ_d are the saturated and dry thermal conductivity where ρ_d is dry density of the soil in kg/m^3 $\lambda_{sat} = {\lambda_s}^{1-n} \cdot {\lambda_w}^n$ $\lambda_d = \frac{0.135\rho_d + 64.7}{2700 - 0.947\rho_d} \pm 20$ $\lambda_e = 0.7 \cdot log S_r + 1$ for $S_r > 0.05$ (course unfrozen soils) $\lambda_e = log S_r + 1$ for $S_r > 0.1$ (fine unfrozen soils)
Donazzi et al. (1979)	$\lambda = {\lambda_w}^n \cdot {\lambda_s}^{1-n} \cdot \exp\left[-3.08n \cdot (1 - S_r)^2\right]$	Good correlation for sandy soils
Gangadhara Rao and Singh (1999)	$\lambda = 10^{0.01\gamma - 1} \cdot (1.07 \cdot \log w + 0.715)$	Good correlation for sandy soils γ is the unit weight of the soil in lb/ft^3 and w is the moisture content in percent Using this equation for saturation ratios below 0.3 the equation predicts good results. Over the value of 0.3 it significantly underpredicts thermal conductivity [9]
Cote and Konrad (2005)	$\lambda = \left({\lambda_w}^n \cdot {\lambda_s}^{1-n} - \chi 10^{-\eta n}\right) \cdot \left[\frac{a S_r}{1 + (a-1) \cdot S_r}\right] + \chi 10^{-\eta n}$	Good correlation for sandy soils χ and η account for particle shape effects and a accounts for soil texture The author recommends for sandy values 3.55 for a, 1.7 W/m·K for χ and 1.8 for η in case of fine and medium sands
Lu et al. (2007)	$\lambda = [{\lambda_w}^n \cdot {\lambda_s}^{1-n} - (b - an)] \cdot \exp[\alpha \cdot (1 - {S_r}^{\alpha - 1.33})] + (b - an)$	Good correlation for sandy soils The authors formula is a modification of Johansen's model $a = 0.56$ $b = 0.51$ $\alpha = 0.96$
Chen (2008)	$\lambda = {\lambda_w}^n \cdot {\lambda_s}^{1-n} \cdot [(1 - 0.0022) \cdot S_r + 0.0022]^{0.78n}$	Good correlation for sandy soils

aspects: effect of temperature on consolidation behavior, effect of temperature on shear strength and on soil-concrete interface.

The influence of temperature on the volume changes of soil samples can be investigated in the laboratory using oedometer and triaxial tests, specially adapted for temperature variations.

Consolidation behavior of soils subjected to heating/cooling cycles at different stress history was investigated by many researchers [12]. For sands, the behavior shows an increase of volume directly related to the grain thermal expansion coefficient. Due to the drained conditions the water dilatation does not contribute to the volume variation of the material itself.

In case of clays, many influencing factors affect the contraction and expansion under temperature cyclic loading of these types of soils. The experimental tests performed by various researchers showed that thermo-mechanical behavior of soils is dependent especially by the stress history. The temperature variations generate thermo-elastic behavior, for OC (overconsolidated) soils and thermo-plastic behavior for NC (normally consolidated) soils, [13–15]. When the soil is subjected to NC conditions during heating cycles, most of the plastic deformations develop in the first cycle of heating. After the first thermal loading cycle, the soil presents an accommodative behavior. Other parameters that influence the thermo-mechanical behavior of soils are the plasticity index and void ratio. Soils with high plasticity develop higher thermo-plastic deformation. The same behavior was encountered also for soils with high porosity. These aspects confirm the fact that temperature influences the micro-structure of the soil. Lightly over consolidated clays (OCR = 1.5, and 2) samples have a thermal contraction behavior, but less than the normally consolidated samples, while the highly overconsolidated samples (OCR = 12) have a thermal expansion behavior [16].

Regarding the investigation of thermal cycles on normally consolidated inorganic clays the result showed that after a couple of thermal cycles, between 5 and 60 °C, the irreversible volumetric strains stabilized between 0.5 and 1%, the following cycles being reversible. The tests on an overconsolidated samples showed no irreversible volumetric strain, concluding once more that overconsolidated soils develop elastic behavior during heating [16].

Research related to soil-structure interface behavior is an important development within the frame of behavior understanding and designing methods of energy geostructures [17]. Based on existing data the temperature at the soil-pile interface of energy piles/walls or tunnels vary between 1 and 38 °C [18–20]. Different studies showed that in sands, temperatures cycles on the mobilization of the shear strength at the soil-concrete interface is negligible. In addition, these temperature cycles lead to a slight sample densification in case of sand [21]. In case of silt, extended experimental test were done by Xiao et al. [22]. The results showed that the shear strength of silt is proportional to the temperature and that the cyclic thermal loads increase the shear strength of the silt, with peak values between 30 and 90% larger than the soil-concrete interface at the same normal stresses and water contents. Regarding adhesion of the soil-concrete interface, it tends to increase after large heating cycles, with friction angles increase by 3° to 4° after 10.5 temperature cycles (maximum temperature of 42.5 °C and minimum temperature of 4.5 °C). This can be a results of moisture content change during the tests [23].

In case of clay, extensive research was performed by Hueckel et al., Di Donna, Cekerevac and Laloui, Yavari et al. and others also. The results show that there is a temperature dependence of the frictional angle for kaolin clay, whereas this is not the case for smectitic or ilitic clay. The higher plasticity index or initial void ratio the higher thermo-plastic deformation is. Additional mechanically cyclic stress induced by the thermoelastic expansion and contraction is less significant in clay because of the reduced volumetric cyclic contraction of the interface.

7.4.1.2 Energy Structure Behavior Under Thermal and Thermo-Mechanical Loads

From the mechanical point of view, when energy structures are heated (respectively cooled), they expand (respectively shrink) inducing thermal strains and stresses.

Since piles are one of the most used type of energy geostructure, the research is more advanced compared with other types of energy geostructures. When thermal loads are applied, the stress distribution is changing. When a pile is being subjected to thermal loads, the reinforced concrete will tend to expand or contract axially. This expansion or contraction is related to a point, known as the "*null point*". The null point is the point where displacement induced by heating or cooling is zero, and the location of it depends on the restraint at the end of the pile imposed by building on one side, and soil on the other side. The influencing factors in distribution of thermally induced stresses and strains are the side shear resistance, end bearing capacity and buildings restraint. In order to understand the basic principle of how energy piles subjected to thermo-mechanical loads behave, an example of floating piles restrained at one end (head) is chosen, Fig. 7.6. Subjected to thermal loads the thermal axial strain in a free-standing pile is the free-expansion thermal axial strain, defined as, (Eq. 7.1):

$$\varepsilon_{T,free} = \alpha_c \cdot \Delta T \tag{7.1}$$

where ΔT is the change in temperature and α_c is coefficient of thermal expansion of concrete.

In geotechnical engineering the thermal axial strain is defined as positive during compression (heating of the pile) and mobilized shaft resistance as positive when acting upwards. Because structural elements expand during heating (i.e. positive ΔT) α_c is defined as negative [24]. Since in the chosen example the pile is restrained at one end, and in reality, cast in the ground the pile cannot move freely, a supplementary thermal axial stress will be supported by the pile, (Eq. 7.2).

$$\sigma_T = E \cdot (\varepsilon_T - \alpha_c \cdot \Delta T) \tag{7.2}$$

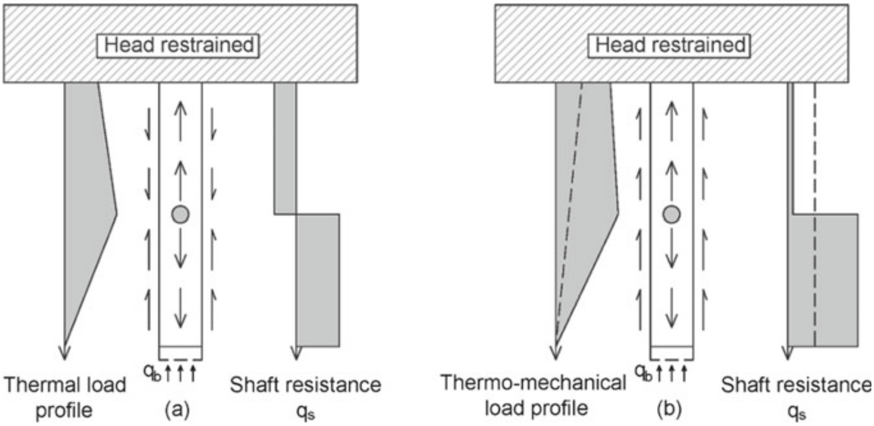

Fig. 7.6 Head restrained, and free toe energy pile subjected to **a** thermal loading and **b** thermo-mechanical loading

where E is the Young's modulus of reinforced concrete and ε_T is the measured axial strain due to temperature change (ΔT).

The research of thermo-mechanical behavior of energy piles was approached at different levels: laboratory tests, in-situ tests and numerical experiments. The laboratory tests (centrifuge tests, soil-concrete interface tests, etc.) provided important data on the thermo-mechanical behavior of the energy piles. The thermal loading of the system can increase the ultimate load and the thermo-hydro-mechanical effects could have a significant impact on the soil-pile interface, [2]. Also, the laboratory investigation carried out by Laloui and Di Donna [16] focused on the soil-concrete interaction, showed that concrete-sand interface is not sensitive to thermal variations while clay-concrete interface is, especially due to the thermal consolidation of the clay.

In situ tests have been carried out also on experimental sites, where the thermal axial stresses ranged between −1 MPa and 5 MPa [25, 13, 26], depending on the pile diameter, soil stratification, end boundary conditions, class of concrete used and imposed temperature interval. The axial displacement ranged between −4.2 mm and 4.0 mm. The research performed so far showed that usually, the strains that appear in the pile are thermo-elastic in nature. Also, the heat propagation in the ground induces limited strains that do not significantly affect the water pressure, [13]. However, the site conditions can differ a lot, and different values can be obtained in different soils and different type of pile foundations. In the case of diaphragm walls, tunnels, retaining structures there is significant less data, which is not yet sufficient to fully understand the thermo-mechanical behavior of such systems.

Table 7.2 Energy volume that can be extracted [18, 3]

Type of element	Energy
Piles	40–100 W/m
Diaphragm walls and tunnels	10–50 W/m^2
Base slabs	10–30 W/m^2

7.4.2 Energy Considerations

7.4.2.1 Energy Demands

In order to design a performant system an evaluation of buildings heating and cooling demand must be done. The design must take into account a series of aspects such as: local climate conditions, undisturbed temperature, building's envelope characteristics, building operation schedule. One of the most important factors in the energy design of energy geostructures is represented by the local climate conditions, where factors such as ambient temperature, humidity, wind velocity and direction, pressure, solar irradiance, cloud fraction or rainfall all play important roles in buildings heating and cooling demand.

An approximation of the energy performance in the pre-design steps of energy geostructures, based on previous implementations can be very useful, Table 7.2. However, the energy design is very important and real energy performance can register higher or smaller values than the existing reported ones, depending on the unique characteristics of each project.

Several applications and references show that energy geostructure systems can cover up to 100% of the energy demand of a building in terms of cooling and heating needs. The energy performance can also be optimized and enhanced when the system is carefully designed and influencing factors and particulates of each project are taken into account in the design steps.

Based on data from Table 7.2, for each 100 m of installed energy piles, there is a minimum energy production of 4 kW and a CO_2 reduction of about 1.28 tons for each 4 kW of energy produced [3]. To compare the emissions with something more familiar, according to EU in 2018 a typical new passenger car emission is of 120 gCO_2/km and per year it runs an average of 12,000 km/year, resulting in 1.44 tons of CO_2 emissions.

7.4.2.2 Principles of Energy Geostructures System

A ground source heat pump (GSHP) system which is the case for energy geostructures systems, is a heating or cooling system that works by using ground as a heat source or heat sink, including the heat pump [11]. The principle of GSHP is to pass a fluid through a constant ground temperature where a cooler fluid will increase in temperature (used for heating) and a warmer fluid will decrease in temperature (used for cooling). The energy geostructure system is composed of three main parts:

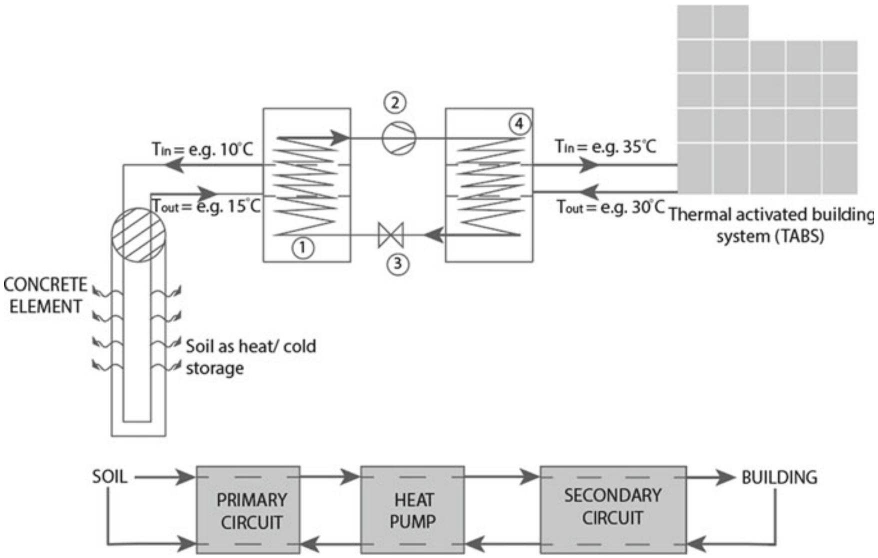

Fig. 7.7 Scheme of a GSHP system mixed with energy geostructure

- primary circuit (concrete embedded elements);
- heat pump;
- secondary circuit (pipework through the receiver for heating and cooling).

Figure 7.7 points 1, 2, 3 and 4 show the main parts of the heat pump: 1—the exterior heat exchanger where the cold liquid refrigerant is warmed by primary circuit and evaporates as its temperature increases; 2—represents the compressor. As the pressure of the gasified refrigerant increases the temperature increases; 3—represents the expansion valve. As the pressure of liquid refrigerants drops, the expansion valve makes the temperature to drop further; 4—is represented the interior heat exchanger. Here the hot gasified refrigerant releases heat to secondary circuit and condenses to liquid as it cools; Energy geostructures are the major part of the primary circuit. Through these elements a carrier fluid is pumped in order to be heated or to dissipate heat. The fluid is a transfer medium, that can be either water, water with glycol or a saline solution, [27]. For carrier fluid most common are used polyethylene pipes with different configurations depending on the type of the concrete element. After being casted the pipes are joined in order to reach a manifold block. From the manifold block the fluid is passed to the heat pump. The heat pump is a type of "transport device" that raises the temperature level of the heat that is freely available in the environment. The majority of heat pumps are able to reverse their working cycle,thus, the same device can be used for heating and cooling operation. For the secondary circuit in order to obtain best energy performance energy geostructures system is to be combined with T.A.B.S (thermal activated building structure). The fluid passes through pipes that are embedded directly in the structure elements of the building (concrete slabs and walls) and dissipates heat or cold through radiation in order to maintain the required thermal comfort conditions. During heating process the fluid that passes through elements have a temperature interval between 25 and 35 °C. Performance of the system is measured by two factors, coefficient of performance (COP) and energy efficiency ratio (EER). For a performant system, the values of COP should be higher than 3, (Eqs. 7.3 and 7.4).

$$COP = \frac{heating\, capacity\, (W)}{power\, input\, of\, the\, unit\, (W)} \tag{7.3}$$

$$EER = \frac{cooling\, capacity\, (W)}{power\, input\, of\, the\, unit\, (W)} \tag{7.4}$$

The seasonal coefficient of performance (SCOP) and seasonal energy efficiency ratio (SEER), (Eqs. 7.5 and 7.6) indicators are given by extended measurements and describe the performance of a specific heat pump device working under the specific measured conditions, on the long term.

$$SCOP = \frac{anual\, heating\, demand\, (kWh)}{annual\, electricity\, consumption\;\, for\, heating\, (kWh)} \tag{7.5}$$

$$SEER = \frac{anual\, cooling\, demand\, (kWh)}{annual\, electricity\, consumption\;\, for\, cooling\, (kWh)} \tag{7.6}$$

7.4.3 Design Considerations

Design of energy geostructures involves an intern-disciplinary approach, where specialists as geotechnical engineer, architect, installation engineer, structural engineer, combine their knowledge for an optimal result, Fig. 7.8.

In order to have a successful implementation in terms of mechanical and energy performance, several aspects need to be carefully considered:

1. The energy geostructures system should be considered from the concept stage of the project so that an optimum solution with consideration of the entire renewable potential of the site could be provided. Feasibility study and pre-design of system is also important for cost/return analysis.
2. Site conditions and design is one of the most important stage of the implementations. For the design site investigation have to be made in accordance to the type of energy geostructure and the design should take into account the thermo-hydro-mechanical (THM) behavior of the structure as well.
3. Monitoring of the system and further optimization after implementation based on real data.

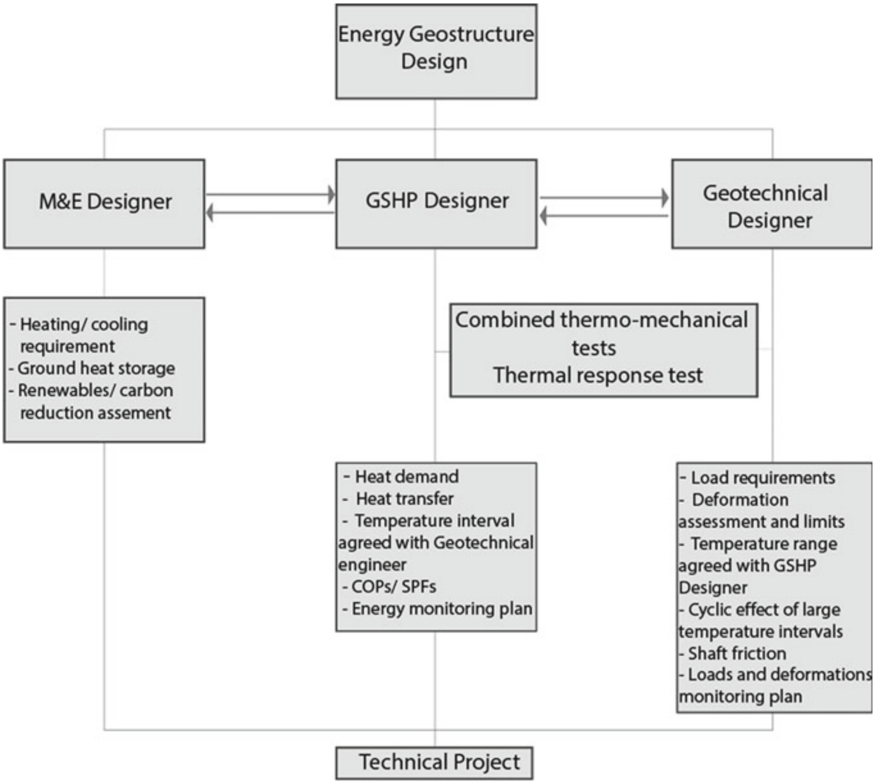

Fig. 7.8 Inter disciplinary design and designer constraints after [11]

Reliable thermal parameters of the soil and concrete are essential in order to design a performant energy geostructure system, while geotechnical parameters are essential for mechanical design of the structure, Table 7.3.

7.4.4 Real Implementations of the Energy Geostructures

Due to their incontestable advantages, energy geostructures implementation number is getting bigger every year. First energy geostructures were built in the mid 80′s in Austria, the country where the technology originates. In terms of types of energy geostructures, most of installations around the world are energy piles, succeeded by energy walls and tunnels. One of the reasons why energy piles are one of the most common used type of energy geostructures is related to the fact that the research done in this direction is the most advanced one. In addition, piles are one of the geotechnical structures that is very common and used for many structural purposes also. Tunnels have the advantage to be an enormous heat exchanger, since the surface

Table 7.3 Key parameters

Type of parameter	Parameter	U.M
Thermal	Soil thermal conductivity, λ	$W \cdot m^{-1} \cdot K^{-1}$
	Soil specific heat capacity, c_p	$J \cdot kg^{-1} \cdot K^{-1}$
	Undisturbed soil temperature, T_u	°C
	Groundwater flow rate, Q	$m^3 \cdot yr^{-1}$
	Thermal expansion coefficient, α_T	$°C^{-1}$
	Thermal resistance of heat exchanger, R_b	$m \cdot K \cdot W^{-1}$
Geotechnical	Soil strength, φ / c / c_u	° / kPa / kPa
	Dilation angle, ψ	°
	Soil stiffness, E, E_{50}, E_{ur}	kPa
	Poisson's coefficient, ν	–
	In situ stress, K_0	–
	Stress history and overconsolidation ratio, OCR	–
	Concrete thermal expansion coefficient, β	$°C^{-1}$
Structural	Concrete thermal conductivity, λ_c	$W \cdot m^{-1} \cdot K^{-1}$
	Concrete specific heat capacity, c_{pc}	$J \cdot kg^{-1} \cdot K^{-1}$

in contact with ground is bigger compared with other types of energy geostructures. However, despite the obvious advantages, implementation of such structures can be sometimes difficult due to the number of institutions involved in the decisions of such constructions and challenges regarding the ownership of the green energy.

In order to illustrate the significant increase of energy geostructures constructed around the world a chart with number of installed energy piles for several European countries is presented in Fig. 7.9.

There are many examples around the world of successful energy geostructures implementation. Among these examples, successful implemented project, and also a monitored one, is the new terminal E of the Zurich airport, where more than 300 energy piles were used for heating and cooling demands. Table 7.4 illustrates a summary of two years measured data. The overall system efficiency is defined as the ration of total energy delivered by the system divided to total electric energy consumed.

Energy geostructures technology has started to spread and cover countries that until recent years had no implementations of such structures. Figure 7.10 shows the implementation of an energy retaining wall that was constructed in Cluj-Napoca, Romania. From energy point of view the energy wall was designed to ensure 100% of heating and cooling demands of the onsite proposed 3 residential buildings that cover in total approx. 900 square meters. The retaining wall consists of 1000 mm diameter energy piles at 21.50 m depth. From the geotechnical point of view, the retaining pile wall was designed to ensure the overall stability of the site and surroundings for a deep urban excavation of approx. 7.5 m. The system has also been equipped with

Fig. 7.9 Number of energy piles implemented in several European countries, after [18]

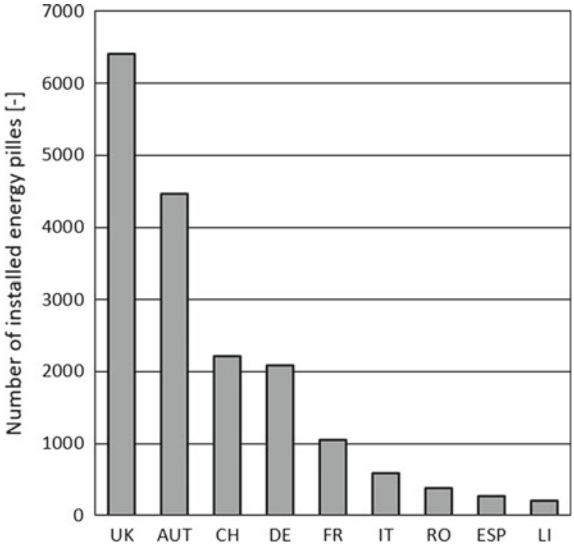

Table 7.4 Measured data from Zurich airport [28]

Data	U.M	Measured values
Coefficient of performance	W/W	4.5
Overall system efficiency	W/W	5.1
Heat extraction rate of piles	W/m	45
Heat injection rate	W/m	16

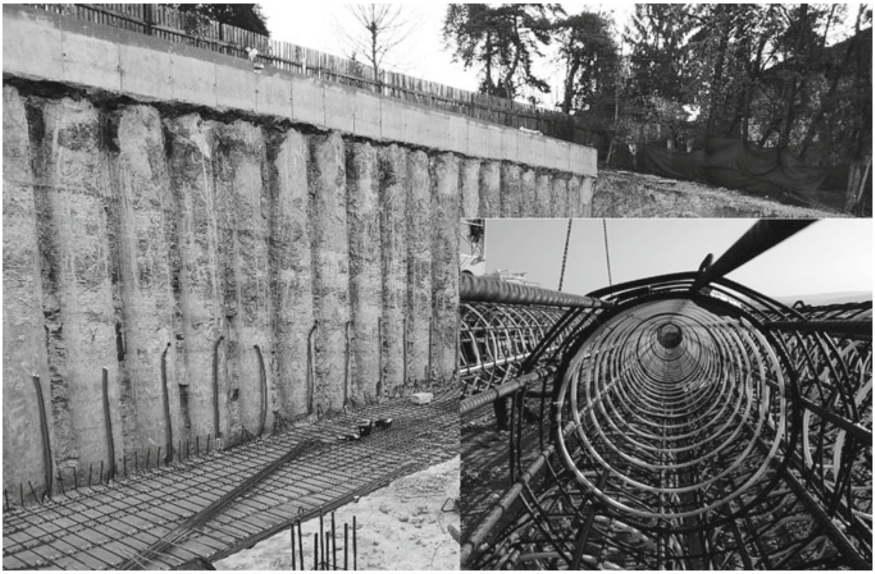

Fig. 7.10 Energy piles retaining wall, Cluj-Napoca, Romania

sensors for monitoring the energy and thermo-mechanical behavior of the in-place system.

7.5 Conclusion

Since the field of energy geostructures is a very complex one, despite the advanced existing research data, certain topics still require more detailed research. Few of these topics are mentioned as follows: local specific correlations regarding soil thermal proprieties that would provide more accurate data and facilitate the successful implementations, energy and thermo-mechanical behavior of unconventional energy geostructures or of less studied types of energy geostructures (e.g. energy diaphragm walls, energy tunnels, other types of foundations different than the classical general raft foundation on energy piles, etc.).

In terms of monitoring of in-situ projects most of the data available is related to experimental sites and very little data is available regarding monitoring of real implemented energy geostructures. The reality can be different in some cases due to particularities related to the site and real time functioning of the system. Thus, long-term monitoring in order to observe the real behavior of energy geostructures both from energy performance point of view, but also from thermo-mechanical point of view is essential. In addition, real monitoring data from different types of energy geostructures (energy tunnels, energy walls, etc.) other than classical energy pile foundations is needed also to fully understand the energy and thermo-mechanical behavior of such structures that have started to be implemented. Another important aspect that will contribute to a better understanding of energy geostructures technology is the long-term monitoring that will contribute to the implementation of more performant energy geostructures.

Successful implementations however depend not only on the results of research. Good practice in all steps of the design and implementation are very important also. To meet these challenges, clear standardization that would consider and approach the interactions and requirements for each domain involved in the process of design and implementation of this technology, is very important.

Energy geostructures are a new and increasing trend of powerful geothermal solutions for heating and cooling, with advantages that certainly overlay any disadvantage. As stated above, the directives regarding CO_2 emissions reductions together with new policies related to energy efficiency are two of the main reasons why energy geostructures implementations are in constant growth. The existing research and real data from practice has proved undeniably the viability of these systems and therefore, the technology is ready for large scale implementation.

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Chapter 8
Environmental Impact of Buildings Heating Systems: Renewable Energy Sources and Energy Hub

Teodora Melania Şoimoşan

Abstract In the current context related to the environmental impact of buildings, in the field of heat generation and consumptions, there is a multitude of approaches following the main axe—processual sustainability. Within the chapter, the representative typologies of buildings as energy consumers, along with their related heating systems are analyzed, and the possibilities of energetic optimization, in order to reduce the environmental impact, are highlighted and assessed. The chapter includes general notions in the field, current and prefigurative stages of the future sustainable energetic concept and the importance of stepping up the optimization process to reach them, in the case of existing heating systems. The concepts of conventional and renewable thermoenergetic hub are presented. The modern concept of energy hub, which allows the correspondence of a single energy output, the buildings' heat demand, with several energy inputs, associated with various energy carriers—conventionals, renewables or alternatives, is analyzed from the energetic and environmental point of view. The performance indicators are defined within the frame of the renewable energy based thermoenergetic hub. The representative indicators regarding the environmental impact, the energy and carbon footprints are highlighted. Based on targeted indicators, the possibilities of decarbonisation of the thermoenergetic systems in the buildings' sector, particularly the increase of the energy efficiency of the buildings and the related heating systems are analysed regardfully for the environment. A case study on the carbon environmental impact of heating systems is presented, followed by discussion and conclusion.

Keywords District · Heating · Hybrid · Carbon · CO_2 emissions · Energy · Efficiency · Performance · Indicator · Solar · Thermal · Decarbonisation · Footprint

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8.1 Introduction

The environmental and human impact of buildings' heating systems presents two major aspects, as it relates to the intensification of the greenhouse effect, respectively to the environmental pollution. From the perspective of buildings and related technical systems, both the contribution to the greenhouse effect and pollution are due to a deficitary management of energy resources by humans, respectively to the various emissions of pollutants associated with the processes. Environmental pollution has its source in the generation of dangerous substances resulting from chemical reactions during the combustion of fuels in outbreaks or combustion chambers.

The greenhouse effect is the result of the balance between the received energy and the yielded energy by Earth in the process of reaching the equilibrium temperature. The greenhouse effect is responsible for sufficiently heating the Earth's crust to allow the development of life as we know it. The limitation in various situations of the received energy leads to the cooling of the Earth's crust, while the restrictions applied to the yielded energy increase the greenhouse effect and lead implicitly to the overheating of the Earth's crust. Certain components of the atmosphere, generically called GHG (greenhouse gases), have the property to charge with thermal energy, an increased emissivity and to emit radiation in the infrared range. Thus, the accumulation of this kind of gaseous components in the lower atmosphere contributes to the overheating of the Earth's crust and to the climate change, with negative effects on a global level.

Worldwide, around 50% of the human population lives in urban areas, with an increase up to 60.8% by 2030 [3]. In Europe's case, 72% of the population lives in cities, this percentage is assumed to increase to 84% by 2050 [4], thus generating urban areas characterized by high energy density, which lead to high GHG emissions related to the technological chain—generation, storage, transport, distribution and utilization of energy.

Since the main validated factor of the negative effects is the increase of carbon dioxide (CO_2) concentration in the atmosphere, the main factor of the intensification of the greenhouse effect respectively [11], the GHG emissions used to be reported in corresponding CO_2 emissions or CO_{2e} (equivalent) emissions, at applicative level.

One of the key outcomes of the basic emissions inventory is the emissions corresponding to urban heating systems. Algorithms used to evaluate the energy performance of a heating systems involve complex quantification, in which the CO_2 emissions have a significant share. In addition to CO_2, the main pollutants emitted by conventional heat sources based on fossil fuels, are sulfur and nitrogen oxides, SO_x and NO_x compounds, ashes, particles of matter, PM respectively. Their accumulation in the urban areas, closely linked to the economic and urbanization development, also negatively affects the local environment [5, 9, 30]. On one hand, fossil fuels still represent the main energy source in buldings' heating sector worldwide, due to an extensive utilization of the natural gases, liquefied petroleum gases and coals. Globally, in 2018, renewable sources represented less than 8% of the entire amount of energy used in district heating. On the other hand, renewable energy consumption within district heating and cooling increased more than two-thirds between 2009 and 2018, mainly as a result of the extensive transition from fossil fuels to bioenergy—biogas and biomass in the European Union [10], representing the current trend.

One of the most important criteria imposed in the configuration of the concept of smart cities is the environmental air quality. Framing urban localities into the synergistic concept of "smart city & smart energy" [26] implies increasing the percentage of clean renewable sources [31] to the production and final use of energy within the urban areas' boundaries. Besides, more and more urban consumers are choosing to become prosumers by supplying energy into the grid, leading to the need to gradually optimize the existing heating systems. The depollution and decarbonisation of buildings' sector are, thus, the main objectives of the developed strategies, in order to protect the environment, and at the same time to increase the quality of life [1]. Indicators of energy performance used to assess sustainability are usually focused on the availability of natural resources, while the efficiency in exploitation is widely neglected [21]. In the next energetic stage, a demarcation line is foreshadowed between the action of harnessing of renewable and clean resources versus the mere action of using them. In this sense, in most countries, the thermoenergetic infrastructure and their energy and environmental assessment must be rethought.

8.2 Carbon Background

In the last fifty years, large quantities of carbon dioxide and methane have been emitted which reduced the permeability of the atmosphere for the caloric radiation reflected by Earth into the cosmic space. This led to the onset of the global warming phenomenon. The increase in CO_2 concentration is mainly due to the burning of fossil fuels and in many cases to the change of the lands' destinations such as deforestation, desertification, etc. The increase in methane concentration in the atmosphere has been attributed to intensive agriculture and also to the fossil fuels' burning. The increase in the concentration of nitrous oxide is mainly due to agriculture. Since the increase of CO_2 concentration is the main factor of the increase of greenhouse effect, the GHG emissions are usually reported in corresponding CO_2 emissions, CO_2 equivalent emissions, respectively. In addition to the direct effect gas emissions summarized in Table 8.1, there are also gases with indirect effect, such as carbon monoxide (CO), volatile organic compounds (COVNM), nitrous oxides (NO_x), sulfur oxides (SO_x), hydrochloric acid (HCl), ammonia (NH_3), etc.

The main greenhouse gases whose concentration in the lower atmosphere is directly influenced by the anthropogenic activities are: carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), ozone (O_3), hydrocarbons, carbon compounds containing chlorine, fluorine, bromine. The way in which these gases affect the intensity of the greenhouse effect is due to several characteristics such as the concentrations in the atmosphere, the absorption factor, the infrared radiations emissivity of the particles and, last but not least, the stationary period into the low atmosphere before

Table 8.1 Characteristics of the main greenhouse gases

Gas type [–]	Volumetric concentration in low atmosphere [ppm]	Stationary period [year]	Relative contribution to the greenhouse effect [–]	Global warming potential, GWP_{100} [kg_{CO_2} equiv./kg]
CO_2	346.0	250 … 400	48%	1
CH_4	1.7	8 … 12	17%	28
N_2O	0.31	120	6%	310

dissipation. In order to quantify the effect of a greenhouse gas, the concentration percentage of the gas in the atmosphere is multiplied by its related emission factor.

The greenhouse effect is quantified by the GWP (global warming potential) indicator, based on the characteristics mentioned above. In particular, the determination of the GWP indicator for a heating system is made by summing the elementary contributions of each effluent gas of the system, multiplied by the corresponding quantity of each component gas "i" by (8.1).

$$\mathrm{GWP} = \sum_i m_i \cdot \mathrm{GWP}_{\mathrm{a,i}} \tag{8.1}$$

where

m_i represents the mass of the component gas "i", in kg/functional unit;

$\mathrm{GWP}_{\mathrm{a,i}}$ = the potential of the greenhouse effect of component gas "i" in the gaseous effluent, within a certain period of time, in kg_{CO_2} equivalent.

In analyzes, the period of one hundred years is usually considered.

Although carbon dioxide does not absorb as efficiently the infrared radiation as the methane or nitrous oxide, CO_2 can be found in the lower atmosphere in proportion of roughly 200 times greater than CH_4, and 1,100 times greater than N_2O, as it can be seen in the Table 8.1, which defines it as the gas with the most important greenhouse effect and whose concentration is directly influenced by the anthropic activities. Different greenhouse gases have different global warming potentials. For example, one tonne of CH_4 is equivalent to 28 tons of CO_2 and one tonne of N_2O with 310 tons of CO_2. To take this into account, the amount of emissions for each greenhouse gas is converted into equivalent carbon dioxide (CO_{2e} or CO_2 equiv.) so that the global impact of the sources can be quantified into one holistic environmental indicator.

The alarming increase in the amount of CO_2 in the atmosphere in recent years has led to the adoption of a series of emission limitation directives. The United Nations Framework Convention on Climate Change, UNFCCC, approved by Decision 94/69/EC, in force from 25.06.2009 (available via Eur-lex.europa.eu) establishes as an objective the stabilization of the greenhouse gases concentrations. It is essential that the annual global temperature does not exceed pre-industrial levels by more than two degrees. In order to respect this limit, GHG emissions should be reduced by 50% until 2050.

Usually, the actions planned to limit emissions have at the starting point the basic inventory of emissions based on the final annual energy consumption. The basic inventory of emissions involves territorial operational data, final energy consumptions in the territories and the GHG emission factors. Currently, there are two main approaches in order to quantify GHG emissions, as follows:

- The IPCC (The Intergovernmental Panel on Climate Change) inventory includes all CO_2 emissions resulting from energy consumption in territories, directly by burning fuels, or indirectly by burning fuels in associaton with the consumptions of electricity and heat. This approach is based on the carbon's content of each type of used fuel. In this type of approache, the use of energy from renewable sources implies zero emissions
- The LCA (Life Cycle Assessment) includes all CO_2 emissions delivered along with the entire technological, energy chain → exploitation/conversion–storage–transport–parametric transformation–distribution–and final use, of the energy. In this type of approach, the use of energy obtained from renewable sources implies positive emissions.

The environmental and human impact analyzes of the technical systems can have as outputs the following indicators, centralized in the Table 8.2, depending on the pursued target.

In order to quantify the greenhouse gas emissions of a heating system, the emission factor, F [t_{CO_2}/kcal/h] is used, determined based on (8.2).

$$\mathrm{F} = \frac{C}{\mathrm{Q}} \tag{8.2}$$

where C represents the amount of greenhouse gases released into the atmosphere, in t_{CO_2}, and Q is the amount of heat embedded in the used fuel, in kcal/h.

One of the key outcomes of the basic emissions inventory (IPCC) is the direct emissions related to heating systems. Direct emissions can be determined for each source from the energy mix, by multiplying the corresponding energy consumption by its emission factor. For example, the calculation of the R_{CO_2} quantity in the case of heat sources equipped with heating boilers can be done by (8.3) [18].

$$\mathrm{R}_{\mathrm{CO}_2} = \alpha_{\mathrm{c}} \cdot \left(\mathrm{Q}_{\mathrm{aux}} \cdot \mathrm{q} - \sum_i H_i \cdot \frac{B_i}{H_e}\right) - \beta_{\mathrm{c}} \cdot \sum_i E_i \tag{8.3}$$

where

α_c is the carbon emission related to the combustion of the conventional fuel unit, in kg_{CO_2}/kg_{ce};

Q_{aux} = useful thermal power delivered to the consumers by the heat source (heating boilers), in GJ;

Table 8.2 Environmental and human impact indicators

Index		Description
Acidification potential	AP	Acid rain: SO_2, NO_x (NO, N_2O). Expressed in kg SO_2 equiv./kg emission
Abiotic resource depletion potential	ADP	Expressed in kg antimony equiv./kg. Expressed as scarcity indicator that combines extraction and reserve of individual elements, in kg reserve/kg extraction: - Extraction: global annual element' extraction, in kg; - Reserve and rate of de-accumulation: estimated ultimate global reserve of the element, in kg
Global warming potential	GWP	Expressed in kg_{CO_2} equiv. Indicates how many times the heating potential of a gas is greater than that of the carbon dioxide (CO_2), for which GWP = 1 is considered
Eutrophication potential	EP	Excessive growth of algae that may result in oxygen depletion of the water. Expressed in kg $PO_4{}^{3-}$ equiv./m^3 water
Fresh water aquatic ecotoxicity potential	FAETP	Expressed in m^3 fresh water/g substance
Human toxicity potential	HTP	Expressed in 1.4-dichlorobenzene equiv./kg emission
Marine aquatic ecotoxicity potential	MAETP	Expressed in m^3 marine water/g substance
Photochemical ozone creation potential	POCP	Expressed in kg ethene equiv./kg emission
Stratospheric ozone depletion potential	SODP	Expressed in kg CFC-11 equiv./kg emission
Terrestrial ecotoxicity potential	TETP	Expressed in m^3 soil/g substance

q = conventional (equivalent) fuel specific consumption of the heat source, in kg_{ce}/GJ;

H_i = net calorific power of the fuel, at the time "i" which the assessment is made, in kJ/kg;

B_i= fuel consumption at the assessment time "i", in kg;

H_e = calorific power of the conventional fuel, in kJ/kg_{ce};

β_c = carbon emission related to the production of 1 kWh_e (electric energy), in kg_{CO_2}/kWh_e;

E_i = electricity consumption of all electrical equipments and devices related to the heat source at the assessment time "i", in kWh_e.

The environmental efficiency of a heating system, respectively the impact on the environment of a heating system can be evaluated through the total CO_2 emissions, Em_{CO_2} [kg/kWh], according to (8.4).

$$\mathrm{Em}_{\mathrm{CO_2}} = PRF \cdot \mathrm{f}_{\mathrm{CO_2}} \qquad (8.4)$$

where

PRF is the primary resource factor, defined as ratio between the net fuel energy supplied and the primary energy, consumed within one year, [–];

$\mathrm{f}_{\mathrm{CO_2}} = \mathrm{CO_2}$ emission factor specific to the conventional fuel, expressed as standard emission factor or as LCA emission factor, as the case, throughout the entire energy chain, in kg/kWh.

Some of primary resource factors of the different fuels and energy sources are listed in Table 8.3.

As it can be seen in Table 8.3, the PRF report is increased in the case of the fossil fuels and tends to zero in the case of renewable fuels. Forwards, in Table 8.4, the CO_2 emissions resulting from the combustion of fuels in the case of heat production

Table 8.3 Primary resource factors of the main fuels/energy sources

Fuel type/Energy source [–]	Estimated calorific power of the fuel [kJ/kg]	PRF[a] [–]
Biogas	49,524 … 55,563	0.00
Industrial waste heat	–	0.05
Municipal waste	–	1.05
Wood	8,120 … (15,000) … 18,800	1.08
Wood pellets	19,000	1.08
Wood briquettes	17,200 … (18,000) … 24,700	1.08
Cobs	17,000	1.08
Liquefied petroleum gas	45,000	1.10
Oil	38,600 … 39,800	1.10
Light fuel	39,700 … (40,000) … 41,800	1.10
Natural gas	55,500	1.17
Charcoal (pit coal)	27,000	1.20
Lignite	6,000 … 15,000	1.30
Thermal energy supplied by thermal solar collectors	–	1.00
Electrical energy supplied by photovoltaic collectors	–	2.62
Free cooling	–	1.00
Thermal energy for heating supplied by electrical heat pumps	–	1.53
Electric energy/Grid	–	2.62
Termofication/Cogeneration	–	0.92
Electric energy/Cogeneration	–	2.80

[a] The lower calorific value of the fuel was taken into consideration

Table 8.4 Specific CO_2 emissions resulting from the combustion of conventional fuels, in the case of heat production

Fossil fuel	**Standard emission factor**	**LCA emission factor**
–	f_{CO_2}	f_{CO_2}
–	$[kg_{CO_2}/\mathbf{kWh}]$	$[kg_{CO_2}/\mathbf{kWh}]$
Oil	0.279	0.310
Liquefied petroleum gas	0.230	–
Natural gas	0.202 …0.205	0.237
Charcoal (pit coal)	0.341	0.380
Lignite	0.334 … 0.364	0.375
Biomass—firewood	0.019 … 0.403	… 0.405
Biomass—wood waste	0.016	… 0.405
Biomass—briquettes, pellets	0.039	… 0.405
Biomass—agricultural waste	0.010	… 0.405
Biogas	0.145	–
Energy type	**Standard emission factor**	
–	f_{CO_2}	
–	$[kg_{CO_2}/\mathbf{kWh}]$	
Electrical energy (from grid)	0.299	
Cogeneration	0.220	
Solar energy	0.000	
Aeolian energy	0.000	
Geothermal/Aerothermal	0.000	

are centralised for the main fuels, determined for the lower calorific power of the fuels.

In Table 8.5, the average non-renewable component of PRF values are centralized, in the case of different types of heating sources.

As it can be seen in Table 8.5, the average PRF value for the heating source in cogeneration operating on natural gas has the lowest value among the other systems,

Table 8.5 Average PRF non-renewable component and specific CO_2 emissions values for different heating sources [17]

Heating source [–]	PRF non-renewable component [–]
Biomass system	0.1
Gas cogeneration system	0.5
Coal cogeneration system	0.8
Heat pump	0.9
Natural gas heating boiler	1.3
Coal heating boiler	1.5
Electric heating	2.5

when producing the same amount of heat, except for the situation in which biomass is used as an alternative fuel. A low PRF non-renewable component indicator implies conventional fuel economy and reduced CO_2 emissions. The values from Table 8.5 represent average values, but in fact, for each individual case, the values may differ quite a lot. Indicators PRF and Em_{CO_2} are particularly useful when comparing existing technologies with the proposed ones, in order to upgrade the heating systems infrastructure and to reach the contemporary target goals in the energy field, to minimize the environmental and human impact respectively.

In the case of monitoring the existing heating systems, the correct emission determination is made on the basis of measurements with specialized equipment and methods such as extractive, in situ, etc. In the case of elaboration of the forecasts and the feasibility studies, alternative methods of operative evaluation of the CO_2 emissions can be used. For example, the calculation method based on the fuel consumption and related emission factors can be used. The specific emission factor of CO_2, f_{CO_2} [kg/kJ] can be determined with (8.5).

$$f_{CO_2} = \left(\frac{M_{CO_2}}{M_C} \cdot \frac{C}{100}\right) / H_i \tag{8.5}$$

where

M_{CO_2} is molecular mass of CO_2, in kg/kmol;

M_C = molecular mass of carbon, C, in kg/kmol;

C = fuel's content of carbon, in mass percentage, %;

H_i = low calorific value of the fuel, in kJ/kg.

The lower calorific value of solid or liquid fuel H_i, in kJ/kg, can be determined with (8.6) [12, 19].

$$H_i = 4.18 \cdot \left[81 \cdot C^i + 280 \cdot \left(H^i - O^i/8\right) + 25 \cdot S^i - 6 \cdot W^i\right] \tag{8.6}$$

where C^i, H^i, O^i, S^i, W^i represent the percentage content of carbon, hydrogen, oxygen, sulfur and humidity, in the initial state of the fuel.

The lower calorific value of a gas fuel H_i, in kJ/Nm^3, can be determined with (8.7).

$$H_i = \frac{1}{100}\begin{pmatrix} X_{CO} \cdot H_i^{CO} + X_{H_2} \cdot H_i^{H_2} + X_{H_2S} \cdot H_i^{H_2S} + X_{CH_4} \cdot H_i^{CH_4} \\ + X_{C_2H_2} H_i^{C_2H_2} + X_{C_2H_4} \cdot H_i^{C_2H_4} + X_{C2H6} \cdot H_i^{C_2H_6} \\ + X_{C_3H_6} \cdot H_i^{C_3H_6} + X_{C_3H_8} \cdot H_i^{C_3H_8} + X_{C_4H_8} \cdot H_i^{C_4H_8} \\ + X_{C_4H_{10}} \cdot H_i^{C_4H_{10}} + X_{C_5H_{12}} \cdot H_i^{C_5H_{12}} + X_{C_6H_6} \cdot H_i^{C_6H_6} \\ + X_{C_6H_{14}} H_i^{C_6H_{14}} \end{pmatrix} \tag{8.7}$$

where H_i^j are the lower calorific values of the component element "j" of the gas fuel.

The lower calorific value of the conventional fuel, to which all fossil fuels can be reported is approximately 29,307 kJ/kg (~7,000 kcal/kg).

The thermal energy production for space heating, ventilation and domestic hot water preparation for buildings is strictly linked to the burning of fossil fuels within the thermic sources, and to the generation of the greenhouse gases at high levels. Delivered into the atmosphere, the amount of CO_2 undergoes a process of dispersion having the effect of decreasing the concentration, proportional to the following factors:

- the technical characteristics of the heating source, the outbreaks, combustion chambers and the combustion type: the velocity and the temperature of the exhaust gases and the quantity of discharged pollutants
- the technical characteristics of the flue gas exhaust system: the useful height of the chimney, the free evacuation area at the top of the chimney, the characteristic of its thermal insulation
- topographic conditions: the characteristics of the area in which the heat source is located
- climatic and atmospheric conditions: air temperature and humidity, wind velocity and direction, atmospheric pressure, etc. Of these factors, the velocity, the wind direction and the vertical thermal stratification are decisive.

Because carbon dioxide is not a pollutant itself, the CO_2 concentration in proximity of the source and its dispersion in the atmosphere are not relevant from human impact point of view. The situation is different in the case of carbon monoxide, CO emissions resulted from an incomplete combustion, usually due to an insufficient combustion air. The pollutants within the resulted gases from burning process of the fossil fuels, with their emission limit values are centralized in Table 8.6.

The total amount of CO_2 emissions associated with the production of thermal energy for buildings represents one of the main environmental indicators in the analysis of existing heating systems, while the total avoided amount of CO_2 emissions related to the production of thermal energy represents one of the main indicators when comparatively evaluate different configurations of the future heating systems.

Table 8.6 Emission limit values of the pollutants related to the heat production

Pollutant (in flue gas)	Process	Fossil fuel		
–	–	Solid [mg/Nm^3]	Liquid [mg/Nm^3]	Gas [mg/Nm^3]
SO_x (SO_2, SO_3)	Sulfur burning	2,000	1,700	35
CO	Incomplete combustion of carbon	250	170	100
NO_x (NO, NO_2)	Oxidation of azote	500	450	350
Ashes, PM	Flying ash and soot	100	50	x

Source IPCT-SA 2003

Finding and validating efficient technical solutions in order to integrate technologies based on renewable and clean energy sources, as well as to develop working tools and methodologies for assessing hybrid heating systems represent issues of great importance in the thermoenergetic field.

8.3 Environmental Impact of Buildings' Heating Systems

8.3.1 Problem Formulation

There is a close connection between increasing technological systems efficiency and the reducing of the emitted amount of CO_2. This chapter synthesizes partial results of a larger study, regarding a hybrid thermoenergetic solution for the heat supply of buildings, based on the integration of the renewable energy sources (RES) into the existing heating systems, on-site, as well as at the level of the district heating (DH) source. The solar energy resource has been chosen for the overall characteristics of it. On one side, the solar resource is widespread, relatively inexhaustible, easy to use even in crowded urban areas, while on the other side, solar energy represents a recognized clean form of energy. Two scenarios, for different optimized configurations of the heating source were set and analyzed from the avoided CO_2 emissions' point of view, IPCC methodology respectively. The optimum energetic and environmental performances achieved were illustrated, in a comparatively way, and the role of RES, solar thermal energy in this case, in the decarbonisation of the district heating system was highlighted and quantified. In this regard, the optimization criterion applied to the heating system was to reduce the total amount of annually emitted CO_{2e}, in the following restrictive conditions:

- the covering of the buildings' heat demands
- the securing of the optimal values for systemic energy efficiencies, in conditions of achieving the highest values for both, annual operating efficiency of the hybrid heating system and annual operating efficiency of the integrated solar fields.

8.3.2 Energy Hub Modeling

Heating sources use a multitude of conventional energy carriers, fossil energy such as coal and hydrocarbons, as well as renewable and alternative ones, such as biomass, geothermal energy, solar energy, wind energy, waste heat from various industrial processes, municipal sewage and waste. Conventional fuels directly emit significant amounts of CO_2 by burning them in outbreaks, while the renewable and alternative ones, which do not involve combustion processes are indirectly associated with reduced amounts of CO_2 emissions, tending to zero, as it can be seen in Table 8.4.

The heating sources are configured and designed in order to provide consumers with the required amount of heat, under conditions of energy efficiency, at a reasonable price. The concept of the multi-energy hybrid system, with the use of increased shares of RES is expected to be the future model for the thermoenergetic infrastructure. The energy hub is the energetic element in the vision of future district energy sources [6, 7]. The raised issue is related to an efficient integration of the renewable energy sources, along with the increase of its participation within the energy mix. Since in most cases district heating systems are already operational, it remains to meet the targets through a gradually optimization.

The concept of "energy hub", as in electrical energy field [6, 7, 22], was used for the holistic modelation of DH system. The energy hub is the energetic unit at which multiple energy carriers undergo conversion, parametric transformations and storage. The synergy of various primary forms of input energy gives the energetic system an increased degree of security in power supply and operational flexibility. Monitoring and optimizing the energy flows along the energy hub allows the districtual thermoenergetic system to achive the optimal parametric in operation, in order for it to get closer to the "smart city & smart energy" concept. The district heating schematically represented in Fig. 8.1 serves an urban locality located in Northwest Romania, having around 200,000 inhabitants (according to 2012 census).

where

SG is steam generator;
CB = thermoenergetic collector bar;
ST = steam turbine;
HE = heat exchanger.

The transformations undergone by the energy carriers within the hub (Fig. 8.1) are defined in matrix form by (8.8 and 8.9) and in linear form by (8.10).

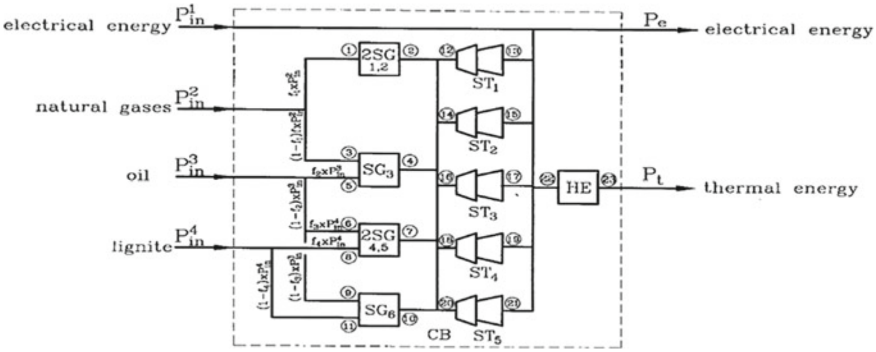


Fig. 8.1 Energy model of the conventional thermoenergetic hub. District heating plant (Reproduced from [26])

$$\begin{bmatrix} e_{1\mathrm{e}} & e_{2\mathrm{e}} & e_{3\mathrm{e}} & e_{4\mathrm{e}} \\ e_{1\mathrm{t}} & e_{2\mathrm{t}} & e_{3\mathrm{t}} & e_{4\mathrm{t}} \end{bmatrix} \cdot \begin{bmatrix} P_{\mathrm{in}}^{1} \\ P_{\mathrm{in}}^{2} \\ P_{\mathrm{in}}^{3} \\ P_{\mathrm{in}}^{4} \end{bmatrix} = \begin{bmatrix} P_e \\ P_t \end{bmatrix} \tag{8.8}$$

where

$E(e_{je,t})$ is the matrix of performance indicators, energy efficiencies of conversion, storage, transport and distribution at the energy hub level; $_{je,t}$ represent primary energy, electrical energy, thermal energy, respectively;

1–4 = energy carrier indices, “j”;

$P(P_{in}^{j})$ = input vector energy matrix, primary energy consumptions, respectively;

$P(P_{e,t})$ = output vector energy matrix, electrical and thermal energy, respectively.

$$\begin{bmatrix} \mathrm{P}_{\mathrm{in}}^{1} \\ \mathrm{P}_{\mathrm{in}}^{2} \\ \mathrm{P}_{\mathrm{in}}^{3} \\ \mathrm{P}_{\mathrm{in}}^{4} \end{bmatrix} = \begin{bmatrix} c_{1e} & c_{1t} \\ c_{2e} & c_{2t} \\ c_{3e} & c_{3t} \\ c_{4e} & c_{4t} \end{bmatrix} \cdot \begin{bmatrix} P_e \\ P_t \end{bmatrix} \tag{8.9}$$

where $C(c_{je,t})$ represents couple matrix, $c_{je,t} = \begin{cases} e_{je,t}^{-1}, e_{je,t}^{-1} \neq 0 \\ 0, e_{je,t}^{-1} = 0 \end{cases}$ the other terms having the previous meanings.

$$\mathrm{P}_{\mathrm{e,t}} = \sum_{j=1}^{4} e_{je,t} \cdot P_{in}^{j} \tag{8.10}$$

Equation 8.10 allows to link a single output from energy hub—the buildings’ heat demand, to several energy inputs, associated with the analyzed energy carriers.

If the heating source is equipped only with heating boilers, the modulation can be realised as in Fig. 8.2.

where HB is heating boiler, the other notations having the previous meanings.

The matrix expression related to the thermic component P_t, attached to the thermoenergetic model from Fig. 8.1 is (8.11).

$$\begin{bmatrix} P_{\mathrm{in}}^{1} & P_{\mathrm{in}}^{2} & P_{\mathrm{in}}^{3} & P_{\mathrm{in}}^{4} \end{bmatrix} \cdot \begin{bmatrix} a & b & c & d \end{bmatrix} \cdot \eta_{CB-22}^{ST} \cdot \eta_{22-23}^{HE} \cdot \eta^{TN} = P_t \tag{8.11}$$

where

$a = 0$;

$b = f_1 \cdot \eta_{1-2} + (1 - \mathrm{f}_1) \cdot \eta_{3-4}$;

$c = f_2 \cdot \eta_{5-4} + f_3 \cdot \eta_{6-7} + (1 - \mathrm{f}_3) \cdot \eta_{9-10}$;

$d = f_4 \cdot \eta_{8-7} + (1 - \mathrm{f}_4) \cdot \eta_{11-10}$;

f = distributive factor of the primary fuel on each energy conversion equipment, $f \leq 1$, [–];

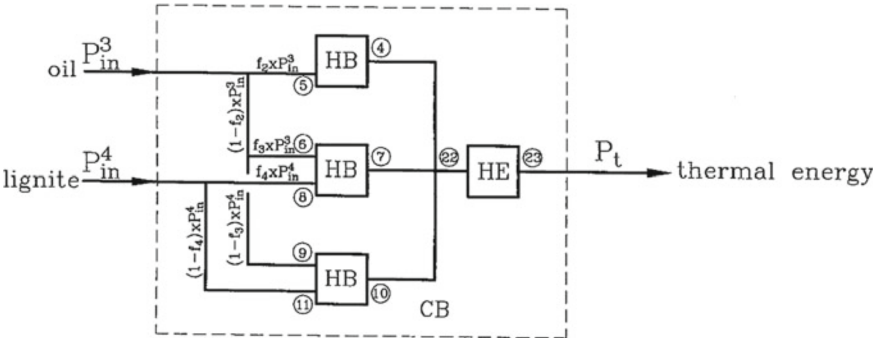


Fig. 8.2 Energy model of the conventional thermoenergetic hub. Heating boilers (Reproduced from [26])

η = yield of each technical conversion system, [–];
η^{HE}_{22-23} = yield of thermal heat exchangers, [–];
η^{TN} = yield of thermal network, [–];
η^{ST}_{CB-22} = yield of steam turbines installation, which, based on the multiplicativity property of the global efficiency, can be determined by (8.12).

$$\eta^{ST}_{CB-22} = \eta^{ST}_{12-13} \cdot \eta^{ST}_{14-15} \cdot \eta^{ST}_{16-17} \cdot \eta^{ST}_{18-19} \cdot \eta^{ST}_{20-21} \tag{8.12}$$

For annual energy values, (8.11) can be written in the form (8.13).

$$\begin{Bmatrix} P^2_{in} \cdot \left[f_1 \cdot Ef_{a1-2} + (1-f_1) \cdot Ef_{a3-4} \right] + P^3_{in} \cdot \left[f_2 \cdot Ef_{a5-4} + f_3 \cdot Ef_{a6-7} + (1-f_3) \cdot Ef_{a9-10} \right] \\ + P^4_{in} \cdot \left[f_4 \cdot Ef_{a8-7} + (1-f_4) \cdot Ef_{a11-10} \right] \end{Bmatrix}$$
$$\cdot Ef^{ST}_{aCB-22} \cdot Ef^{HE}_{a22-23} \cdot Ef^{ST}_{aCB-22} \cdot Ef^{TN}_{a} = P_t \tag{8.13}$$

where Ef_a represents the annual energy efficiency of each technical subsystem, [–].

Pursuing energetic optimization of a conventional heating source based on the cogeneration principle, with the integration of renewable sources within the energy mix, the following schematic hub is achieved (Figs. 8.3 and 8.4).

where

CHP (combined heat and power) represents a power plant using heat engines in order to generate electricity and useful heat simultaneously—cogeneration energy source, which includes gas turbines, recovery boilers, internal combustion engines, peak boilers, auxiliary equipments and installations;

HB = heating boilers;

RES = renewable energy sources conversion system, consists of solar collector fields, solar loops, heat exchangers, auxiliary equipments, etc.

TES = thermal energy storage;

f = distributive factor of primary—conventional fuels, on each energy conversion equipment, [–];

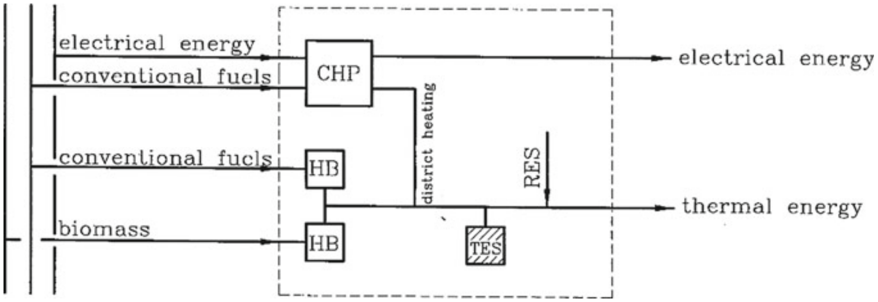


Fig. 8.3 Hybrid thermoenergetic hub. District heating plant schematic (Reproduced from [26])

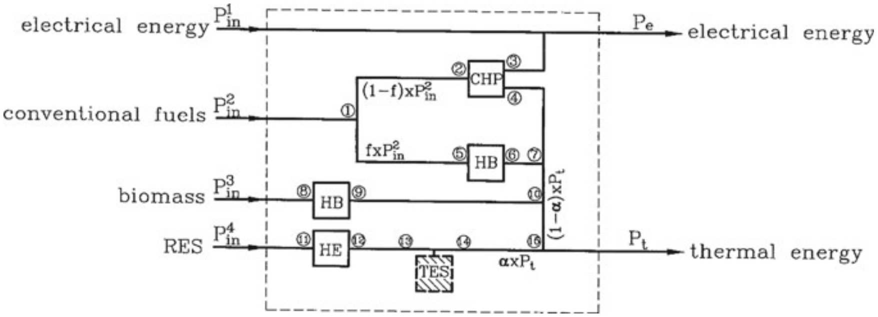


Fig. 8.4 Energy model for the hybrid thermoenergetic hub. District heating plant (Reproduced from [26])

α = participation factor of the renewable energy sources within thermal energy mix, [–].

For the hybrid thermoenergetic system, taking into account the thermal energy storage TES, (8.10) can be written as (8.14).

$$\mathrm{P_t} = \sum_{j=1}^{4} e_{jt} \cdot P_{in}^{j} + \eta_s(\tau) \cdot \frac{\Delta E}{\Delta \tau} \tag{8.14}$$

where

$\eta_s(\tau)$ is the thermal energy storage's yield;

ΔE = energy gradient in storage system, in the time interval $\Delta\tau$.

The matrix relation attached to the energy model from Fig. 8.4 is as (8.15).

$$\begin{bmatrix} 1 & (1-f)\cdot\eta_{2-3} & 0 & 0 \\ 0 & (1-f)\cdot\eta_{2-4} + f\cdot\eta_{5-6} & \eta_{8-9} & \eta_{11-12} \end{bmatrix} \cdot \begin{bmatrix} P_{in}^{1} \\ P_{in}^{2} \\ P_{in}^{3} \\ P_{in}^{4} \end{bmatrix} \cdot \eta_{13-14}^{TES} \cdot \eta^{TN} = \begin{bmatrix} P_e \\ P_t \end{bmatrix} \tag{8.15}$$

where

f is the distributive factor of primary fuel on each energy conversion equipment, $f \leq 1$, [–];

η = yield of each technical system of conversion, storage, transport and distribution of energy, [–].

The matrix expression related to the thermal output component is as (8.16).

$$\begin{bmatrix} 0 & (1-f)\cdot\eta_{2-4} & f\cdot\eta_{5-6} & \eta_{8-9} & \eta_{11-12} \end{bmatrix} \cdot \begin{bmatrix} P_{in}^{1} \\ P_{in}^{2} \\ P_{in}^{3} \\ P_{in}^{4} \end{bmatrix} \cdot \eta_{13-14}^{TES} \cdot \eta^{TN} = P_t \tag{8.16}$$

And in the linear form as in (8.17).

$$P_t = \left\{ P_{in}^{2} \cdot \left[(1-f)\cdot\eta_{2-4} + f\cdot\eta_{5-6} \right] + P_{in}^{3}\cdot\eta_{8-9} + P_{in}^{4}\cdot\eta_{11-12} \right\} \cdot P_{13-14}^{TES} \cdot \eta^{TN} \tag{8.17}$$

For Node 15 from Fig. 8.4, Eqs. (8.18, 8.19) can be written as (8.18) and (8.19).

$$\left\{ \left[(1-f)\cdot\eta_{2-4}\cdot P_{in}^{2} + f\cdot\eta_{5-6}\cdot P_{in}^{2} + \eta_{8-9}\cdot P_{in}^{3} \right] \right\} \cdot \eta^{TN} = (1-\alpha)\cdot P_t \tag{8.18}$$

$$\eta_{11-12}\cdot\eta_{13-14}^{TES}\cdot\eta^{TN}\cdot P_{in}^{4} = \alpha\cdot P_t \tag{8.19}$$

where α represents the degree of heat demands' coverage from renewable energy sources, RES participation level within energy mix, respectively.

For annual values, (8.18) and (8.19) can be written as (8.20) and (8.21).

$$\left\{ \begin{bmatrix} (1-f)\cdot Ef_{a\,2-4}\cdot Q_{in}^{2} \\ +f\cdot Ef_{a\,5-6}\cdot Q_{in}^{2} + Ef_{a\,8-9}\cdot Q_{in}^{3} \end{bmatrix} \right\} \cdot Ef_{a}^{TN} = (1-\alpha_a)\cdot Q_c^{a} \tag{8.20}$$

$$Ef_{a11-12}\cdot Ef_{a13-14}^{TES}\cdot Ef_{a}^{TN}\cdot Q_{\mathrm{in}}^{4} = \alpha_a\cdot Q_c^{a} \tag{8.21}$$

where

α_a is the degree of coverage of the annual heat demand from renewable energy sources, RES annual participation level within energy mix, respectively, [–];

Ef_a = annual global energy efficiency of each technical heating subsystems, [–].

8.3.3 Indicators of Performance

In Fig. 8.4, the following optimization criteria were identified:

- Global energy efficiency of the heating system, Ef [%]

  It can be expressed by (8.22).

$$Ef = \frac{P_t}{P_{in}^2 + P_{in}^3 + E_p} \tag{8.22}$$

where E_p is the electricity consumption related to all auxiliary equipments, such as pumping and automation systems, in kW, the rest of the terms having the previous meanings.

- Annual global energy efficiency of the heating system, Ef_a [%]

$$Ef_a = \frac{Q_c^a}{E_{aux} + E_{pa}} \tag{8.23}$$

where

Q_c^a represents the annual amount of heat consumption for space heating, ventilation and domestic hot water preparation of buildings, in kWh;

E_{aux} = annual consumption of primary energy, electricity and energy related to the fuels, at the level of auxiliary, conventional heating sources, in kWh;

E_{pa}= annual electricity consumption for pumping and automation systems, in kWh.

The annual energy efficiency of the heating system reflects the degree of annual use of the solar energy, in conditions in which buildings heat demand are permanently covered.

- Annual solar fraction, α_a [%]

  It can be determined by (8.24).

$$\alpha_a = \frac{Q_{sol}}{Q_{aux} + Q_{sol}} \tag{8.24}$$

where Q_{sol} is the amount of heat, annually delivered by RES into the hybrid heating system, in kWh, and Q_{aux} is the amount of heat, annually supplied in the heating system by conventional heating sources, in kWh.

In order to assess global performances of the hybrid heating system, achieved in different working scenarios—representing different stages of optimization, the following energy performance indicators, listed in Table 8.7 were defined and secured within the case study.

Table 8.7 Performance indicators

Performance indicator	Symbol	U.m.
Annual solar fraction	α_a	[%]
Annual global efficiency	Ef_a	[–]
Annual fossil fuel consumption of the conventional heating source[a]	C_a	[Nm^3/year]
Quantity of CO_{2e} emissions, maximum annually avoided[a]	Em_{CO_2}	[kg_{CO_2}/year]
Specific quantity of CO_2 emissions, maximum annualy avoided[a]:		
Indicator of equivalent emissions	E_{mCO_2}	[kg_{CO_2}/m^2year]
Specific indicator of equivalent emissions	e_{mCO_2}	[kg/pers.year]

[a] Natural gases as a reference fuel

By following the performance indicators defined above, in order to secure them within analyzing and comparing the heating systems in different working scenarios, the simulations were carried out for four urban thermal areas, A_1–A_4, characterized by different thermal energy densities, in two hypotheses of energy efficiency of the buildings:

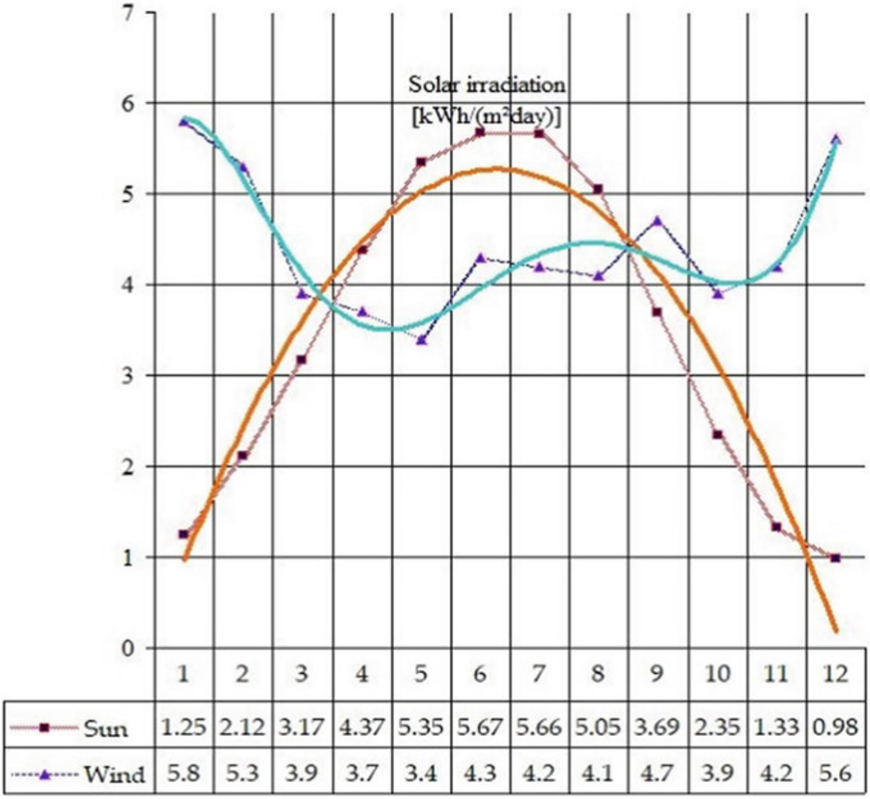
- Hypothesis BR, before the buildings' retrofitting
- Hypothesis AR, after the buildings' retrofitting,

for different scenarios of configuration of the districtual heating source, DH_1–DH_4, as in Table 8.11. Computational simulations were conducted with Polysun Software [28], based on deterministic, numerical models. Optimization of the heating system is of multi-objectives type with restrictive conditions related to the following criteria: uncovered heat demand, annual yield of thermal solar collectors, annual global efficiency and avoided carbon dioxide emissions. In addition to the restrictions imposed by ensuring the buildings' heating demand in performance conditions, when using solar resource in urban areas there are also significant restrictions related to the physical land print of the solar systems, the actual occupied areas, given by the gross surfaces of the collectors fields that must be taken into account.

8.4 Case Study

8.4.1 Solar Resource

Solar irradiation, clearness index and wind velocity values are based on NASA Data Report 2015. The climatic values are synthetized in Fig. 8.5 [26]. Following data values, the thermal energy converted on-site by solar collectors' fields was determined. The main advantage of using solar energy as primary fuel consists in the heat production without any polluting effects. Specific for the location and climate



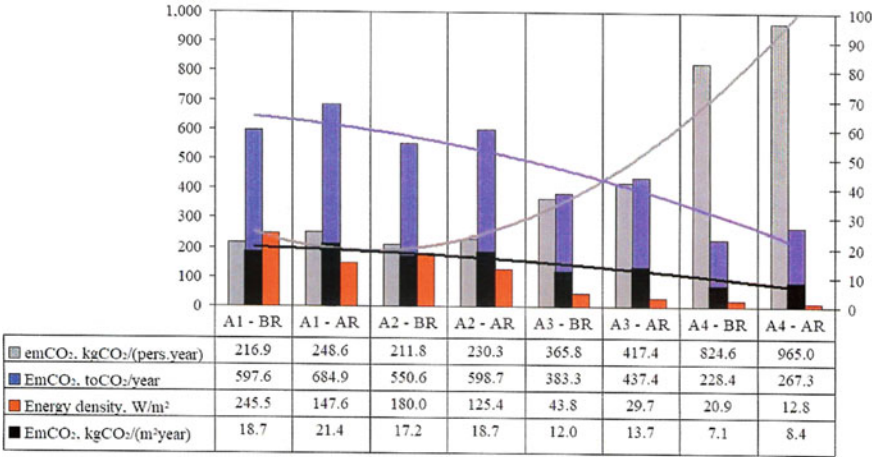
	1	2	3	4	5	6	7	8	9	10	11	12
■ Sun	1.25	2.12	3.17	4.37	5.35	5.67	5.66	5.05	3.69	2.35	1.33	0.98
▲ Wind	5.8	5.3	3.9	3.7	3.4	4.3	4.2	4.1	4.7	3.9	4.2	5.6

Fig. 8.5 Availability of the solar resource. Characteristic of the site

of the site, the highest values of solar irradiation was recorded in July, and the lowest values in December, during the heating season. In order to compensate the differences between the solar feature and the heating's characteristics of the final consumers, in most cases it is imposed to store the thermal energy converted from solar resource. Within the case study, depending on the available technical space, the storage was achieved on short or medium term, in thermal buffers indoor mounted, having water as a storage medium.

8.4.2 Consumers Profile

The case study was developed for four urban areas, A_1–A_4 from a reference urban locality situated in Northwest Romania, where the thermal consumers, residential, commercial, administrative and office buildings were analyzed in two thermoenergetic scenarios, before the buildings' retrofitting, BR and after the buildings'



	A1 - BR	A1 - AR	A2 - BR	A2 - AR	A3 - BR	A3 - AR	A4 - BR	A4 - AR
▨ emCO$_2$, kgCO$_2$/(pers.year)	216.9	248.6	211.8	230.3	365.8	417.4	824.6	965.0
🟦 EmCO$_2$, toCO$_2$/year	597.6	684.9	550.6	598.7	383.3	437.4	228.4	267.3
🟥 Energy density, W/m^2	245.5	147.6	180.0	125.4	43.8	29.7	20.9	12.8
■ EmCO$_2$, kgCO$_2$/(m^{2}year)	18.7	21.4	17.2	18.7	12.0	13.7	7.1	8.4

Fig. 8.6 The influence of thermal energy density on CO$_2$' emissions related to the heating systems

retrofitting, AR, achieved in order to frame the buildings in higher classes of energy performance, according to the actual trends and rules in force [13, 14].

The followings are identified and analyzed: representative thermal consumers—buildings and the representative types of buildings' heating systems. The possibilities of decarbonisation of the thermoenergetic systems in the buildings sector are identified, as well as those of the increasing energy efficiency of buildings and heating installations.

8.4.3 Hybrid District Heating System. Working Scenarios

The following thermal consumers and urban areas were taken into account as centralized in Table 8.8 and Table 8.9. The following hypotheses were taken into consideration:

- BR—before buildings' retrofitting, that also represents the reference hypothesis
- AR—after buildings' retrofitting.

An energy modeling software [38] was used, developed based on rules in force in Romania, aligned with EU standards, such as Standard regarding thermotechnical calculation of construction elements of the buildings, 2006, Calculation methodology of the energy performance of buildings, 2006, Heating installations. Heating demand calculations, 2016 etc., in order to modeling the buildings from thermotechnical point of view, in a non-stationary regime.

The supply of thermal energy in urban areas is realized as follows:

- in a partially decentralized way, at the heating station of each urban area

Table 8.8 Buildings. Working hypotheses

Building type	Hypothesis	Compactness factor A/V[a]	Average heating characteristic
–	–	[m^{-1}]	[W/m^3K]
Residential—condominial, dwelling	AR	0.29 … 0.45	0.71 … 1.12
	BR		0.50 … 0.63
Residential and commercial spaces at the ground floor	AR	0.49	1.13
	BR		0.63
Administrative, Office, Commercial, Educational	AR	0.36	0.83
	BR		0.60

[a] *A* represents the area of the building's heat transfer interface, the total area of the building's elements involved in the heat exchange process with the environment, and *V* is the heated volume

Table 8.9 Urban areas. Working hypotheses

Urban area	Annual thermal energy demand	
–	BR [MWh/year]	AR [MWh/year]
A_1	15,441.6	9,686.0
A_2	12,602.2	8,782.0
A_3	3,575.4	2,819.8
A_4	1,363.0	1,027.8

- in a centralized way, at the district heating source, that provide heat for the entire locality/district.

In the first case, the solar collector fields are integrated on-site, at the areas' heating stations. In the second case, the four scenarios, DH_1–BR/AR, DH_2–BR/AR, DH_3–BR/AR, DH_4–BR/AR represent intermediate stages in the process of retrofitting and optimizing the existing district heating source, as in Table 8.11. In this case, the solar collector fields are integrated at the district heating source. α_a represents the annual solar fraction achieved for each working scenario. The computational modeling and setting the operational frames of the heating systems' simulations for scenarios listed in Table 8.10 and 8.11 were achieved [27]. The simulations were carried on Polysun computing simulation software [28], during a calendaristic year.

8.5 Results and Discussion

The most representative results secured within the case study were synthesized, tabular presented and graphically illustrated, in order to highlights the following criteria: the annual energy performance and the avoided CO_{2e} emissions within the working scenarios. Indicators of performance have been determined, in order to

Table 8.10 Energy performance and maximum quantities of CO_2 annually avoided. On-site integration of the solar systems at the area's heating stations

Urban area	Hypothesis	Thermal energy density	Indicator of energy performance, α_a	Em_{CO_2}	E_{mCO_2}	e_{mCO_2}
–	–	[W/m^2]	[%]	[kg_{CO_2}/year]	[kg_{CO_2}/m^2year]	[kg/pers.year]
A_1	BR	245.5	21.0	597,554.5	18.7	216.9
	AR	147.6	36.8	684,905.0	21.4	248.6
A_2	BR	180.0	26.0	550,609.5	17.2	211.8
	AR	125.4	38.1	598,661.5	18.7	230.3
A_3	BR	43.8	48.2	383,309.0	12.0	365.8
	AR	29.7	66.0	437,429.0	13.7	417.4
A_4	BR	20.9	60.0	228,411.0	7.1	824.6
	AR	12.8	85.6	267,299.5	8.4	965.0

establish configurations with the highest energy efficiency for the district heating systems based on available clean energy. The sustainability issue consists in the aspects related to the environmental impact, to the avoided amounts of CO_2 and other pollutants emissions. The impact of optimizations on the reduction of greenhouse gas emissions is graphically illustrated in Fig. 8.7, for the analyzed thermic areas within the working scenarios, for two types of integration of the thermal solar systems: on-site integration, at the area heating station, as in Table 8.10, and at the district heating source, as in Table 8.11. The annual avoided CO_2 emissions, related to buildings' heating systems, have been reported to the number of consumers (persons), thus obtaining the specific CO_2 emission indicators listed in Tables 8.10 and 8.11 [26].

As a conclusion, the urban thermic areas characterized by high thermal energy density are characterized by higher specific CO_2 emissions, annual values per m^2, respectively by lower specific CO_2 emissions, annual values per person. This is due to the fact that within areas with high energy densities, the heating systems operate within higher efficiencies conditions, the stagnation time periods being shorter. In this sense, the amount of CO_2 emissions released into the atmosphere increases considerably with the decrease of the area's thermal density, respectively with the decentralization degree of the thermoenergetic system based on conventional fuels, as it can be seen in Fig. 8.6.

The annually avoided amount of CO_2 emissions related to the production of heat in urban areas increases significantly with gradual optimization of the heating system, as it can be seen in Figs. 8.8 and 8.9.

Besides the avoided CO_2 emissions, the fossil fuel economies achieved in the different scenarios represent a significant indicator of the depollution of urban areas. The following Table 8.12 shows the achieved fossil fuel savings, as well as the related emissions of avoided pollutants.

As a conclusion, in the following chart Fig. 8.10, the annualy avoided pollutans

Table 8.11 Energy performance and maximum quantities of CO_2 annually avoided. Central integration of the solar systems at the district heating source

District Heating		Heating source: fuel		Annual consumption of fossil fuel			Indicator of energy performance		
–		–		C_a		α_a	Efa	Em_{CO_2}	e_{mCO_2}
–		–		value	u.m.	[%]	[-]	$[t_{CO_2}/year]$	$[t_{CO_2}/pers.year]$
DH_1	BR	Heating boilers:	oil fuel	734,423.9	kg/year	–	0.74	0.0	0.0
			lignite	28,698.9	t/year				
	AR		oil fuel	738,069.6	kg/year	–	0.76	4,580.4	1.7
			lignite	21,296.8	t/year				
DH_2	BR	Heating boilers: natural gas		3,264,505.6	Nm^3/year	10.0	0.97	886,804.7	341.1
	AR			2,338,662.2	Nm^3/year	17.4	1.07	1,196,817.7	460.3
DH_3	BR	Heating boilers: natural gas		2,999,288.0	Nm^3/year	29.0	1.23	2,992,183.9	2,855.1
	AR			1,747,996.5	Nm^3/year	46.6	1.65	3,697,154.6	3,527.8
DH_4	AR	Cogeneration and peak boilers: natural gas		2,027,760.7	Nm^3/year	50.0	1.50	6,827,755.5	24,648.9

DH_1—Heating boilers: oil fuel/lignite; DH_2, DH_3—Heating boilers: natural gas; DH_4—Cogeneration and peak boilers: natural gas

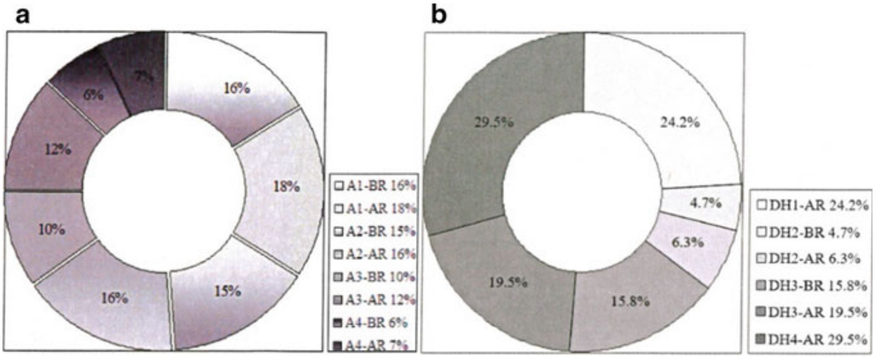


Fig. 8.7 Percentages of CO_2 emissions annually avoided within hypotheses BR and AR. **a** partially decentralized integration of solar systems at the level of the heating stations of urban areas A_1–A_4, **b** Centralized integration of solar systems at the level of district heating source within working scenarios DH_1–DH_4

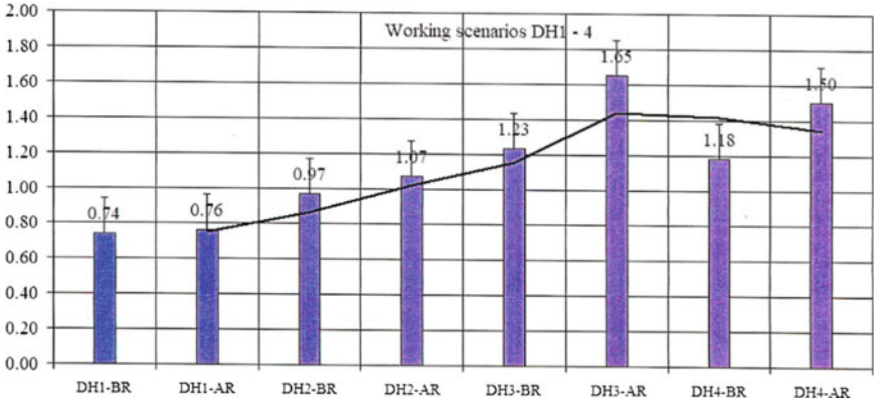


Fig. 8.8 Heating system. Annual efficiency, Ef_a. Working scenarios DH_1–DH_4

emissions are represented within the four stages of up-grading of the district heating source, in transition process to the RES-based energy hub.

8.6 Solutions and Recommendations

For the holistic thermoenergetic modeling of the district heating system, the energy hub has been used, which allows the association of a single energy output—the thermal energy demand, associated with thermal consumers (buildings), to several energy inputs, associated with various energy carriers. At the level of the hybrid thermoenergetic hub, the performance indicators used to comparatively assess the heating

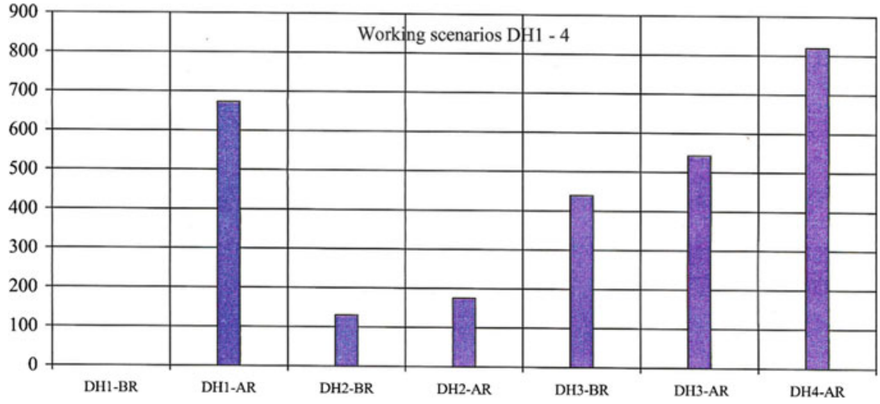


Fig. 8.9 Specific emissions of CO_2, annually avoided. Working scenarios DH_1–DH_4

systems were highlighted and defined. In order to optimize the heating system, respectively in order to increase the annual thermoenergetic efficiency and minimize the environmental impact, the following general solutions are emphasized:

- Increasing the energy performance of buildings
- Lowering the operating temperatures in the district heating networks
- Configurating hybrid heating systems by integrating renewable and clean energy sources with low temperature potential
- Increasing the participation share of renewables, in particular solar resource
- Integrating of solar systems into district heating networks, on-site.

8.7 Conclusion

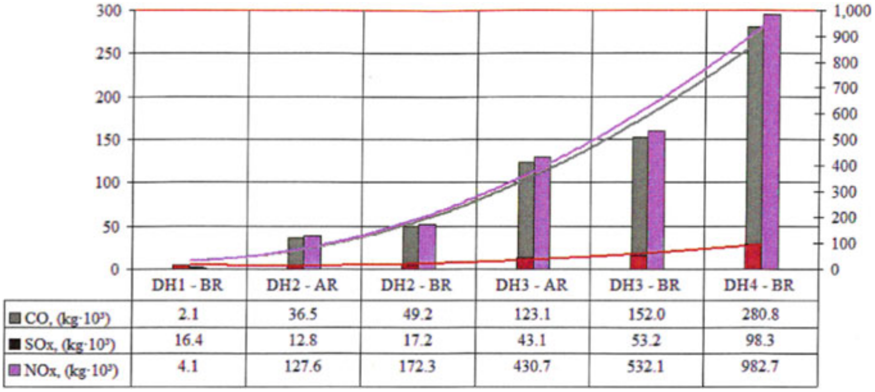
There is a close connection between increasing the efficiency of the heating system and reducing the emitted amount of CO_2 and pollutants as well. In this regard, in quantifying the impact of buildings' heating systems on the environment, the indicator of associated carbon emissions, respectively of avoided carbon emissions by switching from conventional systems based on conventional fuels to hybrid systems, based on renewable and clean sources, offers an energetic perspective on different technical systems. The environmental indicators can be reported to the number of consumers (inhabitants), or heated surface, thus obtaining specific indicators, in which case they can be extrapolate for other localities, districts or areas with similar thermal energy density and heating characteristics.

Following on-site integration of technologies for harnessing solar thermal resource in the conventional heating systems, the following objectives in the urban energy field are fulfilled:

- Saving significant quantities of fossil fuels

Table 8.12 Maximum quantities of pollutants, annually avoided. Central integration of the solar systems at the level of the district heating source. Working scenarios DH_1–DH_4

District heating scenario	Fossil fuel	α_a	Maximum annual fossil fuel economy		Maximum pollutant emission, annually avoided			
					SOx	CO	NOx	PM
–	–	[%]	value	u.m.	[kgx10^3]			
DH_1	BR–Oil fuel/lignite	–	–	m^3/year	–	–	–	–
	AR–Oil fuel/lignite	–	8,224.6	m^3/year	16.4	2.1	4.1	0.8
DH_2	BR–Natural gas	10.0	364,689.0	Nm^3/year	12.8	36.5	127.6	–
	AR–Natural gas	17.4	492,178.5	Nm^3/year	17.2	49.2	172.3	–
DH_3	BR–Natural gas	29.0	1,230,503.7	Nm^3/year	43.1	123.1	430.7	–
	AR–Natural gas	46.6	1,520,415.5	Nm^3/year	53.2	152.0	532.1	–
DH_4	BR–Natural gas	50.0	2,807,841.2	Nm^3/year	98.3	280.8	982.7	–



	DH1 - BR	DH2 - AR	DH2 - BR	DH3 - AR	DH3 - BR	DH4 - BR
▨ CO, (kg·10³)	2.1	36.5	49.2	123.1	152.0	280.8
■ SOx, (kg·10³)	16.4	12.8	17.2	43.1	53.2	98.3
🟪 NOx, (kg·10³)	4.1	127.6	172.3	430.7	532.1	982.7

Fig. 8.10 Maximum emissions of pollutants, annually avoided, within working scenarios DH_1–DH_4

- Reducing CO_2 emissions related to the heating systems
- Depollution and decarbonization of crowded urban areas
- Allowing the implication in energy generation process of the final users, by the “feed-in energy” principle
- Increasing the degree of energy security and flexibility of primary energy flows at the level of the district heating system.

Key Terms and Definitions

Carbon Footprint

The carbon footprint represents the total amount of greenhouse gases emissions, measured in tonnes of equivalent carbon dioxide, CO_{2e}, related to a process, activity, system, etc. When calculating the carbon footprint of an energy system, all emissions—the emissions generated directly and indirectly, as a result of the processes within the system, will be taken into account.

CO_2 Equivalent Emission

The total amount of a CO_2 gas having the same global warming potential as the amount of the converted greenhouse gas.

Energy Footprint

The energy footprint of a heating system represents the result of the energy balance of the heating system, taking into account all input energies as well as output energies related to the balance outline of the respective heating system.

Thermoenergetic Hub

A multi-carrier thermo-energy system consisting in a multiple technologies of energy conversion, storage and/or use, equipped with local control systems. It can exist at the level of a single building, of a group of buildings, or at the district level, according to the centralization degree of the heating system. It is characterized by a great flexibility in the supply of thermal energy, because it enables the use of different primary sources, and by integrating the thermal storage, it also enables the use of intermittent renewable energy sources, thus resulting the hybrid thermo-energy hub.

Energy Balance's Outline

Represents the hypothetical outline of an energy system to which are related the incoming and outgoing energies of the energy balance. The outline of an energy balance may coincide with the physical outline of a machine, an equipment, an installation, or a complex assembly as an energy system (an energy hub).

Annual Efficiency of the Hybrid Heating System

Indicator of performance which consists in the ratio between annual heat demand, or annual heat consumption in the case of an existing system, and total amount of primary energy used at the auxiliary thermic source, based on conventional—fossil fuels [27].

Annual Solar Fraction

Indicator of performance which consists in the percentage of annual heat demand, or annual heat consumption, covered through solar energy within a hybrid heating system.

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Chapter 9
Performances of Solar Thermal Collectors in Different Climatic Conditions

Octavian G. Pop, Ancuta M. Magurean, Adrian G. Pocola, Mihaela Ciocan, Anass Zaaoumi, and Mugur C. Balan

Abstract The chapter presents the fundamentals for performance evaluation of different types of solar thermal collectors (STC): flat thermal collectors (FTC), evacuated thermal collectors (ETC) and concentrated thermal collectors (CTC). All the STC can be integrated in the built environment. The chapter presents the mathematical modelling of the solar geometry and of the thermal efficiency of STC. The mathematical model was implemented in Excel and proved its capability to provide accurate results. The performance parameters of the collectors that were evaluated are the thermal efficiency and the specific thermal energy production (W/m^2). The mentioned parameters of performance were evaluated in the different climatic conditions specific to multiple locations worldwide (Europe, USA and Africa), available from the data provided by the typical meteorological year (TMY). The input data of solar radiation and of ambient temperature were considered based on hourly variation. Real technical data and characteristics of each solar collector were made available by independent testing laboratories and by technical leaflets were considered in the investigation.

Keywords Solar geometry · Collector's efficiency · Flat collectors · Evacuated collectors · Parabolic through collectors · Solar radiation

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9.1 Introduction

The Sun represents the main source of energy for the Earth [25]. Without the Sun, the temperature on the planet would be in the vicinity of 0 K like in the rest of the interstellar space, making life on Earth impossible [18].

The diameter of the Sun is $1.39 \cdot 10^9$ m $\approx 1.4 \cdot 10^6$ km and it is situated at about $1.5 \cdot 10^{11}$ m $= 150 \cdot 10^6$ km from Earth [12]. Despite the high dimension of the Sun, due to the huge distance from Earth, it can be considered that the solar beams reaching the surface of the Earth are parallel to each other. The Sun's source of energy is represented by the nuclear fusion reactions taking place in its core, where hydrogen is transformed into helium. The actual masic composition of the Sun is of about 71% hydrogen, 27.1% helium, 0.97% oxygen and other elements in insignificant participations [7]. At the actual rate of about 4.26 millions of tones per second (Machacek 2009, [30], it is estimated that during the next 10 millions of years another 1% of the actual quantity of hydrogen will be converted into helium and the Sun will still continue to live for (4…5) billions of years.

In principle, the energy received from the Sun as radiation, generically called "solar energy", can be converted in different forms of usable energy: heat, cold or electricity.

Figure 9.1 presents the possibilities of conversion of solar energy into useful energies.

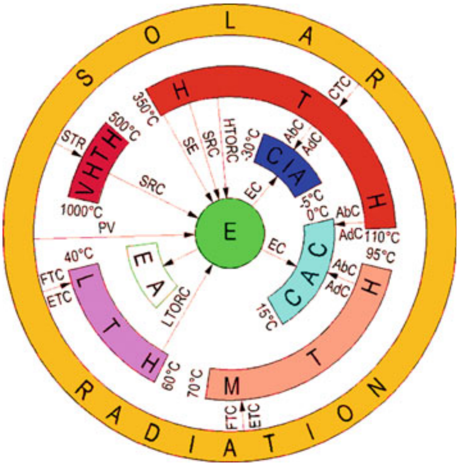


Fig. 9.1 Scheme of possibilities of converting solar energy into usable forms of energy. LTH—Low temperature heat (40–60) °C; MTH—Medium temperature heat (70–95) °C; HTH—High temperature heat (110–350) °C; VHTH—Very high temperature heat (500–1,000) °C; FTC—Flat thermal collectors; ETC—Evacuated thermal collectors; CTC—Concentrated thermal collectors; STR—Solar radiation reflectors; E—Electricity; PV—Photovoltaic collectors; SRC—Steam Rankyne Cycle; LTORC—Low temperature organic Rankine cycle (50–200) °C; HTORC—High temperature organic Rankine cycle (200–300) °C; SE—Stirling Engine; AbC—Absorption refrigerating Cycle; AdC—Adsorption refrigerating Cycle; EC—Electric Cooling; CAC—Cooling for Air Conditioning; CIA—Cooling for Industrial Applications; EA—Electrical Applications.

The solar radiation can be converted directly into heat and electricity. At its turn, the heat can be also converted into cold or electricity.

The conversion of solar radiation into heat can be achieved with solar thermal collectors (STC) that uses a thermal agent to transport the heat. The following types of thermal agents are used: water, antifreeze, diathermic oils, etc.

The direct conversion of solar radiation into electricity can be achieved using the photovoltaic effect.

The conversion of heat into electricity can be realized with the Rankine cycle. If the heat source presents a sufficiently high temperature, over 300 °C, the working agent can be the water /steam and the cycle is named steam Rankine cycle (SRC). If the heat source presents low temperatures (70…300) °C the working agent will be an organic one and the cycle is named organic Rankine cycle (ORC). Depending on the heat source temperature, the ORC cycle can be of low temperature (70…200) °C (LTORC) or of high temperature (200…300) °C (HTORC).

The conversion of heat into cold is carried out through a refrigerating cycle based on the absorption or adsorption.

The information related to the performances of solar thermal collectors is relevant from the energy perspective on the environmental problem because solar energy can contribute to the energy efficiency of several systems and can reduce the energy impact on the environment. From the human impact of buildings point of view, the solar thermal collectors can contribute to improve the visual aspect and architectural integration of buildings into modern residential or business centers.

The goal of the chapter is to present the mathematical modelling basics in order to calculate the position of the Sun, the incidence angle on the STC, the thermal efficiency of the conversion of solar radiation into heat and the specific thermal power. The calculations will be realized for different types of STC: flat, with evacuated tubes and of parabolic through type, situated in different locations in Europe, America and Africa. The calculations will be based on hourly variation of the climatic parameters, available for different location as the typical meteorological year (TMY).

TMY is an hourly based collection of meteorological data, usually including ambient temperature and humidity, components of the solar radiation, etc., for a period of one year, characterizing a given location. TMY is generated from hourly measured data in long periods of time (usually minimum 10–12 years). Each month of the TMY, with all the contained meteorological data, can originate from different years, resulting annual long term averages for the considered location.

9.2 Background

The physical operating principle of the STC is based on the fact that when solar radiation strikes a surface, a part of this radiation is absorbed by that surface increasing its temperature. From this perspective, the STC are a particular case of heat exchangers that transform the solar radiation energy into heat embedded into a transport media (or thermal agent) [24]. The efficiency of the solar energy receiving surface of the STC depends on both absorption efficiency and thermal losses to the environment [19]. Different materials and technologies were developed in order to increase the absorption rate of solar radiation and to decrease the heat losses. Thus different types of STC were developed. The operating thermal regime of these STC ranges from (5…10) °C above the ambient temperature (in unglazed STC) to above 1000 °C (in solar radiation concentrators based STC) [19].

The STC can be classified into non-concentrating solar radiation or stationary and concentrating solar radiation. The non-concentrating STC are operating in a fixed position, while the concentrating STC are equipped with Sun tracking systems [24].

There are three types of fixed non-concentrating STC: flat plate collectors; compound parabolic collectors and evacuated tubes collectors. The useful heat provided by these types of STC can be delivered at temperatures up to 100 (120) °C [12].

The concentrating STC were developed to increase the temperature of the thermal agent. This target can be reached by concentrating a large amount of solar radiation on relative small receiving surface [24]. The most common concentrating STC are: parabolic through collectors (up to 400 °C); linear (Fresnel) concentrators (up to 400 °C); parabolic dish (up to 1500 °C) and heliostat field collectors with central receiver, also named solar (or power) towers (up to 2000 °C).

Another classification criterion is based on the nature of heat transfer fluid: air, water, antifreeze, oil, molten salts, etc.

Detailed description of several types of solar collectors is provided in [13] while innovative technical solutions can contribute to the improvement of STC efficiency [8].

The problem of STC integration in built environment presents a high importance and was successfully approached in [22, 42, 44, 45] while an extensive study related to the environmental aspects together with payback analysis and evaluation of recycling is presented in [26].

Numerical models for different types of STC are presented in [12, 19, 24, 38, 47].

9.3 Fundamentals of Solar Radiation

The solar radiation available at the superior limit of the Earth's atmosphere (IS [W/m^2]), also designated as the solar constant, can be determined with the relation:

$$\mathrm{I_S} = \frac{\mathrm{P_S}}{\mathrm{S_S}} = \frac{\mathrm{P_S}}{4 \cdot \pi \cdot \mathrm{D}^2} \tag{9.1}$$

where:

- $\mathrm{P_S}$ [W] is the power emitted by the Sun;

- S_S [m^2] is the surface of the sphere with the center in the Sun, on which the energy emitted by the Sun is distributed (tangent to the superior limit of the Earth's atmosphere);
- D = 149,597,871 km = $1.496{\cdot}10^8$ km = $1.496{\cdot}10^{11}$ m is the distance between the Sun and the Earth, equivalent with the radius of the same sphere [12].

The power emitted by the Sun can be calculated with the relation obtained from the equation of Einstein, divided by the time (τ [s]) [29]:

$$P_S = \frac{E}{\tau} = \frac{m \cdot c^2}{\tau} = \dot{m} \cdot c^2 \tag{9.2}$$

where:

- E [J] is the energy emitted by the Sun;
- m [kg] is the mass lost in the fission reactions inside the Sun;
- c [m/s] is the speed of light;
- $\dot{m}$ = 4.26 million t/s = 4.26·109 kg/s is the mass flow lost in the fission reactions inside the Sun [28, 30].

The actual accepted value of the solar constant is $I_S = 1367$ W/m^2. Different values of the solar constant, accepted in the literature are presented in [29].

The variation of the instantaneous solar radiation available at the superior limit of the Earth's atmosphere (I_i [W/m^2]), determined by the variable distance between the Sun and the Earth, can be determined with the relation [12]:

$$I_i = I_S \cdot \left(1 + 0.033 \cdot \cos\frac{360 \cdot n}{365}\right) \tag{9.3}$$

where n is the number of the day in the year.

The solar radiation reaching the Earth's surface is lower than the solar constant, because while crossing the atmosphere with a thickness of about 50 km, even in clear sky condition, the solar radiation is gradually reduced mainly by absorption and diffusion (scattering).

Due to the interaction between the solar radiation and the atmosphere, the following components of the solar radiation can be defined:

- The direct (or beam) solar radiation normal to the horizontal surface (I_{dir} [W/m^2]) is the solar radiation that reaches the Earth's surface without being affected (absorbed or diffused) by the atmosphere.
- The diffuse solar radiation on the horizontal surface of the Earth (I_{dif} [W/m^2]) is the solar radiation that reaches the Earth's surface after its direction was modified by diffusion (scattering).
- The global (or total) solar radiation on the horizontal surface of the Earth (I_{gh} [W/m^2]) is the sum of the direct and the diffuse solar radiation.

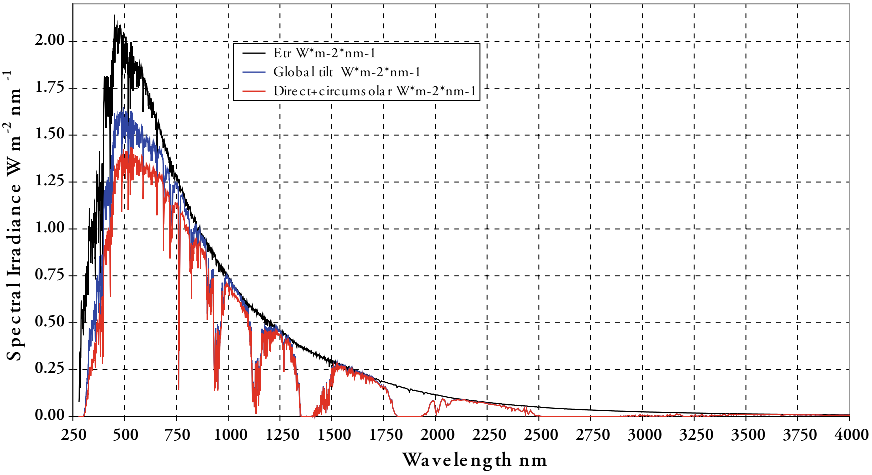


Fig. 9.2 The specter of the solar radiation

- The ground reflected solar radiation (I_{gr} [W/m^2]) is the solar radiation reflected by the Earth's surface.

Figure 9.2 presents the specter of the solar radiation, according to the American Society for Testing and Materials (ASTM) at the web address: https://rredc.nrel.gov/solar/spectra/am1.5.

The significance of the curves, indicated by the notations from the legend is as follows:

- ETR: Extraterrestrial Radiation—solar spectrum at top of the atmosphere—at mean Earth-Sun distance (the black curve);
- Global Tilt: Spectral radiation from solar disk plus sky diffuse and diffuse reflected from ground on the south facing surface tilted 37 degrees from the horizontal plane (the blue curve);
- Direct + circumsolar: Direct = Direct Normal Irradiance Nearly parallel (0.5 degree divergent cone) radiation on surface with surface normal tracking (pointing to) the sun, excluding scattered sky and reflected ground radiation; Circumsolar = Spectral irradiance within ± 2.5 degree (5 degree diameter) field of view centered on the 0.5 degree diameter solar disk, but excluding the radiation from the disk (the red curve).

The emissive spectral power (E_λ [$W/(m^2 \cdot \mu m)$] or [$W/(m^2 \cdot nm)$]) also designated as the intensity of the radiation emitted on each wavelength by an absolute black body, can be calculated by the relation [21, 36]:

$$E_\lambda = \frac{C_1}{\lambda^5 \cdot \exp\left(\frac{C_2}{\lambda T} - 1\right)} \tag{9.4}$$

where:

- $C_1 = 2\pi hc^2 = 3.742 \cdot 10^8$ $(W \cdot \mu m^4)/m^2$ is the first constant of radiation;
- $C_2 = hc/k = 1.439 \cdot 10^4$ $\mu m \cdot K$ is the second constant of radiation;
- λ [μm] or [nm] is the wavelength;
- $h = 6.626 \cdot 10^{-34}$ J·s is the Plank constant;
- $k = 1.381 \cdot 10^{-23}$ J/K is the Boltzmann constant;
- $c = 2.998 \cdot 10^8$ m/s light speed in void;
- T [K] is the black body surface temperature.

Two significant temperatures of the Sun behaving as a black body can be considered [12]:

- T = 5777 K = 5504 °C is the surface temperature of a black body that emits the same amount of energy as the Sun;
- T = 6300 K = 6027 °C is the surface temperature of a black body that emits a radiation specter having the same wavelength corresponding to the maximum radiation intensity as the solar radiation.

Figure 9.3 presents both the specter of the solar radiation and the emissive spectral power curves corresponding to the two considered surface temperatures of a black body.

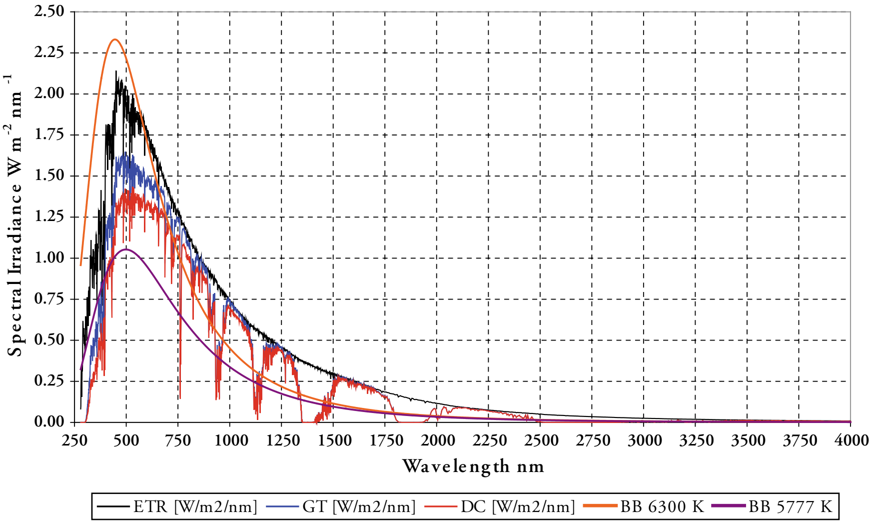


Fig. 9.3 Specter of the solar radiation and the emissive spectral power curves corresponding to the surface temperatures of a black body. ETR: extraterrestrial radiation; GT: global tilt radiation; DC: direct + circumsolar radiation; BB 6300 K: black body at 6300 K radiation; BB 5777 K: black body at 5777 K radiation

It can be observed that none of the two black body emissive spectral power curves fit perfectly with the specter of the solar radiation, but the curve corresponding to the value of 6300 K is closer than the one corresponding to the temperature of 5777 K.

9.4 Elements of “Solar Geometry”

One of the problems raised by the use of solar energy is that it presents significant diurnal and seasonal variations, due to the position of the Sun relative to the area on the surface of the Earth, where solar energy is to be used.

The position of the Sun in the sky can be calculated with the help of an algorithm presented in [12, 38, 47], or in different studies carried out at the Technical University of Cluj-Napoca [1, 5, 6, 35, 41, 42].

The position of the Sun in the sky evidently depends on the location of the observer, and this is defined by the geographical coordinates: latitude (parallel) (φ) and longitude (meridian) (λ).

The other parameters of the mathematical model are presented below.

The day angle (y) is calculated as:

$$\mathrm{y} = 360^\circ \frac{\mathrm{n}}{365}\ [^\circ] \tag{9.5}$$

where n is the day number of the year.

The declination angle of the Sun (δ) (or simply the declination) is the angle between the Sun rays and the equatorial plane. This angle depends on the day angle (y).

There are several approximations of the declination, available in the literature, of smaller or greater precision. In this study the equation provided in [38, 47] is used:

$$\begin{aligned}\delta(\mathrm{y}) = 0.3948 - 23.25559 \cdot \cos(\mathrm{y} + 9.1^\circ) - 0.3915 \cdot \cos(2\mathrm{y} + 5.4^\circ) - \\ - 0.1764 \cdot \cos(3\mathrm{y} + 105.2^\circ)\end{aligned} \tag{9.6}$$

The declination has the same numerical value as the latitude at which the Sun is directly overhead at solar noon on a given day. The extreme latitudes where the Sun reaches the overhead position at least once in a year are the tropics of Cancer (23.45°N) and Capricorn (23.45°S) [19].

Declinations in northern hemisphere (during summer) are positive, and declinations in southern hemisphere are negative [24].

Details about the declination angles are presented in [12, 19, 24, 38, 47].

The maximum value of the declination angle is $\pm\ 23^\circ 27'$ corresponding to the summer solstice ($\delta = +\ 23^\circ 27'$) and the winter solstice ($\delta = -23^\circ 27'$), respectively, in the Northern hemisphere.

The minimum value of the declination angle is 0° corresponding to the equinoxes.

In order to verify the implementation of the presented equation, the calculated values were compared with the mean real values, corresponding to a four year cycle, available on the internet at:

https://www.wsanford.com/~wsanford/exo/sundials/DEC_Sun.html (28.01.2016).

The comparative results are presented in Table 9.1.

It can be observed that the differences between the calculated values and the real values are lower than $20' = 0.3°$.

The highlighted values (bold) correspond to the equinoxes ($\delta = 0°$; 20–21.03 and 22–23.09) and the solstices, respectively.

The equation of time (EQT) [min] is the difference between the apparent solar time (also designated as the solar time, based on the apparent angular motion of the sun across the sky—which can be followed on a sundial) and the local time. The EQT variation throughout the year can be calculated using the following relation [38, 47]:

$$\begin{aligned}\mathrm{EQT}y) = {} & 0.0066 - 7.3525 \cdot \cos(\mathrm{y} + 85.9°) + 9.9359 \cdot \cos(2\mathrm{y} + 108.9°) + \\ & + 0.3387 \cdot \cos(3\mathrm{y} + 105.2°)\end{aligned} \tag{9.7}$$

The difference between the solar time and the local time presents a maximum variation of approximatively ± 15 min.

The Mean local time MLT [min] depends on the local time (LT), on the time zone (TZ) and on the longitude (λ).

$$\mathrm{MLT} = \mathrm{LT} - \mathrm{TZ} + \lambda \cdot 4\mathrm{min}/° \;[\mathrm{min}] \tag{9.8}$$

The last term of the equation is added due to the fact that the motion of the Sun in the sky is at an angle of 4°/min.

The Solar time ST [h] is calculated as follows:

$$\mathrm{ST} = \frac{\mathrm{MLT} + \mathrm{EQT}}{60} \;[\mathrm{h}] \tag{9.9}$$

The hour angle of the Sun (ω) [°] is the angle between the direction of the Sun and the plane defined by the Earth's axis and direction of the zenith.

$$\omega = (12 - \mathrm{ST}) \cdot 15°/\mathrm{h} \tag{9.10}$$

The angle of the solar altitude γ_S [°] and *the angle of solar azimuth* α_S [°], are the polar and angular coordinates, that define the position of the Sun in the sky relative to a reference point (observer) on the surface of the Earth.

The two angles are presented in Fig. 9.4.

The two angles are calculated as follows:

$$\gamma_S = \arcsin(\cos(\omega) \cdot \cos(\omega) \cdot \cos(\delta) + \sin(\phi) \cdot \sin(\delta)) \tag{9.11}$$

Table 9.1 Real and calculated values of the declination angle

Day	2008.01	2008.02	2008.03	2008.04	2008.05	2007.08	2007.09	2007.10	2007.11	2007.12
21	−20°05′	−10°52′	**0°00′**	+11°39′	+20°04′	+12°19′	+0°57′	−10°29′	−19°47′	**−23°26′**
22	−19°52′	−10°30′	+ 0°24′	+12°00′	+20°16′	+11°59′	+0°33′	−10°50′	−20°00′	**−23°26′**
23	−19°38′	−10°08′	+ 0°47′	+12°20′	+20°28′	+11°39′	**+0°10′**	−11°12′	−20°13′	**−23°26′**
↑ Real values ↑										
↓ Calculated values ↓										
21	−19°53′	−10°59′	**0°06′**	+11°59′	+20°21′	+12°27′	+1°09′	−10°35′	−19°57′	**−23°17′**
22	−19°41′	−10°38′	+0°30′	+12°20′	+20°32′	+12°08′	+0°45′	−10°57′	−20°10′	**−23°17′**
23	−19°28′	−10°17′	+0°54′	+12°40′	+20°44′	+11°48′	**+0°21′**	−11°19′	−20°23′	**−23°16′**

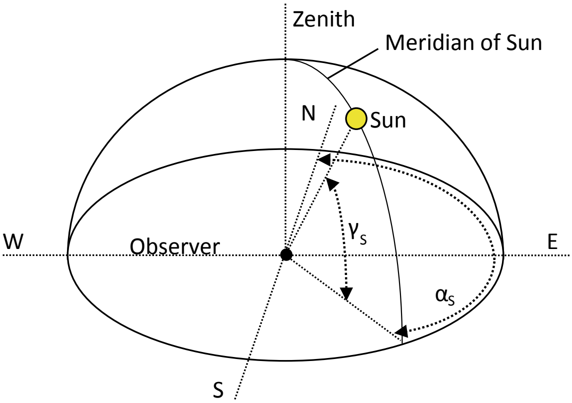


Fig. 9.4 The angle of the solar altitude γ_S and the angle of solar azimuth α_S

$$\alpha_S = 180° \pm \arccos\frac{\sin(\gamma_S)\cdot\sin(\phi) - \sin(\delta)}{\cos(\gamma_S)\cdot\cos(\phi)} \tag{9.12}$$

$\pm$ = " + " if ST > 12:00 and "-" if ST < 12:00

With the help of the two angles (polar coordinates), diagrams indicating the position of the Sun in the sky can be drawn.

For solar energy applications, the calculation of "solar geometry" relative to a tilted surface, which represents the characteristic surfaces for solar collectors, is of interest regardless of the type and orientation towards the horizontal plane and towards the direction of the geographic south.

The geometrical elements required for these types of calculations are presented in Fig. 9.5.

The tilt angle γ_t [°]. For this angle, the value of 0° means that the surface is horizontal, and the value of 90° means that the surface is vertical.

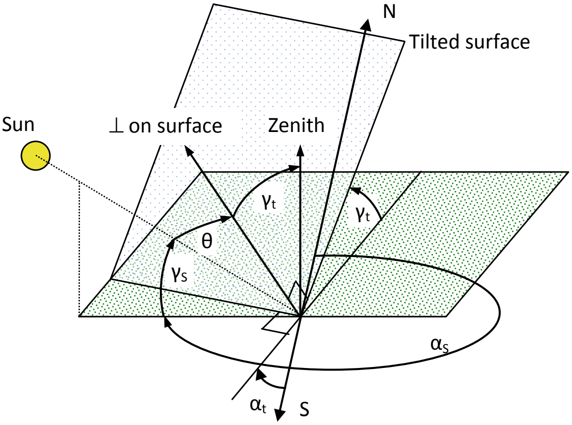


Fig. 9.5 Elements of "solar geometry" relative to a tilted surface

The Orientation angle towards the azimuth (towards the South) (azimuth angle of the tilted surface) α_t [°].

This angle is measured from South to West, North, East. For this angle some significant values are as follows: 0° means that the surface is oriented towards south, 90° means that the surface is oriented towards west, 180° means that the surface is oriented towards north, and 270° means that the surface is oriented towards east.

The Solar angle of incidence on a tilted surface (θ) [°], is the angle between the direction of the solar rays and the normal to the tilted surface. The direction of the solar rays depends on the two angles that define the position of the Sun in the sky (γ_S and α_S) and the direction normal to the tilted surface depends on the two angles that define the position of the tilted surface (γ_t and α_t). Thus, θ depends on all four angles mentioned above (γ_S, α_S, γ_t, α_t).

$$\theta = \mathrm{ar}\cos(-\cos(\gamma_S) \cdot \sin(\gamma_t) \cdot \cos(\alpha_S - \alpha_t) + \sin(\gamma_S) \cdot \cos(\gamma_t)) \tag{9.13}$$

The global solar radiation on a tilted surface (I_{gt} [W/m^2]) has generally three components:

$$I_{gt} = I_{dirt} + I_{dift} + I_{grt} \tag{9.14}$$

where:

- I_{dirt} [W/m^2] is the direct solar radiation, normal to the tilted surface;
- I_{dift} [W/m^2] is the diffuse solar radiation, normal to the tilted surface;
- I_{grt} [W/m^2] is the solar radiation reflected by the ground, normal to the tilted surface.

The direct radiation normal to the tilted surface (I_{dirt}) [W/m^2] is determined as follows:

$$I_{dirt} = I_{dir} \cdot \cos\theta / \sin\gamma_S \tag{9.15}$$

where I_{dir} [W/m^2] is the direct solar radiation, normal to the horizontal surface.

The diffuse solar radiation normal to a tilted surface (I_{dift}) [W/m^2] can be determined based on two hypotheses:

- considering that the diffuse solar radiation is uniform (I_{difti}) (the hypothesis of isotropic diffuse solar radiation):

$$I_{difti} = I_{dif} \cdot 1/2 \cdot (1 + \cos\gamma_t) \tag{9.16}$$

- where I_{dif} [W/m^2] is the diffuse solar radiation, normal to the horizontal plane.
- or.
- considering that the diffuse solar radiation is non-uniform (I_{difta}) (the hypothesis of non-isotropic diffuse solar radiation) [38, 47]:

$$I_{difta} = I_{difi} \cdot (1 + F + \sin^3(\gamma_t/2)) \cdot (1 + F + \cos^2\theta \cdot \cos^3\gamma_S) \tag{9.17}$$

where F is a correction factor that can be determined as follows:

$$F = 1 - (I_{dir} / I_{gh})^2 \tag{9.18}$$

where I_{gh} [W/m^2] is the global solar radiation on a horizontal surface.

The solar radiation reflected by the ground normal the tilted surface (I_{grt}) [W/m^2] is determined as follows:

$$I_{grt} = I_{gh} \cdot A \cdot (1 - \cos\gamma_t) \tag{9.19}$$

where A is the albedo, that defines the measure of reflected solar radiation from the horizontal surface on the tilted surface.

The albedo depends on the material of the horizontal surface. The value of the albedo can vary in the range of (0…1). For unknown material, it can be considered that $A = 0.2$ [38, 47]. The influence of solar radiation reflected by the ground is low. Thus, in the case of $A = 0.2$ and for a surface tilted at 45° southern orientation, the value of $I_{grt} = 0.06 \cdot I_{gh}$ is obtained (the solar radiation reflected by the ground represents 6% from the global solar radiation on the horizontal surface).

Observation: *The presented algorithm produces unrealistic results for calculated values of diffuse and direct solar radiation normal to the tilted surface, for very low values of the angle of solar altitude (γ_S). The limit of the mathematical model is known and mentioned in the literature:* [12, 38, 47]. *In order to eliminate false unwanted values, the algorithm was only used for angles of the solar altitude that satisfy the condition ($\gamma_S > 10°$).*

9.5 The Efficiency of Thermal Solar Collectors

9.5.1 The Efficiency of Thermal Solar Collectors Without Solar Concentrators

The efficiency of the solar collectors (η [−]), is the conversion efficiency of solar radiation into heat:

$$\eta = \frac{q_u}{I_{gt}} \tag{9.20}$$

where:

- q_u [W/m^2] is the useful heat flux density per unit surface area, stored in the heat transfer fluid from the collectors;
- I_{gt} [W/m^2] is the global solar radiation, normal to tilted plane of the collector.

A simplified method of calculating the efficiency of solar collectors uses the following formula:

$$\eta = \frac{q_u}{I_{gt}} = \frac{q_0 - q_p}{I_{gt}} = \frac{q_0}{I_{gt}} - \frac{q_p}{I_g t} \tag{9.21}$$

where:

- q_0 [W/m^2] is the heat flux density per unit surface area produced by the absorption area, or the fraction from the heat flux density per unit surface area of the global solar radiation, that reaches the absorption surface and is effectively converted into heat transferred to the heat transfer fluid of the solar collector;
- q_p [W/m^2] is the heat flux density lost from the heat transfer fluid to the environment.

The ratio between q_0 and I_{gt}, represents an important characteristic parameter of the solar collectors, called optical efficiency and noted with η_0:

$$\eta_0 = \frac{q_0}{I_{gt}} \tag{9.22}$$

Using this notation, the efficiency of solar collectors can be calculated with the following formula:

$$\eta = \eta_0 - \frac{q_p}{I_{gt}} \tag{9.23}$$

The heat flux density q_0 produced by the solar collector depends on both the glass properties of the solar collector and on the properties of the materials from which the absorption surface is manufactured. The optical efficiency can be determined based on the properties of the materials used to manufacture the STC, using the formula:

$$\eta_0 = \tau \cdot \alpha \tag{9.24}$$

where:

- τ is the transmission coefficient of the transparent material (usually glass), that covers and insulates the collector assuring also the mechanical resistance of the collector, having the values presented in Table 9.2 for some common materials;
- α is the absorption coefficient of the absorption material.

Table 9.2 The values of the transmission coefficient for different materials

Material	Thickness [mm]	Transmission coefficient τ	
		Direct radiation	Diffuse radiation
Glass with iron	4	0,81	0,74
Solar glass (low in iron)	4	0,87	0,8
Double polycarbonate sheets	8…16	0,77	0,83

Table 9.3 The absorption coefficient for different materials

Material	Absorptance (α) Emissivity (ε)	
	Visible	Infrared
Black enamel for metals	0.9	0.9
Non-selective absorbent	0.97	0.97
Black chrome	0.87	0.09
Black nickel	0.88	0.07
Copper without oxygen	0.95	0.04
Selective absorbent TiNOX	0.95	0.05

The absorption process of solar radiation on the absorption surface of the collectors is characterized by the absorption coefficient of the material. Thus, the black enamel for metals has an absorption coefficient of $\alpha = 0.9$, that means that 90% of the solar radiation that reaches this material is converted into heat. Commonly, the absorption materials used in the manufacturing of solar collectors assure values of the absorption coefficient within the range of $\alpha = 0.85\ldots0.98$, as can be observed from the Table 9.3.

Observation*: The glass used for the construction of the solar collectors, aside from the high values of the transfer coefficient, due to the composition low in iron, is also characterized by a high mechanical resistance. Thus, numerous manufacturers test the mechanical resistance with the help of iron spheres with the diameter of about 1 inch (1 inch ≈ 2,54 cm). These spheres are dropped on the solar collectors, during the tests, from the height of approximately 1 m. Considering that the majority of collectors can withstand such a test concerning the mechanical resistance, there is great probability that the collectors can operate in both the most favorable and the most harsh conditions that can occur during use, such as hail with large pieces of ice. However, the manufacturers recommend that the costumers sign insurance policies that fully cover the cost of the solar collectors.*

Returning to the calculation of the efficiency of solar collectors, the heat flux density loss to the environment q_p, can be determined with the following type of formula:

$$\mathrm{q_p} = \mathrm{k} \cdot \Delta t \tag{9.25}$$

where:

- k [W/m^{2}K] is the overall heat transfer coefficient between the collector and the environment. The most common values of the overall heat transfer coefficient are in the range of 2…4 W/m^{2}K;
- Δt [K] is the temperature difference between the mean temperature of the collector (that can also be considered the mean temperature of the heat transfer fluid) and the temperature of the environment.

By substituting $\mathrm{q_p}$ in the formula presented previously for the calculation of the collector efficiency, the following formula is obtained:

$$\eta = \eta_0 - \frac{\mathrm{k} \cdot \Delta t}{\mathrm{I_{gt}}} = \eta_0 - \mathrm{k}\frac{\Delta t}{\mathrm{I_{gt}}} \tag{9.26}$$

Considering that the material from which the solar collectors are manufactured is solar glass, with the mean value of the transmission factor of $\tau = 0.84$, which is between the values of 0.87 corresponding to direct solar radiation and 0.80 corresponding to diffuse solar radiation (according to Table 9.2) and considering that the absorption material is of the best quality, having an absorption coefficient of $\alpha = 0.98$, the obtained value of the optical efficiency is $\eta_0 = \tau \cdot \alpha = 0.84 \cdot 0.98 = 0.82$. Considering a mean value for the overall heat transfer coefficient k = 3 W/m^{2}K, with the help of the formula (9.26), the variation of the efficiency of the solar collectors can be determined through calculation, as a function of the temperature difference Δt for different values of the global solar radiation on the tilted plan of the STC ($\mathrm{I_{gt}}$).

The presented simplified method of calculating the efficiency of the STC is useful only to highlight the physical principle of calculation, meaning that only a part of the incident solar radiation on the STC, is effectively transformed into useful heat.

A corrected method of calculating the efficiency of solar collectors, recommended by numerous studies in the field, can be applied for both flat solar collectors and for more efficient solar collectors (for example collectors with evacuated tubes or thermal tubes). The corrected formula is:

$$\eta = \eta_0 - \mathrm{k}_1\frac{\Delta t}{\mathrm{I_{gt}}} - \mathrm{k}_2\frac{\Delta t^2}{\mathrm{I_{gt}}} \tag{9.27}$$

where:

- η_0 is the optical efficiency that takes into account the efficiency at which the solar radiation energy is absorbed;
- k_1 [W/m^{2}K] and k_2 [W/m^{2}K^2] are correction factors that take into account thermal losses;

- Δt [K] is the difference between the mean temperature of the heat transfer fluid of the collector and the temperature of the environment;

The corrected calculation method is capable to accurately evaluate the STC efficiency, which is depending on the same Δt and I_{gt}, but the dependence on Δt is of second grade order.

By analyzing the Eq. (9.27) it became obvious that the higher the global solar radiation on the tilted plane of the STC, the higher the efficiency of the STC.

The thermal losses depend on the construction of the solar collector and occur due to the temperature difference between the heat transfer fluid heated by solar radiation and the environment.

Table 9.4 presents the values of the optical efficiency and the values of the correction coefficients k_1 and k_2 for some types of solar collectors. Analyzing the values from this table, it can be observed that although the flat collectors have the highest values of the optical efficiency, they also have the highest values for thermal losses.

Observation: *Such data is available on the websites of independent testing laboratories or in the technical literature. Such a laboratory is Solartechnik Prüfung Forschung of Swiss* (https://www.spftesting.info/collectors).

Observation: *It should be mentioned that if comparisons are carried out between the performance of solar collectors with evacuated tubes and solar collectors with thermal tubes, it would be difficult to evaluate which of these collectors are more*

Table 9.4 Typical values of the optical efficiency and of the correction factors for different types of collectors

The type of collector	Collectors model	η_0 [%]	Correction coefficients	
			k_1 [$Wm^{-2} K^{-1}$]	k_2 [$Wm^{-2} K^{-2}$]
Uncovered	Energie Solaire	94.8	12.28	0.0235
Flat	Winkler VarioSol A-antireflex	82.5	3.13	0.0152
Flat	Rehau Solect Fassadenkollektor	78.5	3.66	0.0070
Flat	Arge Integral Holz	77.7	4.36	0.0101
Evacuated	Riomay Ecotube	79.4	1.02	0.0032
Evacuated	Enertech EnerSol HP	73.9	1.08	0.0056
Evacuated	Spring Solar SK-8 CPC	62.0	0.94	0.0070
Evacuated	Thermomax Mazdon 20	76.0	1.09	0.0061
Evacuated	Dallinger Sonnenpower 22	61.7	1.34	0.0101
Evacuated	Kilimeko KS 1800/58–18	53.3	1.30	0.0125

efficient. Therefore, for some manufacturers the evacuated tubes solar collectors are more efficient than those with thermal tubes, or those with thermal tubes available at other manufacturers and vice-versa. The differences between the performances of these types of collectors are relatively low. Consequently, the two types of collectors can simply be named: collectors with evacuated tubes, since collectors with thermal tubes are also equipped with evacuated tubes in which the thermal tubes are mounted.

Figure 9.6 presents examples of different types of fixed STC (without solar tracking systems).

If the efficiency of solar collectors is calculated using the corrected formula, the variation of this parameter can be represented graphically as a function of the temperature difference Δt and as a function of the global solar radiation intensity I_g, as presented in Fig. 9.7 for a flat STC (Winkler VarioSol A- antireflexive) and for an evacuated tubes STC (Riomay Ecotube) considering $I_{gt} = 750\ \mathrm{W/m^2}$.

Such curves describing the variation of the thermal efficiency of solar collectors are presented in the data sheets of manufacturers or of independent testing laboratories.

a. Unglazed STC b. Flat STC c. Evacuated tubes STC

Fig. 9.6 Different types of fixed STC

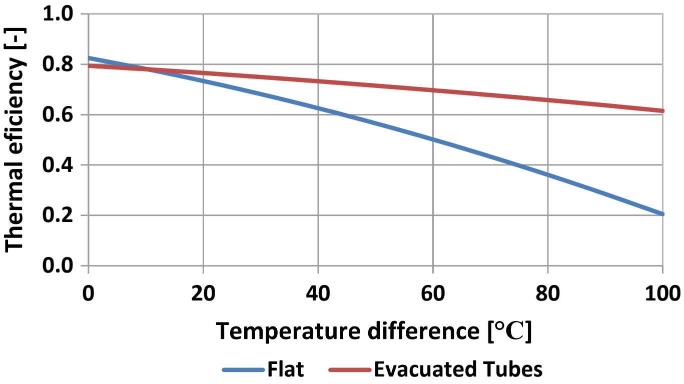


Fig. 9.7 The influence of the temperature difference on the thermal efficiency for $I_{gt} = 750\ \mathrm{W/m^2}$

The uncorrected formula leads to high calculation errors especially for collectors with evacuated tubes and with thermal tubes for high temperature differences. For this reason, only the corrected formula shall be used from here on for the determination of the thermal efficiency of thermal solar collectors.

This statement is also justified by the fact that the curvature of the variations determined using the corrected formula is in agreement with the curvature of the experimentally determined variations.

In unsteady working conditions, both the intensity of solar radiation, as well as the temperature differences vary permanently. Diurnal, monthly, seasonal and even yearly variations can be mentioned. Therefore, the values of the thermal efficiency can only be used to compare the performance of STC with each other, but they cannot be used to describe the behavior of the solar collectors in unsteady working conditions.

In order to analyze the unsteady working conditions, it must be mentioned that the value of the solar radiation intensity, that is taken into account in the corrected formula, represents the value normal to the plane of the solar collector and the angle between the normal to the plane of the solar collector and the direction of the Sun varies continuously. The tilt and orientation angle of the solar collector relative to the southern direction are also variable and represent important parameters for this type of analysis.

9.5.2 The Efficiency of Thermal Solar Collectors with Solar Concentrators

For the collectors with concentrators the efficiency depends on the position of the angle of incidence of the solar rays relative to the normal to the plane formed by the sides of the parabolic concentrator. This type of collector is characterized by two angles a transversal angle of incidence (α_T) and a longitudinal angle of incidence (α_L).

For these types of STC, the direct beam solar radiation, or direct normal irradiance (DNI) is to be considered in all the calculations.

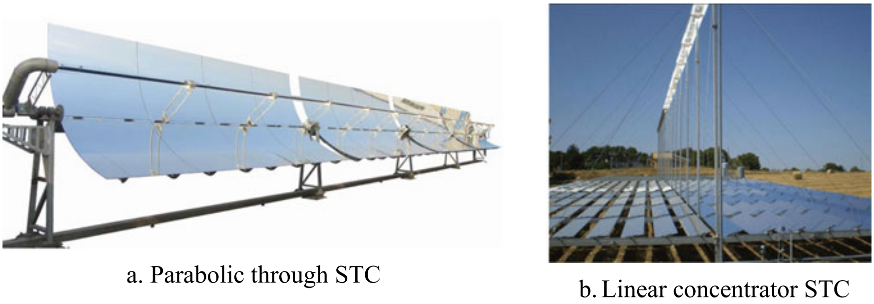
Figure 9.8 presents examples of STC with parabolic through concentrator and of linear concentrators type.

These types of STC are characterized by the presence of a solar tracking system capable to maintain the concentrated radiation on the linear absorbers in which the thermal agent flows.

For the collectors with parabolic concentrators the two angles of incidence are represented in Fig. 9.9.

Usually, due to the use of tracking systems, for the collectors with parabolic concentrators the transversal angle of incidence is 0.

The longitudinal angle of incidence presents seasonal variations and depends on the altitude of the Sun in the sky.



a. Parabolic through STC

b. Linear concentrator STC

Fig. 9.8 STC with concentrators

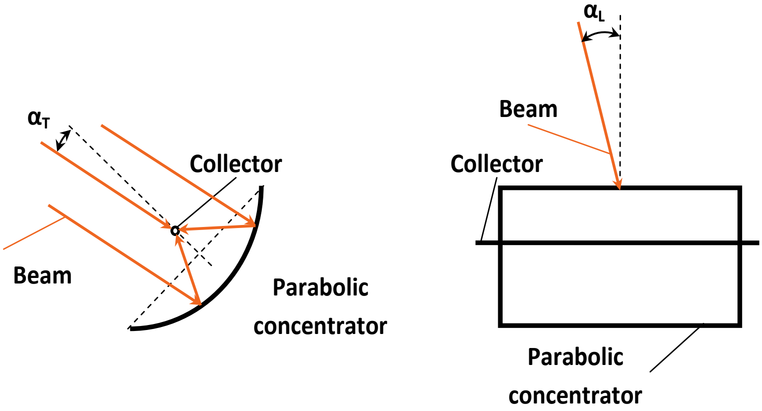


Fig. 9.9 The transversal angle of incidence (α_T) and the longitudinal angle of incidence (α_L) for parabolic collectors

For the collectors with linear concentrators the two angles of incidence are represented in Fig. 9.10.

For the calculation of the efficiency of the collectors with concentrators the following formula can be used:

$$\eta = \mathrm{k_T} \cdot \mathrm{IAM} \cdot \eta_0 - \mathrm{k_1}\frac{\Delta t}{\mathrm{DNI}} - \mathrm{k_2}\frac{\Delta t^2}{\mathrm{DNI}} \tag{9.28}$$

where:

- η_0 is the optical efficiency, that takes into account the efficiency at which the solar radiation energy is absorbed;
- $\mathrm{k_T}$ is the correction coefficient, due to the transversal angle of incidence (α_T); ($\mathrm{k_T} = 1$)

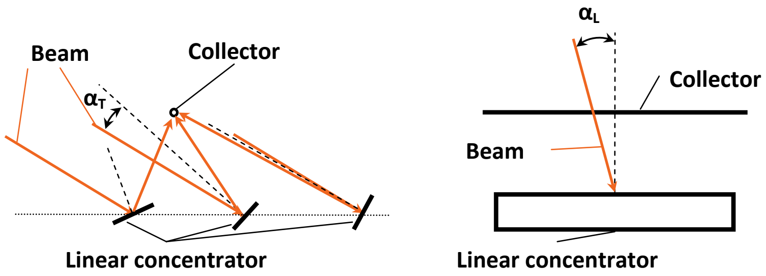


Fig. 9.10 The transversal angle of incidence (α_T) and the longitudinal angle of incidence (α_L) for linear collectors

- IAM is the correction coefficient due to the longitudinal angle of incidence (α_L), also named incident angle modifier;
- k_1 [W/m^{2}K] and k_2 [W/m^{2}K^2] are the correction coefficients that take into account thermal losses;
- Δt [K] is the temperature difference between the mean temperature of the heat transfer fluid of the collector and the temperature of the exterior environment;
- DNI [W/m^2] is the direct beam solar radiation, or direct normal irradiance.

Since for collectors with parabolic concentrators, the transversal angle of incidence is 0, the coefficient of correction (k_T) is 1.

9.5.3 Incidence Angle at Collectors with Parabolic Concentrators

One of the most important problems that must be solved for the mathematical modelling of the collectors with parabolic concentrators is the determination of the incidence angle, respectively the angle between the direction of the solar beam and the normal direction to the collectors' plane, for the case in which these collectors are equipped with tracking systems.

Figures 9.11, 9.12 and 9.13 present the characteristic angles of the collectors with parabolic concentrators, in an isometric view, in a lateral view and in a top view, respectively.

The position of the Sun is defined by the two angles: the angle of the solar altitude (γ_S) and the angle of solar azimuth (α_S).

The orientation of the parabolic collector was considered towards the North–South direction, which ensures the harvesting of a higher amount of energy than the orientation towards the East–West direction [9, 10, 20, 23, 32]. For this reason there are very few applications with the collectors oriented on the East–West direction.

The projection of the angle of the solar altitude on the transversal plane of the collector was noted with γ_{st}. The collector must always be tilted in such a way that γ_{st}

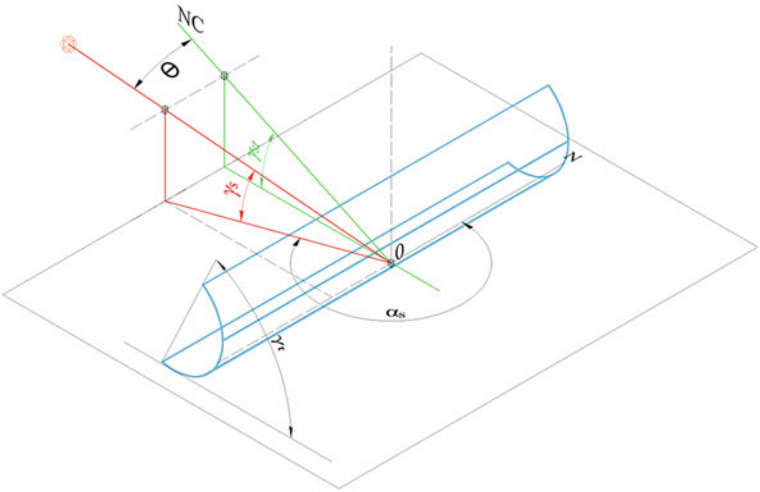
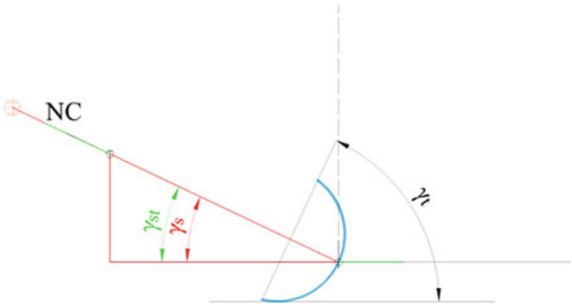


Fig. 9.11 Representation of characteristic angles for parabolic collectors in isometric view. N—North direction; NC—Normal to the collector direction

Fig. 9.12 Representation of characteristic angles for parabolic collectors in lateral view



$= \gamma_S$ because the projection of the solar beam on the transversal plane must always normal to the plane of the collector.

Under these circumstances the tilt angle of the collector (γ_t) can be calculated as:

$$\gamma_t = 90^\circ - \gamma_{st} \tag{9.29}$$

The projection of the solar altitude angle on the transversal plane of the collector (γ_{st}) can be calculated as a function of γ_S and α_S with the relations:

$$\gamma_{st} = \text{arctg}\frac{\text{tg}(\gamma_s)}{\cos(90^\circ - \alpha_S)} \quad \text{for } \alpha_S < 180^\circ \text{ and orientation East } (\alpha_t = 270^\circ) \tag{9.30}$$

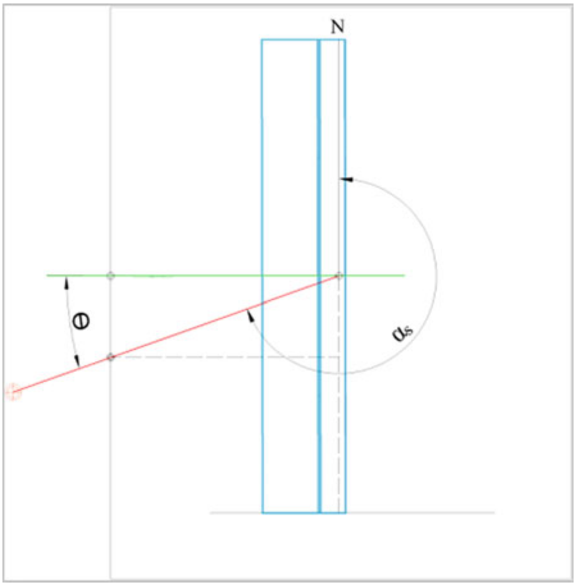


Fig. 9.13 Representation of characteristic an-gles for parabolic collectors in top view

$$\gamma_{st} = \text{arctg}\frac{\text{tg}(\gamma_s)}{\cos(270^\circ - \alpha_S)} \quad \text{for } \alpha_S \ge 180^\circ \text{ and orientation West } (\alpha_t = 90^\circ) \tag{9.31}$$

With the determined tilt angle of the collector (γ_t) and the orientation of the collector (α_t), the angle of incidence which is the angle between the direction of the solar beam and the normal direction to the collector plane (θ) can be determined with the same relation used for the collectors without concentrators:

$$\theta = \text{arc}cos(-\cos(\gamma_S)\cdot\sin(\gamma_t)\cdot\cos(\alpha_S - \alpha_t) + \sin(\gamma_S)\cdot\cos(\gamma_t)) \tag{9.32}$$

The same angle can be also calculated with the relation [12]:

$$\theta = \arccos\left(\sqrt{\cos^2(90 - \gamma_S) + \cos^2\delta\cdot\sin^2\omega}\right) \tag{9.33}$$

The angle of incidence (θ) calculated with the two relations presents identical values.

In the case of the East–West orientation of the collectors, for the calculation of the incidence angle (θ), the following relation can be used [12]:

$$\theta = \arccos\left(\sqrt{1 - \cos^2\delta\cdot\sin^2\omega}\right) \tag{9.34}$$

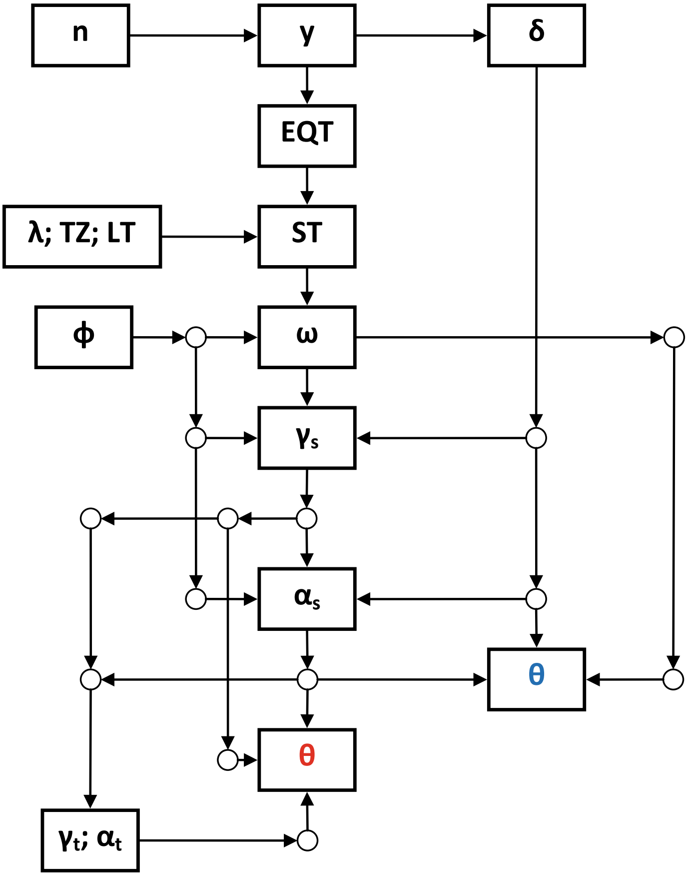


Fig. 9.14 The relation between the parameters used in the calculation of the incidence angle

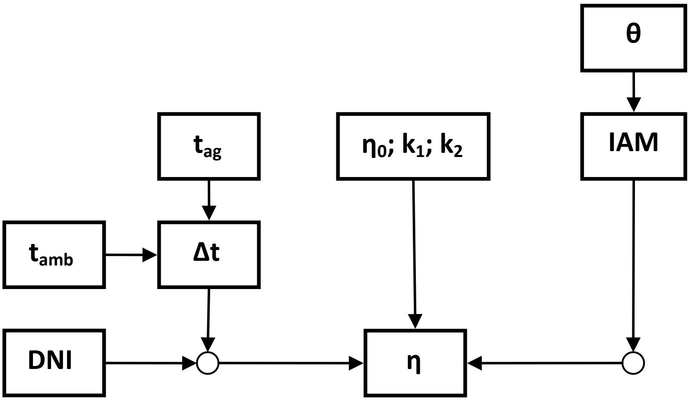


Fig. 9.15 The relation between the parameters used in the calculation of the parabolic collector efficiency

The relation between the parameters used in the calculation of the incidence angle is presented in Fig. 9.14.

The incidence angle was marked with different colors because it can be calculated with the two different equations.

The relation between the parameters used in the calculation of the parabolic collector efficiency is presented in Fig. 9.15.

The significance of all notations is already presented.

9.5.4 *Incidence Angle Modifier*

The correction coefficient, due to the longitudinal angle of incidence is also named in the literature *incident angle modifier (IAM)*.

Table 9.5 presents some characteristics of parabolic collectors for which information and calculation recommendations for the IAM are also available.

Table 9.6 presents some equations obtained through interpolation, recommended for the calculation of the IAM of some parabolic collectors.

Table 9.5 Characteristics of some parabolic collectors

Type of collector	Reference	Thermal agent	Temperature [°C]
SEGS LS-2	Dudley et al. [11]	DOW Syltherm 800	400
EuroTrough (ET100; ET150)	Geyer et al. [15]	NA	NA
EuroTrough ET150	Montes et al. [33]	Therminol VP-1	400 (370)
EuroTrough II	Morin et al. [34]	Steam	280–411
EuroTrough (ET-100)	Giostri et al. [17]	Therminol VP-1	400
FLAGSOL	Al-Maliki et al. [2]	Therminol VP-1	295–393
UrssaTrough	Valenzuela et al. [43]	NA	293–393
INDITEP	Fraidenraich et al. [14]	Steam	NA
NEP PT1800	Larcher et al. [27]	NA	100–300
SKAL-ET	Schenk et al. [40]	Solar salt	450 (500)
SOLTIGUA PTMx-36	Soltigua [37]	NA	250

Table 9.6 Equations recommended for the calculation of the IAM

Reference	Equations	Obs
Dudley et al. [11]	$\mathrm{IAM} = \cos(\theta) - 0.0003512 \cdot \theta - 0.00003137 \cdot \theta^2$	Measurments
Geyer et al. [15] Montes [31] Giostri et al. [16] Giostri et al. [17] Morin et al. [34] De Luca et al. [10] Al-Maliki et al. [2] Rohani et al. [39]	$\mathrm{IAM} = \cos(\theta) - 0.000525097 \cdot \theta - 0.00002859621 \cdot \theta^2$	
Fraidenraich et al. [14]	$\mathrm{IAM} = \cos(\theta) - 0.00044 \cdot \theta - 0.00003 \cdot \theta^2$	Steam
Schenk et al. [40]	$\mathrm{IAM} = 1 - 0.0004 \cdot \theta - 0.00017 \cdot \theta^2$	Experiment
Valenzuela et al. [43]	$\mathrm{IAM} = \cos(\theta) - 0.0007 \cdot \theta - 0.000036 \cdot \theta^2$	East–West
Soltigua [37]	$\mathrm{IAM} = 1 - 0.0018 \cdot \theta - 0.00013 \cdot \theta^2$	Techn. data

***Observation** : In the Best Case Scenario IAM = cos(Θ).*

***Observation**: The IAM interpolation equations presented in the studies:* [2, 10, 15–17, 32–34, 39] *are practically identical.*

Figure 9.16 presents the variation curves of the IAM as a function of the angle of incidence (θ), together with the variation of cos(θ) that should be considered the maximum value of the IAM.

It can be observed that all IAM variation curves based on [2, 11, 15, 32, 33] are almost completely superposed inclusive with the experimental curve from [40].

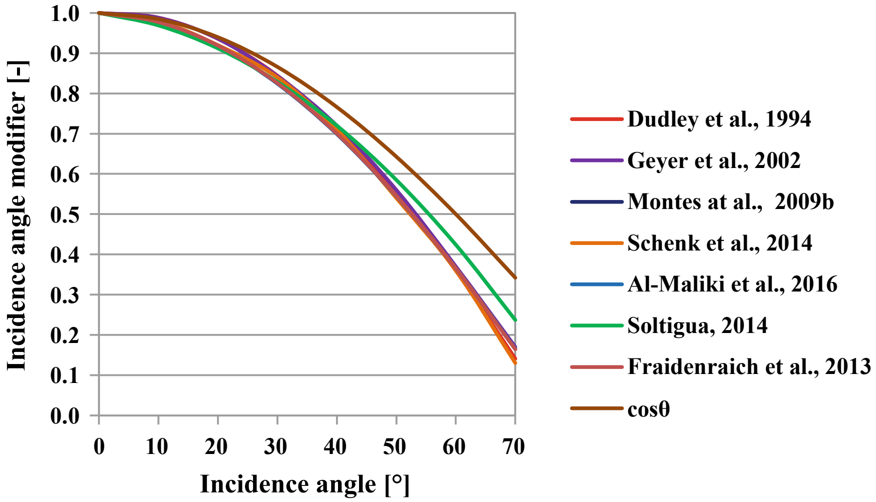


Fig. 9.16 IAM as a function of the angle of incidence

Under these circumstances, the first proposed equation was retained and implemented in the mathematical model [11]:

$$\mathrm{IAM} = \cos(\theta) - 0.0003512 \cdot \theta - 0.0000317 \cdot \theta^2 \tag{9.35}$$

where θ is the incidence angle.

9.5.5 Synthesis of Numerical Modelling

In the case of STC without solar concentrators of flat, evacuated tubes and heat pipes types, the global thermal efficiency was modelled with Eq. (9.27),

All the parameters (η_0; k_1 and k_2) are presented in Table 9.4, for different types of collectors.

It should be mentioned that the solar radiation to be considered in this equation is the global solar radiation, normal on the tilted plane of the collector (I_{gt}).

This equation is recommended in [12, 38, 47] and was already validated and successfully used at the Technical University of Cluj-Napoca in previous studies [1, 5, 6, 35, 41, 42].

In the case of STC with solar concentrators of parabolic through type, the global thermal efficiency was modelled with Eq. (9.28).

In the simulations, the SEGS LS-2 parabolic through STC with the following characteristics: $\eta_0 = 73.3\%$; $k_1 = 0.0306$ and $k_2 = 0.00072$, was considered.

Due to the tracking system, IAM = 1 and the incident angle modifier IAM is calculated with Eq. (9.35), while the incident angle (θ) is calculated with the Eq. (9.32), considering the North–South orientation of the collectors.

It should be mentioned that the direct normal irradiance (DNI) is to be considered in all the calculations related to the parabolic through STC.

Equations (9.27) and (9.28) were chosen for modelling the global thermal efficiency of the STC without and with solar concentrators, respectively, due to their simplicity.

9.5.6 Numerical Example

The presented mathematical models for the thermal efficiency were implemented in Excel, for different types of collectors, considered to operate in different climatic conditions, in Europe, America and Africa.

The types and the characteristics of the STC are presented in Table 9.7.

The locations and the climatic characteristics according to the Köppen-Geiger classification are presented in Table 9.8.

Table 9.7 Types and the characteristics of the STC

Model of thermal collector	Type	η_0 [%]	k_1 [$Wm^{-2} K^{-1}$]	k_2 [$Wm^{-2} K^{-2}$]
Winkler VarioSol A-antireflex	Flat	0.825	3.13	0.0152
Riomay Ecotube	Evacuated tubes	0.794	1.02	0.0032
SEGS LS-2	Parabolic through	0.733	0.0306	0.000720

Table 9.8 Climatic characteristics of the locations

Location	Country	Latitude [°]	Longitude [°]	Altitude [m]	Time zone [h]	Climate
Berlin	DEU	52.517 N	13.389 E	44	1	Dfb
Seville	ESP	37.094 N	2.358 E	499	1	Csa
Phoenix	USA	33.450 N	111.983 W	337	−7	BWh
Ain Beni Mathar	MAR	34.009 N	2.025 E	920	1	Csa

Dfb—Warm humid continental climate; Csa—Hot-summer Mediterranean climate; BWh—Hot desert climate

The climatic data for the considered location is based on the available TMY. The use of TMY is common for studies related to the energy efficiency [3, 4]. TMY provides hourly based variations of many climatic parameters such as: global solar radiation on horizontal plane (I_g [W/m^2]), ambient temperature (t_a [°C]), direct (I_{dir} [W/m^2]) and diffuse (I_{dif} [W/m^2]) solar radiation on horizontal plane but also the direct (beam) normal irradiance (DNI [W/m^2]), etc.

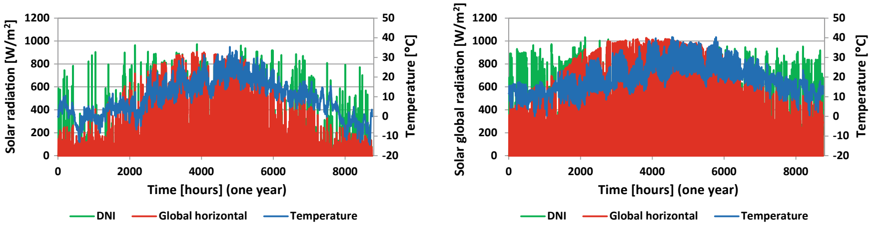
The direct normal irradiance, the global solar radiation on horizontal plane and the ambient temperature, for the locations Berlin, Seville, Phoenix and Ain Beni Mathar, are presented in Fig. 9.17. These parameters are presented because all of them are influencing the collectors' efficiency.

It can be observed that Berlin is characterized by lower values of both direct normal irradiance and global horizontal radiation and also by lower temperatures, in comparison to all the other locations. Phoenix is characterized by the higher values of global horizontal radiation and Ain Beni Mathar is characterized by the higher values of direct normal irradiance.

The efficiency of flat and evacuated tubes collectors is influenced by the global horizontal radiation and by the ambient temperature, while the efficiency of parabolic through collectors is influenced by the direct normal irradiance and by the ambient temperature.

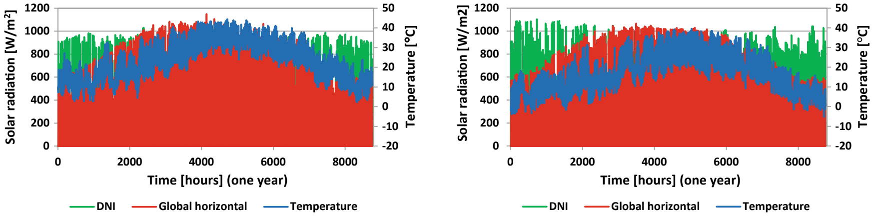
Using these input data, some important results that can be obtained with the described algorithms, are presented: Sun charts, angles of incidence, thermal efficiency of STC and specific thermal power of the collectors.

Figure 9.18 presents the Sun charts for the considered locations, for one day of each month, including the equinoxes and solstices.



a. Berlin

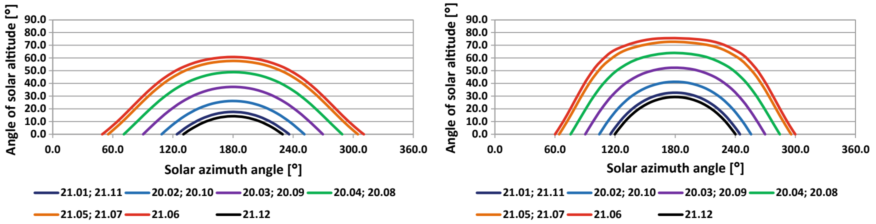
b. Seville



c. Phoenix

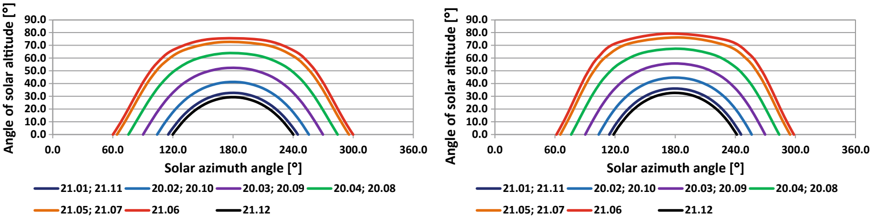
d. Ain Beni Mathar

Fig. 9.17 Solar radiation and ambient temperature variation



a. Berlin

b. Seville



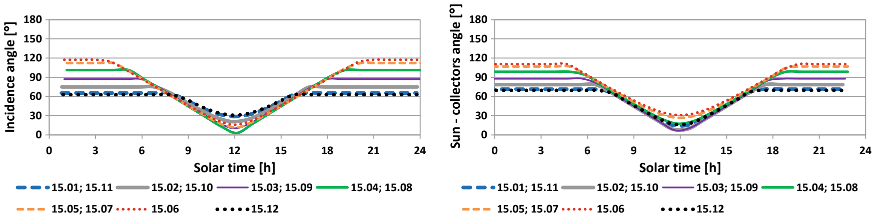
c. Phoenix

d. Ain Beni Mathar

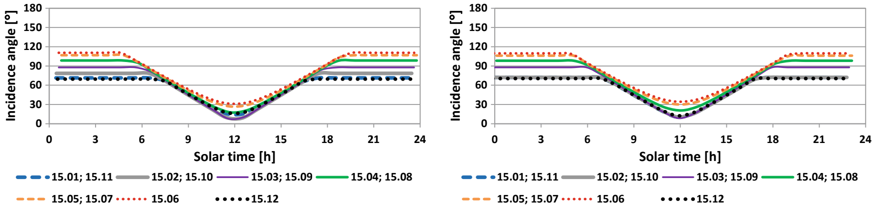
Fig. 9.18 Sun charts

The lower angles of solar altitude correspond to Berlin, while the higher angles correspond to Ain Beni Mathar.

Figure 9.19 presents the angles of incidence for the flat and evacuated tubes collectors, considered tilted with 45° and oriented through south, for the considered locations during the days of 15 of each month, as a function of the solar time.



a. Berlin b. Seville

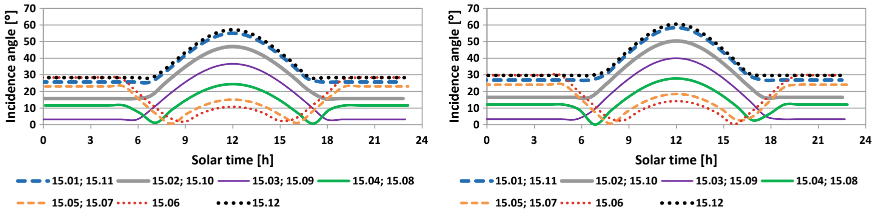


c. Phoenix d. Ain Beni Mathar

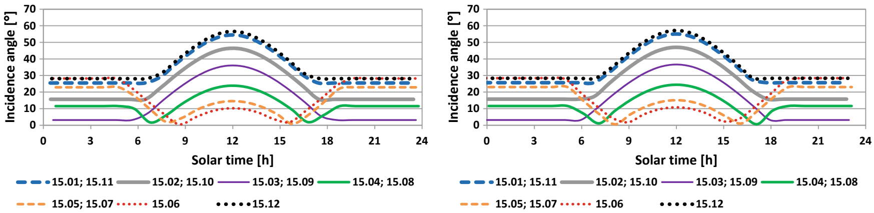
Fig. 9.19 Angles of incidence for the fixed collectors

It can be observed that the best exposure of the fix collectors corresponds to the mid-day (solar time 12:00) when the incidence angle is lower. The incidence angle depends on the collector orientation and can be optimized for each location.

Figure 9.20 presents the angles of incidence for the parabolic through collectors (characterized by one axis solar tracking), for the considered locations during the days of 15 of each month, as function of the solar time.

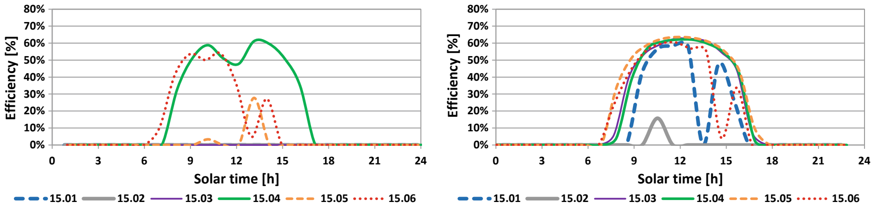


a. Berlin b. Seville



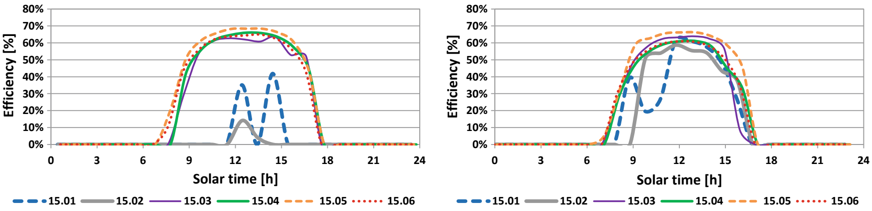
c. Phoenix d. Ain Beni Mathar

Fig. 9.20 Angles of incidence for the parabolic collectors



a. Berlin

b. Seville



c. Phoenix

d. Ain Beni Mathar

Fig. 9.21 Efficiency of the flat collector

The tracking system ensures lower incidence angles during the summer periods when the angle of solar altitude is higher for all the locations.

Figure 9.21 presents the efficiency of the flat collectors, for the average temperature of the thermal agent of 70 °C, for the considered locations during the days of 15 of each month of the first half of the year, as function of the solar time.

It can be observed that solar radiation is essential for the efficiency variation. As examples, for Berlin the efficiency drops to almost near zero in many days, due to the lower values of solar radiation and in Seville it can be observed that during the 15th of June, the efficiency drops when solar radiation drops in the time interval (14:00–16:00). At Ain Beni Mathar, even in February the thermal efficiency can reach high values if solar radiation is high.

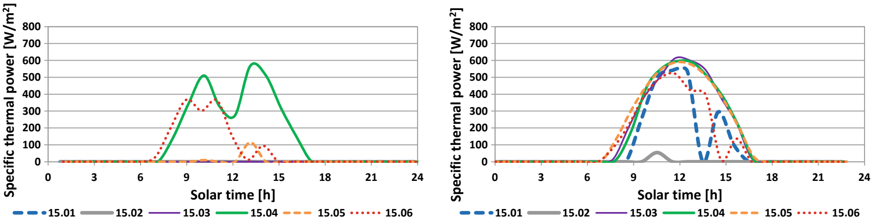
Figure 9.22 presents the specific thermal power of the flat collector, for the average temperature of the thermal agent of 70 °C, for the considered locations during the days of 15 of each month of the first half of the year, as a function of the solar time.

The specific thermal powers are in agreement with the efficiencies. The lower values correspond to Berlin and the higher values to Phoenix.

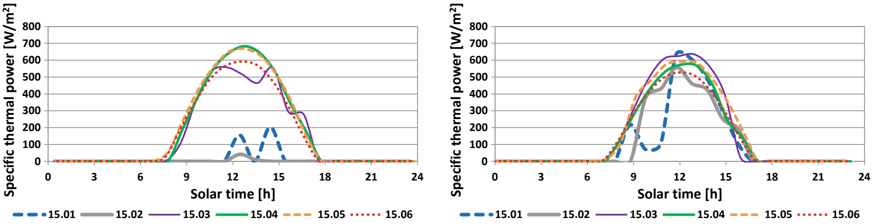
Figure 9.23 presents the efficiency of the evacuated tubes collectors, for the average temperature of the thermal agent of 70 °C, for the considered locations during the days of 15 of each month of the first half of the year, as a function of the solar time.

It can be observed that the values of the thermal efficiency of the evacuated tubes collector are higher and maintained at high values for longer periods than in the case of flat collector, for all the locations.

Figure 9.24 presents the specific thermal power of the evacuated collector, for the average temperature of the thermal agent of 70 °C, for the considered locations

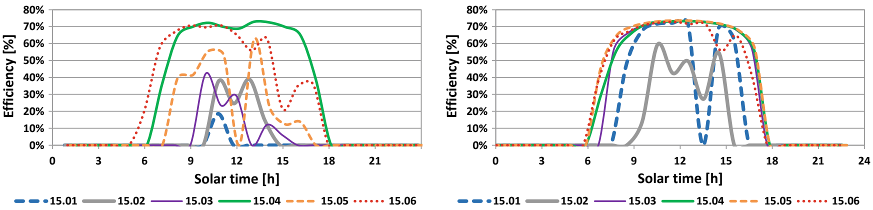


a. Berlin b. Seville

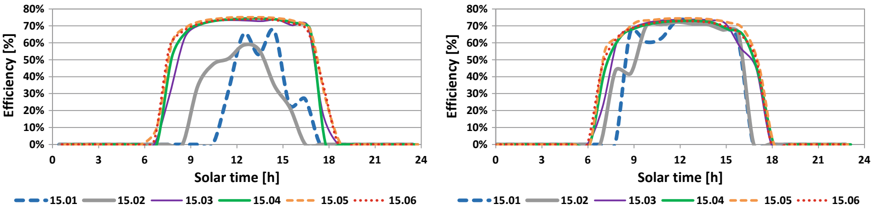


c. Phoenix d. Ain Beni Mathar

Fig. 9.22 Specific thermal power for the flat collector



a. Berlin b. Seville



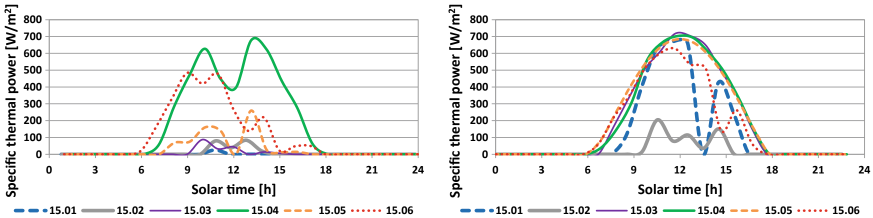
c. Phoenix d. Ain Beni Mathar

Fig. 9.23 Efficiency of the evacuated tubes collector

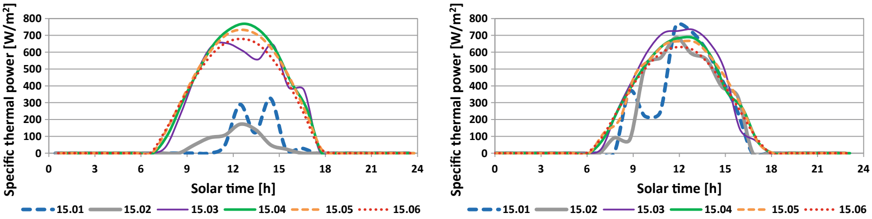
during the days of 15 of each month of the first half of the year, as a function of the solar time.

The values of the specific thermal power of the evacuated tubes collector are significantly higher than the ones of the flat collector, due to the better technology that ensures lower heat losses.

Figure 9.25 presents the efficiency of the parabolic through collectors, for the average temperature of the thermal agent of 350 °C, for the considered locations

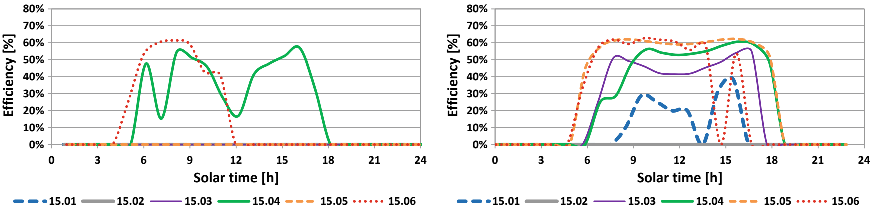


a. Berlin b. Seville

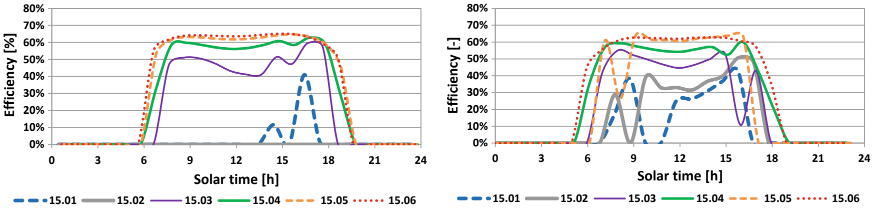


c. Phoenix d. Ain Beni Mathar

Fig. 9.24 Specific thermal power for the evacuated collector



a. Berlin b. Seville

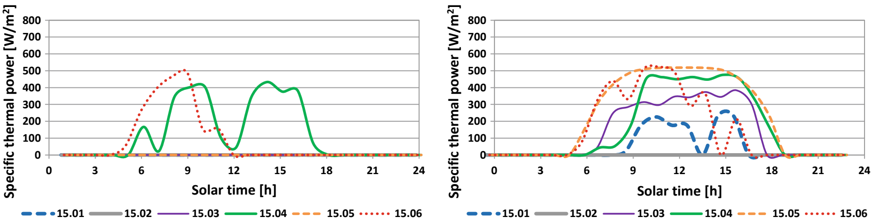


c. Phoenix d. Ain Beni Mathar

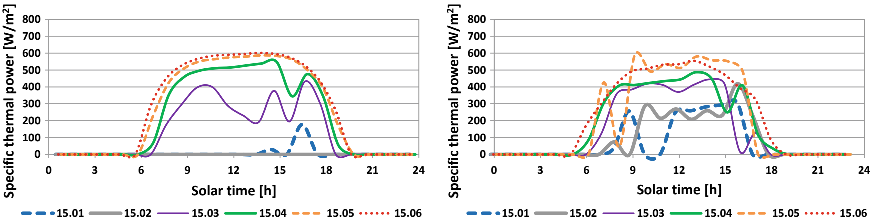
Fig. 9.25 Efficiency of the parabolic collector

during the days of 15 of each month of the first half of the year, as a function of the solar time.

The values of the thermal efficiency of the parabolic through collector are lower than the ones of the evacuated tubes collector, because the much higher temperature of the working fluid determines higher thermal losses. Even so, the values of the thermal efficiency of the parabolic through collector are higher than the ones of the



a. Berlin b. Seville



c. Phoenix d. Ain Beni Mathar

Fig. 9.26 Specific thermal power for the parabolic collector

flat collector. The efficiency of the parabolic through collector is maintained at high values for long periods for all the locations.

Figure 9.26 presents the specific thermal power of the parabolic through collector, for the average temperature of the thermal agent of 340 °C, for the considered locations during the days of 15 of each month of the first half of the year, as a function of the solar time.

The maximum values of the specific thermal power of the parabolic through collector are lower than the ones of the fix collectors, however, the high values of the specific thermal power is maintained almost throughout the entire day, when the Sun shines, because of the tracking system.

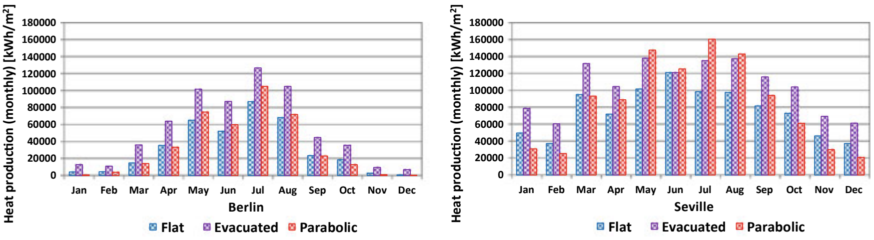
Figure 9.27 presents the monthly cumulated useful heat produced by the studied collectors in the considered locations.

It can be observed that in the cold months (January, February, November and December) the parabolic through collectors provide in all the considered locations the lower amount of useful heat, because in these months the heat loses corresponding to this type of STC are considerably high due to the high average temperature of the thermal agent (350 °C) in comparison to the same temperature of the other types of STC (70 °C).

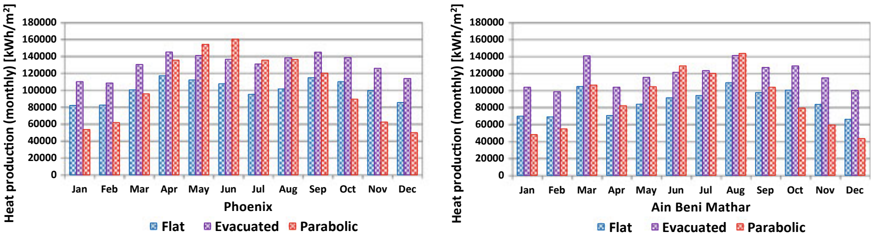
In the warm months (May, June, July and August) the evacuated STC and the parabolic through STC are competing for the higher amounts of provided useful heat.

It is important to observe that the evacuated STC provides more constant useful heat during the year, while the useful heat production of the parabolic through STC is considerably higher in summer than in winter, in all the considered locations.

Figure 9.28 presents the yearly cumulated useful heat produced by the studied collectors in the considered locations.

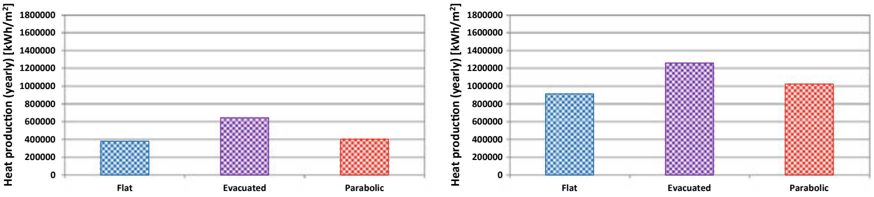


a. Berlin b. Seville

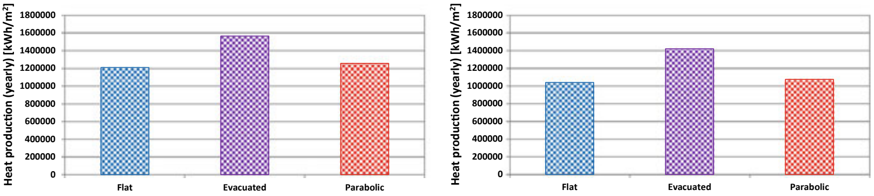


c. Phoenix d. Ain Beni Mathar

Fig. 9.27 Monthly cumulated useful heat



a. Berlin b. Seville



c. Phoenix d. Ain Beni Mathar

Fig. 9.28 Yearly cumulated useful heat

The yearly based analysis reveals that the evacuated STC is capable to provide the higher yearly amount of heat in all the considered locations, followed by the parabolic through STC and by the flat STC.

The choices between the flat and evacuated STC must be made based also on a cost benefit analysis, because the lower efficiency of the flat STC is compensated by the lower price when compared to the evacuated STC.

The parabolic through STC is to be used only in warm locations with high amounts of solar radiation, for applications where high temperature of the thermal agent is required (such as solar power plants).

9.6 Conclusions

The chapter presents the fundamental information needed for the evaluation of the elements of "solar geometry" and of the performance of the STC that can be integrated in the built environment.

The presented mathematical model was implemented in Excel and proved its capability to provide accurate results for flat, evacuated tubes and parabolic through STC.

Using as input data the information about the location, the characteristics of the STC and the climatic data from the TMY, the following parameters can be calculated on an hourly basis: angle of solar altitude, angle of solar azimuth, angle of incidence, thermal efficiency of the STC, the specific thermal power of the STC and the cumulated provided useful heat.

In the case of fixed STC (flat and evacuated tubes), the incidence angle can be optimized for each location, while in the case of the parabolic through STC, the tracking system continuously ensures the best possible orientation.

The maximum values of the thermal efficiency are situated between: (60…70)% for flat STC, (70…75)% for evacuated tubes STC and (60…65)% for parabolic through STC.

The maximum values of the specific thermal power are situated between: (600…700) W/m^2 for flat STC, (700…800) W/m^2 for evacuated tubes STC and (500…600) W/m^2 for parabolic through STC.

The parabolic through STC is compensating the lower values of the maximum specific thermal power, by the more constant values of this parameter, in the vicinity of maximum values, when Sun is shining.

The comparative monthly and yearly based analysis revealed that the evacuated STC provides more constant useful heat during the year, while the useful heat production of the parabolic through STC is considerably higher in summer than in winter, in all the considered locations.

The parabolic through STC are recommended only for warm and very sunny locations and only for applications where high temperature of the thermal agent is required.

The achievements of the chapter can be used in different types of applications such as heating, cooling or conversion of heat into electricity.

Key Terms and Definitions

Solar radiation is the radiant electromagnetic energy emitted by the Sun.

Direct (or beam) solar radiation normal to the horizontal surface is the solar radiation that reaches the Earth's surface without being affected (absorbed or diffused) by the atmosphere.

Diffuse solar radiation on the horizontal surface of the Earth is the solar radiation that reaches the Earth's surface after its direction was modified by diffusion (scattering).

Global (or total) solar radiation on the horizontal surface of the Earth is the sum of the direct and the diffuse solar radiation.

The ground reflected solar radiation is the solar radiation reflected by the Earth's surface.

Solar thermal collectors are a particular case of heat exchangers that transform the solar radiation energy into heat embedded into a transport media.

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Chapter 10
Impact of Heavy Metals from Building and Constructive Materials on Aquatic Environment

Junaid Ahmad Malik

Abstract Heavy metals are commonly characterized as metals with moderately high densities, atomic weights, or atomic numbers. Heavy metals are routinely occurring components that have a high atomic weight and densities at least 5 times more prominent than that of water. Common metals, for example, iron, copper, and tin, and valuable metals, for example, silver, gold, and platinum—are substantial metals. Metals specifically tend to amass and endure food chain magnification. From quite a few decades ecological contamination is considered as a significant worldwide issue for both humans and animals. Substantial metals influence all groups of living beings and biological system forms, including microbial activities. The manufacturing wastes are the significant wellsprings of contamination and are released in water presenting genuine risk to the marine and freshwater fauna. Among the different poisonous contaminations, heavy metals have serious activity because of their propensity of bioaccumulation in fish tissues. Likewise, some on-going investigations illuminated that fishes living in dirtied water bodies collect extraordinary convergence of these metals and consequently exhausting the nature of significant marine food items and fish. Besides, the most broadly observed origins of substantial metals created through the building constituents are copper materials, housetops, zinc rooftops, downpour tubes etc. Regardless of the way that building, and development materials are most likely not using any and all means the main wellspring of substantial metals, they are a critical part of the issue. Activation of heavy metals in construction or other development things describes a critical viewpoint in the evaluation of the potential biological impact due to the effect of water, groundwater or various impacts that enliven weathering. A reasonable use of instruments and a delimited advancement should be implemented and the measures for sustainable utilization should also be encouraged.

Keywords Aquatic · Building materials · Cadmium · Construction · Contamination · Ecosystem · Electroplating · Food chain · Heavy metal · Itai-itai · Minimata · Smelting · Toxicity

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10.1 Introduction

Heavy metals normally occur within different meditations inside soil, air and water. They have blown out generally because of anthropogenic exercises, for example, cement manufacturing, steel engineering, condensation plants, crystal formation, trash and surplus mud burning amenities, excavating exercises, metal castings, tubing and channelling, incineration and transportation [2, 40] (Table 10.2). Substantial metal contamination is a significant environmental issue beheld by the modern world. Fast development and industrialisation prompts constructing progress which causes constant increment in metal concentration and grave contamination issues because of ill-advised dumping and disposing of industrialized surplus items straightforwardly into water bodies and land regions [22].

Water is a common important asset and its nature is of fundamental worry for the humankind as being straightforwardly associated with human well-being and health [39]. Metal extraction is a significant industry for the contemporary standard of living. In any case, entire stages in the lifecycle of a coalmine source can release toxins to rivers, waterways, and other water bodies [58]. These elements break down under liquid besides are excellently consumed by fish in addition to the rest oceanic living beings. Little concentrations (levels) can be hazardous in light of the fact that metals experience bio-accumulation, which suggests that the meditation of these metals in a living being is alarming. Metal poisonousness makes unfavourable organic concerns for the animal survival, movement, development, digestion, or propagation. Metals can be fatal or distress the life form without killing it legitimately. Aggressive consequences for an organism's activity, development, metabolic rate, as well as the propagation are instances of sub-lethal impacts [71]. Altogether, a metal can be dangerous, if it comes into the physique of the unprotected living being and interconnect thru the external or inside of cells. A few pathways are there, by which this process occurs. Aside dissemination into the circulatory system by means of the gills as well as skin, the fishes are also infected by drinking water or ingesting dregs which are already defiled by the toxin, or consumption of different creatures or plants which have been exposed to the contaminants. Individuals are presented to metals through parallel pathways: dispersion into the circulatory system by means of the air and epidermis, consuming sullied water, as well as eating polluted diet [71]. A significant ecological worry because of spreading of modern and city squanders created by anthropoid exercises is the sullying of land and water bodies. Organized and unorganised transfer of discarded materials, unintentional and course leakage, excavating as well as purifying of metalliferous minerals, manure slop presentation to agrarian lands stand liable for moving of impurities towards unadulterated locales by way of residue or leachate besides subsidize towards pollution of our biological system [31]. Substantial metal contamination is known to be the reason for different ailments all inclusive, for example, the minamata (biological mercury exposure), iItai-itai (cadmium poisoning), arsenic exposure as well as aerial contamination linked breathing problems [43].

Aquatic environments are profoundly composite, active as well as dependent on numerous inner and outer connections which are liable to modify after some time. The toxins entering the shallow waters as well as estuaries mark major issues producing wide harm to the development and endurance of the marine creatures besides can cause bulk death. Amongst the contaminants, amassing of substantial metals in aquatic environments is of worldwide significance. Metal contamination of the ocean is not much noticeable than different sorts of marine contamination yet its impacts on aquatic biological systems and human beings are extremely broad. Metal presence and its extent differ amongst the fish types; rely upon age, formative period as well as further physiological elements. Fish amass considerable amounts of Hg within the body and consequently can characterize to a significant nutritive wellspring of mercury for the humans. Biotransformation and conversion of Hg and its compounds establishes a hazardous issue for human wellbeing [23]. Significant contributions have been made about maritime and waterfront appropriation of different heavy and substantial metals. The characteristic sea-going frameworks may broadly be polluted with substantial metals discharged from household, manufacturing and other man-made exercises [67]. Heavy and substantial metal sullying may effectsly affect the biological parity of the ecological balance and a decent variety of amphibian life forms [4, 25, 68]. Amongst animal classes, fishes remain the occupants and can’t escape from the hindering impacts of such contagions [14, 49], [21]. The aquatic animals are generally employed to assess the reliability of sea-going biological systems since toxins develop in the food webs which are accountable for unfriendly impacts and passing in the sea-going organisms [24], [77]. Toxic elements and contaminants, for the most part, enter the marine environs through atmospheric deposition, disintegration of land structure or because of anthropogenic exercises brought about by manufacturing wastes, local wastes and mining squanders. The metallic toxins in oceanic frameworks as a rule remain either in dissolvable or suspension form finally will in general settled at the base otherwise are consumed by the living beings. The dynamic and irremediable aggregation of such toxins in different tissues of aquatic animals prompts metal associated sicknesses over the long haul due to their poisonous quality, accordingly imperiling the oceanic biota and different life forms. Fishes are the fundamental oceanic creatures within the food web may regularly amass a lot of specific metals. Straightforwardly, metals such as iron, zinc, lead, cadmium and manganese are normal lethal toxins for the fishes. The amassing of these components within the living beings and their exaggeration portrays the procedures and paths of such (potential) toxins starting with one trophic level onto the next, displaying the higher bioaccumulation capacity in the life forms concerned. Mounting concentration over the food webs causes complex maintenance time of hazardous substances in comparison with the other typical nutritive constituents. Noxious components including “heavy metals”, contrarily influence animal fitness. In extremely modest quantities a large number of these metals are important for the sustenance of life. In any case, in bigger sum they become harmful. They may develop in organic systems and become a noteworthy wellbeing peril” [53].

The rapid expansion of urbanization and mechanical headway has brought up more substantial metal defilement in the marine deposits and residues. There are many mining, purifying, mechanical production, chemical as well as additional activities (e.g., building material, food and pharmaceutical preparing productions) which are noteworthy wellsprings of substantial metals to their local water bodies and streams. Building substances are in direct interaction with water (such as downpour, drainage water) throughout their administration period and may release possibly destructive mixtures by discharging courses [72]. Constructions and the applied encroachment constituents (like putties, dyes, tiling resources and blocks), as noteworthy components for the nature of water in urban regions, are a fresher arena of investigation. Mass-flow investigation exposed that 50–80% of the stack of substantial metals, for instance, cadmium, copper, lead and zinc in joined drain structures might be due to the overflow from housetops and roads [9]. The occurrence in the environs of elements instigating from developmental stuffs emphasizes the prerequisite for an imminent consideration of such things. The purpose of this chapter is to provide an idea of the effects of some possibly dangerous substances from construction and manufacturing items by contact with water (e.g., downpour or drainage water).

Metals are utilized in a wide scope of materials and activities utilized in developments and different advancements and an incredible portion of these materials are acquainted with conditions where they can be exhibited to decaying, disintegration and degradation, for example housetops and facings, poles, shafts and boundaries, plumbing formations and motor vehicles. A wide extent of materials is potential wellsprings of metal emulsion when they are displayed to destructive conditions. Metal layers and metallic tools are clear candidates, yet different materials, for example, paints, plastics and solids which are utilized in gigantic sums on structures and developments may in like way be perhaps huge wellsprings of metal floods [57].

Lifecycle discharges from the extraction, production, use, and passage of the materials, up and down stream, impact health care system people/patients, visitors, staff, and the community's wellbeing in their homes, offices, and at play. Considerable elements with the most serious prospective for perilous influence whenever utilized in road assembling on a very basic level incorporate the associated constituents; iron, manganese, titanium, aluminum, calcium, magnesium and chromium [32].

10.2 Causes of Heavy Metal Pollution

The consistent utilization of perilous metals in anthropogenic exercises from mechanical sectors like electroplating, painting, tanning, materials and dyes, papermaking, mining, and others has expanded tremendously and has gotten inconvenient for diversity of life on earth [20, 73]. Heavy metal contamination can emerge from numerous sources, yet most normally emerges through the metal decontamination like, copper smelting and nuclear fuel preparation. Electroplating has proven to be the useful wellspring of chromium as well as cadmium. During their ion exchange and precipitation within the soil, the toxins can restrain and are deactivated. In contrast to natural toxins, substantial and heavy metals don't rot and, in this way, represent an alternate sort of trouble for the process of remediation. At present, microphyta or microorganisms are utilized to expel certain heavy metals, for example, mercury. Hyperaccumulating plants can be utilized for expelling the substantial and toxic metals from soils by using them in their metabolism and cellular functions. Substantial elements such as lead, mercury, iron, cadmium, aluminum and magnesium are available within water bodies. On the off chance that such metals remain available in the residue, arrive at the food webs via vegetation and marine creatures. Consequently, it gives rise to heavy metal harming on the off chance that the level in the water is extraordinary. Anthropogenic concerts of electroplating, mining, purifying, pesticides and manure releases, bio-solids, city sewage/ sludge, and textiles and paint productions have become most huge wellsprings of metal tainting [7], [42, 73].

Construction and destruction process and the wastes produced thereby, is probably the greatest reason of solid squanders produced from metropolitan exercises. While seeking after and keeping up a rapid monetary improvement, colossal scale urbanization and building advancement have been expecting a huge activity in extending the metal concentration and dependable tainting issues by participating in the food chain of plants and animals [78]. Hazardous elements and toxins are the result of the construction and demolition processes within some industrial sectors like chemical, metallurgical, light processing and fire/explosion etc. [16].

10.2.1 Smelting

Smelting is a metal extraction procedure in which an ore (typically blended with purifying as well as heat producing substances, for example, limestone and coke) is heated at high temperature in an encased heater. After a reducing reaction, lighter metal parts (impurities called slag or tailing) ascent to the top and buoy on the liquid metal. Smelting is the inverse of roasting which comprises of oxidizing reaction. The process of smelting is a metallurgical method through which a metal is obtained and produced from its ore. The process of smelting utilizes heat and a carbon source which acts as a reducing agent, for example, coke and/or charcoal, towards changing the oxidation condition of the element. Carbon gets oxidized and changed into CO_2 and CO. Due to the impurity of most of the ores; it becomes frequently important to utilize flux, for example, limestone, to evacuate the accompanying rock gangue as slag. Plants, while not utilizing carbon, for the electrolytic reduction of aluminum, are additionally for the most part alluded to as smelters. The chief wellsprings of contamination brought about by smelting are contaminant-loaded air emanations and process squanders, for example, wastewater and slag.

Smelting completely influences the atmosphere and the environment—creating wastewater and slag and releasing such harmful metals as copper, silver, iron, cobalt and selenium into the environment. It similarly releases vaporous sulfur dioxide, adding to corrosive downpour, which ferments soil and water. [41]. Smelter contamination unquestionably decreases the oceanic floral and faunal diversity in its prompt area. Over the range of different examinations, it was found that heavy metals were ample in waters accumulated near the smelters [33].

10.2.2 Electroplating

It is a gilding procedure which utilizes the electrical energy to decrease cations of an ideal substance within a liquid and coat a chargeable item with a skinny sheet of the substance, for example, a metal. This technique is the method of plating one metal onto another by hydrolysis, most usually for enhancing purposes or to avoid erosion of a metal. There are likewise explicit sorts of electroplating, for example, copper plating, silver plating, and chromium plating. Electroplating enables manufacturers to utilize low-cost metals, for example, steel or zinc for bulk of the product and afterward apply various metals outwardly to characterize appearance, protection, and different properties required for the item. The surface can be a metal or even plastic. Electroplating was first established by Luigi Brugnatelli in 1805 through utilizing the electrodeposition procedure for the electroplating of gold. The procedure utilized in electroplating is called electrodeposition. It is corresponding to a concentration cell acting backward. The fragment to be plated is the cathode of the circuit. In one scheme, the anode is made of the metal to be plated on the part. The two parts are drenched in a solution called an electrolyte containing at least one dissolved metal salts as well as different particles that license the progression of energy. A power supply transports a direct to the anode, oxidizing the metal atoms that it includes and enabling them to disintegrate in the solution. At the cathode, the dissolved metal particles in the electrolyte solution are diminished at the interface between the solution and the cathode, with the end goal that they "plate out" onto the cathode. The degree at which the anode is dissolved is equivalent to the rate at which the cathode is plated and in this way the particles in the electrolyte shower are constantly renewed by the anode. Electroplating is basically utilized for putting a coating of material beneath an ideal stuff (e.g., scrape and garb resistance, corrosion defense, lubrication, aesthetic merits and so forth.) to a surface that generally does not have such possessions.

Alternative solicitation utilizes electroplating to develop viscosity on small parts. The toxins through the electroplating ventures are constantly risky, as the effluents sully air, water and soil. A portion of the dirtying specialists have injurious impact on human wellbeing, models being cadmium, lead, nickel and so forth. The natural burden in electroplating industry essentially accompanies process squander water, hydroxide slime and sulphuric corrosive. The untreated washing water has a lot of waste.

Electroplating wastewater is routinely from washing, flushing and group dumps and is at a low pH of ~3–5 and contains dissolvable kinds of the various metals. The effluents discharged from electroplating contains high union of generous metals like Iron, Chromium, Copper and Nickel which subsequently cause grave ramifications for the oceanic life [62].

10.2.3 Industrial Effluents

The pollution of water is mainly a result of release of some hazardous chemicals into the water, leaving it improper for consumption and other purposes. This leaves the water unfit for human consumption besides intimidating the marine lives. Water is polluted by the discharge from household and city sewage, agrarian leftover, impurities and manufacturing trashes.

At the present time, the effluents from industrial units, like oils, grease, pesticides, lubricants, polychlorinated biphenyls (PCBs) and dyes are majorly responsible for the water contamination. Such destructive toxins are the main contributors to several serious illnesses e.g., diarrhea, cholera, cirrhosis, hepatitis, dysentery as well as salmonellosis. Moreover, numerous of these contaminants are likewise cancer-causing. Certain contaminants such as Na are known to give rise to the heart ailments, whereas Hg and Pb cause anxiousness. DDT being another toxicant is known to disturb the chromosomal structure and causes chromosomal alterations.

Marine animal wellbeing is influenced in light of the fact that their lives become endangered by the substantial metal contaminated water. Toxins from the wastewater of mechanical use can kill off marine life or cause differing degrees of ailments to the individuals who devour these marine animals, contingent upon the contaminant [19]. Water contamination can certainly affect the human body with the fundamental ones being diseases from microscopic organisms, parasites, and chemical substances [35]. As is evident from some reports [45, 46], it is distinct that the nature of water and its biotic segments are contrarily affected by certain releases of toxic metals from building constituents and copper sources, for the most part copper and zinc.

10.3 Metals in the Aquatic System

Metals, when present in the aquatic environment, are apportioned into the solvent, solids and biota. Soils and sediments contain some toxic heavy metals which are bound inside the basic matrix as primary constituent [76]. Several metals are in readily available forms which perhaps are made to more bio-available because of relatively mild physico-chemical changes in sediments and surface waters [28]. The metals are mobilized by natural processes like erosion or by the anthropogenic actions [11, 27].

All metals, particularly substantial metals, with the capability of turning out to be toxins are present in trace or ultra- trace concentrations in seawater [47]. Average concentrations [μg L-1 (ppb)] of chose metals, arsenic (As), cadmium (Cd), chromium (Cr), copper (Cu), iron (Fe), lead (Pb), manganese (Mn), mercury (Hg), nickel (Ni), vanadium (V) and Zinc (Zn) in seawater and sea water are given in Table 10.1.

Substantial metals from the leaching of construction materials, buildings and structures can stay in water segment in suspension, precipitate on the base, or be

Table 10.1 Typical Concentrations of some heavy metals in *Sea* and *Ocean waters* [47]

Heavy metal	Typical concentration in µg L-1 (ppb)	
	Sea water	Ocean water
Arsenic (As)	1–3	0.5–3.0
Cadmium (Cd)	0.001–0.1	1–100
Chromium (Cr)	0.1–0.55	$0.1.10^{-3}$–$0.55.10^{-3}$
Copper (Cu)	0.03–0.35	0.05–0.35
Iron (Fe)	0.008–2.0	–
Lead (Pb)	0.001–0.1	0.002–0.2
Manganese (Mn)	0.003–1.0	–
Mercury (Hg)	0.00007–0.006	7.10^{-3}-6.10^{-3}
Nickel (Ni)	0.1–1.0	–
Vanadium (V)	1.9	–
Zinc (Zn)	0.006–0.12	0.006–0.523

Table 10.2 Prospective sources of some metals from manufacturing and agricultural works

Metal	Sources
Cd	Batteries and electrical; pigments and paints; alloys and solids; fuel; plastic; fertilizers
Cu	Batteries and electrical; pigments and paints; alloys and solid; fuel; catalysts; fertilizers; pesticides
Fe	Pigments and paints; fuel; refineries; textile
Mn & Zn	Batteries and electrical; pigments and paints; alloys and solders; pesticides; glass; fertilizers; refiners; fuel
Ni	Batteries and electrical; pigments and paints; alloys and solids; fuel; catalysts; fertilizers
Pb	Batteries and electrical; pigments and paints; alloys and solders; pesticides; glass; fertilizer; refiners; fuel; plastic
Cr	Pigments; fertilizers; textile

taken up by organisms [15]. Along these lines marine organisms are generally great markers for long-term observing of metal accumulation. Heavy metals can arrive at high concentrations in the tissues of aquatic animals along the food chain. Numerous past investigations showed that the metal accumulation levels of aquatic organisms may be identified with number of the variables, for example, size of animals, impacts of sex and seasons, nourishing propensities, living situations, propertyes of metals, bioavailability of chemicals, and physico-compound parameters of aquatic environment [15], [75], [74].

Campbell and Stokes [12] designated two contrasting responses of an organism to a metal toxicity with decreasing pH.

1. If there is little change in speciation and the metal binding is feeble at the organic surface, a decline in pH will diminish owning to rivalry for binding sites from hydrogen ions.
2. Where there is a stamped impact on speciation and strong binding of the metal at the organic surface, the prevailing impact of a decline in pH will be to expand the metal accessibility.

10.4 Heavy Metals and Animal Bodies

Heavy metals are the typical ingredients and part each section of our environment and are a part of the natural chemical cycles and reactions (Table 10.2). Some metals are having low affinity towards oxygen but remain associated with each other. Heavy metals disturb living creatures even after their ecological concentrations are minor. Their deadliness owes not merely to the grade of adulteration of the environment, however likewise to the biological character in metabolic procedures as well as the degree towards which they are engrossed and expelled by aquatic animals. Metals, when bioavailable to the aquatic fauna, create a toxic and poisonous effect and are bio-accumulated within the bodies of the organisms [52].

The organic and poisonous characters of metals have been premeditated broadly during contemporary times. The metals which are measured vital for the living organisms are; As (nonspecific development encouragement), Co (component of vitamin B12), Cr (controller of absorption of glucose as well as cholesterol) as well as Cu. The elevated meditations of copper in amalgamation thru little pH have proven lethal to the fishes (fundamental component of oxidases, significant for redox reaction controls, respiration, mineralization of bone and cartilages). Iron is the utmost abundant metal on the earth which is vital for nearly all animals (for haemoglobin, cytochromes, enzymatic reactions etc.). Manganese, being a transition metal, is also important for the cellular metabolism. It is present in several states within the environs. Other important elements for the cellular and metabolic pathways are Mo, Ni, Se, Sn, V and Zn [3]. The intestine is potentially more significant for zinc uptake however, there is not much known regarding the Zn uptake in fishes [6, 37, 38].

The consumption and utilization of metals by marine animals is a successive two stage process, which includes preliminary fast surface binding and a slower transference inside the cell [17, 36]. At the skin tissues the rate of transference is the factor which determines the rate of mobility in the tissues [10, 26, 29, 51, 57].

Fish are over the oceanic evolved way of life, and their typical metabolic exercises may gather substantial metals which are major, essential, and non-essential components from water, food, or dregs. Past investigations show that amassing of substantial metals from the close by leaching of buildings and constructive working accumulates in the tissues of oceanic animals. Be that as it may, the general amassing and take up by the biotic segments relies upon natural variables, for example, saltiness, seasonal changes, pH, and temperature. Likewise, it is for the most part contingent upon various food propensities (predatory, herbivorous or omnivorous), contrasts in the aquatic environmental lives (demersal, pelagic, or bento-pelagic), growing rates of the species, kinds of tissues analyzed, and different components [74].

The gill and intestine are essential sites for take-up of soluble metals from the sea-going situations. In soft bodied invertebrate species, the body wall may likewise be a significant site of soluble metal take-up. [54] recommended that the metal take-up over the body surface was the transcendent course of passage since fish were always washed in metal-containing water and regularly passed huge volumes of water over respiratory surfaces with the purpose of gas exchange. Be that as it may, for invertebrates and vertebrates, direct take-up from water might be just of minor significance. Beside fish, the invertebrates, for example, cuttlefish, shrimp, shellfish, and mollusks, represent important economic seafood for human utilization. Numerous scientists are researching these aquatic animals as key species in numerous marine biological systems taking into consideration to accumulate organic and metallic pollutants at concentrations of the field condition [65].

10.5 Effects of Heavy Metals on Fishes and Other Marine Fauna

Certain marine animals are able to store and hold the toxic metals up to a definite range (Table 10.1). Experiments from the fish and marine animals have revealed that some important heavy metals are otherwise important for the sustenance of the metabolic pathways, however cause mutagenic effects when present in higher amounts and concentrations which in turn affects the overall fitness and leads to death of the animal [34, 44]. The growth and development of the larvae of fish is very rapid. The environmental factors influencing the growth and development of fish larvae are mainly the temperature and the heavy metal toxicity. The fish, when present in the polluted and sullied water with toxicants like heavy metals, undergoes reversal in some parameters and the overall growth is hindered [61]. The external surfaces of the gills are known to be the prime targets of the aquatic toxins and contaminants [63]. Fishes, being the superior organisms in food chain, can accumulate pre-existing metals in various tissues and organs.

The surface water runoff and the groundwater adjacent to a construction spot become contaminated with various constituents used in the construction work. The following construction contaminants can adulterate the water: VOCs, paints, glues, diesel, oils, other noxious substances, and cement. The building and construction undertakings are the main cause for the contamination of rivers, lakes and consequently the aquatic life and fishes [60]. The environmental dangers are especially inordinate when the constructions are on the highlands, coastal zones, streams and lakes. Substantial metal ions from constructive locales and materials, dirtying the nearby water bodies and waterways have been found to interface with cell segments of the aquatic animals, for example, DNA and nuclear proteins, causing DNA harm and conformational changes that may prompt cell cycle modulation, carcinogenesis or apoptosis [8, 13, 69].

10.5.1 Effects of Cadmium (Cd)

The most widely recognized utilization of cadmium in industry is in the creation of nickel–cadmium (Ni–Cd) rechargeable batteries and as a conciliatory corrosion-protection covering for iron and steel. Other uses include alloys, coatings (electroplating), solar cells, plastic stabilizers, and pigments.

Because of its high toxicity and lethal effects, the cadmium adversely affects the fishes and other marine organisms which disturbs the whole food chain and alters the ecological structure and balance [59].

10.5.2 Effects of Copper (Cu)

Copper has earned a regarded place in the related fields of engineering, building development, and inside structure. From cathedrals to castles and from homes to workplaces, copper is utilized for an assortment of architectural components, including rooftops, flashings, drains, downspouts, arches, towers, vaults, wall cladding, and building expansion joints [64].

Toxicity of Cu to oceanic living beings relies upon its “bioavailability” or its capability to move from water or food to a receptor (e.g., gills, olfactory neurons, and so on.) on a life form where poisonous impacts can happen.

10.5.3 Effects of Iron (Fe)

Iron has become a significant architectural building component. It has been utilized in four normal structures: wrought iron, cast iron, sheet iron, and steel. These days, we in general, utilize iron to make steel, frequently utilized in manufacturing and civil engineering. Stainless steel, which is profoundly impervious to corrosion, it’s regularly utilized in kitchen cutlery, apparatuses and cookware—it’s additionally utilized for emergency clinic hardware. Uses of iron in day by day life incorporate hardware and apparatuses, vehicles, frames of boats, auxiliary components for buildings, extensions, bridges and aircraft.

10.5.4 Effects of Manganese (Mn)

Manganese has proven to be important for iron and steel manufacture because of its unique alloying and sulfur fixing properties. Another biggest use for manganese is in aluminum complexes. Manganese compounds have been utilized as pigments and for the coloring of ceramics and glass. Bigger amounts of manganese are utilized to produce pink hued glass. Manganese oxide is additionally utilized in Portland cement blends [56]. Waterborne manganese has a greater bioavailability than dietary manganese.

10.5.5 Effects of Nickel (Ni)

Nickel is utilized in numerous particular and conspicuous manufacturing and consumer items, like stainless steel, alnico magnets, coinage, rechargeable batteries, electric guitar strings, microphone cases, plating on pipe installations [18]. Around 27% of all total nickel manufacture is bound for industrial purposes, 10% for constructional works, 14% as cylindrical items, 20% as metal products, 14% as transportation, 11% meant for electrical merchandise, and 5% in other uses [48]. Nickel being an important element for aquatic fauna, is however deadly at greater levels [30].

10.5.6 Effects of Lead (Pb)

Lead is being utilized for the bullet manufacturing since their discovery. It is economical; its lower liquefying point implies little weapon bullets and shotgun capsules are known to be casted with insignificant specialized gear; besides it is solider in comparison to other normal metals, which takes into consideration improved maintenance of speed. Lead is known to be the primary material for projectiles, alloyed thru diverse metals as hardening substances [55]. Lead has numerous utilizations in about all production industry; lead leaves are utilized as architectural metals for tiling materials, covering materials, glimmering, canals and drain linkages, as well as on rooftop ramparts [70].

In aquatic animals, lead shows noxiousness in numerous muscle tissue types, destructing the nerves, kidney tissues, sexual organ tissues, blood cells, as well as heart and endothelial systems after its consumption or intake [5].

10.5.7 Effects of Zinc (Zn)

Zinc is utilized predominantly for galvanization of iron, nevertheless is likewise imperative in the manufacture of some alloys. Zinc is also used in the preparation of negative plates in the rechargeable batteries and also in tiling on buildings. Zinc, is utilized in plastic manufacturing, greasepaints, glossy papers, paintings, lithography toners etc. as a pigment, although in elastic and rubber manufacture it acts as a reagent throughout manufacture as well as a temperature disperser during the finishing process. Engineering bases or poisonous sewage places are known to give rise to the higher amounts of zinc in water bodies to touch the heights that can cause major effects on the aquatic fauna [1].

10.6 Diseases Caused by Heavy Metal Poisoning

10.6.1 Minamata Disease

Minamata disease (also referred to as Chisso-Minamata syndrome) was first discovered in 1956 at Minamata city, Kumamoto, Japan and triggered by the discharge of methyl mercury through the wastewater from the industries at Chisso Corporation's organic plant. This chemical got accumulated in the shellfishes and fishes at Minimata Bay and Shiranui Sea, which caused mercury poisoning upon the consumption by the locals. The main symptoms of the disease are; hand and feet numbness, muscular weakness, blurred vision, hearing and speech defects. In its worst cases, paralysis, coma and even death may follow as well. A hereditary effect may likewise affect the foetus in the womb [43].

10.6.2 Itai-Itai Disease

Itai-itai ailment is known to be triggered by cadmium contamination owing to the mining process in Toyama Prefecture. The cadmium along with the subsequent heavy metals amassed equally in the water as well as the river bottom. The contaminated water was afterwards supplied to the rice fields for the irrigation purpose. The heavy metals, particularly cadmium got absorbed into the rice seedlings and accumulated in the main tissues of the rice plants and thereby in the local populace consuming the rice. These mines are in operation still, thus the cadmium levels remain always higher. However, the disease is now known to be diminishing due to the enhanced food and medical maintenance. Cadmium exposure was brought into the rivers by mining companies within the foothills and highlands. Among the worst effects of cadmium exposure is feeble and fragile skeletons. Back and limb discomfort is common, as well as a toddling posture frequently develops owing to the skeletal irregularities instigated by the cadmium. The discomfort ultimately develops incapacitating, with breakages getting extra frequent by way of the skeletal weakness. Other difficulties comprise sever cough, anemia, and renal dysfunction, leading to death [43].

10.7 Assumption and Recommendations

Heavy metals are extremely poisonous, injurious as well as perilous ecological contaminants. Every type of aquatic pollution affecting the bodily processes, growth, development or endurance of fish, consequently affects humans while consuming the fish. The concentration of heavy metals beyond their threshold range may prove dangerous to terrestrial, marine and human wellbeing. Environmental adulteration by the heavy metal contamination damages the aquatic fauna and fish which inturn may affect the ecological equilibrium. Heavy metals are also known to cause impairment to capacity of growth, development, propagation, sustenance as well as fish existence by upsetting physiological, biological, metabolic, general and hereditary properties. Man, being at the extreme of the food chain, is directly or indirectly affected through either end. Therefore precautionary actions should be taken to lessen the concentration of toxic metal contamination in marine environments. There are numerous ways to avoid aquatic pollution and contamination.

So as to appropriately characterize the potential employments of surplus resources in civil engineering, nitty gritty examinations on every material's potential antagonistic impact to the environs and its parts is the need of the hour, basically because of the way that natural adequacy and ecological suitability is a central norm of viable ecological reprocessing. To appropriately characterize potential ecological danger of waste material use in industries and construction, it is important to analyze point by point examinations on all out substantial metal meditations and on draining capability of unsafe materials restricted inside a substantial matrix. Be that as it may, heavy metal ranges, at both aggregate and filtered levels, are deficiently talked in the existing statutes and can't be utilized when addressing resources for civil engineering and structural designing drives.

The manufacture industry must limit and cope with the generation of contaminants which influence the environmental in one or the other way. The control measures may comprise of a mix of development procedures, auxiliary and vegetative actions, and soil maintenance methods. For most extreme impact, it is significant that entirety in the regulating actions to be executed are incorporated into the site advancement strategy [66]. The multifaceted nature as well as the degree of regulating procedures compulsory will be governed to a great extent by the scale and length of the production activity [50]. In general, there is an elevated series of consciousness and obligation as to preserving the environment amongst outworkers and others associated with the manufacturing process.

10.8 Conclusion

In an incredible number of surface water bodies there is an issue fulfilling the quality guidelines. This issue is additionally (yet not exclusively) brought about thru leakage of materials from the building and constructing activities. The heavy metal pollution is essentially intense by the chemical and metallurgical productions, particularly thru the electroplating production line and zinc smelting plants.

The higher and extreme concentration of heavy metals is known to be detrimental for the marine and for human wellbeing as well. Ecosystem contamination from heavy metal adulteration could harm aquatic animals and plants at the cellular level which in the long run affects the ecological equilibrium. The aquatic animals consume heavy metals through diffusion via body surface, gills and food and hence accumulating the metals in their body parts.

While different wastewater treatment techniques are being investigated by industries and different treatment plants, untreated wastewater is as yet being released into the water bodies by certain ventures. Along these lines, effective ecological protection arrangement consistence drive will be of colossal advantage to nature and by expansion to human. Considering these environmental protection policies into the objectives and goals of different actors engaged with ecological disintegration will help strategies execution. This will fill in as a stage forward toward ameliorating water contamination. Chemical assessment is mandatory to distinguish the elements and materials which are known to cause ecological impacts. Both compound examination and ecological adulteration tests are required to help the additional improvement of ecofriendly development resources.

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Chapter 11
Life Cycle Cost Analysis of Energy Efficient Buildings: Theory and Study Case

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Abstract Implementation of energy efficiency and renewable energy in the construction industry has become a main strategy towards a sustainable built environment. One of the pillars of sustainable development, besides the environmental and social aspects, is the economic efficiency. Therefore, economic efficiency throughout the life cycle should be addressed as well when designing highly energy efficient buildings. Buildings are long term investments, which assume that the initial decision on the quality of the investment has long term consequences. The purpose of this chapter is to present the method of life cycle cost (LCC) analysis from the various perspectives existing in the literature and standards. LCC of evaluation is extremely important towards the promotion of energy efficiency measures in front of investors, building owners and authorities. Therefore, it is necessary for architects and engineers to have the basics for applying the LCC analysis and to include it in the design phase of a building.

11.1 Introduction

The attention towards energy efficiency is becoming increasingly present in all fields of activity, as it is an essential action in the climate change mitigation process. Reducing the energy consumption from fossil fuels and use of a higher share of energy from renewable sources are necessary steps in order to cope with the global energy challenge and climate change consequences. According to the International Energy Outlook 2016 (U.S. Energy Information Administration (EIA), between 2012 and 2040 there will be a 48% increase in the worldwide energy need [22]. A major part of this growth is assigned to the Asian non-OECD countries (outside the Organization for Economic Cooperation and Development) where the strong economic

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development and increase of population is assumed to lead to a 45% increase of the energy need by 2040 compared to 2012 [22]. With this prevision ahead, solutions of decoupling the economic growth and development from the energy requirements should be implemented. The high worldwide energy consumption from fossil fuels and also the previsions of future growth of energy need implies the increase of environmental pollution through the greenhouse gas emissions. The climate change phenomena is a consequence of human activities that generate greenhouse gas emissions (burning fossil fuels, emissions from the transport sector etc.), which due to their high concentration lead to heat-trapping in the atmosphere and increase of the global temperature. According to the Intergovernmental Panel on Climate Change's Third Assessment Report [9], over the course of the twentieth century the global average surface temperature increased by nearly 0.6 °C and the concentration of CO_2 in the atmosphere increased by about 80% between 1970 and 2004. During the 21st Conference of Parties in Paris, on 12 December 2015, Parties to the United Nations Framework Convention on Climate Change (UNFCCC) established a new agreement to avoid and combat climate change and also to improve the steps required for a safe and clean natural environment. Under the Paris Agreement, UNFCCC Parties seek to reduce the rise in global average temperature well below 2 °C above pre-industrial rates with a view to reducing the adverse effects of climate change. The Paris Agreement entered into force on 4 November 2016 and requires to all Parties to enhance their efforts in achieving the goals of the agreement. Governments have agreed to submit their contributions every five years in order to establish future objectives. The European Union agreed to continue providing funding for climate change to support developing countries to reduce emissions and strengthen their resilience to climate change. In addition to the well-known targets set through the Climate and Energy Package 2020 adopted in 2007, the European Commission presented a long-term policy plan as a climate action for the European Union. The goals for 2050 are to reduce GHG emissions by 80–95% relative to 1990 rates [2]. In 2014, an intermediate climate and energy policy framework for the period from 2020 to 2030 was released [4]. This brings new perspectives as to reduce greenhouse gas emissions by 40%, to increase the share of renewable energy production by more than 27% and to increase energy efficiency by 27%. According to the data from Eurostat, the evolution of the final energy consumption by sector in the European Union between 1990 and 2015 shows an increase of the consumption in the residential-tertiary sector and transport and a decrease in the industry and agriculture sectors [20]. The continuous development of transport infrastructure and transport in recent years led to a significant increase of energy consumption in this sector (from 26.24% in 1990 to 33.14% in 2015). Significant as well is the decrease of energy consumption in the industry sector. In 2015, the energy consumption in the building sector represented 39% of the total energy consumption in the European Union, registering an increase of almost 4% compared to 1990. The significant share of energy consumption of the building sector from the total energy consumption makes it responsible for 36% of CO_2 emission in the European Union. Thus, a high potential of reducing the energy consumption from fossil fuels lies in the building sector and therefore is a key player in achieving the long-term objectives of the European Union to reduce the greenhouse gas emissions up to 80–95% by 2050, compared to 1990 levels [5].

Buildings are long term investments, considering that the majority of buildings are designed to have a lifetime of 50 years. Moreover, the majority of the existing buildings are inefficient from energetic perspectives and they will most certainly be standing by 2050. Therefore, it is essential to improve the energy efficiency of the existing buildings through renovations but also to construct new buildings that are highly energy efficient. Throughout time, standards that set minimum energy efficiency requirements for buildings were developed at national level of countries in the European Union. Also, there are various international standards of energy efficient buildings such as the passive house standard, which provides energy efficiency criteria in terms of heating energy demand and primary energy consumption but also detailed guidelines on how to achieve the criteria. Regardless of the type of energy efficient building, there are several aspects that must be considered when designing such a type of building. These aspects are related to both building envelope and building systems and include: thermal insulation, advantageous orientation, thermal bridges reduction, envelope airtightness, mechanical ventilation with heat recovery, efficient windows glazing and frames, use of ground-sourced heat exchanger. An energy efficient building can be provided as well with equipment that uses renewable energy or technologies to produce energy on site such as photovoltaic panels. All these energy efficiency measures must be assessed from an economic point of view in order to balance the initial investment with the annual costs on the life cycle of the building. There are situations when a good thermal insulation can assure a maximum efficiency of an investment but if exceeded it can also lead to economic inefficiency. Therefore, it is important to corelate the energy efficiency measures in order to obtain a cost-optimal investment. Marszal and Heiselberg [12] concluded in their study that it is cost-effective to first reduce the energy need to a minimum, and afterwards implement renewable energy technologies to compensate the remaining energy demand. In order to support and increase the energy performance of buildings, the EU has provided a legislative framework, including the recast on the Energy Performance of Buildings Directive EPBD [6], through which Member States are mandated to establish specific plans to implement nearly zero-energy buildings and improve the energy efficiency by using cost-optimal solutions. According to Article 2 of the EPBD recast [6], a nearly zero-energy building is a very high-performance building, where the nearly zero or very low energy requirements should be met to a very significant extent by renewable energy sources, including on-site or local renewable energy sources. At the time when the EPBD recast was launched, each Member State was required to detail a nearly zero-energy building definition by considering their specific conditions and national context. In Romania, a more specific definition was provided in the past years, stating the energy need of a nearly zero energy building must be covered with at least 10% renewable energy produced on site or nearby, while the maximum admissible primary energy consumption depends on the building category and climate zones in Romania. The energy performance of nearly zero-energy buildings must be linked to the economic aspects in order to identify the solutions that have the lowest global cost on the economic life cycle. Thus, the “cost optimal" or "cost-effective" notions have to be considered when developing nearly zero-energy buildings. The cost-optimal level is defined as the level of energy efficiency that leads to the lowest cost during the projected economic lifecycle, where the lowest cost is calculated taking into account energy-related investment costs, maintenance and operating costs, disposal costs and energy-generated earnings [6].

The general approach when it comes to the energy need and consumption of a building is divided in two main aspects:

- building thermal envelope characteristics, which is ultimately translated into energy demand for heating and cooling
- building heating, cooling, ventilation and domestic hot water systems features.

The above-mentioned elements, which ultimately define the energy efficiency of the building, must be balanced so that the initial investment cost is minimum. As it is required through EPBD, the energy performance of buildings must be connected to the economic aspects with the purpose of identifying cost optimal solutions. Nowadays there are a multitude of possible solutions in terms of energy efficiency, for both building envelope and building systems. Therefore, it is important to investigate various scenarios of energy performance and costs, in order to choose the solutions that brings the best benefits in terms of energy savings but is also cost-effective.

This chapter presents the life cycle cost analysis of an existing residential building in three variants of energy efficiency. The case study house was designed and constructed following the passive house design guidelines. This study introduces an upgrade of the existing building by proposing the implementation of photovoltaic panels to cover the electricity demand of the building, thus achieving the nearly zero energy building standard. The two scenarios will be compared with the reference building in Romania, composed according to the minimum energy efficiency criteria that are currently mandatory in Romania and are regulated through the Methodology for Calculating the Energy Performance of Buildings Mc 001/2006, updated in 2017 [17].

11.2 Background

The construction of a building is a long-term investment and therefore the quality and efficiency of the chosen solution has long term consequences. Unfortunately, most of the times, the clients and investors are looking only at the initial costs of a building and not consider the future costs for energy and maintenance. Therefore, very often investors lack the overall approach which leads to the selection of an economically inefficient solution throughout a building's life cycle. Life cycle cost analysis (LCCA) is a good method for evaluating and comparing several building designs options from the perspective of initial cost and future costs [15]. This type of economic assessment can generally be used for predicting and evaluating the cost performance of constructed assets [10] and is extremely useful for comparative cost assessments over a specified period of time. In other words, LCCA provides information about the economic performance of a building throughout its life span. This analysis can be performed for new building in the design phase but also for existing buildings when renovation solutions are needed. The concept of life cycle cost started being used in the construction sector back in 1970s for public investments. Throughout time, there has been a great interest in researching and developing the field of life cycle cost analyses in all parts of the world and the methods include calculating and analysing the present value of all costs that occurs throughout the life cycle of a building. There are a variety of works that use the LCCA of buildings, being frequently used in combination with energy analysis of a building. Furthermore, LCCA is considered a decision-making factor in the building sector projects [7]. Moreover, recent research shows a growing interest towards the integration of economic and environmental analysis by joining the LCCA with life cycle assessment [8]. Badea et al. [1] created a mathematical model to analyse the life-cycle cost of a passive house in 14 different energy efficiency configurations and concluded that it is easier to make a decision for a possible investment by using LCCA classifications. Moran et al. [13] applied the life cycle cost and environmental analysis to assess a number of case study buildings that use various heat sources. Another study applied the life cycle analysis to promote the implementation of maintenance plans as a way of reducing global costs and increasing the life of materials [16]. LCCA was applied to investigate the implementation of a hybrid energy system for a typical residential building [14].

11.3 Life Cycle Cost Analysis Methodology

According to the literature review, a general mathematical model of life-cycle is based on the fact that every category of cost is updated at the present value, considering the discount rates. The life-cycle cost calculations were performed following the mathematical model for global cost calculation presented in EN 15459:2006 [21], which is a standard for economic evaluation procedure for energy systems in buildings. This procedure is based on calculating the global cost, considering the initial investment, the present value of annual costs on the period of analysis and the final value the building and all its components at the end of the analysis period. Following the Delegated Regulation No.244/2012 [3], the global cost calculation must include following cost categories:

- Initial investment cost CI;
- Yearly costs Ca (energy costs, operational costs, maintenance costs, replacement costs);
- Disposal costs (if applicable);
- Costs related to the greenhouse gas emissions (only for macroeconomic calculations).

In other words, the global cost is the sum of all the above-mentioned categories of costs, all updated to present value. The net present value of the future costs depends on the discount rate, price growth rate and period of analysis, which are extremely important factors in the equation. Based on EN 15459:2006 [21], the mathematical model for global cost calculation is presented in Eq. 11.1:

$$\boldsymbol{CC} = \boldsymbol{C_g(\tau)} = \boldsymbol{C_I} + \sum_{j}[\sum_{t=1}^{T}(\boldsymbol{C_{a,i}(j)} \times \boldsymbol{R_d(i)}) - \boldsymbol{V_{f,\tau}(j)}] \tag{1}$$

τ—calculation period.

$C_g(\tau)$—global cost on the considered calculation period (referred to starting year τ_0).

CI—initial investment cost.

$C_{a,i}(j)$—annual cost during year i for measure or set of measures j.

$R_d(i)$—discount factor for year i based on discount rate r.

$V_{f,\tau}(j)$—residual value of measure or set of measures j at the end of the calculation period (discounted to the starting year τ_0).

Using the discount factor, calculated based on the discount rate, the present value of future costs is determined. The discount rate does not only weigh money time value, but also potential cash flows ‘ risk and unpredictability. The discount rate depends on several factors including: interest rate, profit rate, the rate of increase of the national income and can be assimilated to them [20]. In global cost calculations, a real discount rate must be used, which means that the inflation is not considered. The discount factor is calculated using the Eq. 11.2.

$$R_d(p) = \left(\frac{1}{1 + \frac{r}{100}}\right)^p \tag{2}$$

where:

r—real discount rate [%].

p—number of years passed from the starting year of the analysis.

The calculation period is defined as the time period in years for which the global cost calculation is performed. The decision on the period of analysis takes into account the technical lifetime of the building and building components. The calculation period can be the lifetime of the building defined in the design phase, which is usually 50 years for most of the buildings. The calculation period may also be defined as the period of time after a series of major renovations and overall improvements have been made to the building. Major renewal cycles vary from one building to another, but almost never below 20 years. When calculating global costs, future price growth must also be considered in real terms (excluding inflation) by using price growth rates when calculating the annual costs. The future price growth rate is very important, especially in studies that include costs of energy, which frequently changes over time. At the end of the analysis period, the residual value of the building components must be calculated considering the remaining lifetime. Based on EN 15459:2006 [21], the residual value of building components is calculated following the mathematical formula in Eq. 11.3:

$$V_{f,\tau}(j) = V_0(j) \times \left(1 + R_p\right)^{n \times \tau_n(j)} \times \left(\frac{(n+1)\tau_n(j) - \tau}{\tau_n(j)}\right) \times \frac{1}{(1 + {}^{r}/_{100})^{\tau}} \quad (3)$$

where:

$V_{f,\tau}(j)$	final value of component j
$V_0(j) \bullet \left(1 + R_p\right)^{n \bullet \tau_n(j)}$	price of component j considering the evolution of products costs;
$\left(\frac{(n+1) \bullet \tau_n(j) - \tau}{\tau_n(j)}\right)$	straight-line depreciation;
$(1 + \frac{r}{100})^{\tau}$	discount factor value at the end of the calculation period.
n	number of replacements during the calculation period
$\tau_n(j)$	lifespan for building component j.

11.4 Case Study: Comparative Life Cycle Cost Analysis of a Residential Building

11.4.1 Description of the Energy Efficiency Scenarios

The case study building was built in 2011 near Timisoara, being part of a research project developed by Politehnica University Timisoara, entitled “Passive house and Nearly Zero Energy Buildings—sustainable solutions for residential buildings”. The first phase of the mentioned project aimed to build a house based on design principles specific to passive houses and using traditional materials and technologies that are specific to residential constructions in Romania. The investigated building has two floors with a rectangular horizontal plan and prismatic volume. The structural system consists in concrete foundation blocks connected by foundation beams, structural masonry walls with reinforced concrete columns and belts and wooden beams floor. Table 11.1 summarizes the geometric parameters of the building which is characterised by compactness and south orientation of large windowed façade, as it is specific to passive houses.

For this study, three configurations of the case study building were investigated, namely:

- As built house and technical systems—PH
- As built house and technical systems with a 4.8 kW power grid connected photovoltaic panels system—NZEB
- Reference building—RB

Table 11.1 Geometry data for the case study building

Indicator	Value	Indicator	Value
Treated floor area [m^2]	141.8	Exterior walls [m^2]	158.6
Envelope area [m^2]	393.9	Ground floor [m^2]	86.7
South windows area [m^2]	16.5	Roof terrace [m^2]	96.6
East windows [m^2]	12.7	Cantilevered floor [m^2]	6.8
West windows [m^2]	9.7	Interior volume [m^3]	354

Table 11.2 Energy related characteristics of the investigated configurations of the case study building

		PH and NZEB[a]	RB
Thermal insulation	Exterior walls	30 cm polystyrene	8 cm polystyrene
	Ground floor	40 cm polystyrene	20 cm polystyrene
	Roof	42 cm polystyrene	20 cm polystyrene
	Cantilevered floor	50 cm polystyrene and mineral wool	20 cm polystyrene
	Windows	triple glazing windows	double glazing windows
	Technical systems	Air—water heat pump—rated heating capacity 5.2 kW Fan coils installed in the ceiling Air—water heat pump with reversible cycle solar panel 4.92 m^2 Domestic hot water boiler—0.15 m^3 Mechanical ventilation with heat recovery Soil-air heat exchanger for preheating/precooling the fresh air	Condensing gas boiler for space heating and radiators for heat distribution Gas boiler for domestic hot water Multi split cooling

[a] NZEB also has 20 polycrystalline PV panels with a 14.74% module efficiency and 240 W power inverter 5 kW nominal power

The reference building has the same geometrical characteristics, volume and envelope elements areas as the real building, but complies with the minimum requirements required by Romanian legislation in terms of energy efficiency. NZEB is a package that intends to be an upgrade of PH through the implementation of on-site renewable energy production technologies. A more detailed description of the energy efficiency packages is presented in previous papers and reports (Tanasa, [20]. The characteristics of each scenario are presented in Table 11.2, where thermal insulation thickness, technical systems and renewable energy technologies are listed.

11.5 Energy Consumption Evaluation

11.5.1 Energy Models

The energy consumption evaluations of the energy efficiency packages earlier presented was performed using the dynamic building simulation software EnergyPlus. The construction of the models started from the already existing building energy model of the real building by modifying the features to match each of the energy efficiency packages. The simulations were conducted using the typical year weather data file for Timisoara from International Weather for Energy Calculations (IWEC), available on EnergyPlus software web page in section Weather. The heating systems were scheduled to be available from the 15th of October until the 15th of April and the cooling system availability was set between 15th May and 15th September. The heating temperature setpoint was set to 20 °C while the cooling set point to 26 °C. The building was considered to be occupied by a family of three persons. The occupancy schedule was defined for weekdays and weekends, as fraction from the total number of occupants. Thus, a typical occupancy schedule was defined for weekday and weekend. During weekdays, between 23:00 and 07:00, the bedrooms are considered fully occupied, while the living room and kitchen were occupied by two persons between 09:00 and 18:00 and fully occupied between 18:00 and 22:00. The outdoor air flow rate for the mechanical ventilation was set to 0.4 air changes per hour for NZEB and PH, while natural ventilation was considered for RB with fresh air rate of 0.6 h^{-1} [20]. Besides heat gains related to occupancy, a part of the energy consumed by the interior electrical equipment and interior lighting in the building also becomes a heat gain and influences the building energy balance. The internal loads associated to interior lighting and electrical equipment were considered through hourly electricity consumption schedules defined as fraction of lighting and interior equipment power [20].

11.5.2 Simulation Results

Table 11.3 presents the end use energy for each building scenarios and the amount of energy produced. In order to better compare the end use energy of the proposed energy efficiency packages with the energy use of the reference building, the total energy consumption was also converted to primary energy from non-renewable sources.

As it can be seen in Table 11.3, the energy consumption for lighting and interior equipment is constant for all scenarios because no energy efficiency measures were considered for these two ends uses. Differences can be seen with respect to energy consumption for heating, cooling and domestic hot water, which are much lower for PH and NZEB compared to RB.

The conversion to primary energy was made considering the Romanian conversion factors for each type of energy: 1.17 for natural gas and 2.62 for electricity [17]. For

Table 11.3 Energy consumption and primary energy from non-renewable sources

		PH	NZEB	RB
Heating	Electricity [kWh/m^2]	13	13	0
	Natural gas [kWh/m^2]	0	0	95.7
Cooling electricity [kWh/m^2]		2.9	2.9	5.6
Lighting electricity [kWh/m^2]		1.1	1.1	1.1
Household appliances [kWh/m^2]		9.5	9.5	9.5
Pumps electricity [kWh/m^2]		5.7	5.7	6.6
Fans electricity [kWh/m^2]		5.8	5.8	None
Domestic hot water electricity	Electricity [kWh/m^2]	4.5	4.5	0
	Natural gas [kWh/m^2]	0	0	19.6
On site electricity—PV production [kWh/m^2]	None	None	43.2	None
Total energy consumption	Electricity [kWh/m^2]	42.5	42.5	22.8
	Natural gas [kWh/m^2]	0	0	115.3
Primary energy from non-renewable sources [kWh/m^2]		111	− 2	194.5

NZEB, the primary energy from non-renewable sources is calculated as the difference between the primary energy corresponding to the energy imported from the grid and the primary energy corresponding to the energy exported to the grid [11]. According with the current Romanian requirements for residential nearly zero-energy buildings, the primary energy consumption is 111 kWh/m^2 for the climate zone II, where the building is located [18]. Thus, both PH and NZEB are in line with this prescription. Moreover, NZEB configuration leads to a negative value for primary energy, because the electricity production from PV panels is higher than the energy consumption.

11.6 Life-Cycle Cost Calculation

11.6.1 Initial Investment Assessment

The PH building's initial investment was calculated using the specific costs of building construction and equipment, given by the building owner. All taxes and VAT are included in the value. The costs were split into: structural system construction, thermal insulation, windows, technical systems (heating and cooling equipment, ventilation, hot water, heating terminals etc.). These costs have then been adjusted to suit each of the other two scenarios, NZEB and RB. For NZEB, the initial investment is the same as for PH, having only the PV system extra. The costs of building construction and structural system are the same for all three configurations. The initial investment costs are presented in the graph in Fig. 11.1. The highest invest-

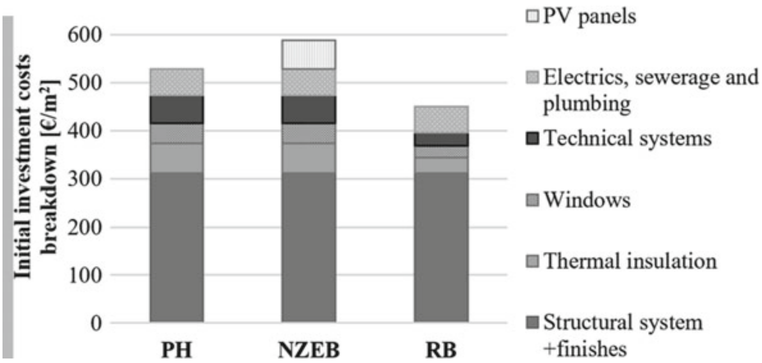

Fig. 11.1 Initial investment costs breakdown

ment costs are for NZEB, which corresponds to real building envelope and technical systems with extra investment for 20 photovoltaic panels. The initial investment of NZEB is approximately 11% higher than the initial investment of PH, due to the implementation of PV panels. Obviously, the lowest investment cost is the one of the reference building, which is 15% lower than PH and 23% lower than NZEB. We can see how the initial investment for structural system and finishes remains constant among the building packages. The costs of technical system of the reference building is the lowest and also the costs of thermal insulation and windows.

11.6.2 Periods of Analysis, Discount Rate and Price Growth Rate

The calculation period was selected following estimated service life of the house, which is 50 years. The discount rate is used in the calculation of the global cost to determine the present value of the amounts of money paid (earned) in the future. The discount rate does not only consider the value of money over time, but also the risk or unpredictability of future cash flows. A discount rate of 3% was used, as it is the same rate used by the Romanian authorities in global cost and cost optimal calculations [19]. The future growth of energy prices has a significant influence on the balance of the costs, especially in case of energy efficiency buildings. In this study, an average price growth rate of 5% was used for the electricity and natural gas prices [20].

11.6.3 Annual Costs, Replacement Costs and Residual Value

Annual costs include the following categories: maintenance costs, replacement costs and energy costs. The replacement costs depend on the lifespans of the different building systems components, which were established using Annex A of EN 15459:2006 [21]. For each component that has a lifespan shorter than the calculation period, a replacement cost is considered in the year of the replacement. The replacement cost is actualized at present value using the discount rates.

The maintenance costs include those cost necessary for the quality conservation of the building systems in time. The costs refer to inspection costs, adjustments, repairs and preventive maintenance. Thus, the global cost is calculated considering that the equipment and building systems are properly maintained and periodically inspected. The maintenance costs were established in compliance to EN 15459:2006 [21], which offers data related to maintenance costs for different types of building components, expressed as percentage of the initial investment of each component. Table 11.4 lists the annual maintenance cost and number of replacements for different building components of the investigated building scenarios. The residual value for each building component was calculated at the end of the analysis period, using

Table 11.4 Lifespan and data for maintenance costs and replacement costs calculation

Component	Life span [years]	Annual maintenance cost in % of the initial investment	Number of replacements
Thermal insulations	50	–	0
Structural system	50	–	0
Windows	30	–	1
Condensing boiler	20	1–2	2
Fan coils	15	4	3
Expansion vessels	30	1	1
Ventilation fans	15	6	4
Heat pumps	20	2–4	2
Heat recovery units	20	4	2
Circulation pumps	20	2	2
Radiators, water	30	1–2	1
Tank storage for hot water	20	1	2
Wiring	30	1	1
Solar collector	25	0.5	1
Piping system	30	0.5	1
Photovoltaics	25	1	1
Split air conditioning	20	4	2

Table 11.5 Annual costs used for life cycle cost calculation

		PH	NZEB	RB
Annual costs	maintenance costs [€]	164	201	150
	energy costs [€]	717	301	1360

Eq. 11.3, and was subtracted from the global cost. The energy costs were calculated using the prices for natural gas and electricity in Romania. In this paper are considered prices of fossil fuels (natural gas) of 0.06 Euro/kWh and also the price for electricity from the National Grid of 0.13 Euro/kWh. In the energy costs calculation, the benefits from electricity exported to the grid were accounted. It was assumed that the electricity exported in the grid is sold with a price of 0.048 €/kWh. In Table 11.5 are listed the annual maintenance and energy costs for the three situations.

11.6.4 Life-Cycle Cost Results

In Fig. 11.2 are presented the results of the global cost calculations on costs categories. As expected, the highest global is the one of the reference building due to the high energy. Maintenance costs have the lowest values from the considered cost categories, followed by cost of replacement and cost of energy. The energy costs decrease proportionally with the energy consumption. Therefore, the lowest energy costs throughout the life cycle correspond to NZEB followed by PH. The global cost of RB is approximately 26% higher than the one corresponding to PH and 47% higher than NZEB. By comparing PH with NZEB, it can be observed that PH has a higher global cost with approximately 16%. Residual values are insignificant for all three configurations as the calculation was performed for a period of 50 years which is also the service life of the house. In Fig. 11.3 is presented the life-cycle cost variation throughout the calculation period. In this graph is noticeable how the high

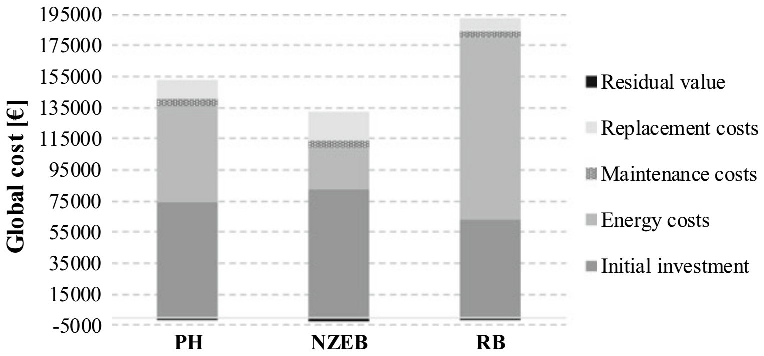

Fig. 11.2 Life-cycle costs breakdown

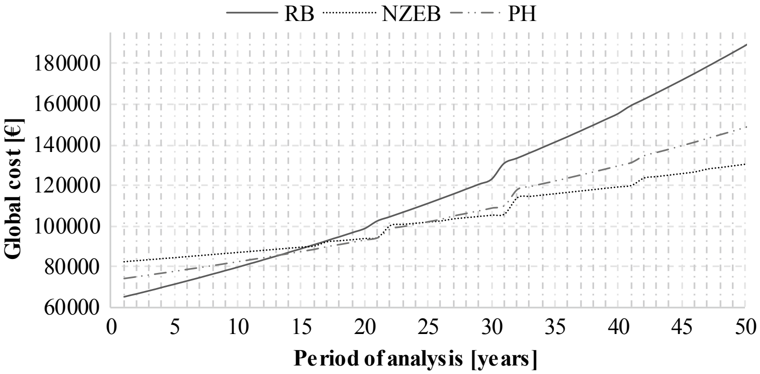

Fig. 11.3 Life-cycle cost variation

annual costs of the RB lead to overcome the global cost of NZEB and PH, despite the lower initial investment. It can be observed that after approximately 14 years, the global cost of RB overcomes the global cost of PH. The global cost of NZEB is exceeded by that of RB after about 16 years. If PH and NZEB life cycle cost variations are compared, it is noticeable that they maintain close values for most of the analysis period. The global cost of PH house slightly increases over NZEB after 23 years.

11.7 Sensitivity Analyses

A sensitivity analysis was performed order to determine the influence that the variables used in the calculation have on the final result. The purpose of this analysis is to assess the output data that are obtained after varying precise input variables such as discount rate and period of analysis. The sensitivity analyses improve the decision-making process because it allows the evaluation of the robustness of the results. The first step in the sensitivity analysis is to define the input variables that could most affect the final result of the evaluation. In this study, the variables considered for sensitivity analyses are the discount rate and the period of analysis. The following variations are proposed:

a. Discount rate:

  - Base case scenario: 3%
  - Scenario 1: 0.5%
  - Scenario 2: 1%
  - Scenario 3: 2%
  - Scenario 4: 4%
  - Scenario 5: 4%

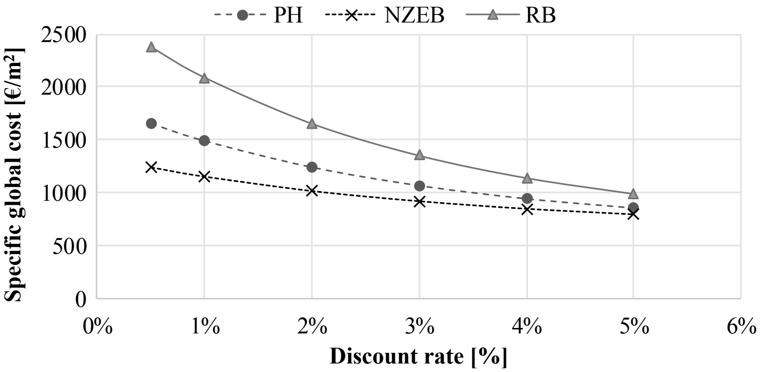

Fig. 11.4 Life-cycle cost change with respect to discount rate variation

b. Period of analysis

- Base case scenario: 50 years
- Scenario 1: 10 years
- Scenario 2: 20 years
- Scenario 3: 30 years
- Scenario 4: 40 years.

In Fig. 11.4 it can be observed how the global cost changes with the variation of the discount rate. By increasing the discount rate, the net present value of the future costs decreases, and thus they comprise a smaller part of the life cycle cost. Applying a 5% discount rate the global cost decreases for all three building scenarios. By still analyzing the results obtained, it is easily intuitive how the variation of the discount rate influences the global costs. The global costs are higher with a lower discount rate and vice versa, global costs are lower by using a higher discount rate. This can be simply deducted from the formula for calculating the global cost (Eq. 11.1), where it is noticeable that the two values are inversely proportional. Therefore, as the discount rate increases, the global cost values will tend to decrease and vice versa. Nevertheless, it can be affirmed that the results of the global cost calculations are robust with respect to the variation of the discount rate. The NZEB scenario remains the option with the lowest global cost over a wide range of discount rates. However, as the discount rate increases, NZEB global cost is almost approaching PH and RB global costs. In other words, a lower discount rate reflects better the benefits that energy efficiency investments bring over the life-cycle. Reversely, a higher discount rate minimizes the benefits of lower annual costs associated to energy efficient buildings, encouraging a purely commercial approach to the valuation of investment.

The second sensitivity analysis has been made by changing the calculation period in order to evaluate how a shorter or a longer investment time perspective influences the final results. Figure 11.5 shows the changes in global costs with respect to the variation of the period of analysis.

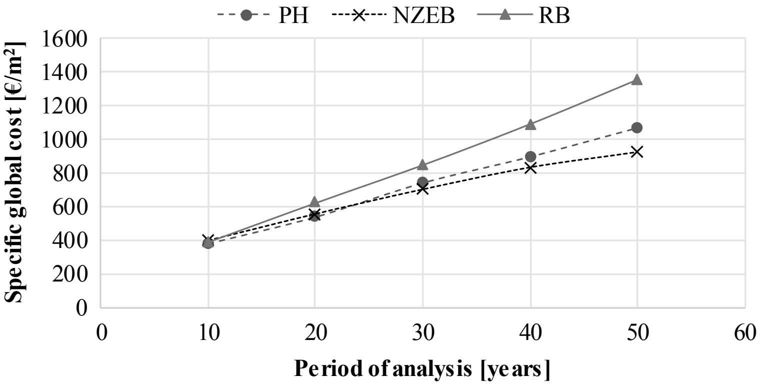

Fig. 11.5 Life-cycle cost change with respect to period of analysis variation

As expected, a shorter calculation period results in lower global costs, while a longer period of analysis of results in higher global costs due to the annual costs required for the operation and maintenance of the building. It is underlined that the gap between the global costs positions among the investigated scenarios increases along with the increase of the analysis period. For the 10 years period of analysis, the difference between the three scenarios is very small and the lowest global cost corresponds to PH, while the highest corresponds to NZEB. In case of 20 years global cost, PH still remain the most cost-effective, while RB global cost is the highest. The highest gap between RB and the energy efficient building packages is noticeable for the analysis performed on a period of 50 years. Intuitively, the longer the period of analysis, the more obvious the disadvantage of RB.

11.8 Conclusion

This chapter presents the life cycle cost analysis in terms of global cost for a residential building in three configurations: passive house (PH), nearly zero-energy building (NZEB) and reference building (RB). The main goal of this study was to assess the long-term advantages of highly energy efficient measures in buildings (PH and NZEB) in comparison to minimum energy efficiency requirements for residential buildings in Romania (RB). The study concluded that the higher initial investment of PH and NZEB can be recovered in approximately 14 years, respectively 16 years when compared to RB, for a discount rate of 3% and energy price growth rate of 5%. The extra investment in photovoltaic panels for NZEB becomes cost-effective after approximately 23 years. It can be concluded that with the current high prices of PV technology and low price of the electricity delivered to the grid, investing in PV panels, besides the other efficiency measures of PH, might not seem such an economically attractive solution due to the high break-even time. The design and construction of buildings with high energy performance, in addition to the energy renovation of existing ones, represents an important step towards decarbonizing the built environment and achieving the EU targets for reducing greenhouse gas emissions. As this study has shown, energy efficient buildings proved to be cost-effective on the long-term perspective. Also, the sensitivity analysis has shown that for buildings that have a lower energy consumption, the discount rate variation does not result in as great changes in global cost as for the reference building (RB). It can be concluded that buildings with high energy performance are not so vulnerable to the changes that financial market might encounter throughout the life-cycle.

11.9 Future Research Directions

This research follows a topic that is of great interest at an international level, among researchers, national authorities but also for the construction market and building owners. Therefore, research activities have still a long run to go in order to ensure an energy efficient built environment, which is cost-effective at the same time. The analyses are based on a series of specific parameters and assumptions such as the location of the building and corresponding outdoor weather conditions, economic indicators, user behavior and energy efficiency measures. The climatic parameters represent essential values in order to evaluate the energy performance of a building. Therefore, it is relevant to extend this study for the other climate zones in Romania. User behavior is as well an important factor in the equation of energy consumption of a building and the associated energy costs. Thus, a future research direction is to perform energy consumption analyses for different user behavior scenarios, to see just how much the way the building is operated can modify the yearly costs on energy. Moreover, life cycle cost analyses for different user behavior scenarios can show how user comportment can influence the energy and economic performance of a building throughout its life span.

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Chapter 12
Life Cycle Assessment, an Integrated Vision to Energy Efficiency in the Building Industry

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Abstract The evaluation of environmental aspects in the early planning phase of buildings supports the reduction of resource use and environmental impacts associated with the construction sector over the whole life-cycle of the building. In this chapter, the current calculation methodology is assessed and critically reviewed with regard to the usability option for the introduction of an automated and time efficient LCA benchmark. In order to derive a new set of benchmarks regarding the LCA, this chapter shall submit as potential data input, as it contains the conclusions of several LCA for non-residential building located in different parts of the world.

12.1 Introduction

In order to reduce the environmental impact of the construction sector, withheld for about 60% of the consumed resources, 35% of the worldwide greenhouse gas emissions (GHGE)[1] and about 40% of the total energy demand of an industrialized country, large amount of effort and resources are dedicated in the current research area to the early planning phases of buildings. These offer a considerable opportunity to reduce the long-term environmental impact of the building industry by means of considering the crucial decisions. Figure 12.1. presents the life cycle phases of a product/building from resource extraction till end-of-life or recycling [1].

According to previous undertaken studies by Asdrubali [2], the usage of green building strategies is effective in saving fossil fuels and reducing greenhouse gasses.

The EU Directives and the national laws include limits and requirements on energy consumption of the buildings aiming to reduce the CO_2 emissions. Recently, more

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[1] **Greenhouse gases**: a gas that contributes to the greenhouse effect by absorbing infrared radiation. E.g. carbon dioxide and chlorofluorocarbons.

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Fig. 12.1 Scheme of the life cycle of a product

and more attention is given to the embodied energy of a building and to the possibility of recycling construction materials at its end of life.

There is a clear interaction between the GHGE generated during all the stages of a building's life. For example, with greater level of building insulation and more efficient technical systems, the emissions produced decrease during operation stage.

But in this case, an increase is noticed during production and construction phases. The first question for designers and owners is, if it is better to invest more in construction phase or in the use and maintenance stages of the building [3–5]?

The application of a Life Cycle Assessment (LCA) is therefore necessary in order to certify the global environmental-impact and energy use during the entire life span of a building [6].

According to previous studies on existing buildings in Germany, the percentage of emissions generated during construction phase varies between 14 and 36% of total emissions in case of using as thermal energy source district heating, 23–46% for heat pump, 28% for geothermal energy source, 23–31% natural gas and 35% in case of electricity mix. All the buildings use electricity mix as a cooling source. The large variation range justifies a mandatory LCA in the design phase of new sustainable buildings which could reduce the environmental impact both in the operation but also in the construction phase [7].

The main objective stated by this chapter is to catalogue the environmental aspects in the early planning phase of several similar buildings. The integration of LCA benchmarks in the early planning phase would assist the reduction of the resource use and environmental impacts associated with the construction sector [3–5].

12.2 Background

The technique that assesses the environmental impact of the stages regarding a product life cycle, beginning with raw material extraction, processing, manufacturing, distribution, use, repair, maintenance, disposal and recycling is called life-cycle assessment (LCA) also known as life-cycle analysis, eco-balance or cradle-to-grave analysis. The main matters evaluated by LCA are:

- Inventory of the environmental emissions, energy and material inputs.
- Potential impacts related to identified inputs and outputs.
- Interpretation of the results in order to take better decisions.

According to the ISO 14040:2006 and 14044:2006, part of the larger environmental standards ISO 14000, the leading standards which specify the requirements for LCA, the assessment is carried out in four independent phases [8, 9].

12.3 LCA Regulations in Construction Industry

Currently, LCA is not used in the construction industry because the process of conducting an LCA, i.e. data gathering and data modelling are very time-consuming and therefore cost-intensive. The implementation of a regular and simple method to assess the life-cycle in the planning phase of buildings, should be established in order to reduce the time-effort.

In Romania, the only certification concerning the energy uses of the buildings is the thermal balance assessment according to the National Methodology Mc001-2006. The thermal balance in use today provides information only regarding the GHGE generated during the operation phase.

The Romanian legislation oversees the energy consumption only during the operation phase of the buildings and has no limitations regarding the emitted greenhouse gases in the production, maintenance and end-of-life phases of a building.

The implementation of an energy assessment in the early design phase of a building could help the owner of the future building understand the implication of the different building materials, envelope solution, heating alternatives and their influence on the initial and global cost including maintenance and GHG emissions.

Within the European Regulations, LCA will be mandatory integrated into the building environment tools according to the European ENSLIC Building Project guidelines for developed and implemented buildings, which provide practitioners guidance on methods to implement the data into the planning and design process.

In Germany, a currently undertaken study [7] show that passive houses (PH) and plus-energy houses (EPH) achieve great savings of GHGE in operation, but these are at the expense of an increased GWP in the construction phase due to an increased use of technologically complex materials. The qualitative shares of operation and construction for three types of buildings years were studied adopting the GHGE as an indicator. The GWP of the PH and EPH are represented in Fig. 12.2 along with the GWP of a building designed according to the German national performance-based code regarding energy use, named Energieeinsparverordnung (EnEV).

The EnEV performance-based code focused on the thermal envelope requirements, energy using and producing technical systems in the calculation along with hot water, lighting, HVAC, bio-climatic design and sustainable energy. The version published in 2009 includes many revolutionary aspects such as: low thermal conductivity values according to exterior climate, computer simulation, airtightness requirements, well established motivation schemes, heating and HVAC systems testing, substantial Engineering Procurement Construction (EPC) programs, energy classes and national targets for carbon free buildings by 2020.

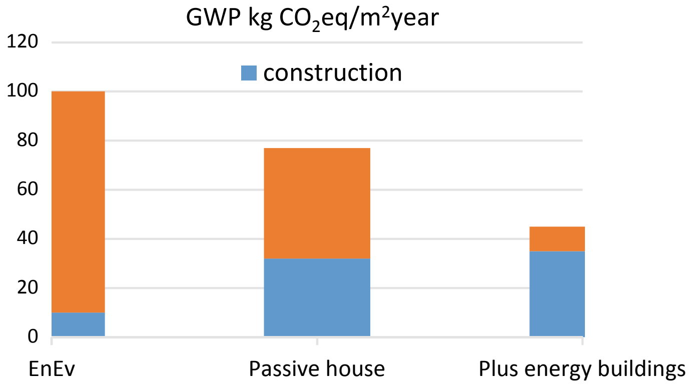

Fig. 12.2 Qualitative development of GWP's share for construction and operation in Germany [7]

Figure 12.2 presents the results of the conducted research; operation is describing the relevant GHGE regarding GWP that are emitted during the use phase whereas construction is referring to the relevant GHGE regarding GWP related to production, maintenance and end of life. On the left, the initial situation is clearly dominated by greenhouse gas GHGE from operation, while the construction phase is characterized by low greenhouse gas GHGE.

12.4 Main Phases of LCA

12.4.1 Goal and Scope

The first stage of the analysis is consisting of a statement regarding the goal and scope of the study. It sets out the context of the study and contains beside the information on the receiver of the LCA the following technical details:

- The functional unit—defines the studied object and the quantification of the service delivered by the product system. In general, meter square is the most used functional units in case of residential buildings, heated volume or heated floor area being also quite often used. The period in which a building is analyzed is assumed and not based on a calculation method. Lifetime assumptions are made for no longer than 100 years. According to statistics an average lifetime for a residential building is reported between 60 and 70 years.
- The system boundaries—delimitations of the included processes in the analysis.
- Assumptions and limitations.
- Allocation methods—i.e. information on the used partition of a process when multiple materials or services share the similar process.

- Impact categories—the quantification of the deterioration caused to human and environmental factors (examples: human toxicity, smog, global warming, eutrophication) [10, 11].

12.4.2 Life Cycle Inventory

The Life Cycle Inventory (LCI) analysis consist of an inventory of flows from and to nature for buildings construction, operation and disposal. Inventory flows encloses inputs of energy, raw materials and water and emissions to air, water and land. The inventory is developed by constructing a flow model of the system using the input (materials, services, energies) and outputs (GHGE, degradations). To develop the inventory, a flow model of the technical system is designed using inputs and outputs data, i.e. inputs level is correlated for each output of the system. The flow model is typically illustrated with a flow chart that includes the activities that are going to be assessed in the relevant supply chain and gives a clear picture of the technical system boundaries [12, 13].

The LCA flow model of a building is presented in Table 12.1.

The input and output data needed for the construction of the model shall be collected for all activities within the system boundary and supply chains, i.e. inputs from the Technosphere.

The LCA represents either a generic collection of data (i.e. representative industry emission averages for a developed good or service) or brand-specific data, that is typically collected through survey questionnaires at an industry level or by a representative sample of producers representing the regional differences due to energy use, material sourcing or other factors.

The Technosphere is defined as the ecosystem created by technology interacting with the natural ecosystem, i.e. that part of the environment that is manipulated or modified by humans. This component is usually the most difficult data to be quantified because the distribution of the resources according to the human-made products is in practical very difficult to establish due to the difficult access on all entire range of necessary data regarding the previous production processes of the product [14, 15].

12.4.3 LCI Methods

12.4.3.1 Process Based LCA Method

The inputs and outputs for a given step in producing a product are cataloged and inventoried. E.g. for 1 m^3 of sand needed on a construction site, the needed inputs could be: the gathering of the aggregate, sifting, packaging and transport of the material. However, for a broad life cycle perspective, the same task must be done across the entire needed processes in the production chain, in other words, the gathering,

Table 12.1 LCA flowchart of environmental performances of a residential building

Activity flow		
Building characterization	• Characteristics and area (project and memorial	• Definition of the object of study
	• Type of building Construction standard	
Goal and scope definition	• Product system Functional Unit Life span	• Delimitation of the product system
	• System Boundary Assumptions Limitations	
Life Cycle Inventory Analysis (LCIA)	• Data collection Technical visit Documentary analysis Bibliography	• Inputs and outputs of unit process
	• Data treatment Organization Conversion	
	• Relevant materials Cut-off criteria	
	• Correlation of data to functional unit	
	• Validation of data Gaps identification	
	• Data input	• Computational modeling
Life Cycle Impact Assessment (LCIA)	• Selection of categories and methods (e.g. ReCiPe, Ecoinvent, ILCD)	• Potential impacts, climate change, human toxicity, eutrophication, acidification, ozone formation, resource depletion, cumulative energy demand
	• Sensitivity analysis; Data analysis; Uncertainty analysis	
Life Cycle Interpretation	• Conclusion, limitation and recommendations	• Improvements in environmental performance; Decision

Source [14]

sifting and packaging machines must be identified and the share of consumption and GHGE for the manufacturing process of the machinery must be estimated [16].

The process based LCA arises two main problems:

- The boundary definition of what processes should be included in the analysis and what processes should be ignored is limiting the results and creates an underestimate of the precise life cycle impact. At the same time, it still leads to a manageable LCA project.
- The circularity effects caused by the interdependence of the current society, i.e. in order to convey 1 m^3 of sand needed on a construction site, multiple machinery would be mandatory, but to produce those machinery, further machinery should produce the first machineries.

12.4.3.2 Economic Input-Output Method

In order to reduce the consumed time and effort invested in LCA, the economic input-output models provide the GHGE distribution according to the monetary transactions between industry sectors in mathematical balance between parts. The economic input-output life cycle assessment method (EIO-LCA) assesses the materials required energy resources and the environmental GHGE based on the economic rates between the activities. The information uses transactions between different industry sectors and the information about direct environmental GHGE of the different sectors in order to determine the total GHGE emissions generated through the supply chain.

The efficiency of the EIO-LCA method is reduced because of its precision level. As a consequence of the considerable complexity of the industries, the method can only simulate the average impact factors of a particular industry. The method is limited in modeling the effect of single products, but it is valuable at modeling the effects of entire industry sectors [16].

12.4.3.3 Hybrid LCA

Hybrid LCA has been developed in order to correct the errors of process based LCA caused by the omission of parallel but interconnected industry processes. This approach provides detailed information, but the missing accuracy of the assessment leads to significant errors of the final results.

The current research shows that due to sectorial aggregation, hybrid LCA, covers a complete system boundary but it is not necessarily more accurate than a process-based model with an incomplete system boundary. Although hybrid LCA reduces the risk of double counting (if one company accounts for the whole amount of its supply chain GHGE and another company from its supply chain does the same, then the same GHGE are counted twice), the approach misses the problem of sectorial aggregation of products with heterogeneous technological and environmental profiles, because products united into a sector can be substantially different and as a consequence some of them are significantly misrepresented by sectorial averages [16].

12.4.4 Life Cycle Impact Assessment (LCIA)

According to ISO 14044:2006, the last mandatory stage of the LCA is the LCIA. In this phase, data about life cycle inventory is collected and delivered in form of environmental impacts values. The LCIA consists of three mandatory stages:

- selection of the impact categories, category indicators characterization models.
- assignment and classification. The concerned substances are sorted into classes according to the effect they have on the environment i.e. the causal relationship

between the environmental intervention (for instance, the emission of a certain chemical) and its potential effects is established.

- characterization—The concerned substances are multiplied by a factor which reflects the relative contribution to the environmental impact, quantifying how much impact a product or service has in each impact category.

In addition to the mandatory LCIA steps, other optional LCIA phases are:

- Normalization—the adjustment of the entire measured values measured on different scales to a common scale at national level.
- Grouping—in order to find a more convenient approach of summarizing and analyzing the variable data are clustered in groups.
- Weighting –although ISO 14044:2006 advises though against weighting, stating that weighting, shall not be used in LCA studies intended to be used in comparative assertions intended to be disclosed to the public, this guidance is often ignored though, resulting in comparisons that reflect a high degree of subjectivity.

Life cycle impacts are also categorized by the several phases of development, production, use and disposal of a product. The impacts can be divided into:

- First impacts—extraction of raw materials, manufacturing (conversion of raw materials into a product), transportation of the product to a market or site, construction/installation, beginning of use.
- Use impacts—physical impacts of operating the product or facility (energy, water, etc.), maintenance, renovation and repairs/maintenance.
- End of life impacts—demolition and processing of waste[2] or recyclable materials.

12.4.5 LCA Results Interpretation

The Life Cycle Interpretation is a systematic technique of identification, quantification, understanding and evaluation of the results of the LCI and LCA. This is accomplished by summarizing the results during the interpretation phase. The conclusions and recommendations of LCA are provided according to ISO 14040:2006 and shall include:

- Identification of the data elements that contribute significantly to each impact category; the most important aspect is the determination of the assurance level of the results regarding the goal and scope of the study.
- The evaluation of the study's accuracy assessing the completeness and consistency.
- Conclusions, limitations and recommendations based on a clear understanding of how the LCA was conducted and how the results were developed.

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[2] **Waste**: a material, substances, or by-products come to its life cycle end.

The most important aspect of the interpretation is the determination of the level of confidence in the final results and its complete and accurate communication. To ensure the validity of an LCA, the data used for completion of the LCA must be as accurate and as current as it is possible. When evaluating multiple products or systems, the calculation premises must be equivalent in order to be able to compare for example the entire construction section at national level.

The results of a LCIA are based on the accuracy and legitimacy of the input information:

- Unit process data, information derived mainly from direct surveys of companies; i.e. the study carried out at unit process level.
- National input-output data, information based on national economic input-output data.

Due to the rapid pace of development in research, industry and economy, the data accuracy is a considerable interest for life cycle analyses. Considering the continuous introduction of new materials and manufacturing methods, the importance and difficulty of LCA are emphasized by the use of up-to-date information.

The life cycle consists of multiple stages including resource (input) extraction, processing and manufacturing, product (output) use and disposal. The impact on the environment can be efficiently reduced if the most environmentally harmfully stages can be determined and by focusing on making improvements for that particular phases.

For example, the most energy-intensive life phase of a residential building is during the maintenance phase. One of the most effective ways to increase the sustainability of the building is, beside a proper insulation of the thermal envelope, the use of a higher efficiency energy source. Although the gas—powered sources are generally more efficient than a standard wood burning source, the question is whether the additional GHGE caused by a construction of a gas pipeline should compensate for the additional GHGE caused by the wood powered source over a chosen lifetime and under the presumed operation requirements (https://www.epa.gov/sites/production/files/signpost/ index.html 2019).

12.5 Data Sources

The life cycle analyses are as reliable as the used data are; therefore, it is crucial that data used for the completion of a life cycle analysis is accurate and current. In a comparison between different life cycle analyses, the equivalency of the data is important for both products and/or processes involved [17, 18].

Currently, a large number of databases are available in order to provide the necessary information needed in order to perform LCA. Several of the most used databases are presented in Table 12.2 along with the related field of activity.

Table 12.2 Classification of several most used LCA databases

Database	Field of activity
Ecoinvent	• Provided energy, transport, biofuels and biomaterials, chemicals, construction materials and waste treatment
Soca	• Added to Ecoinvent v.3.3, it develops the existing database regarding environmental and cost information by social features. It enables the combination of Environmental, Social LCA and LCC using one single database for one product The social indicators for 17 working categories are included: health and safety aspects, fair salary, forced labor, migration, corruption or fair competition. For each process, the information is provided using risk-assessed indicators
EuGeos'	• Includes impact assessment methods that may be used to calculate all of the indicators required by EN 15804 regarding the sustainability of construction works
NEEDS	• Includes international industrial life cycle inventory data regarding future electricity supply systems, material supply and transport services
GaBi	• The largest and one of the most trusted internally consistent LCA database with more than 20 specific sectors—among them being included building and construction; chemicals and materials consumer goods; electronics and ICT; end-of-Life and recycling; energy and utilities; metals, minerals and mining; packaging; plastics; service sector; textiles and transport
ELCD	• Comprises data from EU-level business associations (European reference Life Cycle database)
Social LCA	• Comprehensive generic database for performing Social Life Cycle Analysis using Global Trade Analysis Projects that enables geographic specific supply chain modeling
Ioenergia	• A German database created in order to develop supply chains for provision and conversion of bioenergy fuels (wood, waste-wood, wheat, biowaste)
Ökobaudat	• Construction materials database, provided by the German Federal Ministry of Transport, Building and Urban Development since October 2018

12.6 Allocation Method

Regarding the problem of assignment of the GHGE attributed to multifunctional processes and recycling, the ISO standards leave a large degree of freedom being inexorable in many ways.

This flexibility has resulted in various approaches, such as:

- the British PAS2050 for carbon footprint, the Greenhouse Gas Protocol
- the International EPD System
- the Product Environmental Footprint Guide.

LCI data providers also have multiple points of view on how to handle with the problems. The Ecoinvent data, used in the LCA presented in this study, is available

Table 12.3 The listening of the allocation methods used in LCA

Approach	Information
APOS	• Allocation at the point of Substitution (APOS) is the allocation approach that uses the increase of a product systems in order to avert allocation within certain systems because several activities, e.g. finding appropriate allocation factors such as revenues for the collection of municipal solid waste and the transportation up to the disposal site can raise several question marks. APOS was created in order to avert allocations and assigns the value by products systems together with the activity that develops the material treatment APOS creates datasets for by-products of waste treatments. Because electricity can be produced from several distinct sources, i.e. wheat wastes, municipal wastes, mine operation or others, in order to reduce the complexity, all datasets are merged and named “electricity production, from municipal solid waste incineration”
Conseq.	• The consequential approach to allocation, recognized by many as being the most theoretically correct model dealing with recycling and multifunctional processes. In essence though, many assumptions are needed regarding the assumed avoided burdens
Cut-off	• The most common approach is the cut-off approach. According to this model, burdens are allocated at the point of a product sale and a cut-off is applied at the point of when a recyclable material is leaving the product system

in three separate versions with three different allocation keys, i.e. APOS, Consequential and Cut-off. A basic description on the three allocation methods is carried in Table 12.3.

12.7 Versions of LCA Studies

12.7.1 Cradle-to-Grave

The most comprehensive version of LCA includes all the environmental consequences generated by a product or an activity from resource extraction to use and disposal phases is called cradle-to-grave. For example, the paper produced by harvesting the trees, which can be recycled[3] and used as an energy-saving material compensating probably the energy used in its production. After a period of time in which the insulation properties decrease, cellulose fibers are replaced, and the old fibers are disposed and possibly incinerated and generating heat necessary for households. So, all inputs and outputs are considered and added up for the entire life cycle in order to establish a cradle-to-grave analysis.

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[3] **Recycle**: convert waste into reusable material.

12.7.2 Cradle-to-Gate

A more scattered version of LCA serving as a partial life cycle of a product, comprised from resource extraction to the factory gate, i.e. before it is transported to the consumer, in which the use and disposal phases are omitted is named cradle-to-gate. One of the most significant uses of the cradle-to-gate approach is the adding up of the different materials used in a more complex process in order to develop a new analysis which includes all the GHGE generated by the already contained materials.

12.7.3 Cradle-to-Gate with Options

The third type of EPD is “cradle to gate with options”, which includes all the information relevant for the first type and other optional information for the end of life stage such as impacts during demolition and waste disposal stages.

12.7.4 Cradle-to-Cradle

A specific cradle-to-grave assessment called cradle-to-cradle is the LCA version where the disposal phase is represented by recycling processes. It is a method used to minimize the environmental impact of products by employing sustainable production, operation, and disposal practices and aiming to incorporate social responsibility into product development. In general, the distribution of burden for products in open loop production systems[4] presents considerable challenges for LCA due to the difficult correlation of the input or output to a specific process.

12.7.5 Gate-to-Gate

The gate-to-gate version of LCA represents a partial LCA that considers only of one value-added process belonging the entire production chain. All gate-to-gate assessments that represent the production chain of a product consist together in the complete cradle-to-gate evaluation of the product.

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[4] **Open loop production**: a control system in which an input alters the output, but the output has no effect on the input.

12.7.6 Well-to-Wheel

The specific LCA methodology used for evaluating transport fuels and vehicles is named well to wheel. The analysis is often used by stake holders in order to estimate the emissions, energy efficiency and industrial cost in automotive industry. It can be broken down into multiple stages: well-to-station, well-to-tank, station-to-wheel, tank-to-wheel or plug-to-wheel.

12.8 Impact Categories

The life cycle impact assessment method called ReCiPe2008 developed by [19] provides harmonized impact categories at midpoint and endpoint levels. The midpoint indicators concentrate on a particular environmental question, for example climate change or acidification. Endpoint indicators show the environmental impact on three higher aggregation levels:

- effect on human health
- biodiversity and
- resource scarcity.

The conversion from midpoint to endpoint level simplifies the interpretation of the LCIA results. Nonetheless, the uncertainty in the results increases with each undertaken aggregation step. Table 12.4 provides an inventory of the structure of ReCiPe method.

The ReCiPe 2016 was created by RIVM, Radboud University, Norwegian University of Science and Technology and PRé Consultants. Normalization and weighting factors are not yet published; therefore, the version does not include normalization and weighting. Furthermore, regionalization of the impact categories is not implemented.

Both methods contained in ReCIPe approach, i.e. midpoint and endpoint impact categories, includes aspects according to the three cultural viewpoints:

- Individualist: optimistic; technology will avoid many problems in future.
- Hierarchist: consensus model; often encountered in scientific models and considered by default.
- Egalitarian: long term; based on precautionary principle thinking.

In comparison with the other approaches, the advantages of the ReCiPe include:

- The most extensive set of midpoint impact categories.
- As far as possible, the used impact mechanism has global scope.
- Assume that impact assessment has been included in the inventory analysis; don't include potential impact from future extractions [21–23].

Table 12.4 List of characterization factors available in ReCiPe 2016

Midpoint impact category	Damage pathways	Endpoint area of protection
Particulate matter	• Increase in respiratory disease	• Damage to human health
Ozone formation		
Ionizing radiation	• Increase in various types of cancer	
Ozone depletion		
Human toxicity (cancer)		
Human toxicity (non-cancer)	• Increase in other diseases	
Global warming		
Water use	• Increase in malnutrition	
Freshwater ecotoxicity	• Damage to freshwater species	• Damage to ecosystem
Freshwater eutrophication		
Trop ozone	• Damage to terrestrial species	
Terrestrial ecotoxicity		
Terrestrial acidification		
Land use		
Marine ecotoxicity	• Damage to marine species	• Damage to resource availability
Mineral resources	• Increased extraction costs	
Fossil resources	• Oil/gas/coal energy cost	

Source Huijbregts et al. [20]

The building materials used in order to determine the LCA of the building were selected using the system model “Allocation at the point of substitution” (APOS), associated with the database Ecoinvent Version 3 [24].

Every activity of the Ecoinvent database has a geographic location assigned and each location has internationally accepted shortcuts, presented in Table 12.5.

Because for Romania there are not any internationally accepted databases, the materials where selected using the databases attributed as precise as possible. For example, while the production of concrete has only global databases, the GHGE according to the polyethylene materials are estimated using databases valid at European level.

Table 12.5 Available locations and shortcuts in SimaPro

Shortcuts	Geographic location
CH	• Switzerland
CZ	• Czechia
CN	• China
GLO	• Global
REW	• Europe
RER	• Rest of the world

12.9 Life Cycle Assessment Tools

Currently there are several different automated tools, studied in previous works, on the market but in this case, the LCA software used was SimaPro, a professional tool which analyses and monitors the sustainability performance data of products and services. The software can also be used in order to provide:

- sustainability reporting.[5]
- carbon and water footprint.
- environmental product declarations.
- key performance indicators.

LCA was developed in order to simulate low environmental impact products. In comparison with regular products, buildings are unusual since they have a comparatively longer life, they undergo adjustments, often have multiple functions and contain many different components/processes which lead to an unclear system boundary. This entails that making a full LCA of a building is not a simple process comparable to the other LCA analysis of different, less complicated products.

Due to the large amount of data required to perform an LCA, it is recommended to use a software application that makes the study more efficient. There are various assessment applications on the market, and they allow LCA studies to be carried out to various degrees of detail. In deciding which programs to use, it is necessary to consider several criteria. The life cycle assessment of a building can be performed using a general LCA software, but doing so, the quantification of building materials, energy use, etc., requires a lot of time. Because in practice architects and engineers only have a few days to perform such studies and appropriate interfaces are more convenient, specific applications, presented in Table 12.6 have been developed in order to facilitate the use of LCA in the building sector.

By using LCA software, the material quantities are to be compiled according to a process containing all relevant steps and technologies over the supply chain of the product. The data is based on inputs from industry sector and is completed,

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[5] **Sustainability**: avoidance of the depletion of natural resources in order to maintain an ecological balance.

Table 12.6 Life cycle assessment tools

General assessment tools	
Boustead	www.boustead-consulting.co.uk
Eco-it	www.pre.nl
Ecopro	www.sinum.com
Ecoscan	www.ind.tno.nl
Euklid	www.ivv.fhg.de
KCL Eco	www.kcl.fi/eco
Gabi	www.gabi-software.com
LCAit	www.ekologik.cit.chalmers.se
Miet	www.leidenuniv.nl/cml/ssp/software
Pems	www.piranet.com/pack/lca_software.htm
SimaPro	www.pre.nl
Team	www.ecobilan.com
Wisard	www.pwcglobal.com
Umberto	www.umberto.de
Specific building assessment tools	
Ecoquantum	www.ecoquantum.nl
Legep	www.legep.de
Equer	www.izuba.fr
Athena	www.athenaSMI.ca
Ogip	www.ogip.ch
Eco-soft	www.ibo.at/de/ecosoft.htm
Envest 2.0	www.envestv2.bre.co.uk
Becost	www.vtt.fi/rte/esitteet/ymparisto/lcahouse.html
Bees	www.bfrl.nist.gov/oae/software/bees.html
Greencalc	www.greencalc.com
Ecoeffect	www.ecoeffect.se
Eco-quantum	www.ecoquantum.nl
Legep	www.legep.de
EQUER	www.izuba.fr

where necessary with secondary data[6] e.g. through publications, open literature, other software or LCA libraries. The outcomes are given as mean global GHGE generation potential [25–27].

12.10 LCA Uses and Benchmarking

For a long time in buildings industry, the LCA research has been focusing on the energy efficiency associated to GHGE of the operational phase. This led to intensive efforts made in the area of efficient operation and initial construction phase of buildings. While major corporations all over the world are commissioning LCA studies and governments support the development of the national databases regarding LCA, the current tendency of the research switched to the integration of LCA in building certification systems.

Of particular note is the growing use of LCA for ISO Type labels called Environmental Product Declarations.

The quantified environmental data for a product is based on the ISO 14040 series of certified standards, that provide an increasingly important basis for assessing the relative environmental merits of competing products. Independent and standardized certification can stand first as benchmark and after that as an obligation. In Table 12.7, several input data used in LCA according to several buildings situated along the world (all over the world) are presented for the purpose of delivering a correlation base for the subsequent national benchmarks.

The dwelling in Scotland consist out of three-bedroom semi-detached house. Detailed LCA of five main construction materials i.e. wood, aluminum, glass, concrete and ceramic tiles have been provided to determine their respective embodied energy and associated environmental impacts. Embodied energy of various construction materials involved have been estimated to be equal to 227.4 GJ. The calculation show that concrete alone consumes 65% of the total embodied energy of the home while the share of environmental impacts is even more crucial [28].

For the passive house located in the island state of Cyprus for the implementation of the LCA, the environmental assessment tool EcoHestia was used. According to the authors, the concrete and tile are by far the biggest contributors to the harmful GHGE generation. Table 12.8 presents the results of the assessments undertaken for the Swelling in Scotland and the PH in Cyprus.

Because in Catalonia there are over 200 public edifices built using industrialized solutions, these technologies are submitted to an analyzation from a technical and sustainable point of view in order to determine the quality of the buildings and the possibilities of reducing the environmental impact. The conclusions of the study were that even though highly efficient technologies could reduce the resource consumption and waste generation, a refurbishment process carried out on an old building would

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[6] **Secondary data**: data collected through information found in publications, open literature, software.

Table 12.7 Buildings subjected to LCA and according climate data

Building	Location	Climate	Average temp. (°C)	Structure	Area (m^2)						
School	Montreal (Canada)	Humid continental	4.1	concrete	23,225						
I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
−10.3	−8.8	−2.4	5.7	12.9	18.0	20.8	19.4	14.5	8.3	1.6	−6.9
School	Catalonia (Spain)	Mediterranean	16.5	Prefabricated concrete	–						
I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
10.0	10.3	12.0	13.8	17.0	20.8	23.8	24.5	21.9	18.5	14.0	11.1
PH (P + E)	Cyprus	Subtropical—Mediterranean	20.4	Wooden frame with reinforced concrete slabs	185						
I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
12.5	12.5	14.3	17.4	21.5	26.0	28.9	29.2	26.7	22.9	18.1	14.2
Dwelling Scotland	Scotland	Temperate and oceanic	9.1	Steel frame	–						
I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
4.1	4.3	5.7	7.7	10.6	13.2	15.1	14.7	12.4	9.5	6.5	4.5
High school building	Salonta, Romania	Temperate continental	10.5	Concrete and masonry	3,444						
I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
−0.9	0.5	5.3	11.0	16.3	19.0	21.3	20.7	16.3	11.2	4.6	0.4

Table 12.8 Dwelling Scotland

2007 Dwelling Scotland						
Material	Building material weight	Embodied energy	Environmental impact			
	kg	kg/m^2	MJ	MJ/m^2	kgCO$_2$eq	kgCO$_2$eq/m^2
Timber	5,725	41	30,000	214	664	4.74
Concrete	130,800	934	130,800	934.3	605,4	4,324.7
Glass	314	2.2	4,077	29.1	178.4	1.27
Aluminum	25	0.2	5,870	41.9	48.10	0.34
Ceramic	32,240	230	32,240	230.3	2,301.0	16.44
Plaster	1,080	8	5,400	38.6	286.2	2.04
Damp course	1,889	14	1,889	13.5	25.40	0.18
Cement	2,400	17	2,400	17.1	9,600.0	68.57
Total	1519.1	–	4418.3			
2016 PH Cyprus						
Timber	28,557	154	1,528	8.26	81,427.7	440.15
Concrete	42,330	229	6,475	35.0	417,306.3	2,255.7
Polystyrene	697	4	15,577	84.2	2,125.6	11.49
Mineral wool	8,150	44	953	5.2	3,481.70	18.82
Steel	6,100	33	8,806	47.6	20,227.9	109.3
Ceramic	26,220	142	2,035	11.0	26,073.9	140.9
Plaster	7,506	41	705	3.8	124,238.6	671.6
Damp course	83	0.4	21,18	114.5	188.7	1.02
Paint	202	1.1	7,197	38.9	138.7	0.75
Cement	61	0.3	3,793	20.5	116.5	0.63
Total	368.9	–	3650.4			

Source [28]

never be able to exceed the efficiency of new highly efficient buildings [29]. Table 12.9 presents the results from the quoted study.

According to the study undertaken in Catalonia, the following drawn conclusions may underlie the decision factors in construction industry but also the national legislation in Romania:

- In school buildings, the emissions produced during the manufacturing and construction phases are significantly larger than the emissions produced during the operating phase. This facet emphasizes the importance of the generated emissions of building materials as the thermal performances of the houses improve.
- Prefabricated building materials, elements and modules can improve the building performances and lower the environmental impact of the total GWP according to

Table 12.9 Prefabricated school Catalonia

Phase	Manufacturing and construction phase	Emissions—operating phase	
Unit	$kgCO_2eq/m^2$	$kgCO_2eq/m^2$	$kgCO_2eq/m^2$ year
Non-prefabricated	1359.0	607	12.14
Prefabricated concrete	1229.0	539	10.78
Timber	1106.0	580	11.6
Steel	1461.0	609	12.18

Source [29]

Table 12.10 School buildings in Canada

Structure	Manufacturing and construction stages $kgCO_2$ eq/m^2	Operating stage	
		$kgCO_2$ eq/m^2 year	$kgCO_2$ eq/m^2
Concrete	3,760.0	27.12	1,356.0
concrete and masonry	4,570.0	27.84	1,392.0
Timber	1,630.0	31.37	1,568.5

Source [30]

the manufacturing and construction phases with almost 10% in case of concrete structures. As presented in able 9, the non-prefabricated structure has almost 10% bigger emissions in the manufacturing and construction phase than a similar structure constructed using prefabricated methods

A selection of the most sustainable structure and envelope type for school buildings is undertaken in a recent study on Canadian school buildings. The results of the LCA undertaken on the school buildings are presented in Table 12.10.

Considering the results of the LCA according to the schools from Canada it is to be observed that the highest global warming equivalent emissions are generated during the operation stage (over 90% of the total emissions 27.84 of 30.47 $kgCO_2$ eq/m^2 year).

According to the study undertaken in Catalonia, the following drawn may underlie the decision factors in construction industry but also the national legislation in Romania:

- The structures having as main materials concrete and masonry have higher global warming potential[7] during manufacturing and construction stages in comparison with the timber-based structure. Nevertheless, they have lower environmental impact during the operating stage, as well as for the overall life cycle span.

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[7] **Global warming potential**: is a measure of how much heat a greenhouse gas traps in the atmosphere relative to carbon dioxide.

- The selection of the building materials and different alternatives in the construction industry should be based on their performances in all the life cycle stages over its entire life span.
- By choosing different structure types, the emissions generated during the operation stages vary no more than 13.5% because of the regulations regarding the produced emissions during operation. The emissions produced during manufacturing and construction though can vary with more than 50%. Therefore, the implementation of mandatory ranges regarding the LCA of buildings should be introduced in the national legislation.

12.11 Case Study: Energy Efficient High School Building in Romania

12.11.1 Features of the Building

In order to provide a pattern for the LCA of a whole building, a case study was carried out on an energy efficient high school building located in Salonta, Romania. The high school is one of the first public buildings built in Romania according to the Passive House prescriptions, general concept and details. The construction of the building was started in October 2014 when, due to the inadequate sizes of the existing buildings, the local administration decided to build a new facility with spaces dedicated for learning, dining and accommodation for students.

The architecture of the building was developed so that it fits to the local site requirements, i.e. a central area with old classic buildings. The building has 4 levels and a gross area of 4000 m^2. In order to evaluate the energy consumption of the building and to understand the behavior of materials over time, a complex monitoring system has been developed and several sensors where mounted in specific elements of the building envelope. The system consists out of 660 measuring elements i.e. a multitude of temperature, humidity, CO_2, air flow and electric consumption meters all of them being connected to multiple data acquisition stations in order to store the real-time data [31–33].

The walls of the envelope consist out of autoclaved aerated concrete (AAC GBN25) having a thickness of 250 mm insulated by a system of rock wool panels. The insulation panels have a thickness of 150 mm [34].

The thermal agent for heating, cooling and generation of domestic hot water is prepared in an independent mechanical room by one soil-water and one water to water heat pumps, each having a power of 75 kW and 12 drillings measuring 120 m each. The heat distribution system of the building consists of floor and ceiling fan-coils operated independent by digital thermostats.

In order to simulate the exterior climate, the actual measurements from a local weather station were used [35].

12.11.2 Features of the Assessment According to the Construction and Operating Phases

The life cycle of is connected to a large number of substances, GHGE and resource extractions processes, which essentially vary in their environmental relevance. Through the life cycle impact assessment (LCIA) the interpretation of the LCA studies was undertaken by translating these GHGE and resource extractions into a multiple number of environmental impact scores, i.e. characterization factors which indicate the environmental impact per unit of stressor (e.g. per kg of resource used or emission released) [36–38].

In SimaPro, the transport process is indicated in ton-kilometers (tkm). One ton-kilometer means the transport of one ton over one kilometer, or one kg over one thousand km. In the conducted LCA for the high school an amount of 50 tkm/m^2 was assumed. An amount of 1.5 t/m^2 of building materials was estimated and an additional of 20% weight of the construction tools and equipment carried out over 27.7 km. The Processes simulated in SimaPro are presented in Table 12.11.

The load of excavated soil per square meter was estimated based on the excavation and foundation plans. Table 12.11 contains the amount according to each process considered in the LCA of the high school.

The necessary energy consumed by the building in the construction stage, i.e. the emissions caused by the implementation of the building materials are presented in Table 12.12.

Because information regarding emissions at national level for the production of building materials does not yet exist, the simplified LCA determined for the high school building was estimated by means of the global and European databases provided in SimaPro.

The data registered by the monitoring systems are concluded to the following figures:

- The gas consumption of the kitchen: 3.3 kWh/m^2 year (monitoring period 10 months).
- The electricity consumption used in order to power the heating pumps, which serves the heating and hot water systems, the air-conditioning, ventilation and lighting systems: 21.3 kWh/m^2 year (monitoring period October 2017–November 2019).

The measured energy consumption is presumed to increase according to the following hypothesis:

Table 12.11 List of processes attributed to the LCA of the high school of Salonta—Romania

Process	Amount	Emissions
		(kgCO$_2$eq)/m^2
• Transport tkm/m^2	50	3.32
• Soil excavation kg/m^2	312.5	0.631

Table 12.12 List of materials and assemblies attributed to the high school of Salonta—Romania

Building material	Density	Volume	Total amount	Embodied Energy[a]		Emissions
	kg/m^3	m^3	kg/m^2	MJ/kg	MJ	(kgCO_2eq)/m^2
Timber	700	700	25.07	8.5	213.1	6.79
Concrete	2500	1488.7	821.47	1.2	985.7	3802.1
AAC	450	393.0	43.79	3.6	157.6	20.6
Rockwool	155	435.8	16.73	16.8	281.0	16.89
Glass	2600	9.6	6.18	15.0	92.7	1.67
Aluminum	2700	2.4	1.60	155.0	248.7	4.89
Ceramic tiles	1100	293.1	79.83	12.0	957.9	70.9
Plaster	1400	160.3	63.74	6.9	386.2	8.83

[a] C. I. Jones, Embodied energy and carbon footprint database

- The gas consumption of the canteen kitchen was increased with 0.27 kWh/m^2 month due to an intensive operating.
- The electricity consumption is estimated to increase in time, due to home appliances, with 0.25 kWh/m^2 month.

To conclude, the energy consumption used for operating the building is increased from 21.3 to 30.84 kWh/m^2 year. The CO_2 emissions were determined with SimaPro. According to the Ecoinvent3, the emissions associated with the generation of electricity are at national level (Romania) 0.449 kgCO_2/kWh. Since there are no emissions according to the energy production with a gas source provided at national level, the emissions provided by the software were determined at European level to 0.275 kgCO_2/kWh. The total emissions produced by the high school of Salonta are presented in Table 12.13.

The unusual great initial emissions of the high school building from Salonta (3903.61 kgCO_2eq/m^2) are caused by the high efficiency of the thermal envelope. The higher initial emissions will be voided by the saved emissions during operating stage.

By analyzing in comparison all the buildings mentioned in this chapter (dwelling Scotland, house Cyprus, school building Catalonia, Canada and Salonta) they could

Table 12.13 List of materials and assemblies attributed to the high school of Salonta

Life stages	Emissions	Emissions
	kgCO_2/(m^2 year)	(kgCO_2)/m^2
Construction and manufacturing	78.07	3903.61
Operating (electricity)	10.61	530.5
Operating (energy production by gas source)	1.98	99.0

be classified in residential and non-residential, respectively by means of insulation level, in regular insulated and high insulated buildings. Neglecting the rigorous building design, differences between the different climate zones and buildings destination, it can be concluded that the emissions produced during the manufacturing and construction stages vary between (1,106–4,418.26) $kgCO_2eq/m^2$. The emissions during operation vary between 10.78 and 31.37 $kgCO_2eq/m^2$ year in case of the different structures of the presented school buildings.

Both in case of the school models from Catalonia and also in case of the schools in Canada, the use of a timber structure reduces the emissions generated during the manufacturing and construction with 25–65%.

The two considered residential buildings (Scotland and Cyprus) have emissions produced during manufacturing and construction stage comprised between (3650.41–4418.266) $kgCO_2eq/m^2$, even three times more than the school buildings of Catalonia built of concrete or masonry, (1229–1359) $kgCO_2eq/m^2$. The great value of the difference can also be attributed to the difference of the climate zone and therefore to the difference of the insulation level and type.

12.11.3 Implementation of the LCA in the National Legislation

The LCA benchmarks can be calculated using the databases provided by the software as average values using several methods based on statistic values. This data should be structured in a way which enables to answer questions arising during the planning process. Depending on the data basis, the software generally provides the possibility to generate both a rough and a detailed data analysis.

In order to integrate average LCA values of buildings in their planning phase in the future, it is necessary to analyze the current state of the database of green building certification system, in other words what is the current state of the building stock.

Before large-scale development of LCA benchmarks, a standardized and uniform submission format of results of LCA software results, needs to be developed and officially approved at national level.

The calculation of LCA should be carried out when all of the material quantities have been identified and the data for all of the materials and processes are available. Software tools intended for this purpose make the calculations much easier.

12.12 Conclusion

Despite the major improvement in reducing the harmful GHGE generated both during the operation and building or disposal stages, the multitude and in places various information regarding the resource requirements of the building processes and materials gives the current research and development to be aimed at providing benchmarks, i.e. arithmetical averages of the LCA results.

In this chapter, LCA results of several buildings were examined in order to build up a database that should serve in the future as a mandatory benchmark for early planning phases. The benchmarks are needed as a starting point in order to reduce the resource consumption of future buildings. In this regard, several consequences can be drafted based on the considered buildings:

- As expected, the emissions generated by the manufacturing and construction of highly efficient buildings are higher than the other regular insulated buildings both in case of school buildings and also in case of residential ones.
- The variation of the structure type of a building has limited effect on the total emissions generated over the entire life cycle.
- The different climate, insulation level and information of the producing industries have a major influence of the LCA that should be considered.
- For a more precise LCA at national level, the implementation of national databases regarding the emissions of the main building material produced in Romania is necessary.
- The implementation of a proper insulation system can lead to emissions decrease that can balance the whole amount of emissions generated during the manufacturing and construction phases.

Because of the relatively high energy consumption during the construction phase of high efficient buildings in comparison with existing buildings, it is justified to implement an LCA analysis. The analysis can determine and estimate the emissions generated during all the building phases and can and can support approach of rucing emissions during operation phase by preserving the emissions generated during construction phase.

The current database of LCA results provide a solid foundation to define benchmarks. However, the current research states the lacking data in terms of data structure and detail level. To ensure a comprehensive data sufficient in order to derive general and automatically calculated benchmarks at national and international level, several recommendations should be followed in order to structure a standardized rating system:

- The interface of the different LCA software should be standardized in order to provide the template with harmonized data collected from all the existing databases.
- The development of automated quality checks that should monitor the planning process and ensure a high-quality database and data integrity.
- The presumed standardized rating system should easily be extended and updated to new building materials and building processes.

The German Institute for Acoustics and Building Physics (IABP) states that the interaction between operation and construction is particularly important. The great potential to reduce the environmental impacts of the construction phase without increasing them in the operation phase is being investigated at the Collaborative Research Centre SFB 1244 “Adaptive Building Skins and Structures for the Built Environment of Tomorrow” at the University of Stuttgart, Germany [7]. Nevertheless, the use of Life Cycle Assessment assessing the environmental impact of a construction in the designing phase should represent a significant part of the designing process of a new sustainable building.

The work provided in this chapter can serve as a foundation for the ambitious goal of reducing the resource consumption and environmental impacts of building for future buildings.

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