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THE SYNERGY PROJECT: A STUDY OF HIGH ENERGY-EFFICIENT BUILDING ELEMENTS ASSESSED UNDER INTEGRATED PROTECTION CRITERIA AND LIFE CYCLE DESIGN ASPECTS

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ABSTRACT

This paper presents the first steps of a project that focuses on the research and development of high energy-efficient building elements, assessed under integrated protection criteria and life cycle design aspects. More specifically, it concerns a holistic approach in designing and evaluating the building elements of new and existing constructions in Greece, with regard to their energy, hygrothermal, fire and environmental performances.Apart from the knowledge and the theoretical results that will be derived during the project, there are also more practical products, such as a catalogue and computational tools with numerous constructional details and information regarding their thermophysical, hygrothermal, fire resistance and environmental properties. These tools are very useful for all engineers, especially during the design and the decision-making phases of a new building or a renovation project. The expected products of the proposed project will not only act as a guideline for the technical community, but it will promote the use of building materials, which are efficient from every aspect of view.

1 INTRODUCTION

This paper presents the first steps of SYNERGY project that focuses on the research and the development of high energy-efficient building elements, assessed under integrated protection criteria and life cycle design aspects. More specifically, it concerns a holistic approach in designing and evaluating the building elements of new and existing constructions in Greece, with regard to their energy, hygrothermal, fire and environmental performances.

The SYNERGY program is funded by the Action COOPERATION 2011 of the National Strategic Reference Framework. This Action supports the cooperation between enterprises and research institutions of the country, through the joint implementation of research and technology projects that promote green development, competitiveness and extroversion of Greek enterprises, as well as improve the quality of life of the citizens. Key objective of the Action is the motivation of the private sector to undertake Research and Development activities and increase the funding from own resources.

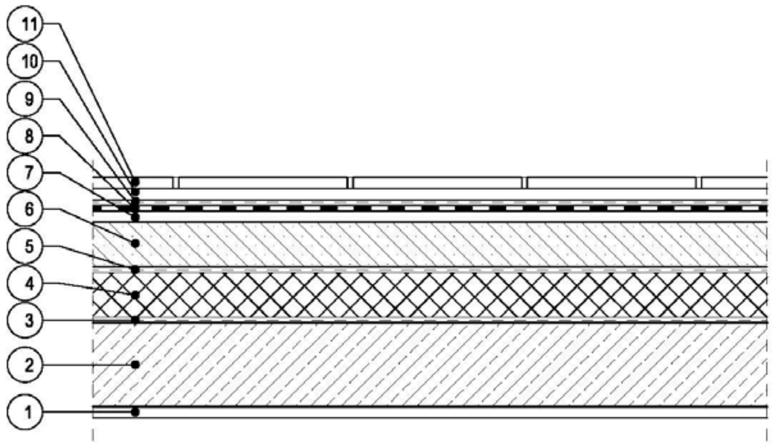
It is elaborated by two academic units of the Aristotle University of Thessaloniki (the Laboratory of Building Construction and Physics and the Laboratory of Metal Structures) and two SMEs, FIBRAN, which plays a leading role as a producer of insulation materials both in Greece and in Europe, and TESSERA MULTIMEDIA, an ICT company that is active on the development of software and applications as well as on web design.

The project started on the beginning of 2013 and is going to last 30 months. During this period a detailed analysis of all building elements met in the majority of constructions in Greece will be conducted with reference to their energy, hygrothermal, fire and environmental performances, as well as catalogues and computational tools for their properties' estimation will be developed. Although the above aspects may have been studied individually in the past, there is still a lack of information regarding their combination at a national and international basis, which has led to the vulnerability of their proper practical implementation.

It has to be highlighted that such an approach is crucial for the development of efficient buildings in the view of the implementation of the forthcoming EPBD recast, which aims at the promotion of nearly zero energy buildings and the enhancement of their environmental characteristics during their entire life cycle. Apart from the knowledge and the theoretical results that will derive during the project, there are also more practical products, such as the catalogues and the computational tools with numerous constructional details and information regarding their thermophysical, hygrothermal, fire resistance and environmental properties. These tools are very useful for all engineers, especially during the design and the decision-making phases of a new building or a renovation project. In fact, their importance will come to light in a few years, when the design and the construction of a building will take into account several energy related criteria due to the near zero-energy building requirements.

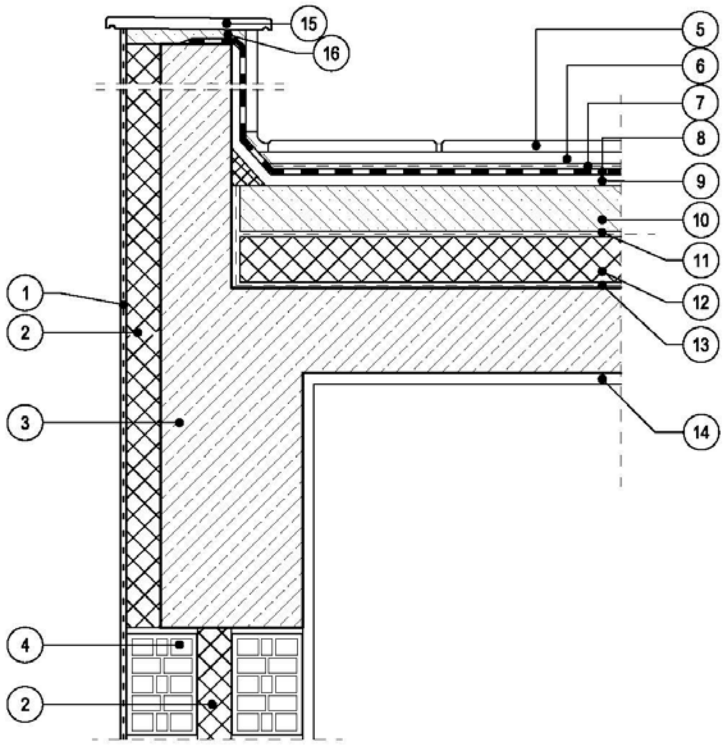
2 THE SYNERGY CURRENT AND FUTURE OUTCOMES

Within the context of the SYNERGY project all the common construction element configurations that can be found in the building envelope of typical Greek buildings (load bearing elements, walls, roofs, floors) have been recorded, designed and systematically classified. In order to include the vast majority of building typologies in Greece, buildings with bearing elements made of reinforced concrete and steel have been studied. Additionally, the study refers to new building constructions (with envelope elements thermally protected according to the requirements of the building energy performance legislation) as well as to existing buildings with poor or no insulation protection. Beyond the 180 construction details that have been produced for the individual building elements, details of their junctions have been elaborated, giving all necessary information for the appropriate layers' succession, the associated materials and the finishes. An example of the produced details is presented in Figure 1, representing the individual building component, i.e. a flat roof, and Figure 2, portraying the junction between a vertical and a horizontal building element, i.e. between the wall and the flat roof.



1. Lime-cement mortar
2. Reinforced concrete
3. Vapour barrier
4. Thermal insulation
5. Polyethylene membrane
6. Lightweight concrete for slopes
7. Cement based leveling compound
8. Water proofing membrane
9. Geotextile
10. Cement mortar
11. Cement tiles

Figure 1. Construction detail of a conventional flat roof.



1. Lime-cement mortar
2. Thermal insulation for walls
3. Reinforced concrete
4. Brick masonry
5. Cement tiles
6. Cement mortar
7. Geotextile
8. Water proofing membrane
9. Cement based leveling compound
10. Lightweight concrete for slopes
11. Polyethylene membrane
12. Thermal insulation for roof
13. Vapour barrier
14. Reinforced concrete

15 Marble tile

16. Cement mortar

Figure 2. Construction detail of the junction between the vertical wall elements and the flat roof.

The holistic approach employed in the SYNERGY project for the evaluation of the building elements' performance includes the aspects of energy efficiency, hygrothermal behaviour, resistance to fire and environmental impact. The examined parameters and the methodologies that are used for the analysis are described below for each individual issue.

2.1 The energy performance of the building elements

The energy performance of a building element is mainly represented by the value of its thermal transmittance (U-value), which is defined as the rate at which the heat transfer is conducted through its unit area per temperature difference between its two sides. The U-value is the reciprocal of the total thermal resistance of the building component, R_T, i.e. the values of thermal resistance of all layers that constitute the building component, R_i, as well as of the inner (R_{si}) and the outer surface (R_{se}) of the building component (eq 1). The thermal resistance of each layer is equal to the ratio between its width (d) and the thermal conductivity (λ) of its material, whereas the thermal resistance of the outer and inner surface of the component differentiate with regard to the direction of heat flow [1].

$$U = \frac{1}{R_T} = \frac{1}{R_{si} + \sum_0^i R_i + R_{se}} = \frac{1}{R_{si} + \sum_0^i \frac{d_i}{\lambda_i} + R_{se}} \quad (1)$$

Within the project's context, the U-value of each building element that has been identified and included in the analysis was calculated for different widths and thermophysical characteristics of the thermal insulation layer. For the remaining layers, the conventional widths and materials used in Greek constructions were taken into account. Given that among the objectives of the current project is to deliver catalogues and tools for engineers, a practical table was formulated for each building element, presenting the building element assembly along with the layers' configuration and a matrix presenting the thermal transmittance values that are derived for the different widths and thermal conductivity values of thermal insulation (Figure 3). The width of thermal insulation starts from 0.0m, representing existing buildings with no thermal protection and continues with a width that ranges from 0.03m to 0.14m with a step of 0.01m. For the thermal conductivity, typical values of the insulation materials that are available in the Greek market were taken into account, i.e. values ranging from 0.027 W/(m K) to 0.055 W/(m K) with step of 0.02 W/(m K), as well as the values 0.065 W/(m K), 0.075 W/(m K) and 0.085 W/(m K). The combinations of d and λ that result in U-values lower than the maximum allowed values per climatic zone are indicated in the matrix with different color. The practical merit of this matrix is that the engineer can make a quick estimate of the required thermal insulation, while at the same time the accurate and comprehensive construction detail is at hand.

Furthermore, one can perceive at what extent the thermal behaviour of the existing buildings can be enhanced, since such constructions have either inadequate (i.e. 0.03 m – 0.04 m) or no thermal protection. This information can be of great interest, since due to the expected adaptation of the national legislation on the thermal protection requirements to the EPBD recast, it is very likely to expect significant decrease of maximum acceptable heat transfer coefficients in some Greek climatic zones. In every case, the direct assessment of the energy performance of the construction elements with enhanced, conventional and limited thermal protection can present the potential benefits that can arise from the thermal insulation of existing buildings.

Beyond the thermal transmittance, another significant parameter for the evaluation of the overall thermal behaviour of the building envelope is the estimation of the linear thermal transfer coefficient of the thermal bridges located in composite building elements and at the intersection between the construction elements. Thermal bridges are more intense in areas where the thermal flow is increased due to the geometry of the building envelope or due to significant differences in thermal resistance of the adjacent elements in contact. Especially in Greek building constructions, thermal losses due to the existence of thermal bridges are very important due to the presence of relatively many balconies in the building facades that interrupt the continuity of the thermal protection and due to the dominant construction practice (external thermal protection of bearing, concrete elements and cavity insulation in walls).

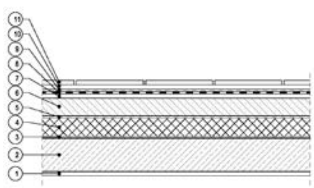
The influence of thermal bridges in the energy performance of the building envelope is taken into account by the linear thermal transmittance coefficient Ψ. Values of Ψ for certain construction elements joints had been calculated for typical configurations of the Greek constructions and are included in an atlas published by the Technical Chamber of Greece. However, this atlas provide values only for the case of buildings with concrete bearing elements and brick walls, while it neglects the influence of the material thickness and thermal properties on the linear thermal transfer coefficient. This information is of great importance in cases where, beyond the fulfilment of regulation requirements, a more accurate estimation of the building's actual heating and cooling needs is required.

Within the context of the SYNERGY project, the linear thermal transmittance encountered at the junctions between the examined construction elements -and their variations- have been calculated, resulting in a prolonged atlas for thermal bridges. Moreover, the Ψ values resulting for different widths of thermal insulation have been calculated, and in parallel the possible positions of the thermal insulation layers are taken into account. For every examined case, apart from the calculation of the linear thermal transmittance, the temperature profile within the construction element is calculated and presented on the elements' cross-section. This representation has a twofold merit: firstly it assists non-specialists to understand the thermal bridging effect and secondly it constitutes valuable information when estimating the probability of vapour condensation.

The calculations of Ψ values and the temperature profiles within the joint building elements were conducted with the help of a 2-D energy analysis software and in line with ISO 10211. The presentation of the results for each building element follows the example of Figure 4.

BUILDING ELEMENT	Δσα-130B
Flat roof with thermal insulation above the concrete slab with no air gap	
Zone A'	U max = 0,500 W/(m²·K)
Zone B'	U max = 0,450 W/(m²·K)
Zone C'	U max = 0,400 W/(m²·K)
Zone D'	U max = 0,350 W/(m²·K)

A. CONSTRUCTION DETAIL



1. Lime-cement mortar
2. Reinforced concrete
3. Vapour barrier
4. Thermal insulation
5. Polyethylene membrane
6. Lightweight concrete for slopes
7. Cement based leveling compound
8. Water proofing membrane
9. Geotextile
10. Cement mortar
11. Cement tiles

B. LAYERS' DESCRIPTION AND THERMOPHYSICAL CHARACTERISTICS

A/A	Layers	Density ρ kg/m³	Layer's width d m	Thermal conduct. λ W/(m·K)	Thermal resist. d/λ m²·K/W
1	*Cement tiles*	2100	0,030	1,500	0,020
2	*Cement mortar*	2000	0,020	1,400	0,014
3	*Geotextile*	80	0,001	0,040	0,025
4	*Water proofing membrane*	1100	0,007	0,230	0,030
5	*Cement based leveling compound*	2000	0,010	1,400	0,007
6	*Lightweight concrete for slopes*	1000	0,080	0,350	0,229
7	*Polyethylene membrane*	1390	0,0005	0,170	0,003
8	*Thermal insulation (selection from the table below)*				
9	*Vapour barrier*	1390	0,0005	0,170	0,003
10	*Reinforced concrete*	2400	0,200	2,500	0,080
11	*Lime-cement mortar*	1800	0,015	0,870	0,017
12					
13					
	Internal thermal resistance **Rsi =** *0,100* m²·K/W				
	External thermal resistance **Rse =** *0,040* m²·K/W				

C. THERMAL TRANSMITTANCE VALUES in W/(m²·K)

for different widths and thermal conductivity values of the thermal insulation material

λ \ d	0,000	0,030	0,040	0,050	0,060	0,070	0,080	0,090	0,100	0,110	0,120	0,130	0,140
0,027	1,759	0,595	*0,488*	*0,413*	*0,358*	0,316	0,283	0,256	0,234	0,215	0,199	0,186	0,174
0,029	1,759	0,624	0,513	*0,436*	*0,379*	0,335	0,301	0,272	0,249	0,229	0,212	0,198	0,185
0,031	1,759	0,651	0,538	*0,458*	*0,399*	*0,354*	0,318	0,288	0,264	0,243	0,225	0,210	0,197
0,033	1,759	0,677	0,562	*0,480*	*0,419*	*0,372*	0,334	0,303	0,278	0,256	0,238	0,222	0,208
0,035	1,759	0,701	0,584	0,501	*0,438*	*0,389*	*0,350*	0,318	0,292	0,269	0,250	0,233	0,219
0,037	1,759	0,725	0,606	0,521	*0,457*	*0,406*	*0,366*	0,333	0,306	0,282	0,262	0,245	0,230
0,039	1,759	0,748	0,627	0,540	*0,475*	*0,423*	*0,382*	0,348	0,319	0,295	0,274	0,256	0,240
0,041	1,759	0,769	0,648	0,559	*0,492*	*0,439*	*0,397*	*0,362*	0,332	0,308	0,286	0,267	0,251
0,043	1,759	0,790	0,667	0,578	0,509	*0,455*	*0,412*	*0,376*	0,346	0,320	0,298	0,278	0,261
0,045	1,759	0,810	0,686	0,595	0,526	*0,471*	*0,426*	*0,389*	*0,358*	0,332	0,309	0,289	0,272
0,047	1,759	0,829	0,704	0,613	0,542	*0,486*	*0,440*	*0,403*	*0,371*	0,344	0,320	0,300	0,282
0,049	1,759	0,847	0,722	0,629	0,558	0,501	*0,454*	*0,416*	*0,383*	*0,355*	0,331	0,310	0,292
0,051	1,759	0,864	0,739	0,646	0,573	0,515	*0,468*	*0,429*	*0,395*	*0,367*	0,342	0,321	0,302
0,053	1,759	0,881	0,756	0,661	0,588	0,529	*0,481*	*0,441*	*0,407*	*0,378*	*0,353*	0,331	0,312
0,055	1,759	0,898	0,772	0,677	0,603	0,543	*0,494*	*0,454*	*0,419*	*0,389*	*0,364*	0,341	0,321
0,065	1,759	0,971	0,845	0,748	0,670	0,608	0,556	0,512	*0,475*	*0,442*	*0,414*	*0,389*	*0,367*
0,075	1,759	1,032	0,908	0,810	0,731	0,666	0,612	0,565	0,526	*0,491*	*0,461*	*0,434*	*0,411*
0,085	1,759	1,085	0,962	0,864	0,785	0,718	0,662	0,614	0,573	0,537	0,505	*0,477*	*0,451*
Total width of the building element (including the thermal insulation)													
d	0,364	0,394	0,404	0,414	0,424	0,434	0,444	0,454	0,464	0,474	0,484	0,494	0,504

Figure 3. A practical table for estimating the thermal transmittance of a particular building element for different widths and thermal conductivity values of the thermal insulation material.

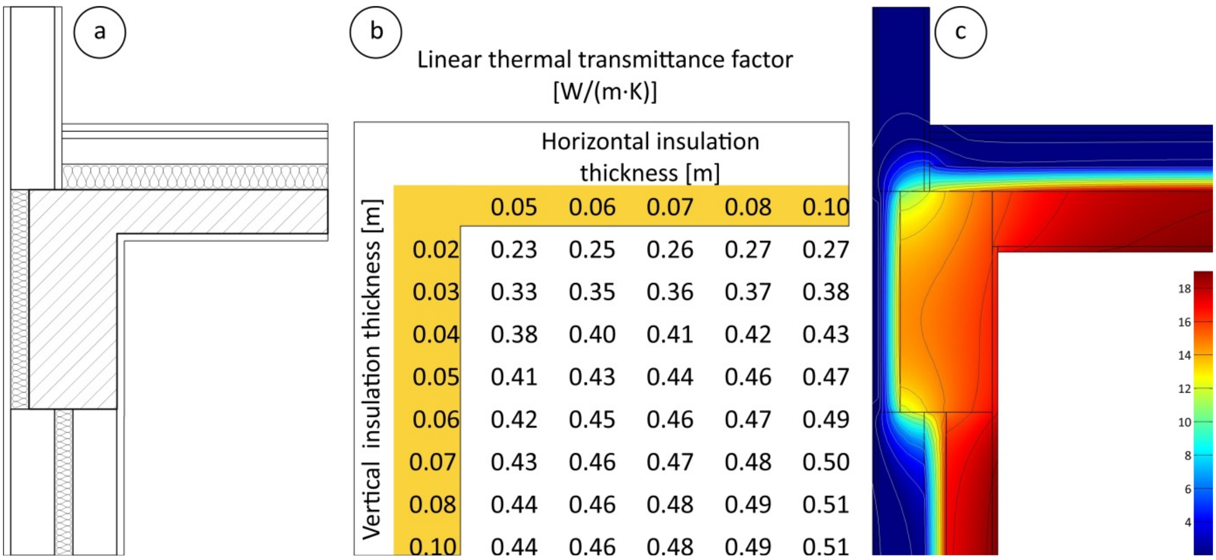


Figure 4. The temperature distribution at the junction of a flat roof and a vertical wall element and the resulting values of linear thermal transmittance Ψ for various widths of thermal insulation.

Apart from the different widths and positions of the thermal insulation layer, different finishes of the vertical building elements were taken into account into the study, representing the most common façade configurations, i.e. conventional coating (cement-lime mortar), decorative ceramic tiles and natural stones. It is assumed that the latter are installed on the building façade with the help of a metallic grid, which forms either a close, unventilated or a ventilated air gap.

2.2 The hygrothermal performance of the building elements

The study of the hygrothermal behaviour of the building elements reflects their performance against the presence, accumulation and variation of moisture in their mass or on their surface, as these phenomena are induced by various factors. More specifically, two main axes can be discerned: first the estimation of vapour condensation risk inside and on the surface of the building elements, as well as their performance against rain and driving rain.

For the estimation of vapor condensation risk a calculation tool has been developed. It can be used for the determination of the temperature and the vapour pressure profiles prevailing across the building element, as well as the risk of interstitial condensation. If the latter occurs, the amount of the condensation is calculated, along with the amount of evaporation. The comparison between the condensation and evaporation rates follows, which indicates whether moisture is accumulated in the building element on an annual basis. The algorithm employed by the tool is in line with the international standards [2-3]. The basic steps are summarized as follows:

- Selection of the boundary conditions for the building element analysis (i.e. city, for the climatic data, and usage density, for the vapour production).
- Determination of the building element's position and composing layers, as well as the materials of each layer. The tool is equipped with a database containing the common building elements and materials, which can be enriched with new assemblies.
- Calculation of the saturation vapour pressure and the water vapour pressure (Figure 5) for the assessment of the interstitial condensation phenomenon on a monthly basis.
- If interstitial condensation occurs, the first month of the condensation is determined. The accumulated condensate is calculated till the rate of condensation becomes negative, i.e. till evaporation occurs.
- Determination of the condensation and evaporation rates on an annual basis in order to assess whether moisture remains in the building element.

Additionally, the performance of the building components against rain for the horizontal elements and driving rain (rain, the velocity of which has also a horizontal component due to wind) for the vertical elements are studied. The accumulation of moisture in building components due to rain water may occur not only in horizontal but also in vertical elements; the latter ones are affected by the moisture load induced by driving rain

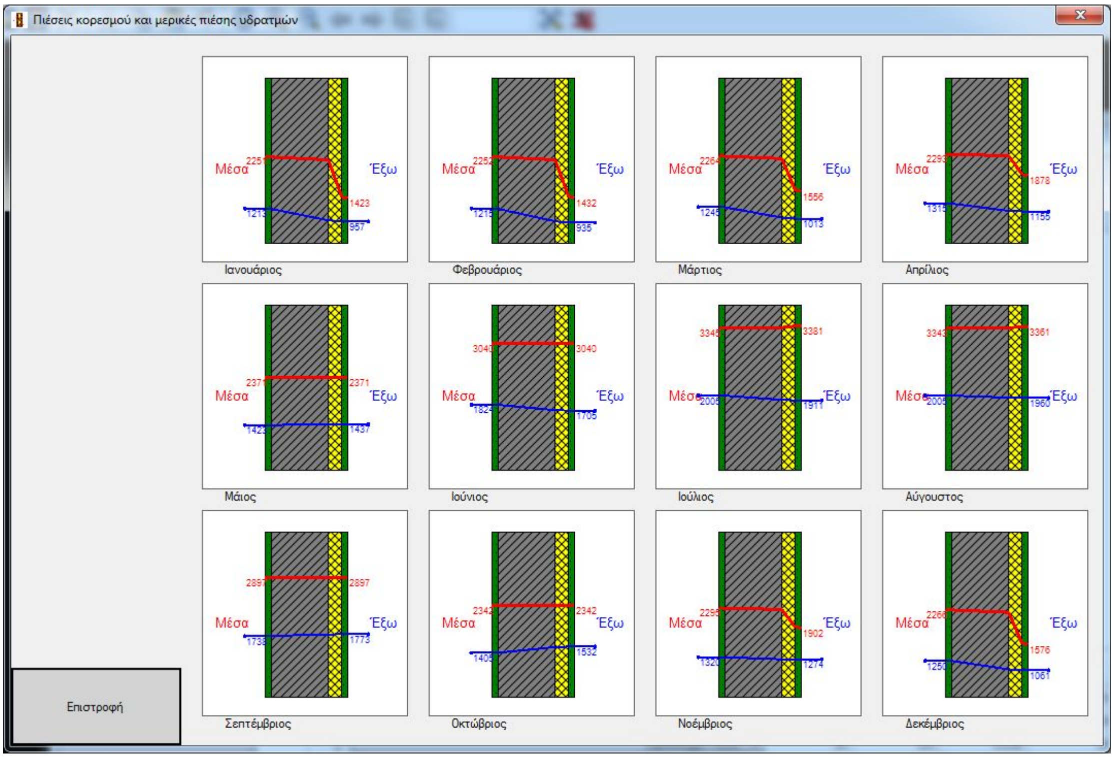


Figure 5. The water vapour diffusion and the saturation vapour pressure in a multi-layer building element, when no interstitial condensation occurs.

(i.e. rain, the direction of the velocity of which obtains a horizontal component due to wind). The horizontal building components examined in the context of the research project are effectively protected against rain and therefore the study is limited to vertical building components. The approach adopted is the assessment of water accumulation risk inside each element due to driving rain. Towards this assessment, the main question dealt with is the quantity of water that can be absorbed by each component under the influence of various driving rain loads (combinations of driving rain intensities and driving rain incidents' duration). The calculation of this quantity comprises a series of simplifications and assumptions. The core of the mathematical background of the calculation has been developed on the basis of the sharp front model theory [4-6] and on relationships derived for the description of rain water absorption by an exterior surface [7]. The mathematical formulations used for the calculations were derived on these bases with the appropriate modifications, when needed, in order to be readily usable in terms of the available material data and also take into consideration the necessary parameters.

2.3 The fire resistance performance of the building elements

The study concerns the fire dynamics of building enclosures, i.e. the detailed analysis of the fire performance of common building elements adopted in the majority of constructions in the Greek district. It is critical to point out that the propagation and spread of fire from one space to another is a highly complicated and multifaceted phenomenon. Evidently, the prediction processes to quantify the behavior of fire and to extort the means to reduce the impact of fire on people, property, and the environment is extremely valuable. In order to undertake the above study FDS is applied; Fire Dynamics Simulator (FDS) is a computational fluid dynamics (CFD) model of fire-driven fluid flow developed by the National Institute of Standards and Technology (NIST). The above software solves numerically a form of the Navier-Stokes equations appropriate for low-speed, thermally-driven flow, with an emphasis on smoke and heat transport from fires. The exploitation of CFD and FEM research models is important in order to predict precisely the actual fire scenario, determine accurately the time-history temperatures at each discrete point (evolution of temperature profiles T(t)) and override the need of large-scale fire experiments.

The present study concerns a typical building volume which consists of two adjoined and similar indoor spaces (Fig. 6(a)). The investigated indoor spaces are separated by an interior wall and a corridor permits their connection by means of the inside doors facing the corridor. The other two walls of both interior spaces split the indoor environment from the outdoor environment. These exterior walls incorporate window openings with a particular geometry and specific characteristics. Furthermore, the structure of the involved opaque surfaces that form the building enclosure vary within a wide range of possible solutions. More specifically, the fire resistance analyses of the building envelope configurations take into account: (a) the category of structural members (reinforced concrete or steel), (b) the type of the insulation materials (extruded polystyrene XPS or rockwool MW), (c) the varying thickness of insulation (from 0 cm to 15 cm), (d) the position of insulation (internal surface, center and external surface), and (e) the type / thickness of the assumed coatings. Aiming to acquire a broad range of outcomes the transient problem is carried out for three typical fire scenarios, which cover a representative width of possible fire incidents (Fig. 6(b)).

Although several of the above aspects may have been studied in the past individually, there is a lack of information on their combination. This setback, which leads to the vulnerability of designing efficiently building shells, is intended to be answered within the context of this project. The extracted outcomes are important in order to reduce the fire risk of buildings that describe the construction practices in Greece. In conclusion, recommendations for the determination of the efficient use of fire insulation materials and the benefits that can be obtained in comparison to non-insulated structural elements will be specified.

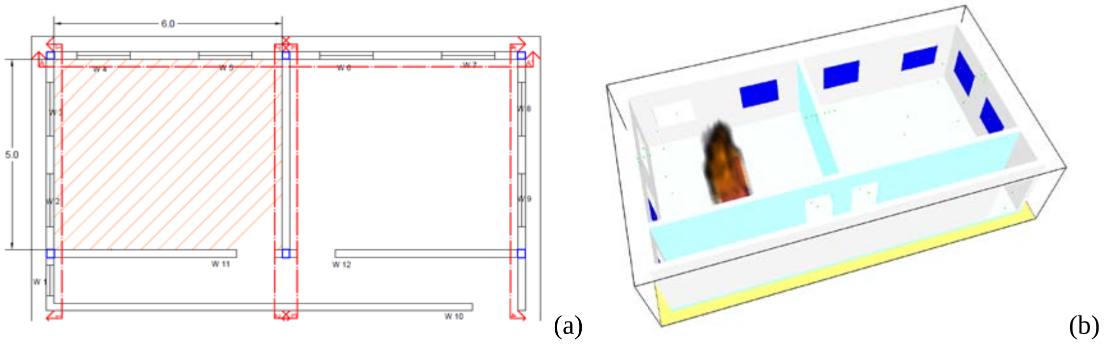


Figure 6. (a)Plan view of the investigated building enclosure; (b) transient analysis of an assumed fire scenario via FDS.

2.4 The environmental performance of the building elements

Under this task the aim is to study and estimate the environmental impact in the different levels of building materials, elements and whole buildings, according to life cycle principles, with the use of LCA tools. The intention is to show clear results and provide useful practical information of the environmental performance of the building materials, elements and whole buildings to engineers and to construction industry professionals.

In accordance with the principles of sustainable construction, the minimization and reduction of the impacts on nature and environment depends on the performance of the building during all the phases of its life. It is well known that the life-cycle of a building is a process, which starts with the formulation of a need to build and the preliminary planning. The phase of construction itself covers a rather short period, in contrast to the use and reuse of various building elements and buildings as wholes, eventually ending in the demolition of the building and waste management, or deconstruction and reuse of building elements. During every phase of the life cycle, decisions are made concerning the performance of the building, with or without consideration of the full potential impacts of these decisions. The LCA is a technique that evaluates the inputs and outputs of raw material and emissions in each step of the material life, adding the resource extraction impact and the emission of pollutants. Its origin is the immediate products industry and it was adapted to the environmental evaluations of building. However, the construction process, the use and demolition of the buildings are still more or less artisanal, and there is no precise information on the inputs and outputs of resources and emissions. On the other hand, the performance and the operation of a building depend on the integrity of each building system, which consists of materials, connections and interfaces. As the application of LCA in the construction industry is based on the analysis of each material used in the construction system, the result of this analysis is the sum of partial results of each material. However, a building is formed by constructive systems that are connected, forming the whole. For this reason, the positive outcome of the evaluation of materials does not guarantee that a building system composed of these materials is also positive. The application, assembly form and use of equipment in the building system modify its environmental performance. It is worth noting that the absence of database of materials of the Greek market makes the use of LCA software, created in other countries, difficult because these are supplied by local databases or similar. Considering this difficulty, it is very important to transform the results of an LCA in data understandable to architects and engineers responsible for the selection of building materials, elements and systems. At the beginning of any decision, before setting their own priorities, architects and engineers need to be aware of the great variety of issues that should be re-evaluated from the perspectives of life-cycle and environmental sustainability. LCA is very important to compare possible alternative solutions, which can bring about the same required performance. The facility of using the system and understanding of the results are considered crucial in the use of the life-cycle principles for selecting building systems.

3 CONCLUSIONS

The need for energy conservation in buildings is an urgent priority both for Europe and at a national level. The requirements of current regulations and the more stringent requirements specified in the foreseeable future (EPBD recast, EUROCODES 2 and 3, EPD-Environmental Product Declarations) necessitate the thorough analysis and development of reliable component solutions that will ensure high energy and hygrothermal performance, fire safety and minimized environmental impacts in the lifecycle of the building components and buildings.

The project not only focuses on the development and organization of theoretical knowledge, but also aims at the wide dissemination of its results, mainly through the development of user-friendly databases and calculation tools for the basic axes of the study. The unified tool that incorporates all the results obtained from the estimation of thermophysical, hygrothermal, fire and environmental performance of building elements with respect to their constructional configuration and the climatic conditions is web-based in order to facilitate its distribution and use by multiple users.

It is important to highlight that the expected products of the SYNERGY project will not only act as a guideline for the technical community, but it will promote the use of building materials, which are efficient from every aspect of view. Subsequently, the private companies that participate in the project will not only benefit from the transfer of knowledge, but will also support their products, as well as gain important information for their further development. Within this context, the SYNERGY project can lead to significant energy savings and reductions in greenhouse gas emissions through the implementation of its results.

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