PROJECT FINAL REPORT

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Project Profile

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Advanced Composite Fibers

1. SUMMARY REPORT

1.1. EXECUTIVE SUMMARY

The MF-Retrofit project aims to deal with the numerous requirements of facade panel retrofitting by developing a light-weight, durable, cost effective and high performance panel. Its layered structure allows for separate but also synergistic function regarding high thermal insulation, excellent mechanical properties, flame retardation and photocatalytic activity. In order to achieve these tasks, a multitude of techniques and technologies have been combined in research and development level, with a vast array of raw materials employed. The individual components have a definite environmental orientation, taking advantage of recycled materials and biomass foams, low energy and low toxicity processes. Finally, project viability and sustainability has been ensured by performing a Life Cycle Analysis in order to optimize individual processes.

Scaled-up prototype panels have been produced and tested. Hygrothermal behaviour and thermodynamics have been simulated and modeled to ensure the high performance of the panel and evaluate its function under varying climatic conditions.

The project's advancements are:

- Customization possibilities: Apart from panel thickness which can be easily tuned, integrated encapsulated PCMs can be tailored along the customer needs regarding temperature of phase change. The integration of the layer materials in the prototype panel is designed in a way that enables customization based on user requirements as well as overarching conditions such as climate and location.
- Easy and fast to install: It is calculated that 10 m^2 can be installed in less than 2 hours by 2 workers
- High thermal insulation: The three internal layers offer varying degrees of insulation, with an inorganic insulation aeroclay layer providing fire protection.
- Photocatalytic activity offering self cleaning and antimicrobial behavior, virtue of the surface coating. In addition, the surface coating also contributes to flame protection due to materials acting as heat inhibitors
- Reduction in weight and volume by 40%, as a result of applying polymeric and light-weight materials therefore improving the panel mechanical properties.

1.2. DESCRIPTION OF PROJECT CONTEXT AND OBJECTIVES

1.2.1. Importance of retrofitting

In Europe, more than 40% of the overall energy consumption and 36% of the overall CO_2 emissions are produced in/by buildings. In the face of Global Climate Change increasingly stringent sanctions on CO_2 emissions are passed. Indeed, European policy regarding the environment is gradually becoming stricter, translating into a series of directives and legislation. In fact, Europe is leaning towards the reduction of the total energy consumption and CO_2 emissions, as a means of protecting the environment. The new Directive 2010/31/EU states that the aim of European Union is a 20% reduction of the Union's energy consumption by 2020. Decision No 406/2009/EC of the European Parliament and of the Council of 23 April 2009 emphasises the effort the state members should make, by setting national binding targets for CO_2 reduction, in order to conform with the EU greenhouse reduction commitments by 2020.
On the other hand, only 1% -1.5% of the European building stock is newly built each year. This translates to only around 1.0–3.0% energy end-use per annum for the replacement of existing building stocks, [3-7] while the most energy consumed is by already existing buildings.
During the last decade, many governments and international organisations have put significant effort towards energy efficiency improvement in existing buildings. The EU recommends a two step approach, i.e. application of energy efficiency measures to a cost optimal level and suppression of the remaining energy needs through on-site renewable energy production.
As a result of these policies, ambitious energy standards and passive house energy standards have been set, both for new buildings as well as refurbishments. However, while in new buildings these standards can be easily adhered to, refurbishment-projects require a bigger effort. In refurbishment projects high energy savings and reductions of greenhouse gases can be achieved by using facade systems. One of their main applications is for fast thermal refurbishment of the existing building stock. They often fulfil high thermal requirements, avoid thermal bridges and achieve higher air tightness targets compared to "on site" construction. Although energy efficiency of old buildings can be drastically improved by exterior wall panel installation, such systems lacks of multi-functionality and thus are consider as obsolete.

MF-Retrofit project aims in the development of multifunctional facades by employing innovative technologies that can improve all aspects of an exterior facade panel, while significantly reducing weight and thickness, installation time and increasing length of life. These facades aim to improve **thermal insulation**, provide **protection from fire**, offer **self-cleaning properties** through **photocatalytic layers**, **control humidity** and **moisture** as well as provide a structurally **stable exterior walling**.

1.2.2. Current refurbishment methodology – Need for innovation

The retrofit technologies can be categorised into: supply side management and demand side management, while significant role plays the human factors. The retrofit technologies for supply side management include building electrical system retrofits and the use of renewable energy, such as solar hot water, solar photovoltaics (PV), wind energy, geothermal energy, etc., as alternative energy supply systems to provide electricity and/or thermal energy for buildings. In the last 5 years, there has been an increasing interest in the use of renewable energy technologies as building retrofit solutions due to the increased awareness of environmental issues. The use of renewable energy technologies may bring more benefits for commercial office buildings where a utility rate structure includes time-of-use differentiated electricity prices and demand charge is applied. The retrofit technologies for demand side management consist of the strategies to reduce building heating and cooling demand, and the use of energy efficient equipment and low energy technologies. The heating and cooling demand of a building can be reduced through retrofitting building fabric and the use of other advanced technologies such as air tightness, windows shading, etc. Low energy technologies may include advance control schemes, natural ventilation, heat recovery, thermal storage systems, etc.

Regarding the latter category the façade systems are considered to be the market leaders for many years. **However, as new standards and legislations push for more efficient systems and at the same time advancements in science and technology – mainly nanotechnology – open new horizons, the traditional façade systems seems to be anachronistic and obsolete.** Specifically, the problems that the existing systems present are:

- **Existing façade materials present high Carbon footprint.** The existing façade systems target in the reduction of energy consumption from users of buildings by providing adequate thermal insulation that leads to reduction of energy losses. However, at the same time due to the fact that the materials that are utilized for the fabrication of the panels are considered to be of high energy intense, the existing façade systems are considered to be high energy embodied construction components. So, a clear need for production of façade systems by utilization of "greener" materials is evident.
- **Moisture problems.** Moisture problems in building envelopes have been long considered as a source of a reduced quality of living and as a reason of a permanent damage of building structures. The penetration of moisture into the substrate often leads to damages to the façade system. In addition, the accumulation of water in conventional insulation materials (e.g. mineral wool) may start a slow degradation processes that has as a result to decrease insulating properties rapidly.
- **Size and weight of existing façade systems.** The existing façade systems follow the rule that the insulation efficacy of the system depends primarily on the insulation product thickness. Thus, in order to achieve efficient thermal insulation, façade of high thickness are used. On the other hand, by using glazing system facades has as a result a high weight burden on the building. It should be mentioned that such massive and weight construction components not only have far-reaching consequences for the building itself but also other side effects such as the high cost of transportation of the systems and long installation times.
- **Luck of multi-functionality.** The majority of existing façade systems focus mainly on the efficient thermal insulation and the aesthetics. However, apart from the insulation efficacy, a successful façade system must also exhibit very good mechanical properties, high resistance to mechanical stress, as well as permeability to CO_2 and to water vapour and finally has to be at least of limited combustibility. The advancements in materials science and technologies allow the development of new composite materials that will present multi-functionality in terms of enhancement of existing properties (thermal insulation, mechanical properties, moisture control, lightweight) as well as new ones like the self cleaning character, photocatalytic degradation of air pollutants, enhanced fire protection etc.

Therefore, a clear need for innovative solutions in the exterior walling retrofitting sector is evident. This need can be satisfied by developing a customizable solution of multi-functional lightweight façade system based on integration of novel materials and technologies.

1.2.3. MF-Retrofit Concept

The building envelope has significant impact on indoor quality. Depending on the insulation materials, indoor temperature might deviate from comfort ranges, inadequate fire protection places the lives of inhabitants in direct danger, humidity can cause various health related issues while acoustic insulation and the aesthetics of the building itself contribute to quality of life. As in Europe however, the vast majority of buildings are from several years it is clearly that a new retrofitting system is necessary. In order to fabricate façades that will not only be thinner but will also provide a series functionalities, a **multifunctional layer** approach is optimal.

A schematic representation of the MF-Retrofit project is depicted in the Figure 1. The Retrofit panel system consists of five layers and a surface coating:

- ✓ **The anchored layer** is the foundation of the panel, compressed against the outer wall, covering all defects and protrusions and offering a first layer of insulation. PCMs are incorporated in this layer in order to provide also energy storage capacity. The anchored layer is fabricated by molded polyurethane foam, reinforced by fire inhibitors. The polyurethane foam used has a high content of biopolyols, reducing cost and dependency on petroleum products.
- ✓ **The main insulation layer** of the façade is made from a novel inorganic aerogel based on clays. This material provides excellent thermal insulation and at the same time significant fire protection for the panel system.
- ✓ **The third layer (durable layer)** consists of lightweight geopolymer. This layer protects the inside layers from humidity, offer the necessary mechanical properties of the component and at the same time, being inflammable, provides fire protection to the system.
- ✓ **The external layer** is fabricated by reinforced polymer. This layer provides additional flame protection and mechanical stability.
- ✓ **The intumescent layer** is a composite material of reinforced latex matrix. The main purpose of the layer will be the fire protection of the internal component as well as anti-corrosion properties.
- ✓ **The surface coating** gives the final aesthetics of the panel and at the same time photocatalytic properties - based on TiO_2 nanoparticles - such as photo-induced self cleaning character and pollutants degradation.

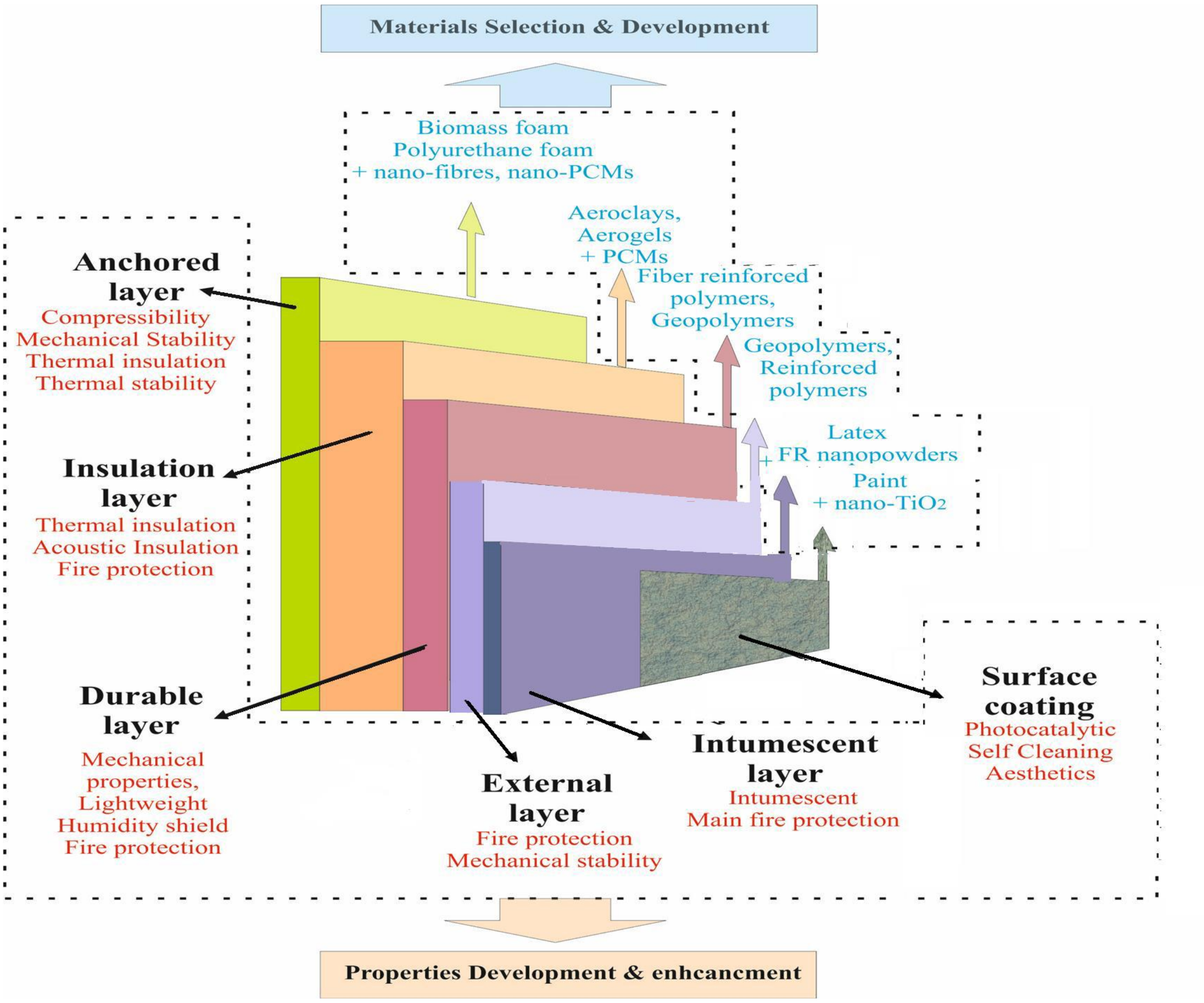


Figure 1 Schematic concept of the MF-Retrofit

1.3. DESCRIPTION OF THE MAIN S&T RESULTS/FOREGROUNDS

The main target of this project is the development of a multifunctional facade panel system that can combine reduced weight, improved durability, low cost and high performance. In order to achieve all these objectives, a layered structure was designed, integrating a variety of materials with individual as well as synergetic functions.

In order to achieve this, a multitude of techniques and technologies were combined in research and development level, employing a variety of raw materials processed via low energy and low toxicity ways. PCMs were integrated in the panel in order to provide thermal storage capacity. The PCMs were modified in order to improve their functionality.

All the raw and final materials were fully characterized as far as their structure and properties are concerned. Mechanical, insulating and fire resistance properties of individual layers and integrated panels were measured according to the relative standards.

An innovative nanoparticle dispersion method into polymeric and inorganic matrices, was developed employing High Energy Ball Milling process (HEBM). A wide variety of nanoparticles were produced in this way and they were tested in order to upgrade certain properties or processing of materials.

Four models (Thermal, Hydrothermal, Fluid Dynamics and Structural Mechanics) were developed in order to predict the thermal, hydrothermal and mechanical behavior of the panel. In addition, appropriate models were developed for the evaluation of panel performance throughout the year, at different climatic zones.

The production of panels was scaled-up and field trial evaluation of the assembled panels was performed using a prototype cube located at Coimbra, Portugal.

Finally, the project's viability and sustainability was ensured by performing Life Cycle Analysis (LCA) and Life Cycle Cost Analysis (LCCA).

1.3.1. Development of materials

In total, 7 different novel materials have been developed and combined in one retrofitting panel. In addition their reinforcement with nanoparticles has been examined aiming to the improvement of their performance. The main S&T results, concerning the development of the materials, are described below.

1.3.1.1. Insulation layers

The main objectives concerning the insulation layers were:

- To develop an elastic, mechanically stable, insulating layer from biomass foam or recycled textile and plastic
- To ascertain the above properties by pre- or post- processing treatments or reinforcement
- To fabricate a light-weight, elastic layer with high thermal insulation

The insulation layer of the panel, included a sequence of hard and soft PU foam covered with an inorganic aeroclay. A PU formulation with high bio-contend was developed and reinforced with flame inhibitors in order to improve fire performance.

In the case of the inorganic insulation materials, both silica and clay aerogels were developed. Due to cost and performance issues, the aeroclays were chosen as the material for the main insulation layer. Furthermore, PCMs were integrated in the insulation layers in order to provide thermal storage capacity. The optimum content of PCMs and the exact location of their integration was selected based on modeling of the thermal behavior. Figure 2 presents the final design of these layers.

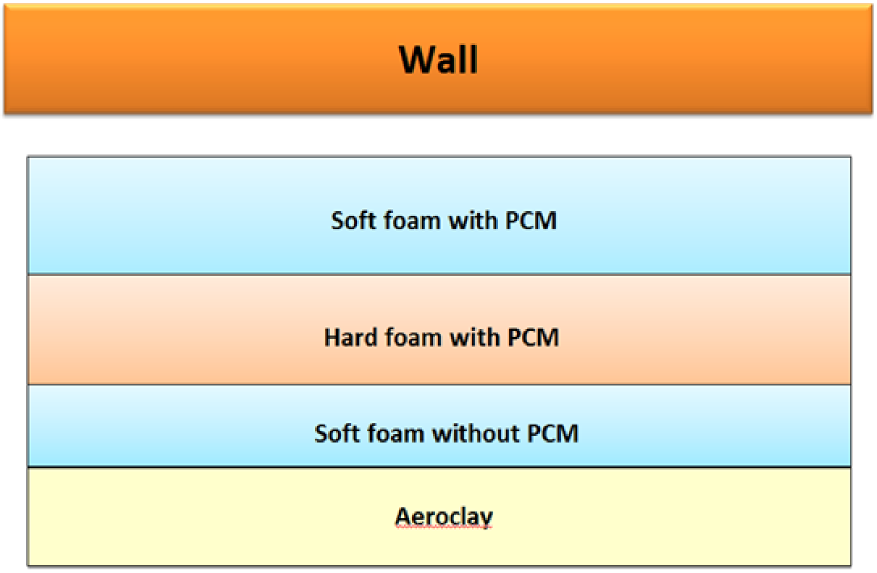


Figure 2. Final design of the insulation layer

1.3.1.2. Structural layers

The main objectives concerning the structural layers were:

- To develop a durable, mechanically stable layer with inherent fire protection employing geopolymeric materials.
- To fabricate a light-weight, mechanically stable layer employing fiber reinforced polymers

The first structural layer was developed through the alkali activation of fly ash. The processing involves mixing of fly ash with an alkaline activation solution, molding and curing at low temperature. As a result the final product has much lower embodied energy and CO_2 footprint compared with conventional structural materials. Lightweight geopolymers were developed through the incorporation of expanded polystyrene (EPS) or foaming agents (H_2O_2 Al, Si, Zn, silica fume) on the geopolymer synthesis. EPS particles were selected to achieve lightweight layer. The choice was based on MF-Retrofit requirements, cost issues and the impact of additives on LCA.

The second structural layer consists of a fiber reinforced polymer (FRP). The development of the external layer involves i) the choice of the resin system, the reinforcement and the curing curve and the definition of the fabrication protocol, step by step. An epoxy resin was reinforced by four layers of bidirectional glass fibers. A finite element model simulating the distribution of the stresses determined the optimal number of fibers' layers.

Figure 3 shows photos of the two structural layers.

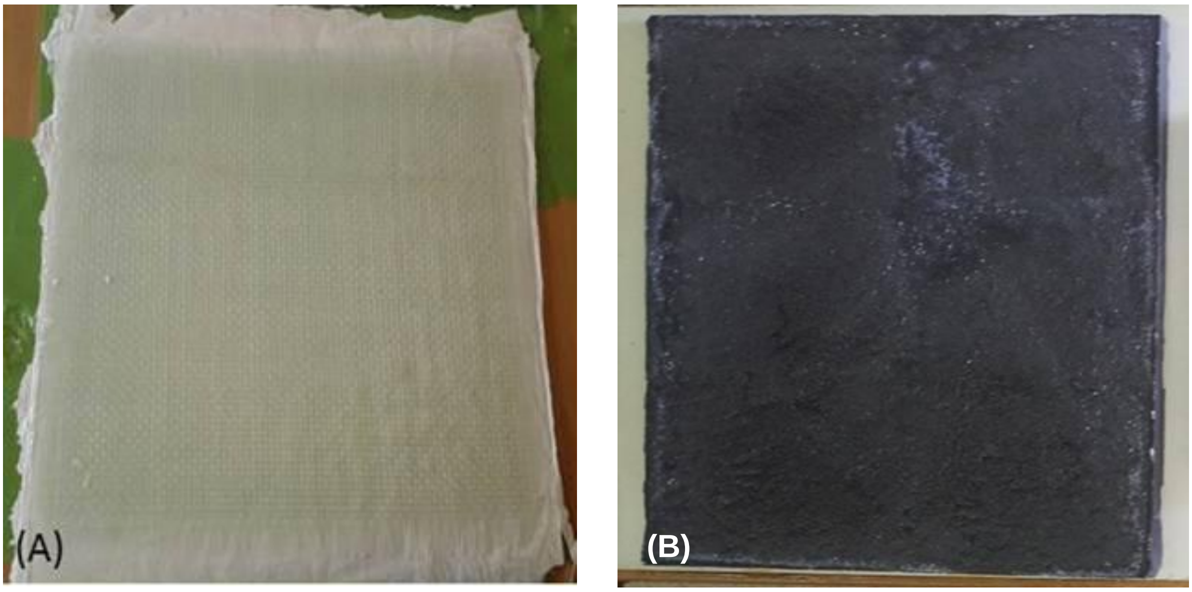


Figure 3. Photos of FRP (A) and geopolymer (B) layers

1.3.1.3. External layers

The main objectives concerning the external layers were:

- To develop an intumescent coating
- To optimize the above solution's rheological properties
- To examine and develop an appropriate doping formulation for TiO_2
- To develop an efficient photocatalytic surface coating using the doped TiO_2 nanoparticles

The function of intumescent layer is to provide a good level of insulation to the panel during fire. Both the integration of heat inhibitors and the replacement of organic solvents with inorganic ones, were tested. Finally, a solvent-free hybrid intumescent material was developed and showed a satisfactory performance. By decreasing the level of organic combustible plasticizer and replacing it with phosphate based plasticizer, the spread of flame result was significantly improved.

Regarding the photocatalytic agents to be applied on the intumescent layer, various TiO_2 nanopowders, with metal and non metal elements, were developed and tested. The powders were incorporated in a paint formulation and a photocatalytic coating was produced.

1.3.2. Development and incorporation of PCMs

The main objective concerning the PCMs is the development of high thermal conductivity, nano reinforced PCMs, that exploit more than 50% of their latent heat potential, leading in more than 30% of PCM efficiency regarding indoor temperature manipulation. The integration of PCMs in the panel layers has been assessed by two major approaches. First, the development of nano-PCMs containing nanofillers, a process that increase their thermal conductivity. Second, the encapsulation of PCMs into inorganic shell with high thermal conductivity to enhance heat transfer performance and improve fire resistance.

In order to develop PCMs containing nanofillers, the addition of carbon based nanofillers, graphene oxide (GO) and multi-walled carbon nanotubes(MWCTNs) were tested. There was observed a lack of compatibility between the paraffin and the fillers, what prompt the need to chemically modify the surface of the nanofillers in order to improve their dispersion into the paraffin. In order to improve compatibility between paraffin and GO, alkylamination methods were performed. However, a satisfactory dispersion of the nanofillers in the PCM matrix was not achieved.

In a second stage, microencapsulated PCMs with paraffin as core and an inorganic shell (silica or calcium carbonate), were prepared and tested. Inorganic shell allows overcoming some limitations that polymeric shells have, such as flammability, poor thermal and chemical stability, and low heat conductivity. Silica encapsulation was achieved by a sol-gel process, through an in-situ emulsion interfacial hydrolysis and polycondensation process of tetraethyl orthosilicate (TEOS). The microencapsulation of paraffin with $CaCO_3$ was carried out via a self-assembly precipitation reaction on the surface of the paraffin micelles in an oil-in-water (O/W) emulsion templating system. Based on the characterization of the modified PCMs, it was decided to engage in the encapsulation with calcium carbonate due the higher reaction yield, higher latent heat storage capacity and also cost issues related to the raw materials need in the synthesis. Furthermore, it was observed that the CaCO3 as a shell material also has a more rigid and compact nature than the other inorganic ones, thus imparting a much better mechanical protection to the PCM cores and resulting in a longer working lifespan for the microencapsulated PCMs.

In order to optimize the functionality of PCMs, their incorporation in the PU foam, aeroclay and geopolymer were tested. PCMs can be uniformly dispersed in both geopolymer and PU foam. Effective and thorough dispersion of PCMs in the aeroclay matrix cannot be achieved, since PCMs are lighter than water. Aeroclay specimens containing PCMs in one or two layers, located either on the top or in the middle of the sample, were prepared and tested. The thermodynamic simulations carried out demonstrated that the use of PCMs have a significant impact on indoor temperature regulation when incorporated into the anchoring layer (PU foam), rather than into the aeroclay or geopolymer layers. Based on these simulations, the optimum content of PCMs in the anchoring layer was also determined. Finally, it was found that the efficiency of the modified PCMs increased by 30 - 50% depending on boundary conditions.

1.3.3. Processing and incorporation of nanoparticles

The main objective concerning this part of the project is to evaluate and optimize the dispersion of nanofiller within the appropriate layer. An innovative nanoparticle dispersion method into polymeric and inorganic matrices was developed employing High Energy Ball Milling process (HEBM). A wide variety of nanoparticles were produced in this way and they were tested in order to upgrade certain properties or processing of materials. In all cases, the formation of nanoparticles was confirmed using analytical techniques such as X-Ray diffraction, Scanning Electron Microscopy, nitron absorption and BET analysis

In the case of the structural layer, the incorporation of fly ash nanoparticles was tested in order to enhance the reactivity of the precursor. In addition, the incorporation of silica fume plus metakaolin and metallic foaming agents (Al, Zn, Si) nanoparticles was tested in order to prepare foamed geopolymer with lower density. In all cases, the dispersion of nanoparticles was homogenous and finally, geopolymers with a wide variety of densities (0.45-1.57 g/cm^3) were obtained.

In the case of the FRP layer, the dispersion of nano flame retardant fillers in epoxy resin precursor has been tested by HEBM and supported by SEM imaging and XRD. The dispersion in bisphenolic matrix was successful and homogeneous and FRP layers were produced, with satisfactory layer finishing.

In the case of intumescent layer, the integration of nanostructured Aerogel, E-spheres, Fillite, Glass Bubbles and Expancel in latex-based formulation has been tested, exploring different concentrations. It clearly resulted that the inclusion of all the lightweight fillers has degraded the performance of intumescent layer rather than improve it, even if homogenous and stable dispersions were achieved.

Finally in the case of photocatalytic paint, TiO_2 nanoparticles were successfully prepared and dispersed in the surface coating, as well as commercial benchmarks, achieving homogeneous and stable paint formulations that can be applied both by brush and by spray gun on MF-Retrofit panel.

1.3.4. Material characterization and properties

All raw materials were fully characterized via chemical analysis and certified methods (XRD, SEM, TEM, FTIR etc.). This extensive characterization of raw materials helped to better understand their nature and led to the selection of the most appropriate ones for the production of the multifunctional facades.

A complete characterization of the final products was also performed in order to optimize their processing and verify their suitability for the multifunctional façade. In addition to structural characterization techniques (XRD, SEM, FTIR), more specialized techniques were applied to each layer material. More specifically, the PU foams were investigate in regard of viscosity (to be able to determine their application e.g. spraying), polyol miscibility, water content as well as OH-Number and Acid number. The characterizations relevant to the insulation layer included density, thermal conductivity and water vapor absorption measurements. The specific characterizations applied for the evaluation of the durable layer performance are a) the mechanical properties defined by compressive strength and flexural strength measurements, b) the apparent density, c) the insulation capacity assessed by thermal conductivity measurements, d) the humidity control by moisture absorbance and sorptivity tests. The relative characterizations for the intumescent layer included density and viscosity measurements. The surface coating was characterized towards photocatalytic activity by degradation of methyl-orange as well as degradation of NOx and self cleaning properties. Finally, the phase-change performance and thermal storage capacity of PCMs was evaluated by Dynamic Scan Calorimeter (DSC) testing and Thermogravimetric Analysis (TGA).

The performance of the individual components of the panel was evaluated by measuring the appropriate properties according to the relative standards. The mechanical properties of the structural layers are measured according EN-196-1, ASTM D 3039 and ASTM D2344**.** The thermal conductivity of the insulation layers are measured according to EN 12667 and ASTM C518. The aging tests for the external layer are performed according ASTM G155. The fire performance is evaluated according to FAR 25.853 F1, DIN 4102. The water-vapor sorption of the main insulation layer is measured according to ASTM C1104, while the water absorption and sorptivity of the durable layer is measured according to ASTM C140 and EN 12667, ASTM C518, respectively. Finally, the photocatalytic activity of the surface painting will be tested according to ISO 27448:2009, ISO 10678:2010 and ISO 22197:2007.

The fire performance of the layers was evaluated according to FAR 25.853 F1, DIN 4102. The anchored layer after being modified with flame inhibitors passed both FAR 25.853 and DIN 4102-B2 tests, even after the integration of PCMs. The durable layer passed the more severe FAR 25.853

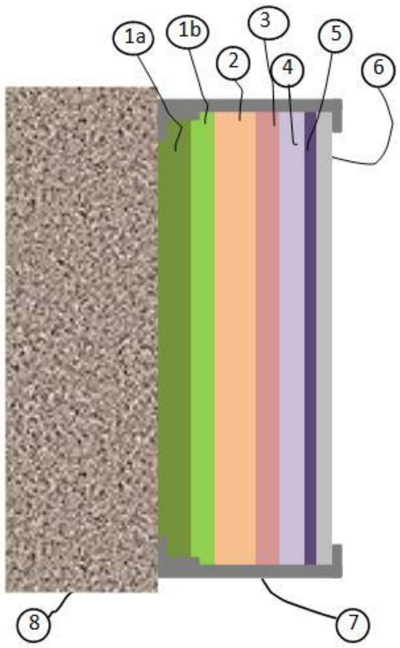
without being affected by the incorporation of flammable polystyrene. The compact aeroclay-geopolymer layer also passes both FAR 25.853 and DIN 4102-B2 tests. Finally, the intumescent coated external layer showed that the developed painting formulation has an improved ability to limit the rate a fire expands across the façade system.

All the characterizations performed, have been collected in a characterization database for MF-Retrofit project. The relevant data and files have been collected in a storage disk and a characterization register has been filled in by the partners, allowing to browse the database. In this file each sample is identified by a name, with reference to the specific characterizations performed, with a short description and with a reference to the deliverable in which results are reported. This database (Figure 4) is kept by the project's coordinator for future uses.

Figure 4. Indexing of the measurement data base.

1.3.4. Façade integration

The final configuration of the Retrofit panel is shown in Figure 5.



Layers:

1a – Soft layer of Polyurethane

1b – Hard layer of Polyurethane

2 – Insulation layer

3 – Durable layer

4 – External layer

5 – Intumescent layer

6 –Surface coating

7– Light-weight steel frame

8 – Existing wall

Figure 5. Configuration of Retrofit panel

The combination of individual layers during the processing of each component was considered in order to facilitate the integration of the panel and improve its performance. The anchored layer was produced out of three separate polyurethane layers. The soft PU layer is compressed against the outer wall, covering defects and protrusions and offering a first layer of insulation. The rigid PU layer supports the thermal insulation and mechanical stability of the panel. These two layers also contain PCMs in the most efficient concentration, as defined through simulation of thermal behaviour. Finally a soft foam layer is in contact with the aeroclay and protects it against mechanic forces (Figure 6).

The combination of aeroclay and geoplymer layers was also performed in order to solve the issue of coherence between these layers. The procedure involved the installation of a pre-fabricated aeroclay layer into a mold and the casting of the geopolymeric paste on the top (Figure 6). The compact double-layer was tested after the curing and it was found that the thermal properties and the performance of each individual layer were not affected by the integration process.

Finally, in order to obtain the required resistance against fire, the external layer was combined with the intumescent layer. The production procedure was modified and in one-step production both individual layers were closely linked with the expected thickness (Figure 6).

		
anchoring layer	**aeroclay + geopolymer layer**	**FRP + intumescent layer**

Figure 6. Photos of combined layers

Several options of layer assemblage and panel integration were examined. The final solution was to adopt a welded framing method that could encapsulate all the layers with the minimum profile and thickness possible (Figure 7).

Figure 7. MF-Retrofit panel

1.3.5. Panel characterization

In addition to the characterization of individual and combined layers, mechanical, thermal and ageing characterization of the whole panel was also performed.

The U value of the panel was found to be 0.32 W/m^2K and the weight 29 and 10 kg/m^2, with and without the structural layers, respectively. The thickness of the façade is 12 and 10 cm, with and without the structural layers, respectively. The overall performance of the panel has been determined by means of laboratory, in-situ and virtual tests. The reduction of the internal temperature variation in respect to the external one was found to near 70%. When the mean external temperature is near the fusion temperature of PCMs, the efficiency of the panel was near 30%-50%. In all cases, the behaviour of MF-RETROFIT improves the commercial panel, optimizing the benefits when the external mean temperature is near 20°C.

Regarding the mechanical behavior of the panel, flexural properties were measured and 3-point bending tests were performed. In addition, the final MF_RETROFIT panel was mechanically compared with a commercial panel. The commercial panel was chosen to be similar in a functional point of view with the MF-Retrofit panel. It was found that MF-Retrofit panel shows an increase of the maximum stress and the elastic modulus by 75% and 85%, respectively, compared with the commercial panel.
Accelerated ageing tests of the panel were also performed under high UV, humidity and temperature conditions. The tests showed satisfactory durability of the panel, significant protection of the FRP layer by the intumescent layer and indicated a gradual loss of self cleaning properties after 10 years of life span.

1.3.6. Demonstration activities

The overall performance of the panel has been evaluated by means of laboratory, in-situ and virtual tests. The laboratory tests has permitted to determine the U-value of the panel and the efficiency, comparing the temperature curves exterior and indoor.

In situ test has been performed by employing the produced panels in a building retrofitting prototype (Figure 8). Sensors for the measurement of temperature, moisture and heat flux were also installed (Figure 9). A weather station was already installed at the site and weather data are available for the

last 10 years. The collected data were used to develop a model for the evaluation of the panel performance throughout the whole year as well as at different climatic zones. The thermal bridging introduced by the still frame was also simulated.
This test was modelled numerically, and the comparison of the numerical results with the experimental data permitted the validation of part of the theoretical tools used in the project. In addition some small specimens have been realized and characterized before and after exposure in order to evaluate the self-cleaning performances of photocatalytic surface coating.

Virtual tests have been used to evaluate the performance under different weather conditions. Four European cities with diverse climate have been selected: Coimbra, Athens, Birmingham and Poznan. In each of the location, several configuration: comparing the panel with and without PCMs with an equivalent panel, and different boundary conditions. The virtual tests show clearly the effect of the PCMs. In all cases analysed, the behaviour of the MF-RETROFIT panel improves the commercial one, increasing significantly the advantages of PCMs when the mean external temperature is near 20°C.

Figure 8. Prototype with the probes installed (red-arrow points north)

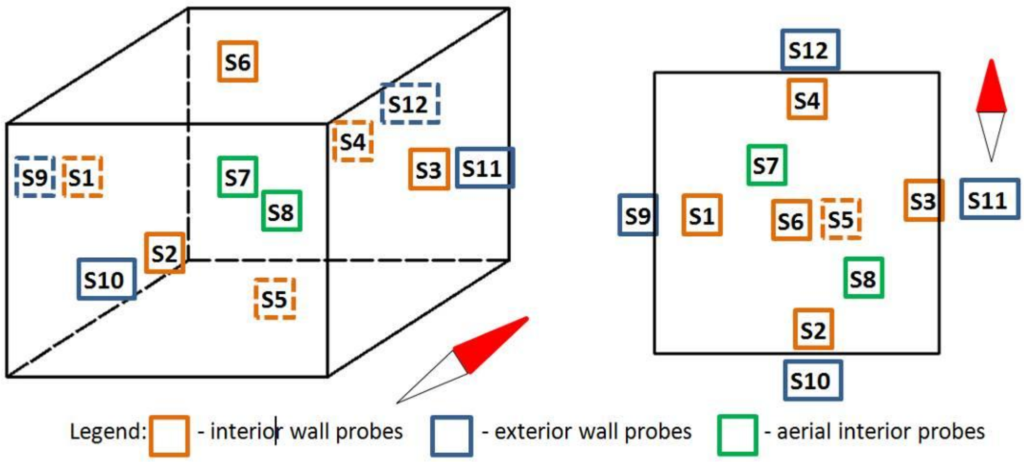


Figure 9. Layout of the probes installed on the Prototype

1.3.7. Simulation and modeling of panel performance

Four models (Thermal, Hydrothermal, Fluid Dynamics and Structural Mechanics) were developed. The simulations permitted to predict the thermal, hydrothermal and mechanical behaviour of the panel. Numerical models were also developed for predicting the thermal performance of the panel in the project. The models were used for four different objectives: to calculate the optimum thickness distribution, to study the losses in thermal bridging, to optimize the PCMs fraction and position, and finally, to evaluate the effect of the MF-RETROFIT panel in the testing building.

In addition, appropriate models were developed for the evaluation of panel performance throughout the year and at different locations, based on the in-situ measurements taken at the prototype cube.

Finally, possible real applications of MF-RETROFIT panel were examine, determining the U-value improvements with retrofitting on existing walls. Four standard walls, with and without insulation, were studied. In al cases, an improvement of U value by 30-75% was found after retrofitting with the MF-RETROFIT panel.

1.4. POTENTIAL IMPACT

Building energy efficiency is generally recognized as a crucial axis in the global effort for environmental protection given that buildings represent almost 40% of total final energy consumption. Likewise, older buildings that represent the majority of the building stock are mostly of low energy performance and efficient renovation work is considered more than imperative. The MF-Retrofit project is expected to significantly contribute to the improvement of buildings' energy performance, helping the EU reach the Europe 2020 priorities. The wide adoption of the novel products by the European building retrofitting market can offer multi-dimensional benefits to the EU, as energy savings and CO_2 reductions will have vital macro-economic benefits for the wounded EU economy, while new jobs will be created, private and public organizations' collaboration will be enhanced and European citizens quality of life will rise.

1.4.1 Socio-economic impact

The building envelope has significant impact on indoor quality. Depending on the insulation materials, indoor temperature might deviate from comfort ranges, inadequate fire protection places the lives of inhabitants in direct danger, humidity can cause various health related issues while the aesthetics of the building itself contribute to quality of life. As in Europe however, the vast majority of buildings are from several years it is clearly that a new retrofitting system is necessary. In order to fabricate façades that will not only be thinner but will also provide a series functionalities, a multifunctional layer approach is optimal.

The novel components present improved properties in comparison to existing solutions. Regarding thermal performance, MF-Retrofit facades will offer improvements thanks to a multilayer approach and insulation enhancements. Insulation in the MF-Retrofit panels is achieved through synergistic function of the three innermost layers, the first component of the sandwich panel. Polyurethane foam, aeroclays and geopolymers are expected to achieve substantial gains in insulation value that will be quantified and evaluated by thermal conductivity measurements as well as other methods such as field trials. MF-Retrofit is also expected to dramatically decrease the dead load of the building components and therefore reduce construction time. Panel assembly will follow a committed prefabricated approach leaning heavily towards minimization of installation time and effort required. CoolHaven has developed and patented a method consisting of a Lego approach to panel installation, requiring 90% of assembly and installation effort to be performed before the panels are even transported, resulting in a drastic reduction of on-site activities. Furthermore, the application of optimized nanocomposites on several layers, as well as the focus on lightweight materials in the remaining layers will sum up a significant reduction of total panel weight. This reduction is calculated with relevance to panel performance in specific core functions, that is to say that where previously traditional materials would require 1kg of panels to provide thermal insulation, MF-Retrofit will achieve the same amount of thermal insulation with only 50% of that load. This will substantially affect transportation time and costs as well as further increase ease of installation.

The Consortium partners are aware of the fire resistance issue for buildings and guarantee the achievement of at least the same results to conventional material consuming solutions. Component mass will be significantly reduced as insulating layers will be thinner than conventional ones. Traditional façade panel materials will be replaced by aerogels and fiber reinforced polymers thus reducing the mass. An important advantage of composite materials is the freedom available to tailor material properties. The application of current opaque insulating layers concerning efficiency and thickness by developing clay aerogel (aeroclays) nanocomposites displaying low thermal coefficients.

The novel components' manufacturing cost is expected to reach low levels in comparison to currently used solutions. Thanks to the novel panels' low weight and high mechanical properties, the use of composites in many applications reduces manufacturing, shipping installation and maintenance costs in comparison to traditional materials such as steel.

The façade market can be divided into two major segments relating to the dominant material used for the façade: the curtain walling market and the structural glazing market. MF-Retrofit will apply for the curtain walling market. Based on Tremco's own research executed in an internal market study, the estimated volume of curtain walling façade is 7.214.000 m^2 totalized for Italy, UK, Finland & the Baltic countries, France, Germany, Poland and the Czech Republic. These countries are core targeted markets for Tremco illbruck for this product type in Europe at the moment.

It is calculated that the remaining European countries in total add some additional 800.000 m^2 to these strategic markets, therefore the assumption for the European Union (EU 27) consists of a total curtain walling market of roughly 8 million m^2. An assessment on the potential building retrofitting market has to consider the fact that the novel advanced functionalities is estimated to be of greater relevance only for half of the total market currently served by façade membranes. For example, there is a large share in public buildings, where an estimated 80% require fire protection due to regulation; whereas in the private sector (business & residential buildings) the rate is much lower with an estimated demand of 20 % due to lack of regulation towards fire protection.

Thus the realistic market volume is about half of the overall façade surface, still more than 4 million m^2 in the European Union. Taking into account the conservative structure of the building construction market a replacement rate of 10-15 % of the overall volume within the first five years after product launch is expected. Therefore, partners calculated with annual sales of around 0.75

million m^2 of façades after five years of launch. With a calculated price of 100 Euros per m2 this volume creates annual sales of 75 million Euros.

1.4.2 Societal implications

The wide dissemination of the project results will also contribute to the revitalization of urban quarters and potentially to the rehabilitation of certain building types in the new Member States of Central and Eastern Europe. The renovations applied are expected to have important impact to the elevation of the quality of life of the habitants. Individuals will enjoy reduction of energy costs avoiding “fuel poverty” given that nowadays energy costs represent a disproportionate and unsustainable share of disposable income. Besides, the quality of living and working spaces is expected to get improved through energy performance improvement. Furthermore, these changes will improve the buildings’ aesthetic value highlighting regional touristic attractions and benefitting local economies, while enhanced fire resistance will protect local communities from conflagrations. In long term, thanks to energy savings will help the EU economy gradually become less dependent from fuels and eventually will contribute to the objective of sustainable development, which is a formal commitment of European countries, and will back the EU climate change strategies. MF-Retrofit will also promote the creation of interesting and high technology new jobs in the areas of building retrofitting, façade construction and building design. European SMEs adopting the new products and procedures will maintain the EU market and claim the global market of building retrofitting and façade manufacturing, based on the knowledge attained during the carrying out of the programme, a fact that will strengthen their competitiveness. This will conclude in creation of new employment, which will partially contribute to solving heavy societal problems interconnected with the currently high unemployment in Europe, concerning mostly the highly skilled unemployed people. Improving energy efficiency in buildings is also important to the buildings energy service industries that are important employers in Europe.

1.5 DISSEMINATION OF RESULTS

In the course of the MF-Retrofit project a number of dissemination activities of knowledge have been performed. These activities include the posters and leaflets that have been initially created and updated throughout the project. These posters have been widely used by all partners during the dissemination activities of the project in various events. Regarding the electronic disseminations, the MF-Retrofit website (http://www.mf-retrofit.eu/) has been created since October 2013 and is constantly updated. Additionally, the project’s Twitter (https://twitter.com/mf_retrofit?lang=el) is running since March 2015 and a page in MBN’s website has been also created that is dedicated to the MF-Retrofit project (http://www.mbn.it/eng/research-detail.php?id=26&id_cat=4). Moreover, the MF-Retrofit project participated in many Coordination and Support Actions (CSAs), i.e. AMANAC, EeB CA^2, EEbers, EeB PPP. Regarding the participation of the project in scientific and industry related events, the project has been presented by all the partners of the consortium in eighteen Industry related events and in ten Scientific events. Fourteen scientific papers have been published until the end of the project and five more papers are under review and manuscript. Finally, the project’s video is available in Youtube (https://www.youtube.com/watch?v=xcoXTT-eN9c).

The products' dissemination will help EU maintain its competitive edge in technological development by exporting the innovative monitoring technology to other parts of the world that are eager to address the building energy efficiency problem. The projects' outcomes and innovations aim to contribute to the technology shift in building retrofitting practices from traditional methods to knowledge based global methods that will direct the energy efficiency technology to a more holistic approach.

1.6 EXPLOITATION OF RESULTS

During the implementation of the MF-Retrofit project, twelve exploitable results have arisen. These include: 1. the formulation of phase change material (PCM) encapsulated with paraffin RT18 as core and an inorganic shell (calcium carbonate) that may find application in improved insulation materials in construction sector, 2. the laminate pre-preg made of fiber reinforced polymer (FRP) with nanoparticles for enhancing fire resistance properties that can find application in construction/retrofitting sector, 3. the development of auxiliary numerical tools to simplify the façade design with PCMs, 4. the development of doped nano-TiO_2 powders – via sol gel and HEBM methods - providing self-cleaning and photocatalytic activity, with applications in a variety of structural materials, such as paints, spray coatings, surface finishes, cement, lime, concrete, asphalt as well as in water treatment systems and filters, 5. a sandwich of flexible and rigid PU foam with enhanced fire resistance properties and high bio polyol content for retrofitting panels in construction market and insulation application market, 6. the formulation of lightweight structural elements from geopolymeric materials applicable in the building sector, 7. the formulation of insulation material based on clay aerogel that can be applied in the insulation material sector in construction industry, 8. a Solvent-Free Intumescent Coating as a A "Green" high-build intumescent coating would be unique in the marketplace, 9. a durable hybrid intumescent Coating as a On-site and off-site steel coating; coatings for other substrates; coatings for external building elements, 10. An Intumescent Coating with improved efficiency, 11. a self cleaning top coat, that will be a Push for intumescent coatings to look decorative, and to lessen dirt pick-up on site and finally 12. a multifunctional panel for an exterior façade with applications in panel manufacturing and retrofitting companies.

Project public website: http://www.mf-retrofit.eu/

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2. PUDF

TEMPLATE A1: LIST OF SCIENTIFIC (PEER REVIEW) PUBLICATIONS, STARTING WITH THE MOST IMPORTANT ONES										
NO.	Title	Main author	Title of the periodical or the series	Number, date or frequency	Publisher	Place of publication	Year of publication	Relevant pages	Permanent identifiers (if available)	Is/Will open access provided to this publication?
1	Durability of Fly Ash Geopolymer Mortars in Corrosive Environments, Compared to that of Cement Mortars	Aristeidis Asprogerakas	Advances in Science and Technology	Vol 92	Advances in Science and Technology	13th International Ceramics Congress-Part F	2014	84-89	Adobe Acrobat Document	Yes
2	A Taguchi Approach for the Synthesis Optimization of Metakaolin Based Geopolymers	Alexandros Tsitouras	Advances in Science and Technology	Vol 92	Advances in Science and Technology	13th International Ceramics Congress-Part F	2014	44-49	Adobe Acrobat Document	Yes
3	Geopolymers of Reduced Density for Application as Structural Elements in Energy Efficient Buildings	V. Pavlakou	EinB2014 - 3rd International Conference		Proceedings	Athens, Greece	2014	EinB25	Adobe Acrobat Document	Yes
4	The Effect of Synthesis Parameters on the Structure and Properties of Aeroclays	A. Skaropoulou	EinB2014 - 3rd International Conference		Prceedings	Athens, Greece	2014	EinB27	Adobe Acrobat Document	Yes
5	Self-cleaning coatings of doped TiO_2 nanostructured powders for applications in construction industry	I. Deligkiozi	EinB2014 - 3rd International Conference "ENERGY in BUILDINGS 2014"		Proceedings	Athens, Greece	2014		Adobe Acrobat Document	Yes
6	Synthesis of lightweight geopolymers based	Kioupis D.	10th PanHellenic Conference of Chemical	P0147	Proceedings	Patra, Greece	2015			Yes

	on Fly ash		Engineering						Adobe Acrobat Document	
7	Improved visible light response of metal/non metal doped TiO_2 nanoparticles utilization in organic pollutants degradation	Maria E. Pappa	10th PanHellenic Conference of Chemical Engineering	P 0184	Proceedings	Patra, Greece	2015		Adobe Acrobat Document	Yes
8	Synthesis of fly ash based geopolymers for use in multifunctional facades	Kioupis D.	4th PanHellenic Conference of Industrial By-Products Research and Development Association (EVIPAR)			Thessaloniki, Greece	2015		Adobe Acrobat Document	Yes
9	Thermal characterization of polyurethane foams with phase change material	C. Amaral	Ciência & Tecnologia dos Materiais				2015			Yes
10	Thermal Insulating Geopolymers Based on Inorganic Foaming	D. Kioupis	5th International "ENERGY in BUILDINGS 2016			Athens, Greece	2016		Adobe Acrobat Document	Yes
11	Two-Component Layer for Retrofit with Insulating and Structural Properties	A. Skaropoulou	ENERGY in BUILDINGS 2016			Athens, Greece	2016		Adobe Acrobat Document	Yes
12	Synthesis of Inorganic Sourced Insulating Materials	A. Skaropoulou	11th PanHellenic Conference of Chemical Engineering			Thessaloniki, Greece	2017		Adobe Acrobat Document	Yes

13	Development of Building Elements with Combined Structural and Insulating Properties	A. Skaropoulou	11th PanHellenic Conference of Chemical Engineering			Thessaloniki, Greece	2017		Adobe Acrobat Document	Yes
14	Design and Development of Green Building Materials Through Alkali Activation of Industrial Wastes or By-Products	G. Kakali	11th PanHellenic Conference of Chemical Engineering			Thessaloniki, Greece	2017			Yes

TEMPLATE A2: LIST OF DISSEMINATION ACTIVITIES								
NO.	Type of activities	Main leader	Title	Date/Period	Place	Type of audience	Size of audience	Countries addressed
1	Project Video	CERTH	MF-RETROFIT : Multifunctional facades of reduced thickness for fast and cost-effective retrofitting	28 March 2017	YouTube https://www.youtube.com/watch?v=xcoXTT-eN9c	Free public access in the internet	190 views so far	International
2.	Website	CERTH	MF-RETROFIT	October 2013	http://www.mf-retrofit.eu/	Free public access in the internet	1000	International
3.	Twitter	IZNAB	MF-Retrofit project	March 2015	https://twitter.com/mf_retrofit?lang=el	Free public access in the internet	300	International
4.	Page in MBN website	MBN	MF-Retrofit Project	January 2017	MBN official website http://www.mbn.it/eng/research-detail.php?id=27&id_cat=2	Free public access in the internet	1000	International
5.	Posters	CERTH, NTUA	MF-RETROFIT : Multifunctional facades of reduced thickness for fast and cost-effective retrofitting	Presented in many dissemination events	Presented in many dissemination events	Industry, Scientific Community, Engineering Community	N/A	International
6.	Leaflets	CERTH, NTUA	MF-RETROFIT : Multifunctional facades of reduced thickness for fast and cost-effective retrofitting	Presented in many dissemination events	Presented in many dissemination events	Industry, Scientific Community, Engineering Community	N/A	International

7.	Interview from EeB-CA[2]	ACF, CERTH	EeB-CA[2] Innovation audit report	March 2016	Phone call	N/A	N/A	N/A
8.	Participation in EEbers	AMS, University of Aveiro	ICT technological developments within the MF-Retrofit	December 2015	N/A	N/A	N/A	N/A
9.	Cluster meeting	CERTH, NTUA	AMANAC	8 April 2014	Athens, Greece	Industry, Scientific Community	255 EU project partners	International
10.	Cluster meeting	University of Aveiro, NTUA	AMANAC	8-10 October 2014	Chambery, France	Industry, Scientific Community	300	International
11.	Workshop	CERTH, NTUA	4th Workshop on Impact of the EeB PPP	1-2 April 2014	Brussels, Belgium	Industry, Scientific Community	300	International
12.	Contribution in the EeE PPP project Review	CERTH, NTUA	Yearly EeB PPP Project Review 2015	December 2015	N/A	N/A	1000	International
13.	Contribution in the EeB PPP project Review	CERTH, NTUA	Yearly EeB PPP Project Review 2015	March 2016	N/A	N/A	1000	International
14.	Research Meeting of the Civil Engineering Department of the University of Aveiro	University of Aveiro	RISCO Research Meeting 2015	28 October 2015	Aveiro, Portugal	Scientific community	34 PhD students	Portugal
15.	Conference	University of Aveiro	MatCel´2015 First National Conference of Cellular Materials	7-8 September 2015	Aveiro, Portugal	Scientific community	50 participants	Portugal
16.	Conference	AMS	10th International Conference on Advances in Experimental Mechanics	1-3 September 2015	Edinburgh, Great Britain	Industry, Scientific Community, Engineering Community	150 delegates	International

17.	Conference	CERTH, NTUA	10th Greek Scientific Conference in Chemical Engineering	4-6 June 2015	Patras, Greece	Scientific Community	500	Greece
18.	Research event	University of Aveiro	Research Day, University of Aveiro	20 May 2015	Aveiro, Portugal	Scientific Community	50	Portugal
19.	Workshop	University of Aveiro	2nd Edition Workshop, Advanced Lightweight Materials and Structures	29 April 2015	Aveiro, Portugal	Scientific Community	50 delegates	Portugal
20.	Conference	University of Aveiro	40th IAHS World Congress on Housing	16-19 December 2014	Funchal, Portugal	Scientific Community	300 participants	International
21.	Conference	University of Aveiro	ANM2014 5th International conference on advanced nanomaterials	2-4 July 2014	Aveiro, Portugal	Scientific Community	300 participants	International
22.	Conference	NTUA	CIMTEC 2014-13th International Conference on Modern Materials and Technologies	8-19 June 2014	Tuscany, Italy	Scientific Community	500	International
23.	Workshops	Fraunhofer	First Workshop High Performance Thermal Insulation (HPI) 2013	27-28/11/2013	Wurzburg, Germany	Scientific Community, Industry	100	International
24.	Conference	University of Aveiro	12th Conference on Advanced Building Skins	2-3 October 2017	Bern, Switzerland	Scientific Community, Industry	300	International
25.	Symposium	University of Aveiro	MATERIAIS 2017	9-12 April 2017	Aveiro, Portugal	Scientific Community, Industry	100	International

26.	Trade Fair	Fraunhofer	BAU 2017	16-21 January 2017	Munchen, Germany	Scientific Community, Industry	250.000 visitors, 2120 companies	International
27.	Conference	NTUA, CERTH	7th ECTP Conference Innovative Built Environment	17-18 November 2016	Brussels, Belgium	Scientific Community, Industry	166 participants	International
28.	Conference	NTUA	Energy in Buildings	12 November 2016	Athens, Greece	Scientific Community, Industry	350 participants	International
29.	Conference	University of Aveiro	Sustainable Built Environment Conference, ETH	14-17 June 2016	Zurich, Switzerland	Scientific Community, Industry	250 participants	International
30.	Conference	University of Aveiro	20th International passive house conference 2016	22-23 April 2016	Darmstadt, Germany	Scientific Community, Industry	500 participants	International
31.	Conference	ACF	MATCOMP' 15	6-8 July 2015	Madrid, Spain	Industry	100	Conference
32.	Conference	NTUA	EVIPAR	11-12 June 2015	Thessaloniki, Greece	Industry	50	Conference
33.	Conference	NTUA, CERTH	EuroNanoForum 2015	10-12 June 2015	Riga, Latvia	Scientific Community, Industry	1200	Conference
34.	Conference	AMS	33rd Spanish Conference on Fracture and Structural Integrity. GEF, Grupo Espanol de Fractura	27-29 April, 2015	Spain	Scientific Community, Industry	100	Conference
35.	Conference	University of Aveiro	18th International passive	25-26 April 2014	Aachen, Germany	Scientific Community, Industry	300	Conference

			house conference 2014					
36.	Conference	Fraunhofer	Green Polymer Chemistry	18-20 March 2014	Cologne, Germany	Scientific Community, Industry	300	Conference
37.	Conference	NTUA, CERTH	Industrial Technologies	9-11 April 2014	Athens, Greece	Scientific Community, Industry	1300	Conference
38.	Conference	University of Aveiro	NanoPT 2014 International Conference	12-14 February 2014	Porto, Portugal	Scientific Community, Industry	150	Conference
39.	Cooperation fair	ACF	9th EU-China Business & Technology Cooperation Fair	21-23 October 2014	Chengdu, China	Industry	1000	Cooperation fair
40.	Conference	CERTH	Energy in buildings 2013	9 November 2013	Athens, Greece	Scientific Community, Industry	400	Conference
41.	Trade Fair	CERTH	Building Green	4-6 October 2013	Athens, Greece	Industry	8000	Trade Fair
42.	Conference	CERTH	EuroNanoForum 2013	18-20 June 2013	Dublin, Ireland	Industry, Scientific Community	N/A	Conference