Development of sandwich panels of customized functionalities for the rehabilitation of the built patrimony
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Development of sandwich panels of customized functionalities for the rehabilitation of the built patrimony

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ABSTRACT

The future of the construction in the next decades in most European Countries, especially those of Southern Europe, will mainly lie in the renovation of the existing building stock constructed over the past 40 years. Thousands of uncharacteristic buildings will need renovation in the next coming years forcing EU member states to reach the EU 2020 targets and implement the Energy Performance of Buildings Directive (EPBD), which recommends that by 31 December 2020 all new and retrofitted buildings in Europe will have to be nearly-zero energy buildings (NZEB). Sustainability and energy efficiency are closely linked to the building sector, having each country to address this problem now by investing in new buildings that can meet the highest standards of energy efficiency, but mostly by renovating the immense quantity of existing inefficient buildings where most of the population still lives. Seeing this crisis as an opportunity, this work aims to develop a concept for prefabricated customizable sandwich panels for the multifunctional renovation of buildings. More than a conventional solution, this proposal aims to combine sustainable building materials, available technologies and systems with advanced design and manufacturing tools within an integrated and mass-customizable approach of advanced building renovation prefabricated solutions. The adoption of the proposed solutions would not only contribute to the reduction of the energy inefficiency in buildings, but also minimize related construction problems, enabling some advanced features like the incorporation on the façade layout of advanced modules such as solar panels, to improve the system’s energy performance.

Keywords: Prefabricated, Modulated, Panels, Renovation, Façade.
P. Sá Costa, Painéis Sandwich Customizados para a Reabilitação do Património Edificado
RESUMO

O futuro da construção nas próximas décadas, na maioria dos países europeus e especialmente nos do Sul da Europa, residirá principalmente na renovação do parque imobiliário existente construído ao longo dos últimos 40 anos. Milhares de edifícios incaracterísticos terão de ser renovados nos próximos anos para obrigar os Estados-Membros a atingir as metas energéticas da UE para 2020 e implementar a Diretiva Europeia relativa ao Desempenho Energético de Edifícios (EPBD) que exige que todos os edifícios novos e reabilitados a partir de 31 de dezembro de 2020 passem a ser Nearly-Zero Energy Buildings (NZEĐ). A sustentabilidade e eficiência energética estão intimamente ligados ao sector da construção, e cada país terá agora de encarar esse problema investindo em novos edifícios que possam atender aos mais altos padrões de eficiência energética, principalmente renovando a imensa quantidade de edifícios existentes e ineficientes onde a maioria da população vive. Vendo esta crise como uma oportunidade, este trabalho tem como objetivo desenvolver um conceito de painéis sandwich pré-fabricados customizáveis para a renovação multifuncional de edifícios. Mais do que uma solução convencional, esta proposta visa combinar materiais de construção sustentáveis, sistemas e tecnologias disponíveis com ferramentas de fabrico e design avançado, numa abordagem integrada e personalizada de soluções de pré-fabricação em massa para a reabilitação do parque habitacional. Pretende-se com a adoção das soluções propostas contribuir não só para a redução da ineficiência energética dos edifícios, mas também minimizar os problemas de construção existentes, permitindo também a incorporação no layout da fachada de módulos avançados, como painéis solares, para melhorar o desempenho energético do sistema.

Palavras-chave: Pré-fabricados, Modulares, Painéis, Renovação, Fachada
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Note: All the sources for the remaining figures that are not listed here are mentioned in the corresponding caption and referenced at the Reference Chapter. The remaining Figures without explicit source belong to the author of this work.
1 INTRODUCTION

1.1 Motivation

The current global crisis has revealed enormous fragilities in the model of development followed by many countries in recent times, especially those where the construction sector played a major role in the economy. Fuelled by cheap credit, the housing sector has been particularly responsible for this situation, having been built in the past decades in Europe millions of new homes - especially in southern European countries - that were made available at affordable prices to the great majority of the population. However, this mass construction driven by low standards and high demand led most of these buildings to lack the necessary quality, both at the level of indoor environment and aesthetical appeal. Another problem was the rise of private and public debt in southern Europe to unsustainable levels that led construction almost to a standstill. The consequence is a situation with many new unsold empty buildings without buyers due to the lack of credit and a vast quantity of existing inefficient buildings constructed over the past 40 years where most of the population still lives (Figure 1).

![Figure 1. Examples of large private owned buildings (a) and public social housing (b) with poor construction and repetitive façades](image)

The constructive façade systems in this kind of buildings consists mostly on double walls with insufficient thermal insulation, which associated to poor framing contributes to high energy losses, often making the cost of heating unaffordable and forcing people to live with thermal discomfort for
most of the year. Other common construction related problems are thermal bridges, which cause condensations that affect the interior air quality and deteriorate the health of the occupants. Considering that the available housing stock has already reached a level that can guarantee the needs of the European population for the next decades, thousands of uncharacteristic buildings like these will need renovation in the next coming years as EU member states are required to fully implement the Energy Performance of Buildings Directive to meet new high demanding energy efficiency standards until 2020 (Concerted, 2014). The rehabilitation of this immense built patrimony will undoubtedly also be an essential opportunity to revitalise the construction sector, finding a more sustainable development model that can create new jobs and business opportunities based on innovative construction methods and energy efficient solutions.

### 1.2 Objectives

Considering this scenario, this project is based on the development of a prefabricated system of customizable sandwich panels for the multifunctional renovation of buildings, especially those built in the past four decades that are characterized by repetitive and monotonous façades, which present an ideal opportunity for modular renewal solutions. Most of the existing systems for the renovation of façades only increase the level of insulation and minimize thermal bridges, not solving other important pathologies.

More than a conventional solution, this prefabricated customized system consists of a new external skin that can not only renovate the outdated and unappealing aesthetics of the building but improve indoor environmental quality, minimize energy inefficiency and also other existing construction related problems. It proposes to combine building renovation with technologic innovation, incorporating sustainable and recycled building materials, available technologies and systems with advanced design and manufacturing tools within an integrated and mass-customizable approach of advanced building renovation prefabricated solutions. This modular solution will be based on a prefabricated Fibre Reinforced Cement Composite (FRCC) panel with an inner insulation core incorporating sustainable and recycled materials. FRCC panels would not only provide high mechanical stability to the façades but also offer a new possibility to explore interesting visual solutions to upgrade the visual aspect of existing buildings. For increased energy performance, technical components, such as photovoltaic (PV) or solar panels would also be incorporated in the panels, integrating harmoniously these elements on the façades. Advanced solutions to be explored in future works could include more sophisticated
systems like energy efficient windows featuring control units connected to a domotics system that would monitor the indoor environmental quality of each compartment.

This work plans to determine whether these more advanced materials that constitute the panel, properly positioned on an underperforming façade, can result in an efficient and competitive system, assuming that the panels will be used to improve both energy and structural performance, but could even be applied on new construction in the future.

1.3 Outlines

In the First chapter of this thesis plan, the main reasons to elaborate this work are provided, including motivation and the main objectives, as well as the main outlines.

The Second chapter is divided in three sections, being the first dedicated to the framework of building renovation in Europe, explaining its challenges and differences in the European context and in Portugal in particular while enhancing the main hurdles to be still overcome by most countries in order to reach a high level of energy efficiency in the existing building stock to comply with the new EU regulations. The second section explains the advantages and challenges of prefabrication, discusses the inconveniences of one of the most common solution used nowadays in building renovation (External Thermal Insulation Composite System – ETICS) and finally presents a selection of some of the most advanced solutions regarding prefabrication with the Multifunctional Façade Systems. The final section introduces a major reference in prefabrication that motivated the development for this work, the LEGOUSE Project.

The Third chapter explains the proposed concept, exploring the proposed materials that can constitute the panel, the technical modules to be included in the customization of the solution and a final section devoted to the potentialities of robotization and BIM in the fabrication and installation of the panels.

The Fourth chapter is dedicated to the execution and testing of the two prototype panels presenting the results, comparing the two solutions in terms of mechanical and thermal efficiency, as well as cost-efficiency.

Chapter five is dedicated to the presentation of the relevant results and potential future developments of the proposed concept, followed by Chapter six presenting a preliminary layout of the proposed panel concept assembled on two façades in a case-study building to illustrate the potential of the solution, concluding this work with the References.
2 STATE OF THE ART

2.1 Framework of building renovation in Europe

2.1.1 Introduction

Building renovation nowadays is a necessity not only because most buildings need to upgrade their outdated or neglected visual aspect, but mostly because they underperform in what concerns energy efficiency. The first Energy Performance of Buildings Directive (EPBD), published in 2002, required all EU countries to improve their building regulations and to introduce energy certification schemes for buildings, while upgrading inefficient and obsolete heating or cooling systems. This was an important step to raise public awareness to energy efficiency in buildings, but also a great challenge to implement the Directive at national levels. EPBD was recast in 2010, forcing each EU member state to move towards new and retrofitted Nearly-Zero Energy Buildings (NZEB) by 2020 (Official, 2010). It required also that each country should apply a cost-optimal methodology for setting minimum requirements for both the technical systems and the building's envelope. Additionally, environmental issues, the world economic crisis and the rise of energy prices in recent years have also increased the level of consciousness, leading people to look for renovation options that can effectively reduce energy costs.

In this current negative scenario, most of the European population, especially in southern countries where the economic situation does not seem to improve, still cannot afford high investments in the necessary building renovations to optimize energy performance. However, this process can no longer be postponed if European member states are to move towards new and retrofitted Nearly-Zero Energy Buildings until 2020. Despite the negative economic environment, Europe has already implemented effective strategies to respond to this immense challenge putting forward in March 2011 the "Energy Efficiency Plan 2011", which aims at saving more energy and create substantial benefits mostly for households, while improving EU's industrial competitiveness and promoting the creation of more employment (European, 2011). Meanwhile, with Europe’s Energy Efficiency Directive (EED) coming into force in 2014, enthusiasts are pushing for the EU to come forward with a more realistic target for 2030 and adopt proposals to dramatically cut energy use in Europe's building stock by 2050 (European, 2012). This directive was approved by the EU parliament in December 2012 after it became clear that the EU was not on track to meet its non-binding 20% energy savings target for 2020, and the main goal is to put EU member states back on the right path through a set of ambitious measures concerning all stakeholders, from public bodies to energy companies, industry and
consumers. Once again, as building renovation takes centre stage again and debate heats up over energy efficiency targets for 2030, much of the work is still to be done, as member states have to be able to implement what they committed to do in their national action plans on buildings (EurActiv, 2013). Figure 2 illustrates the expected results in each one of the three main EU 20-20-20 sustainability goals, clearly indicating that the reduction in energy consumption will not be achieved by 2020, as expected.

![Figure 2. Expected results in each of the "EU 20-20-20 by 2020" goals (Source: Lowe, 2011).](image)

Energy efficiency is a complex issue that deals with the whole economy and depends on a strong commitment of all European countries - and the world, at a global scale - but is necessary to change the mind-set concerning buildings, as they are expected to significantly contribute to the 80-95% greenhouse gas (GHG) reduction target set for 2050 in Europe (BPIE, 2011a). This means that, on average, each building will have to reach very low carbon emission levels and decrease energy consumption dramatically, as Europe heads towards a low carbon power sector, based more and more on renewable energy sources. This goal may seem hard to reach, but it will be attainable if building renovation is to be taken seriously by both governments and citizens, but the reality is that Europe as a whole is not responding in the same way, as explained in the next chapter.

### 2.1.2 Differences on building renovation in Europe

According to the report "High-rise Refurbishment: The energy-efficient upgrade of multi-story residences in the European Union", an extensive study published in 2006 by the International Energy Agency concerning research done on the energy-efficient refurbishment of the high-rise residential
European building stock, one in six of all households - or approximately 36 million European households - are in high-rise buildings, many of which are in urgent need of renovation. The energy efficiency of the European existing building stock varies according to the country of origin, building age, materials and techniques used in the construction and - most importantly - the public and governmental consciousness about this important issue.

In northern and most central European countries, encompassing Scandinavia, Benelux, Germany, Austria and France, where climate is more extreme, society and governments have been for a long time aware of the need to reduce energy consumption in existing buildings by increasing insulation levels. As buildings in these countries are usually kept in good condition due to state incentives and legislation that forces building owners to invest periodically in renovation, this process is done on a regular basis mostly by retrofitting the building envelope to reach the highest level possible of energy efficiency, while simultaneously upgrading existing heating and ventilation systems for new, more energy efficient ones. These countries represent the most advanced economies in Europe and have also reached the highest benchmark at the European level in terms of high energy efficiency in construction and reconstruction, where building refurbishment is already of a very high standard and the rehabilitation of the existing housing stock is widely considered as essential to promote sustainable building methodologies and to reach high energy efficiency levels. As a result of this already high level of energy efficiency, the cost-effectiveness of investment in high rise building renovation in this region is considered to be average (Waide et al, 2006), although there is still potential for improvement.

Eastern European countries face similar climate conditions to northern and central European countries but, as a result of a completely different political regime and mass style house building projects done in previous decades, the existing building stock in these countries presents a high degree of energy inefficiency, most of the times consisting of poorly insulated prefabricated concrete panel walls, flat concrete roofs and ground floors above unheated basements, being the main heat system provided by district heating. This group encompasses cold climate countries and as a rule presents a rather standardized high-rise building stock with the highest dwelling proportion, a very high level of energy inefficiency and high energy saving potential and CO2 reductions. However, low local energy prices and the effects of the ongoing economic crisis contribute to a low cost-effectiveness in the investment, despite EU regulations and several incentive measures to promote building rehabilitation (Waide et al, 2006).

Southern European countries - Portugal, Spain, Italy, Greece and France, also classified as warm climate countries - can be considered to be the biggest and the most homogeneous group under study,
Despite regional differences in countries located in more than one climate zone, such as France. The high rise building stock in southern Europe is considered to encompass a staggering 19.5 million dwellings in approximately 650,000 buildings, which account for 24% of the dwellings in the region. This translates in an energy-saving potential in stock of 25%, equivalent to 1.3% of region's final energy demand, which makes the cost-effectiveness of investment in building renovation in this region to be amongst the best, mostly due to the low initial thermal quality of the many buildings to be refurbished. These consist mostly of poorly insulated double brick or in situ concrete walls, flat concrete roofs and concrete floors, with single-glazed inefficient metal frame windows, and heating based mostly on inefficient energy electric systems or independent appliances (Waide et al, 2006). Additionally, the relatively low investment cost (depending on the solution to be adopted) and the high price of energy also contribute for the high return of the investment. Possibly excluding France, in this group building rehabilitation has been taken less seriously not only because of a warmer climate, but mostly due to the lack of incentives from central governments associated to the economic crisis and a less well informed society that does not see urban retrofitting and energy efficiency as a real priority. The nature of private ownership of many of the apartments that compose the existing building stock, which most of the times translates in a lack of agreement between homeowners on what to do and how much to spend on the rehabilitation, is an additional problem.

In Portugal the current crisis in the construction sector can be seen as the turning point from focusing exclusively on new construction - as it has been done until recently - embracing now rehabilitation. AECOPS, the Portuguese Association of Construction Companies, Public Works and Services, estimates in its 2009 report that the impacts of rehabilitation on the construction sector could increase its productivity, reaching a share of 6% of the country’s GDP and increasing it even further in the period 2011/2030 (AECOPS, 2009). According to the same report, this would also have a positive impact on the creation of approximately more 196,000 direct and 587,000 indirect new jobs and estimated energy savings around 106.1 million Euros on the same period. It is important to note that these savings were only calculated considering interventions in existing buildings improving only thermal insulation and glazing, which is the basic approach commonly accepted as building rehabilitation in Portugal. If other measures were to be considered, such as integrating solar thermal energy systems, energy savings would be expected to more than double.

Energy efficiency in the Portuguese Residential Buildings Stock is also analysed according to the current national legislation, namely the SCE (National Energy and Indoor Air Quality in Buildings Certification System), RSECE (Regulation of Climate Energy Systems in Buildings) and RCCTE
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(Regulation of Thermal Performance of Buildings). These regulations promote the rational use of energy in buildings and encourage the use of energy sources with low environmental impact in new and existing buildings, being SCE a national transposition of the Energy Performance of Buildings Directive (Directive 2002/91/EC, EPBD), materialized with the "Energy and Indoor Air Quality Certification", a mandatory certificate that home owners must obtain when selling, licensing or renting new or existing buildings. This mandatory document, however, does not require home owners to undertake any kind of renovation works to improve the energy performance of an underperforming building, which associated with the lack of real incentives for building rehabilitation results in little progress. Considering that in Portugal the existing building stock is estimated around 3.160.043 buildings of which 57% were built after 1971, most of it presenting a high degree of energy inefficiency, the potential for improvement is immense (AECOPS, 2009).

2.2 Existing Solutions

2.2.1 Traditional Renovation vs. Prefabricated Building Renovation

In most cases, rehabilitation only addresses partial solutions to solve visible problems, like thermal bridging, water leaks or condensations. In Portugal, this way of interpreting building renovation is widely spread, consisting mainly on solving specific problems and not addressing them in a comprehensive solution that encompasses all the possibilities to efficiently and sustainably upgrade a building. The consequences, as a rule, will probably be a less inefficient building, but not an efficient one.

Traditional renovation can hardly be considered a process with a bright a future to be adopted on large scale projects, as it involves most of the time ineffective construction processes with low quality levels, depends excessively on the craft skills of the workers (and the human error factor associated with it) and end up most of the time in too many technical compromises and poor on site coordination. This process may be an adjusted and realistic option when addressing a small scale project, as it deals more with detail and specific requests made by the homeowner, and in this sense good craftsman skills are an advantage.

Prefabrication is the future when thinking of large building renovations, as it addresses the building as a whole, focusing on specific problems that must be resolved a priori, such as the compatibility of the architectural elements with all the installations and the existing façade. This method allows rapid construction due to the fast assembly of the modular elements, requiring also fewer companies
involved in the process, few workers on site, less coordination than the traditional approach and technical compromises reduced to a minimum, showing great potential for costs reductions. Another advantage of prefabrication is that modular elements can assure their final expected quality level already at the production line. If well planned, this process may also avoid major disturbances to the occupants during the renovation process, something that could hardly be accomplished with a traditional method.

While it may seem that prefabrication is all about advantages, there are still many challenges for the future concerning the development of integral optimized solutions - a difficult task when buildings to be rehabilitated have always different features and requirements - which lead to the difficulty in implementing standardization in the construction process. For the same reason, detailing and customization possibilities are also limited, sometimes making all prefabricated buildings look alike. Other drawbacks related to this process are the lack of specialized workers and sometimes, the complexity of logistics and process organization, especially if the whole process is not well defined on the planning phase.

2.2.2 ETICS - External Thermal Insulation Composite System

Most efforts to increase thermal performance in buildings today consists in applying insulation materials to the entire wall, ideally as an added layer of external insulation that is applied to the structural or brick wall before the final rendering or cladding is added. The most common approach in Europe is to use an External Thermal Insulation Composite System (ETICS), which uses most of the times Expanded or Extruded Polystyrene (EPS or XPS) panels with different thicknesses, according to the thermal requirement specifications, embedded in a thin topcoat of cementitious material finish. This type of exterior solution, if properly executed, is air and moisture tight and offers significant energy efficiency improvement by eliminating thermal bridges and adding additional insulation to the entire wall but requires recladding the entire building and is only cost effective in a major refurbishment when other benefits can be also executed, such as the upgrading of the heating and ventilation systems of the building. Although ETICS can be considered a good, widely available and cost effective exterior insulating solution for new construction and rehabilitation, it also presents some disadvantages to have under consideration. This main one is that it consists of layers of different materials to be manually installed and depends exclusively on the skills of the workers in order to follow all the specifications of the manufacturer and the details of the project, making it more related to traditional renovation methods, with all the associated disadvantages already mentioned above. ETICS is also a light weight
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insulating system, which per se is an advantage as it does not overload the building structure, but on the other hand it is a relatively fragile solution that can be easily damaged by impact, puncturing or abrasion. Moreover, if the system is not properly mechanically attached to the existing wall there is a strong possibility of system delamination from the substrate, as parts of the new façade may detach and fall over (Peter, 1996). The thin outer cimentitious layer also requires skilled workers to present a smooth continuous water tight surface wall, but if it is not properly executed and cracks, water might get inside the system causing major damages to the entire wall. On the other hand, if this solution is placed over existing walls with untreated moisture problems resulting from capillarity or other permanent sources of infiltrations, the water will most likely stay inside the wall creating serious problems in the future. Other problems with ETICS arise when using dark colours in the finishing layer along with the most typical insulation materials used in this system (EPS or XPS), as under direct sun exposure the walls can reach high superficial temperatures, causing the polystyrene in the insulating panels to self-extinguish and creating permanent damage to the façade and to the whole building. Additionally, EPS and XPS are also not fire resistant and fire regulations prevent their use in high rise buildings, having to be replaced in these cases by others, like rock wool, increasing the final price of the solution and most times its competitive edge.

ETICS presents many advantages, but when used alone in rehabilitation projects it is somehow limited to protecting the outer skin of the building against temperature oscillations not addressing other problems like upgrading of all the technical installations - which, in this case, still has to be done on the inside of the building, causing major inconveniences to the occupants. It is then necessary to search for a more integrated retrofit intervention and explore new solutions that effectively address this problem in a more holistic perspective.

2.2.3 Multifunctional façade systems

Prefabrication of modulated façade systems was initially used on the construction of large multifamily buildings in the 70's in Europe to cater to a large demand of housing resulting from population growth and the expansion of the cities. Examples of this kind of construction can be seen especially in northern and central European countries, but this system was especially popular is Eastern Europe, where a large percentage of the existing building stock consists today of mass prefabricated (and mostly energy inefficient) buildings. Today, Multifunctional Façade Systems are a new solution intended to be used in modular construction methods with the highest possible level of prefabrication. While this system was initially designed for new construction it has been also used on the rehabilitation of the existing
building stock. Modulated panels can be designed to fulfil high thermal requirements, eliminating thermal bridging in buildings, and also make use of the advantages of prefabrication, such as reducing on site construction time, achieving a high air tightness level when compared to traditional construction or renovation methods and - most importantly - they can integrate all the necessary installations, such as new windows, ducting and cabling, making the rehabilitation process more efficient. Moreover, this solution is open to the integration of new technologies, such as solar thermal and photovoltaic panels that can increase the building's energy efficiency levels, along with more advanced solutions like domotics and "smart materials" (temperature-responsive materials like PCM, self-cleaning materials, etc.), opening a new chapter on the industry of prefabricated façade panels, combining the flexibility of the manufacturing process to adapt each solution to a specific type of façade or need. The options are immense but the main challenge will be the development of sustainable solutions that can reach a high cost optimisation level and the return of the investment on a reasonable period. Another important aspect will be the adoption of new design and work methods such as IPD (Integrated Design Project) and BIM (Building Information Modelling) to promote an efficient inter and trans-disciplinary planning from the project start – topics to be addressed ahead on chapter 3.3 "Fabrication and installation using robotization and BIM". According to the study "New technical solutions for energy efficient buildings" conducted by Sci-Network, an European initiative to connect public authorities to procure innovative and sustainable solutions within their construction projects, multifunctional façade systems can be divided in five main categories, according to the several systems already available on the market, relying the main differences in the integration of materials, renewable energy or solar energy concepts, which are briefly described in the following sub-sections:

2.2.3.1 Wood façade systems

2.2.3.1.1 TES Energy Façade

Consists on a prefabricated building system of large scale wood frame elements that, according to the authors "introduces the benefits of modern timber construction to the modernisation process of the existing building stock" (Treberspurg and Djalili, 2010). The main advantages are the precise off site prefabrication methods, the fast assembling of the panels on site and the possibility to reduce to a minimum the disturbance to the inhabitants through noise and dirt. Moreover, this system also allows for the integration of the panel with windows, balconies and installations (electricity, plumbing, etc.) or technical modules (solar panels). While the authors state as an advantage "the ecological
performance of timber and other biogenic building materials”, drawbacks can be the scarce availability of this material in most southern European countries where this solution would also underperform in the hot summer due to the lack of thermal inertia, as it was probably designed having in mind colder climates and specific heating needs. Other disadvantages are related to the considerable dimensions of each module, as their manipulation and application to large scale buildings may not be feasible. Examples of this panel are shown in Figure 3.

![Figure 3. Pilot project in Norway, Risør Technical College; existing façade (a) and rehabilitation (b) (Source: Treberspurg and Djalili, 2010).](image)

Despite the use of timber as the main construction material, TES Energy Façade is an interesting case-study as it already uses the most advanced methods for on-site surveys (using photogrammetry and laser scanning) to generate precise data of the buildings to be retrofitted, converting this data in a 3D BIM model (BIM -Building Information Modelling to be explained more in detail in chapter 3.3) that is used to define the exact dimensions of the prefabricated modules to be produced for each existing façade. The generated dataflow also defines all the requirements for the digital process that controls all the different stages of the fabrication process, from site measuring to planning, prefabrication and on-site assembling (TES, 2015). Figure 4 illustrates this concept (left image), showing the use of photogrammetry and laser scanning for the on-site survey to obtain data that can be processed and converted in a 3D BIM model used to fabricate tailor-made panels (visible on the right image) to be finally assembled to the existing building.
Figure 4. Main concept for the TES Energy façade (a) and the production of wood framed modules (b) (Source: TES, 2015)

This concept, using BIM as the preferential design tool, also claims to define in a basic element all the necessary details and technical solutions, material qualities and fire safety issues, reducing to a minimum the incompatibilities in the production chain between the various processes and ultimately making the whole process more cost and energy efficient. As this methodology is still recent, it would be interesting to adopt and further explore it in other contexts (such as in southern European countries) using other combination of materials (e.g. cement composite sandwich panels) for the renovation of the existing building stock.

2.2.3.1.2 PHI-Wood façade systems Naumann & Stahr

This solution was developed by a German architecture studio to be used both on new construction and on the rehabilitation of the existing building stock, having the system been certified by the Passive House Institute in Darmstadt, Germany. Figure 5 exemplifies in an axonometric view and horizontal section the wall concept used for new construction consisting on a wood frame structure made of I-wood beams (A) and OSB (Oriented Strand Board) panels (B) filled with insulation (C), with an outer casing made of thermo-wall plaster tiles (D) that are nailed to the beams, including a thermal image of the wall showing the very high insulation level of the solution, with low heat transfer between the heated interior (in red) and the cold exterior (in blue).
Development of sandwich panels of customized functionalities for the rehabilitation of the built patrimony

Figure 5. Concept of the Wood Façade System for new construction – axonometric view and horizontal section: I-wood beams (A); OSB (Oriented Strand Board) panels (B) insulation (C), thermo-wall plaster tiles (D), including a thermal image of the wall (Source: Treberspurg and Djalili, 2010).

2.2.3.2 Solar-active façade systems

This category encompasses solutions that use and store solar radiation in passive energy concepts. The systems featured in this section were also designed for cold climates where energy storage is the main concern to reach maximum energy efficiency, meaning that its use in southern European climates would probably not reach the same performance levels.

2.2.3.2.1 GAP solution façade system

Investigating new ways to retrofit the existing building stock, the International Energy Agency promoted in 2006 the development and research of prefabricated systems for the renovation of existing residential buildings in order to increase energy efficiency. This program, which lasted until 2011, was the "IEA ECBCS Annex 50 / Prefabricated Systems for Low Energy Renovation of Residential Buildings" consisting on a joint venture of many institutions in some European countries dedicated to study the development and impact of prefabricated solutions that could not only reduce significantly energy consumption in low efficient existing residential buildings, but also adapt the solution according to the specificities of each country's reality. The countries involved in this project were Austria, Belgium, Czech Republic, France, Netherlands Portugal and Switzerland, covering diverse climate zones in Europe. The objectives were the development and demonstration of innovative concepts for the retrofitting of the building envelope in typical apartment buildings dating from the 50's, 60's and 70's. This research defined prototype solutions that could be prefabricated and integrate
simultaneously all the necessary technical installations for the rehabilitation of buildings. HVAC, water and solar systems would be integrated in the new highly insulated envelopes in order to upgrade or replace the existing heating, cooling and ventilation installations. This project focused on five research areas, from a comprehensive concept definition and specification to a more envelope oriented solution featuring integrated roof systems and façade elements, including also an area dedicated to HVAC and solar systems and finally a chapter on the monitoring of the solutions and dissemination of results. According to the study, the main goals of these prefabricated modules would be the retrofitting of existing apartment buildings in order to reach the same level of comfort found on the most advanced and energy efficient buildings. Prefabrication would also allow the optimizing of construction processes, insuring a high level of quality and cost control. Furthermore, the rehabilitation would allow existing buildings to create new additional areas within the building, by retrofitting attics and incorporating existing balconies into the living spaces. The final main advantage would be a rapid renewal process with minimal impact on the life of the inhabitants, as most of the works would be carried outside the apartments. This experimental project resulted in a business opportunity, as the solution is presently available on the market. GAP® solutions GmbH, an Austrian company, is selling prefabricated panels for the renovation of the existing building stock based on the initial concept developed for the GAP panel (Figure 6).

![Figure 6. Basic concept of the GAP Façade System (Source: Almeida, 2014).](image)

The system consists on a honeycomb core structure made of natural materials that can store solar radiation, increasing its temperature and reducing heat loss and thermal bridging to almost zero. Designed specifically for cold climates, depending on the orientation of the building the improvement
of the U-value of the exterior wall can reach up to 90% or more, being U-Value the thermal transmittance of the wall, considering that a well-insulated building wall system will have a much lower U-value than an uninsulated or poorly insulated system (Insulation, 2009). However, the solution is also not suitable for the southern European climate, where any heat storage in the summer is a problem to be avoided. As part of this experimental project, the University of Minho also developed a prototype to attend to the specificities of the Portuguese climate featuring an inner insulation core of agglomerated black cork and an outer aluminium finishing layer, with interior space for technical installations. Unlike the GAP panel, this solution was based on a lightweight module with reduced dimensions, easy to be manipulated by average skilled workers with available working tools, making it a compromise between a fully customizable and mass produced system and a traditional renovation made with a high performance solution (Figure 7).

Figure 7. UMinho Prefabricated façade renovation module (Source: Almeida, 2014).

2.2.3.2.2 GLASSXcrystal - Phase Change Materials (PCM)

A more high-tech solar-active façade system, this solution consists of a quadruple glass with an inner layer of a salt hydrate PCM that absorbs solar radiation when in the liquid state, releasing heat during recrystallization to the interior space. The system also features a prismatic glass that allows solar radiation to pass in the winter, when the angle of incidence is low, protecting the space from excess
heat in the summer. Developed in Switzerland, the whole system appears as a translucent/transparent wall, but it may certainly be too high-tech to be used in standard building rehabilitation projects. Figure 8 illustrates the main concept.

![Figure 8](image)

**Figure 8.** Left: concept: above/summer, below/winter / Right: Ref. building, Arch. D. Schwarz, CH, 2004 (Source: Treberspurg and Djalili, 2010).

### 2.2.3.3 Energy façade systems

Another type of multifunctional façade systems, these solutions are designed to integrate optimised building equipments in the façade panels (heating, cooling and ventilation) and/or renewable energy modules, which are mainly used for new construction and office buildings.

#### 2.2.3.3.1 i-modul façade

This system is a building cladding solution consisting of 20 cm thick panels with integrated building services for heating, cooling, ventilation, heat recovery, lighting and sound installations. This solution may be energy effective but also cost forbidding for rehabilitation works, aiming more at private investors looking for a high performance and state of the art new building (Figure 9).
2.2.3.3.2 Photovoltaic (PV) integration

Multifunctional façade systems with photovoltaic modules are solutions already provided by most of the major manufacturers of aluminium framed windows. The available solutions, however, are expensive and usually more appropriate for new construction. The adoption of such systems always require a thorough cost-benefit evaluation in order to assess its feasibility and its use in building rehabilitation will hardly become mainstream due to high price and poor thermal insulation of the façade system.

2.2.3.4 Hybrid façade systems

These solutions feature new "smart materials" such as nano materials, aero gel and vacuum insulated panels integrated in a façade system. As most of these materials are too recent and still need further development, more research is necessary to consider these solutions as a realistic alternative for new construction or even building rehabilitation. Nevertheless, some renovation and new modular building projects have already been executed using Vacuum Insulated Panels (VIP) and the results were promising, as the insulating effect of this kind of solution is 5 to 10 times better than any conventional insulating system. VIP panels consist on an amorphous silica based low thermal conductivity core with added infrared opacifiers encased in a multi-layered metallised barrier film, resulting in a much thinner insulation solution when compared to conventional alternatives - such as Polyurethane Foam (PU), Extruded Polystyrene or Fiberglass - and reaching a U-value of just 0,10 W/m²K, also much lower than the ones obtained from these materials (Kevothermal, 2015).
Figure 10. Comparison between a VIP panel and the most common insulating materials available on the market for the same thermal performance (Source: Kevothermal, 2015).

Figure 10 compares the reduced thickness of a VIP panel with the most common insulating materials available on the market for the same thermal performance: Polyurethane Foam (PU), Extruded Polystyrene and Fiberglass. This lightweight and thin solution is already available in some prefabricated building elements, such as sandwich panels, but one of the main drawbacks is the fragility of the panel, as it may be easily damaged when manipulated on site. Further research must be done also on some aspects, such as its effectiveness on correcting thermal bridges, moisture problems, its fire resistance, the durability of the vacuum (which currently is 30 years), as well as maintenance, manipulation and replacement of single panels. Figure 11 illustrates a pilot project in Germany using VIP insulating panels with precast concrete.

Figure 11. Precast Concrete with VIP, Demonstration project in Ravensburg, Germany (a); Façade elements (b) (Source: Treberspurg and Djalili, 2010).
Although the constructive details of these panels are not made available for consultation, it is visible in the right image the existence of an outer thin concrete layer with the VIP panel inserted between this material and an inner OSB (oriented strand board) wood panel. The house resulting from this pilot project is already built and resulted in a “modern and energy-optimized building with passive house standard” (Weinbrenner, 2015), opening a new chapter for the manufacturing of high performance precast concrete insulating panels.

### 2.2.3.5 Green façade systems

Green façades can be a good solution, both for new construction and building rehabilitation, as they can help prevent overheating by providing shade to the façades and reduce air pollution in the cities by filtering dust and dirt particles while absorbing CO2. Green façades also promote biodiversity and present aesthetically appealing solutions, providing passive thermal control and reducing energy demand for air-conditioning up to 40 - 60% in Mediterranean climates (Haibo, 2013) (Peck et al., 1999) (Perini, 2013). The main challenges are costs concerning the right type of solution to be adopted and regular maintenance. In a specific context green façades may be an option to have under consideration, depending on type of building and client, however in housing rehabilitation its adoption seems to be a more difficult choice. Figure 12 illustrates the visual aspect of a green façade in an urban context.

![Figure 12. Green façade by Patrick Blanc in Paris (Source: InHabitat, 2015).](image)
2.3 The LEGOUSE Project

The Legouse project is based on the assemblage of prefabricated sandwich panels, whose constitution is made by outer layers of steel fibre reinforced self-compacting concrete (SFRSCC) connected by glass fibre reinforced polymer (GFRP) connectors. This project was developed in 2010 by the companies Mota-Engil, CiviTest, the ISISE/University of Minho and PIEP (Barros et al, 2012a) (Barros et al, 2015). Despite being destined to new construction and not building rehabilitation, this project was one of the main influences in the development of this work, as it developed a prefabricated and innovative thermally efficient sandwich structural panel for the structural walls of a modular housing system to be executed at controlled costs, being essentially based on a structural load bearing sandwich panel composed of two outer layers of concrete separated by an inner layer of insulating material (extruded polystyrene panels - XPS) linked by connectors made of composite materials (Lameiras et al, 2013a) (Lameiras et al, 2013b).

The SFRSCC applied in the external layers, of a thickness of 60 mm per layer, has the following composition: Portland cement, limestone filler, type 2 (5-12mm) gravel, sand, Viscocrete superplasticizer and Dramix steel fibres. As this panel was developed to be a load bearing wall destined for new construction, special care was given to avoid thermal bridging between the two external surfaces of the panel investigating the use and efficiency of Glass Fibre Reinforced Polymer (GFRP) connectors, as this composite material presents low thermal conductivity and high resistance. Subsequent tests demonstrated that this solution not only avoided significant loss of thermal performance to the panels, but several pull-out tests performed in laboratory also attested its mechanical efficiency as an alternative to the more common steel connectors (Lameiras et al, 2010, Barros et al, 2012b).

This solution was eventually tested with success in a prototype house built in Rio Maior, Portugal, and proved not only to be highly effective as a load bearing prefabricated structure, but also presented good thermal insulation levels with no thermal bridges between the outer layers of the panel and an excellent mechanical performance, allowing the solution to withstand very high wind load factors due to the panels’ ductile behaviour (Barros et al, 2015). Figures 13, 14 and 15 show the main concept for the modules, the assembling phase and final aspect of the prototype solution.
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**Figure 13.** Proposed building system for sandwich structural panels comprising thin-walled SFRSCC and FRP connectors: a) components of the devised load-bearing sandwich wall panel; b) cross-section (Source: Barros et al, 2012b)

**Figure 14.** Assembling of the roof (a) and wall (b) modules. (Source: Barros et al, 2015)

**Figure 15.** Views of the built prototype: rear view (a); front view (b) (Source: Barros et al, 2015)
3 PROPOSED CONCEPT

This work is the first step towards the development of a prefabricated customizable sandwich panel based on Fibre Reinforced Cement Composites (FRCC) intended to be used on the multifunctional renovation of buildings by combining FRCC with other materials of complementary performances. Although initially based on the LEGOUSE sandwich structural panels, the main goal was now to reduce the weight of the solution to a minimum, setting the panels’ thickness to just 100 mm and defining a possible maximum dimension compatible with the prefabrication method to be adopted in the future in a mass scale production (robotization), in order to obtain a light modular building solution to be easily manipulated and assembled in the renovation of high multi-storey buildings. As in this process oversized elements are to be avoided, the maximum dimension of each panel to be fabricated at the factory was set to be around 300x200 cm, big enough to cover floor to floor heights but small enough to allow a more simplified assembling of all modular units on the façade. Despite these assumptions, the final layout will always have to be custom made, as it ultimately depends on the proportions and openings of the existing building, but this assembling solution will be versatile enough to allow some panels to include openings for new windows or technical modules or to place them around the existing openings, creating a modulated pattern where more than one layout can be studied before choosing the final version. The proposed layout for the type-panel, including possible openings for technical modules, is presented on figure 16.
While the solution to be studied at this stage is focused not merely on upgrading the visual aspect of the building, but on the improvement of the overall mechanical behaviour and energy performance of existing façades, ultimately it must be seen also as part of a more comprehensive proposal that should encompass the optimization of the whole building envelope, namely the roof and floor, incorporating energy efficient windows, along with all the other necessary installations to improve the overall performance.
performance of the building, like new water pipes and electricity circuits or ducts for mechanical ventilation with efficient heat recovery systems to reduce heating and cooling needs (BPIE, 2011b). As Nearly Zero Energy Buildings (NZEB) are the ultimate goal for renovation works in Europe after 2020, passive solar design – another essential aspect in this kind of buildings - will also be explored in this work through the study of the installation and compatibility of technical modules in openings to be executed on the panel or integrating them in the panel layout, such as solar collectors for domestic hot water and space heating or photovoltaic panels for electricity generation.

The development of this investigation in a subsequent phase will make possible to assess whether this solution and the proposed materials that constitute the panel, correctly positioned on an underperforming façade, can result in an efficient and competitive system that outperforms the already available solutions.

3.1 New and existing materials for the prototype panels

When designing a sandwich panel to rehabilitate an existing building and improve its level of thermal efficiency it is essential to understand which are the implications of choosing a specific material, so that the final solution can have the highest performance level possible. As each material possesses its own intrinsic characteristics, the main goal is to combine all the different components in a way that the final result is a lightweight, energy efficient and mechanically resistant panel.

The chemical and physical properties of a material are what characterize its mechanical resistance, durability and comfort, helping us to decide about its potential to be part of a constructive solution. The chemical properties are important when assessing the performance of a material against the external agents, such as humidity and air pollution or even fire, determining its resistance and durability. These properties are also essential to classify a material in terms of its environmental footprint, as a very resistant material can also be a wrong option when thinking of safety (e.g. asbestos and cement based roof plates known as “fibrocement”, a life-long but also cancer prone material that are now banned from construction in most countries). By interpreting the chemical components of a material and its embodied energy one can assess the potential risks that it may present to the environment at the end of its lifecycle. Resistant materials with incompatible compositions in the same constructive solution may also cause chemical reactions that ultimately can affect its performance, durability, aesthetics and eventually cause the release of greenhouse gases (Mendonça, 2005). On the other hand, the physical properties of a material can determine its hygrothermal and acoustic
performances and also luminosity. Concerning properties with energy implications, one can consider not only density, transparency and translucency, but also mechanical properties (resistance, elasticity modulus, shear modulus), rheological properties (thermal expansion), thermal properties (conductivity, specific heat) and finally wavelike properties (absorption, reflection, transmission, refraction, emissivity) (Mendonça, 2005). Apart from the chemical and physical characteristics of a material, other essential aspects to have under consideration are the economic and environmental factors, as these will ultimately assess the cost of the solution, as well as its embodied energy, the material resources necessary to obtain it, impact on ecosystems, toxicity levels and recyclability, helping us to determine if the final solution is a sustainable option at all levels - socially, economically and environmentally.

As the manufacture of prototypes with the dimensions set for the type-panel (300x200x10cm) was not possible at this stage, two smaller panels, each with 199x133x10 cm and featuring two different types of Fibre Reinforced Cement Composites (FRCC) were executed and tested to assess their mechanical and thermal properties, as explained more in detail in Chapter 4. However, the process of choosing the adequate materials to be tested on each prototype was not linear, having been considered many possibilities - from the solutions already tested in the LEGOUSE project to more sustainable and economic alternatives – in order to achieve a good balance between lightness, energy performance and the best cost for the proposed solution.

### 3.1.1 Fibre Reinforced Cement Composites (FRCC)

Technology has recently made possible the use of a wide variety of fibres in Fibre Reinforced Cement Composites (FRCC), a concept that includes all fibrous materials that can be applied to structural applications combined with concrete. It comprehends, for instance, the use of natural fibres as a concrete reinforcement material – an interesting concept that relates to sustainability, but that is still in an early stage of development and testing – but is mostly focused on the benefits of using artificial fibres such as steel, polypropylene and glass fibres in structural reinforcement. As this material is the main component of the proposed sandwich panels, a more detailed investigation is now presented in order to understand the main options that had to be taken in order to find the most adequate solution to be tested in the two prototype panels.

FRCC present a mechanical behaviour that results from a balance of several factors, namely the interfacial bonding and fibre pull-out properties, the parameters of the materials, the distribution of material flaw sizes in the cementitious matrix, as well as fibre orientation and their dispersion in the
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matrix (Pereira, 2012). These are complex parameters to be studied individually, as they perform in a combined manner, being this a research field where investigation is still underway, despite the considerable knowledge already available today about the micro-mechanisms and composite behaviour of these materials.

Concerning structural design, one of the most important is the material’s pseudo-strain hardening ability in tension, translated on the steady crack propagation mode and the real capacity of the composite to withstand increasing tensile loading after cracking under the imposed deformations. This property represents a dual advantage in engineering as while more cracks develop for the same tensile stress, the crack opening for each one is considerably smaller and energy dissipation is higher, resulting in improved durability, high tolerance to damage in tension and in the maintenance of the functional properties of the structural elements (Pereira, 2012). The design of FRCC, in order achieve multiple cracking and strain hardening in tension, is fundamentally related to the different aspects of the mechanical properties of the matrix, the fibres and their interaction, being necessary to thoroughly select the constituents in order to obtain a balance between strong and deformable fibres and the weak and brittle matrix.

Steel Fibre Reinforced Concrete (SFRC) was one of the first examples of fibre reinforcement used in concrete structures and can be described as "any material of cement matrix to which we add short steel fibres" (Barros, 2000). The main advantages of this composite material is that its post cracking residual strength can be much higher than in plain concrete of the same strength class due to fibre reinforcement mechanisms provided by fibres bridging the cracks, which in turn provide a high level of stress redistribution and significant deformation capacity of a structure between crack initiation and its failure, increasing the structural safety, especially in structures of redundant number of supports.

When well-conceived, this technique can replace partially or totally steel reinforcement for the flexural and shear resistance of concrete elements. However, fibre geometric characteristics, fibre material properties, concrete properties, and the used method of SFRC application can influence the level of the post-cracking residual strength (Barros, 2011).

Adding the benefits provided by the fibre reinforcement to those resulting from the properties of self-compactness, it is possible to obtain Steel Fibre Reinforced Self-Compacting Concrete (SFRSCC), a high performance material that was used in the LEGOUSE experimental prefabricated house and is adequate for the casting of prefabricated and lightweight sandwich panels (Barros et al., 2005).

One of the most important notions obtained from this investigation was that by reinforcing concrete with fibres, the fibre alignment and distribution tends to be determined by the concrete’s flow in the
fresh state. As previous works had already shown that fibres are more efficient if they are oriented according to the principal tensile stresses, a recent study investigated how the fibre orientation and distribution affect the post-cracking behaviour of SFRSCC (Abrishambaf et al, 2013). As the casting process can strongly affect the dispersion and orientation of fibres and its mechanical performance, in this study the method adopted to minimize this phenomenon was to cast the panels with a uniform flow velocity, diffusing the mixture radially from the centre outwards, which led to a predisposition to have higher number of fibres orthogonal to the concrete flow direction, resulting in a more efficient solution. Having in mind this positive result, this methodology was also pondered to be used in the casting of the two prototype panels, but considering that this process would be exclusively manual, it was assumed that the final result would necessarily differ, eventually affecting the ideal dispersion and orientation of the fibres in the mixture. The evaluation if this phenomenon could also eventually affect the panels’ mechanical performance would be something only possible to assess upon their execution and testing.

Concerning prefabrication, research conducted under the PABERFIA project investigating a method for conceiving cost competitive SFRSCC and studying lightweight sandwich panels executed in this material pointed out that "when installed in building façades, the panel’s flexural strength is the principal design property since significant bending moments result from wind loading, which has the greatest impact on the most unfavourable load combination" (Barros, 2005). After testing different compositions for SFRSCC, this experimental project concluded that not only the panel's structural configuration and ductility provided by the fibres allowed a high stress redistribution level and increased punching resistance, but the final designed composition was also able to meet all the requirements of self-compatibility, validating its applicability to industrial production. In the end, the tested panel proved to have sufficient structural properties to withstand wind actions and punching, even when its thickness reached at times only 30 mm - coming close to the 20 mm that the first prototype panel (panel 1) will be featuring.

Having in mind that this work is focused on the development of a non-structural modular panel, the use of two different formulations of FRCC on both prototypes will allow reducing the volume and weight of concrete, while keeping its impact resistance and crack-width control capacity through the addition of fibres, allowing great geometric and dimensional freedom and resulting in a lightweight façade renovation solution. Considering the panels and previous results already obtained on the LEGOUSE project using SFRSCC, it is also expected that the FRCC formulations now used for both prototype panels will develop a higher post-cracking tensile strength than the stress at cracking.
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initiation, guaranteeing simultaneously high ductility, high energy absorption and the required flexural capacity (Lameiras et al 2013b). Concerning sustainability, the incorporation of fly ash in FRCC partially replacing cement can help reducing the cost and environmental impact of the solution when compared to current concrete. Moreover, as FRCC is expected to have an excellent mechanical performance and high resistance to corrosion, the durability of the solution – another important indicator of sustainability – is also assured, helping to reduce future maintenance costs to a minimum.

In this work FRCC was studied in two variants: Fibre Reinforced Mortar (FRM) and Lightweight Fibre Reinforced Concrete (LFRC), respectively tested in the first and second prototype. In both cases, the self-compatibility and fluidity of the compositions was a prerequisite due to the geometric characteristics of the panels.

3.1.1.1 Fibre Reinforced Mortar (FRM)

The fibre reinforced mortar under study was a composite material developed under the INOTEC project, promoted by the company CiviTest in collaboration with the University of Minho, for the structural reinforcement of masonry walls in rehabilitation projects concerning the typical historical schist masonry in Portugal. This formulation was designed and tested having in mind the physical and mechanical characteristics of the mortar when subjected to vertical casting, considering that the proposed application on the historical masonry buildings would have to be done via spray (Colombo, 2014) (Valente et al, 2014).

The formulation used for the FRM included 42.5R Cement, Fly ash, Water, Sand, Viscosity Modifying Agent (VMA), Super Plasticizer SP3002, Glass and Polypropylene fibres. The quantities per m³ are described on Table 1.

<table>
<thead>
<tr>
<th>Materials</th>
<th>Quantity [kg]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cement 42.5R</td>
<td>546,5</td>
</tr>
<tr>
<td>Fly ash</td>
<td>669,0</td>
</tr>
<tr>
<td>H₂O</td>
<td>318,0</td>
</tr>
<tr>
<td>Sand</td>
<td>437,0</td>
</tr>
<tr>
<td>VMA</td>
<td>3,42</td>
</tr>
<tr>
<td>SP3002</td>
<td>21,0</td>
</tr>
<tr>
<td>Glass Fiber 12 mm</td>
<td>4,0</td>
</tr>
<tr>
<td>PP Fiber 12 mm</td>
<td>1,0</td>
</tr>
</tbody>
</table>

Table 1. Composition of the FRM (per m³) (Source: Valente et al, 2014)
As this specific FRM was to be applied using shotcrete (spray) methods, the constituents of the mixture were chosen having in mind their contribution to achieve the required rheological characteristics for projection. The cement used contributed to a moderate/low hydration level and fly ash partially replaced cement due to its pozzolanic properties, helping these components, together with the superplasticizer and the VMA, to achieve the desired fluidity of the mixture, providing the sand the necessary compactness. The Glass and PP fibres would, in turn, assure the necessary ductility and pseudo-strain hardening ability in tension mentioned in the previous chapter, allowing this composite material to withstand increasing tensile loading after cracking and a good adhesion between the existing masonry wall and the FRM (Colombo, 2014). In terms of mechanical behaviour, this formulation was tested in order to obtain the values for its elasticity modulus, resistance to compression and flexural behaviour, according respectively to the NP EN 12390-13, NP EN 12390-3 and EN 1015-11 standards. Regarding the elasticity modulus, it was observed that while after 14 days the obtained value was 8.74 GPa, increasing to 14.11 GPa on the 28th day, these values were well below the ones obtained in the same period for a commercial mortar tested as a reference (respectively, 32.43 GPa and 38.24 GPa after 14 and 28 days) (Valente et al., 2014). The compressive behaviour was also tested using four cylindrical samples with 50x100 mm that were subject to permanent loads, resulting in values (approx. 21.0 and 24 MPa after 14 and 28 days, respectively) that were also inferior to the ones obtained for a commercial mortar (30.0 MPa and 36.46 MPa, for the same periods). The flexural performance involved testing samples of 160x40x40 mm3 in a high precision press under a constant deformation speed of 0.2 mm/min and a 10 kN load cell, measuring the registered displacement and the Crack Tip Opening Displacement (CTOD) with two Linear Variable Differential Transformers (LVDT). Table 2 shows the main results of the flexural test.

**Table 2.** Average $f_{r,im}$ for the corresponding crack mouth opening displacements (CMOD), fracture energy, and flexural tensile strength according to the CEB-FIP MODEL CODE (Valente et al., 2014)

<table>
<thead>
<tr>
<th>CMOD [mm]</th>
<th>$f_{R,1m}$</th>
<th>$f_{R,2m}$</th>
<th>$f_{R,3m}$</th>
<th>$f_{R,4m}$</th>
<th>$G_{jm}$ [N/mm]</th>
<th>$f_{cr,β}$ [MPa]</th>
</tr>
</thead>
<tbody>
<tr>
<td>FRM (8 days) [MPa]</td>
<td>9.00</td>
<td>6.03</td>
<td>3.72</td>
<td>2.44</td>
<td>5.26</td>
<td>9.56</td>
</tr>
<tr>
<td>Variation coef. (%)</td>
<td>15.82</td>
<td>18.90</td>
<td>19.10</td>
<td>18.27</td>
<td>17.38</td>
<td>12.67</td>
</tr>
<tr>
<td>FRM (28 days) [MPa]</td>
<td>11.37</td>
<td>6.43</td>
<td>3.64</td>
<td>2.21</td>
<td>5.26</td>
<td>12.55</td>
</tr>
<tr>
<td>Variation coef. (%)</td>
<td>21.73</td>
<td>25.63</td>
<td>25.37</td>
<td>26.04</td>
<td>22.85</td>
<td>18.04</td>
</tr>
</tbody>
</table>
The tests performed with the FRM samples have pointed out the high post-cracking resistance and ductility conferred by the contribution of fibres, being also possible to attest that the values of the residual flexural tensile strength parameters ($f_{\text{cr}}$) remained almost unchanged from the 8th to 28th day after the manufacturing of the samples. When compared to a commercial mortar, which flexural tensile strength is 5.56 MPa and 6.19 MPa, respectively at the 8th and 28th days, it can be demonstrated that the developed FRM presents a better flexural behaviour, with a higher tensile rupture, diffuse cracking patterns and a very high energy absorption capacity, assuring a good connection between the reinforcing material and the substrate (Valente et al., 2014).

### 3.1.1.2 Lightweight Fibre Reinforced Concrete (LFRC)

Lightweight concrete (LWC) presents many advantages in construction, as the self-weight of current concrete still represents a very large proportion of total load on the structure. As LWC weighs less than conventional concrete due to the addition of lightweight aggregates in the mixture - usually corresponding to over 50% of its total volume – a decreased density of concrete for the same strength level permits savings in the dead load that can be used for structural design and foundations, or not used at all, resulting in a lighter construction. In the prefabrication process, the use of structural LWC can not only reduce significantly the self-load of a structure but permit great design flexibility in the execution of larger units with longer spans, better thermal and fire resistance, increased acoustic insulation, thinner sections and less reinforced steel, allowing for an easier manipulation of modules, better onsite time management, ultimately leading to substantial cost savings when compared to prefabricated panels made from conventional concrete (Lo and Cui, 2004). LWC can also be used both as structural concrete and insulation, depending on its load-bearing capacity and elasticity modulus in the first case, and on the thermal conductivity in the second, which tends to increase with the decrease of its density (Valente and Cruz, 2004). Concerning other advantages, one can point out an increased workability, strength, elastic modulus, density and durability. By combining expanded clay aggregates, sand, cement, water and superplasticizers in the correct proportion, it is already possible to fabricate a LWC with high resistance to compression, although with a lower modulus of elasticity, tensile strength and fracture energy than the one expected for normal concrete with the same density and resistance (Valente and Cruz, 2004).

However, the addition of fibres to LWC can not only improve its ductility, impact strength and toughness but also minimize many of the disadvantages previously mentioned. An investigation studying the effect of adding steel fibres to LWC made from expanded aggregates in order to obtain
Lightweight Fibre Reinforced Concrete (LFRC) noted that it was possible to obtain LFRC reaching a compressive strength up to 60.4 MPa and a flexural strength up to 8.88 MPa, corresponding to a density of 1963 kg/m$^3$, with a decrease of the level of brittleness and splitting, along with the improvement of ductility, flexural and shear strength, flexural toughness and impact resistance (Wang and Wang, 2012). Tests performed using a steel fibre volume fraction between 1% and 1.5% showed that its addition resulted in a large improvement in the splitting tensile strength and flexural strength, due to the effect of the fibres bridging the crack surfaces. By increasing the quantity of fibres in the mixture, it was also observed that the impact strength of LFRC also improved considerably, concluding that the higher the volume of steel fibres added to concrete, the greater the improvement of its impact strength (Wang and Wang, 2012). Flexural toughness was also found to significantly increase during the same process, which led to the conclusion that this kind of concrete is especially suitable for designing structures where impact energy absorption is especially important – which can be the case of prefabricated façade panels that have to withstand the impact of objects caused by strong wind. Other experiments studying the effect of adding polypropylene and steel fibres on high strength lightweight aggregate concrete made with fly ash demonstrated that the addition of fibres could increase both its indirect tensile strength and the modulus of rupture by 90% and 20% respectively, with a polypropylene fibre addition at 0.56% by volume of the concrete. By adding steel fibres at 1.7% by volume of the concrete, the results for the same parameters were even superior, reaching about 118% in the indirect tensile strength and about 80% in the modulus of rupture, showing again a significant gain in ductility when fibre reinforcement is used, but not significant improvements in the compressive strength or the elasticity modulus (Kavali et al, 2000).

### 3.1.2 Fibres to be used in FRCC – main properties

Fibres to be used in the reinforcement of concrete can be natural - organic or mineral - or artificial. Artificial fibres can normally consist on Steel (SF), Glass (GF), Polypropylene (PP), Polyvinyl Alcohol (PVA) and Polyacrylonitrile (PAN) fibres, among others.

As each option presents different geometrical properties (section, length, diameter, deformation, etc.), physical and chemical properties (density, roughness, reactivity with the cementitious matrix, fire resistance, etc.) and also mechanical properties (tensile strength, elasticity modulus, strain, adhesion to the surface, etc.) its use must be pondered having in mind the final desired mechanical behaviour of the composite material. Table 3 illustrates the properties of some fibres used for the fabrication of the FRCC tested under the Inotec experiment (Frazão et al, 2014).
Table 3. Properties of the fibres (source: Frazão et al, 2014)

<table>
<thead>
<tr>
<th>Fibre</th>
<th>Length (mm)</th>
<th>Diameter (µm)</th>
<th>Elasticity Modulus (GPa)</th>
<th>Tensile stress (MPa)</th>
<th>Density (kg/m³)</th>
<th>Elongation (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PAN 6 L62</td>
<td>6</td>
<td>16</td>
<td>12,04</td>
<td>690</td>
<td>1,19</td>
<td>15-20</td>
</tr>
<tr>
<td>PAN 6 IP1963</td>
<td>6</td>
<td>26</td>
<td>8,47</td>
<td>482</td>
<td>1,19</td>
<td>14-18</td>
</tr>
<tr>
<td>PAN 12 IP1977</td>
<td>12</td>
<td>58</td>
<td>5,86</td>
<td>226</td>
<td>1,19</td>
<td>13-17</td>
</tr>
<tr>
<td>PP</td>
<td>12</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0,91</td>
<td>-</td>
</tr>
<tr>
<td>GF</td>
<td>12</td>
<td>5-15</td>
<td>70-80</td>
<td>2000-4000</td>
<td>2,58</td>
<td>2,5-4,8</td>
</tr>
<tr>
<td>PVA</td>
<td>8</td>
<td>40</td>
<td>40</td>
<td>1560</td>
<td>1,3</td>
<td>6,5</td>
</tr>
</tbody>
</table>

Regarding PAN fibres, it is possible to observe that for the same material the elasticity modulus and tensile stress decrease with the increase on the diameter of the fibre for the same density, being the option for one or another type a question of obtaining the desired properties in FRCC. The same happens for glass fibre (GF), the fibre that presents the highest values of tensile stress (2000-4000 MPa) and elasticity modulus (70-80 GPa), although the smallest elongation of all the compared alternatives (2,5-4,8%).

Steel fibres, when compared to the previous options, present particular characteristics, such as a mechanical anchoring resulting from the improvement introduced to the fibre geometry by the manufacturing companies in the past three decades that basically consists on the mechanical deformation of the fibre extremities in the form of hooks, cones, paddles, etc. (Cunha et al, 2008). As the efficiency of a steel fibre in the transferring of tensions is frequently determined by pull-out tests and these anchored fibres can also be “straightened” during the pull-out, when compared to the straight alternatives they end up presenting better results, dissipating more energy in this process. However, the mechanical properties of the fibres, such as the tensile strength and the efficiency of the mechanical anchoring may differ between different manufacturers, even considering the same type of fibre. Ultimately, these aspects can determine the final behaviour of the FRCC reinforced with steel fibres (Cunha et al, 2008).

An important aspect under study in this work was that, even if the addition of steel fibres to concrete has been widely used to improve its mechanical properties, in a 20 mm thin layer (the solution to be
tested in the first prototype panel) this option can also present some challenges concerning durability, as the accumulation of the fibres at the surface of the panel and its lack of resistance to corrosion could transport aggressive agents to the inner side of the concrete, ultimately affecting its durability. Despite the fact these effects are not comparable to the examples of extreme corrosion visible in most steel rebar reinforcements in current concrete structures, it is known that the corrosion of steel fibres can ultimately promote the formation of cracks, affecting the structural performance of the composite material. This phenomenon commonly appears as rust spots visible at the surface of the exposed concrete elements, and apart from the aesthetical negative aspect, in extremely aggressiveness conditions, corrosion of steel fibres can induce cracking in concrete and decrease tensile strength of concrete (Frazão, 2013). For this reason, the replacement of steel fibres for other corrosion free alternatives (polypropylene and glass fibres) was studied to determine the most adequate FRCC formulations to be used in the prototype panels.

An additional, but essential, aspect to have under consideration when thinking of sandwich panels for façades is that the proposed solution, apart from achieving a high flexural strength to withstand wind loads, must also resist to high temperatures resulting from fires. Having in mind that fire can cause detachment or spalling of the concrete, it is important to determine if a sandwich panel on a façade - even if is not a load-bearing element - can pose any threat to the safety of the building, to its occupants or to people in its vicinity. Research on this field has been conducted in order to assess how SFRSCC behaves mechanically after being exposed to different levels of heat. This experiment tested some SFRSCC samples exclusively reinforced with steel and polypropylene (PP) fibres, in order to compare how both composite materials react to extreme temperatures over a long period. Although exposing all samples to a temperature of 800°C over some days caused them all to disintegrate, it was noticed that while some spalling had occurred in the samples using steel fibres for the temperature levels of 400, 600 and 800°C, this phenomenon did not occur with any of the specimens reinforced with PP fibres (Lourenço, 2012). This experiment concludes that while the addition of steel fibres does not avoid the spalling of the concrete in SFRSCC its replacement by non-metallic fibres - in this case polypropylene (PP) - improves its behaviour in the cases very high temperatures or fire.

Another research investigating the possibilities of creating a Fibre Reinforced Concrete of Enhanced Fire Resistance (FRCEFR) used several non-metallic fibres to achieve the necessary requisites for the concrete and tested FRCEFR samples 28 days after those had been exposed to distinct levels of temperature: 250°C, 500°C, 750°C and 1000°C (Lourenço et al. 2007). From the results obtained the main conclusion is, again, that all non-metallic fibres can improve the concrete resistance to fire,
avoiding the explosive spalling that occurs when metallic fibres are used. However, only by PP fibres could guarantee an adequate and easy distribution in the concrete, making it the most adequate option. These conclusions were important to ponder the use polypropylene and glass fibres as an alternative to steel fibres in the composition of the FRCC developed under this work, in order to assure a higher level of fire protection and comply with the legal standards, eventually implementing these solutions in the composition of future concrete sandwich panels for the rehabilitation of buildings.

### 3.1.3 Glass Fibre Reinforced Polymer (GFRP) and steel connectors

Connectors are essential in concrete sandwich panels to bind and assure the proper stress transfer between the two outer layers of the panel through the insulating core. Under the LEGOUSE project, the use of Glass Fibre Reinforced Polymer (GFRP) connectors was extensively tested as a substitute for the more common steel connectors, as GFRP presents the same resistance level but is corrosion free, an important feature when the external concrete layers reach minimum thicknesses and may be on the limit of minimum cover requirements to protect the connectors. Another advantage of this composite material is that GFRP minimizes thermal bridges between the inner and outer surfaces of the panel due to its low thermal conductivity, a phenomenon that normally occurs when using steel connectors (Lameiras et al., 2013a). According to Lameiras et al., 2013a, the use of steel pin connectors that represent 0.08% of the sandwich panel area can reduce the insulation performance (R-value) of a wall up to 38%, a decrease that can reach 77% when the connection between the outer layers is made through 0.08% of steel pin connectors and 21.25% of solid concrete zones. This is especially important when the sandwich panel is the only element between the exterior and interiors environments – such as in the LEGOUSE project - but in a prefabricated sandwich concrete panel to be used as a second skin over existing façades this phenomenon tends to be less relevant, as thermal bridges do not reach the inside of the building, confining possible condensations to the existing air chamber located between the panel and the façade.

The LEGOUSE project was based on SFRSCC sandwich panels to be used as exterior load-bearing walls comprising GFRP connectors produced at controlled cost. Under this investigation, the testing of three configurations for GFRP connectors embedded or adhesively bonded to the SFRSCC outer layers was experimentally investigated through a series of pull-out tests where failure modes and load capacity of the connectors were analysed, resulting in the assessment of the feasibility and relative effectiveness of the suggested connections between GFRP and SFRSCC. Figure 17 illustrates the three configurations under study for the connectors.
The tested GFRP connectors were produced not by pultrusion, but by Vacuum Assisted Resin Transfer Moulding (VARTM), a highly automated process that involves a relatively low cost, as it features a polyester resin matrix - which is one of the most common thermosetting resins used in the reinforcement of plastics – to produce items with reduced dimensional variations. After the test, it was concluded that the embedded connectors (a) and (b) visible in figure 17 provided the highest load carrying capacity, despite the restrictions imposed by the relatively small thickness of the SFRSCC layers, with a significant ductility after peak load. However, the best performance was obtained by the perforated connector (a) that, despite its simplicity, presented a relatively high load capacity and an appreciable residual resistance. This connector was also the one that presented less obstacles in the casting process of SFRSCC, being also the simplest to be executed and the one that required less material in its manufacture, with the openings along the connectors’ length performing as expected in terms of structural behaviour, significantly increasing the load capacity to the connection. After all the tests and simulations were performed using several arrangements of GFRP connectors and various thicknesses on the SFRSCC layers to simulate serviceability limit state conditions, it was noted that the maximum tensile stress in the connectors was always much lower than the tensile strength of the material, which leads to conclude that, disregarding local effects in the connections, the weakest components in the panel are the SFRSCC layers, making the use of these composite connectors a viable solution in replacing traditional steel connectors in this type of prefabricated concrete panels (Lameiras et al, 2013b) (Lameiras et al, 2012).

3.1.4 Poltruded Glass Fibre Reinforced Polymer (GFRP) profiles

Apart from being used as panel connectors, GFRP is increasingly considered as an alternative to structural steel profiles in structural applications, as it offers important advantages when compared to
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traditional construction materials, such as high strength, low self-weight, high chemical resistance, ease of installation and electromagnetic transparency. Nonetheless, its use in structural design still needs to overcome some difficulties, like high deformability, sensitivity to instability phenomena, orthotropic and fire behaviour, brittle failure and, above all, the lack of comprehensive design codes and guidelines (Fernandes, 2015). When compared to steel structures, GFRP pultruded profiles used in support sections are very susceptible to concentrated tensile and compressive loads applied transversely to the pultrusion axis, causing the webs of GFRP profiles to collapse under the load. This phenomenon known as web-crippling, resulting in material failure, elastic failure or both (Figure 18).

![Figure 18. Web-crippling at a support section of a hybrid GFRP-concrete beam loaded in four-point bending. (source: Fernandes, 2014)](image)

Tests performed on pultruded I-shaped profiles, with different geometries (I100 to I400), loaded in different configurations and with varying bearing lengths have demonstrated that the ultimate load seems to depend on the material properties, the geometry of the cross-section and the bearing length, while the specimens’ stiffness seems to be almost exclusively linked to the bearing length, provided that elastic failure does not occur (Fernandes, 2014). Despite all the positive and negative aspects, GFRP profiles present an interesting alternative to steel and were initially considered to be tested in the outer frame of the panel due to their high structural resistance, high durability, light weight and the fact that they are corrosion free, but its significant cost and lack of availability ended up being a variable that for the moment could not be overlooked if the final solution plans to be economically competitive. Concerning sustainability, although GFRP presents some benefits - lightweight and corrosion-free - it is obtained by pultrusion, an expensive and energy consuming process that still needs to perfect its eco-efficiency, setting up new clean processes and better managing its production wastes that - unlike steel - end up generally landfilled due to current limitations in the recycling of these materials, even when considering thermoplastic-based products (Castro et al, 2013).
3.1.5 Galvanized Steel Profiles

Galvanized steel is obtained by protecting steel with a thin zinc coating, mostly by hot-dip galvanization in which the parts to be protected are submerged in a bath of molten zinc, offering a high level of protection against atmospheric corrosion with considerable low cost (AGA, 2009). This process has been widely used in the automotive and airspace industries for many years but is also applied to a multitude of small or large scale ordinary items, from street lamp posts to highway guard rails, wall and roof sandwich panels, including elements with complex shapes, hollow forms, etc. Despite the fact that galvanized steel is obtained from hot-dip galvanization - a process that requires a considerable amount of energy - the two main components of this process (steel and zinc) have a high level of recyclability and metal structures protected with this method usually have a very long life span, requiring very low maintenance during their lifetime, being almost fully recyclable at the end of the life cycle and allowing these materials to be reused again (AGA, 2009). For this reason, galvanized steel has been classified as a sustainable material by the LEED® standard, an American green building certification program that recognizes best-in-class building strategies and practices (LEED, 2014). Apart from its American counterpart, the European General Galvanizers Association (EGGA) has also contracted an independent European institution to perform a pan-European life cycle inventory (LCI) study of hot dip galvanized products to deliver life cycle inventory data sets for the galvanizing process, quantifying the average energy, resource consumption and emission of substances to the environment, covering about 937,000 tonnes of steel galvanized by 46 plants in Europe (EGGA, 2014).

![Figure 19. The life cycle of hot dip galvanized steel (Source - EGGA, 2014)](image-url)
Figure 19 illustrates the life cycle of hot dip galvanized steel production, showing that zinc and steel can either provide from new sources or obtained from the reuse and recycling of existing galvanized items. The galvanizing process will ensure high durability and a long service life to the protected objects which, in turn, can be again reused and recycled at the end of their use, re-entering in a new life cycle. Subsequently EGGA has published an Environmental Product Declaration based on this European LCI study demonstrating that recycling and re-use are at the heart of the life cycle of galvanizing. Figure 20 illustrates the recycling of zinc and steel in galvanization, either by using steel recovered from construction waste and scrap zinc from roofs and gutters, and zinc obtained from other sources, such as electric air furnaces, remelting and ash and dross from galvanizing baths. Zinc can then be reused to regalvanize and re-use existing or new steel items and part of it can even be used in other areas, such as rubber additives, cosmetic and electronics, indicating that nothing is wasted in the process.

Moreover, many European companies operating in the construction market and supplying galvanized steel profiles manufactured from hot dip galvanized steel (to be used mainly in the mounting of light plasterboard walls and ceilings and light steel construction) have already obtained Environmental Product Declarations (EPDs) for their products, which are verified documents that report environmental data of products based on life cycle assessment (LCA) and other relevant information and are in accordance with the international standard ISO 14025 (Type III Environmental Declarations). Assuming that corrosion is a common problem of steel structures, it is also well known that it depends essentially of the nature of the material, the pollution levels and climatological factors of the atmosphere to which it is exposed. Galvanized profiles, in normal circumstances, can effectively withstand these aggressive phenomena, although knowing that even this form of steel eventually ends
up by corroding in extreme situations such as maritime environments, for example. As the metal structures to be used on the panels are simple galvanized steel profiles that will be almost invisible on the outside of the panel, the risks of corrosion will be minimal and the required maintenance is expected to be almost unnecessary.

### 3.1.6 Insulation: possible materials to be used in the panels

The importance of insulation in a prefabricated panel is paramount, as the quality and thermal performance of the insulating material to be used is vital to the reduction of the energy consumption levels in the building where the panel system will be installed. The main questions concerning insulation are always related to the thermal efficiency and final price of the material, most of the time disregarding other equally important parameters that now cannot be overlooked, such as the evaluation of the environmental impacts and the consumption of renewable and non-renewable primary energy on its production.

Studies indicate that in Europe the most commonly used materials for thermal and acoustic insulation are the ones obtained from synthetic fibres and foam plastics, such as mineral wool (rock and glass wool), polyurethane (PUR) and extruded and expanded polystyrene (XPS and EPS, respectively), as these present very good performances and a relative low cost. These materials account for approximately 97% of the 3.3 billion euro European building insulation market, and despite the positive aspects related to performance and cost, most are considered to be harmful for human health if their fibres are inhaled or require a great amount of energy in its production, so more natural options with lower impact on the environment must be now also considered in order to provide safer and more sustainable choices (Asdrubali, 2006). As "green" materials have been more and more at the centre of the concerns in the construction sector due to a greater demand from informed clients, the tendency is that European countries start enacting specific building regulations to promote the use of ecological materials in new constructions or on the rehabilitation of buildings. Such is already the case of many Municipalities in Italy that have determined a list of materials to be avoided (e.g. mineral fibres) and allowed a reduction of construction taxes for the promoters who use other more sustainable alternatives (Asdrubali, 2006). Concerning all the available options in the European market, when comparing the estimated Primary Energy Consumption - the necessary energy for the extraction, transport, production and packing of different insulating materials - it can be noticed that sometimes a "green" material (e.g. flax) requires more energy in its lifecycle than a more conventional one (e.g.
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rock wool), and that the materials that show the greatest impact in terms of fossil fuel consumption are the ones made of synthetic plastic fibres, which are precisely the most used (Figure 21).

![Figure 21. Estimation of primary energy consumption of some insulating materials' life cycles (Source - Asdrubali, 2006)](image_url)

In a concrete sandwich panel, insulation is placed between the resistant external concrete layers and the insulating core can vary in thickness according to the type of material to be used and the required thermal resistance of the panel solution.

Considering this system, as the first prototype panel will be assembled in consecutive layers, the insulating material will have to be rigid to be compatible with the concrete in the casting process, keeping its dimensional stability, expansion and compressive coefficient and flexural strengths, avoiding as much as possible transferring shear stresses between the outer concrete layers once the panel is assembled on the façade (Lameiras, 2010). Moreover, as the FRCC mixture to be used includes a great percentage of water, the insulating material must have a low moisture absorption coefficient. The second prototype panel will be incorporating its insulation material (expanded clay lightweight aggregates) in the concrete mixture, so apart from the thermal performance, this material will also have to comply with all the mechanical requisites specified for the Lightweight Fibre Reinforced Concrete (LFRC). Having in mind the requirements already mentioned for the insulation materials to be used in each one of the panels and based on a comparative environmental life cycle assessment (LCA), as well as on their availability in the Portuguese market, a final selection was made to determine which ones can present the best commitment between thermal efficiency, cost and
sustainability levels, having been selected three options: extruded polystyrene (XPS), expanded cork agglomerate (ECA) and expanded clay lightweight aggregates (LWA).

### 3.1.6.1 Extruded polystyrene (XPS)

Extruded polystyrene panels are currently the most popular option in Portugal when considering thermal and acoustic insulation in the renovation of buildings, especially when using ETICS, the most common method of building renovation. XPS is a widely available lightweight synthetic material with a very good cost/efficiency ratio, presenting a low permeability coefficient to water vapour, with a value of 6.3 Kg/(m.s.Pa)x10⁻¹², good mechanical resistance with a minimum compressive strength between 200 and 250 kPa and one of the lowest thermal conductivity levels among all insulating materials, reaching 0.037 W/m °C for 25-40 kg/m³ (Mendonça, 2005) (Santos and Matias, 2006). XPS is not considered to be a good acoustic insulating material and is highly flammable and self-extinguishing, being classified as a category E material, with its heat resistance limited to 70°C, meaning that it would not comply with the current fire safety regulations for the insulation of façades in buildings higher than 28 m (SCIE, 2009). Regarding sustainability, extruded polystyrene is also a non-recycled and hardly recyclable material, except in the internal recycling of production waste generated from the manufacturing of the panels to be used in the production of polystyrene granules that prevent the use of further raw materials. Concerning its LCA, XPS is considered to present the worst performance between all the three materials being compared, as its production involves a great amount of energy, making this material a less interesting option in terms of sustainability, despite its good thermal performance (Pargana et al, 2013).

### 3.1.6.2 Expanded Cork Agglomerate (ECA)

Cork is a natural, renewable and sustainable raw material used for many centuries, with unique properties at the morphological, molecular and chemical level. It is harvested from a tree, the Quercus Suber, every 9 to 12 years and Portugal is the world leader in cork production and processing, having transformed a traditional activity in a modern and sustainable industry, studying multiple applications for this material, from the traditional cork stoppers to insulating panels, flooring, textiles and composites. Cork is a lightweight material, impermeable to liquids and air, consisting of an alveolar structure similar to a honeycomb, with no empty spaces between cells. Research has proved that cork’s unique combination of a high coefficient of friction, high energy absorption, resilience, excellent
insulation properties and near-zero Poisson coefficient makes it the best material for a wide range of applications (Silva et al., 2005). For insulation, cork has been applied mostly in the form of black agglomerate panels, manufactured in a closed autoclave process at high temperature (approx. 300°C) and pressure (around 40 kPa) without the use of any adhesive, using the induced thermochemical degradation of the cork cell as natural adhesives between the granules to form the cork board. All the material used in these panels is a by-product from the production of cork stoppers or the “falca” (cork obtained by the periodic cleaning of cork trees), making it a true sustainable and almost unbeatable choice if compared to any other insulating material, with low embodied energy (the total energy necessary for the entire life-cycle of a material). When compared to other natural or synthetic foams, cork cells are strong and in terms of specific strength, cork could be comparable to any rigid synthetic foam, providing very high levels of thermal and acoustic insulation, being also completely recyclable at the end of its life cycle. Moreover, its thermal conductivity (0.045 W/m °C for 90-140 kg/m³) - although not as good as the one obtained with XPS panels for the same thickness - is still low, presenting a good compressive strength (compression at 10% reaching 220kPa) that still makes it an excellent material for thermal insulation where compressive loads are present (Silva et al., 2005) (Santos and Matias, 2006) (AI, 2014). However, despite its many advantages regarding sustainability - like a Primary Energy Consumption that is under 20% of the one required for the production of Expanded and Extruded Polystyrene - ECA panels are more expensive than their synthetic XPS alternative (with a market price reaching sometimes the double, depending on the brands and panel thicknesses) and its permeability coefficient to water vapour (10 Kg/(m.s.Pa)x10⁻¹²) is superior to the one obtained with XPS, and although being extremely resistant it is still vulnerable to some biological agents, as it can be attacked by rodents, if exposed (Mendonça, 2005). In terms of fire resistance, although not self-extinguishing like XPS and being able to withstand temperatures beyond 70°C, it is still combustible, being also classified as a category E product and presenting the same limitations regarding fire safety regulations. Cork agglomerate panels also present good acoustic properties, especially regarding its alveolar structure, performing better than XPS.

The results of the LCA for ECA have shown that this material makes a low contribution to most of the sustainability impact categories except for EP (Eutrophication potential, which concerns water pollution) due to the operation of the boiler in the manufacturing process (Annex 5, n.d.). Despite having a low consumption of fossil fuels, the environmental impacts associated with the production ECA mainly come from the production phase, but as this material is obtained from only one raw (and natural) product it can be deemed a sustainable choice (Pargana et al, 2013).
3.1.6.3 Expanded Clay Lightweight Aggregates (LWA)

The composition of the FRCC to be used on the second prototype panel is a light concrete mixture with expanded clay lightweight aggregates (LWA) reinforced with polypropylene fibres, now designated as Lightweight Fibre Reinforced Concrete (LFRC). In this case the insulating material (LWA) was used as a component of the LFRC and not as an independent layer, having been chosen two different particle sizes -1/5 mm and 8/12,5 mm – compatible with the formulation tailored to obtain the required level of flowability.

Although the process of producing these aggregates involve considerable embodied energy and CO2 emissions, the incorporation of LWA in LFRC still presents important benefits in the final performance of the panel, as it not only reduces its final weight and provides good thermal and acoustic insulation levels, but also reduces the percentage of cement in the mixture, increasing the overall level of sustainability when compared to conventional concrete. As a component of LFRC, LWA can help to improve the acoustic performance of the solution, as it shows good sound absorption performances in a wide frequency range (higher than 0,80 in the range 500-5000 Hz) (Asdrubali, 2006). Its permeability coefficient to water vapour is the highest among the three insulating materials (62 Kg/(m.s.Pa)x10^{-12}), reaching a value over six times more elevated than Expanded Cork Agglomerate (ECA) (Mendonça, 2005). In terms of thermal conductivity, LWA (8/16) presents a more elevated coefficient than XPS or ECA, reaching 0,16 W/m.ºC, so the assessment of the overall thermal performance in the second prototype panel and its feasibility as an alternative to the solution tested in the first prototype panel is also one of the main conclusions to withdraw from this work. Despite LWA being classified as a non-toxic material, its production is still responsible for significant environmental impacts with the biggest contribution among all the materials being compared in six out of eight environmental impact categories, especially the Acidification Potential (AP) and Global Warming Potential (GWP) that result from the air emissions produced from the kiln during the baking process (Annex 5, n.d.) (Pargana et al, 2013). It is then important to understand why lightweight concrete can still be considered an efficient material in enhancing sustainability when compared to other available options, even if to produce lightweight aggregates it is necessary to expand shale, clay or slate in a rotary kiln at temperatures reaching about 1150 °C, consuming in the process coal, gas or oil. Considering the environmental footprint of this building material, a survey of the industry in North America concluded that lightweight aggregate made by this process ends up with a product with an embodied energy of 2.51 MJ/kg and a carbon dioxide equivalent emission of 129 kg of CO₂ per cubic
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meter (0.16 kg of CO₂ per kilogram) of aggregate produced, considering embodied energy as all the necessary processes and energy needed to put a particular building material in place in a constructed facility (Bremner, n.d.). Although the process of producing the aggregates involved considerable embodied energy and CO₂ emissions, the values obtained were considered to be relatively low when compared with the production of Portland cement, which reaches almost 1 Kg of CO₂ per kilogram. As the incorporation of these aggregates in the concrete, along with fly ash, can reduce the percentage of cement in the mixture and present all the benefits previously listed, it can be concluded that this building material can still be considered a sustainable option in construction.

3.1.7 Finishing materials and other possibilities

Considering concrete (FRCC) as the main material of the panel, this study will primarily try to explore its potentialities to be not only a structural component but also the decorative layer in itself, always considering the compatibility of its physical and mechanical properties with the finishing aspect to be chosen. If not a reality to be fully replicated in the future in this project for economic reasons, nowadays prefabricated concrete presents many finishing possibilities, from the most common options such as abrasive, acidified, ground or washed concrete to smooth surface panels with colour variations and more advanced options featuring reliefs, the incorporation of recycled materials such as glass, retro reflective surfaces and even photo prints, having already developed customized solutions for diverse architectural designs (Hering, 2015).

Bearing in mind that this project is a concrete sandwich panel for the renovation of existing buildings, the final options would naturally have to be adjusted to a specific reality, having in mind the final price of each solution in the competitive rehabilitation market, but customization according to different design options or investment possibilities could still allow each panel to be differentiated. Although the finishing layer of the proposed panel could include ceramic, paint and other current coating materials such a thin coat of recycled glass on the outer surface, at this point the focus on the mechanical and thermal behaviour of the FRCC panels made it unfeasible to test the potentialities of these materials, leaving this option for future works. Even narrowing the scope of the design to the possibilities offered by the proposed large-scale manufacturing process (robotization) and considering the basic standard panel merely as a smooth concrete surface, other advanced (and invisible) possibilities, such as self-cleaning materials, may be even more interesting to be investigated, as they significantly reduce maintenance costs, improve energy performance and carry additional important benefits.
Studies carried out in the past years have been focusing on the properties of self-cleaning concrete and its advantages as a solution for air purification in congested cities. It was recently proved that the application of titanium dioxide (TiO2) photocatalysis to concrete not only promotes a self-cleaning effect on building façades, retarding the aging and degradation of the material, but it can also perform the depollution of congested air simply by using sunlight, atmospheric oxygen and water present as humidity and/or rain water (Folli et al, 2012). The authors mention the advantages of this solution in breaking down nitrogen oxides (NOx) in the atmosphere to NO3−, especially in urban canyons where NOx concentrations, responsible for smog and acid rains can be considerable due to combustion originated from traffic. During the course of this work the incorporation of TiO2 in the FRCC layers was pondered, having been requested samples and technical support, but ultimately the lack of adequate equipment and time to simulate the effects of depollution in the prototype panels led the research team to postpone these tests for future works. Nevertheless, from the previous conclusions, one can then assume that the benefits obtained by using titanium dioxide in the FRCC layers of the panel seem to be immeasurable considering these properties, but the challenge in the future will be to proceed with tests to determine how much of TiO2 should be incorporated in the two concrete mixtures – as the quantities are never the same to different compositions – in order to obtain the previously mentioned self-cleaning and depollution effects.

### 3.2 Technical modules

Apart from the energy efficiency of the whole system, for increased energy performance modular components, such as photovoltaic or solar panels, could also be incorporated in the panels, integrating harmoniously these elements on the façades.

Currently, there are many companies commercializing solar and photovoltaic panels that are often used only on the roof of the buildings and not on the façades. This represents a lost opportunity, as the façades, if properly oriented towards the South so that the panels can get the best exposure to the sun, can represent an important area to install the panels, resulting in more energy efficient solution. Regarding the panels to be vertically installed, the main obstacles in using them in existing buildings tend to be not only a higher price and a lower thermal efficiency (when compared to the same solutions to be installed on the rooftops), but also some difficulty in aesthetically integrating them in an existing façade layout, not to mention also the bureaucratic problems in obtaining all the necessary building permits. When renovating a building, especially a visually uninteresting one, like most of the existing
social housing buildings, the use of solar panels in a façade can be just the right opportunity not only to increase its energy efficiency, but also to improve its outdated visual aspect. Through prefabrication, the integration of these modules in a modulated panel or a new façade layout can be studied in advance, resulting – if well planned - in an interesting visual combination that simultaneously produces energy to be used in the building, reducing its energy dependence from non-sustainable energy sources. The main solutions currently available on the Portuguese market consist on Solar Water Heating Systems, Photovoltaic Panels and a more recent alternative: Thermodynamic Panels. More advanced technical modules could include sophisticated systems like energy efficient windows, a topic that is also addressed in this chapter.

**Solar Water Heating Systems**

These systems are a cost-effective alternative to electric, gas or fuel based systems to obtain domestic hot water for domestic consumption or heating. It basically includes one or several solar thermal collectors, also known as solar flat panels, which absorb energy from the sun and store it in a tank to produce hot water. The system can be active or passive. In the first case, the storage tank is located inside the house and an antifreeze, heat-transfer fluid circulates in a loop between the panel located on the roof and a heat-exchanger placed inside the tank, which in turn heats the water to be used for domestic consumption or heating (USDE, 2015). The active system can be used in most climates, including the ones prone to freezing temperatures, but are more efficient in countries with abundant daylight, hot summers and mild winters, like Portugal. The basic concept is explained in Figure 22.

![Active, Closed Loop Solar Water Heater](image)

**Figure 22.** Active solar water heating system with direct circulation (Source: USDE, 2015)
In the passive mode (Figure 23), the water tank is usually coupled to the top of the panel in a thermosyphon system, so that warm water will rise into the tank. This solution consists on panels with large storage tanks clearly visible on the rooftops of buildings and is now in disuse.

![Passive, Batch Solar Water Heater](image)

**Figure 23.** Passive solar water heating system (Source: USDE, 2015)

Vulcano is one of the most popular brands on the Portuguese market offering a wide choice of Flat Solar Panels (FSP) that can be installed alone or in parallel, up to ten modules, in a vertical or horizontal position. Each unit weighs about 40 kg with an area of approximately 2.37 m² (measuring 1175x2017x87 mm), made of aluminium/copper with a highly selective physical vapour deposition (PVD) coating treatment and solar glass, featuring an embedded tube grid hydraulic circuit insulated with a 55 mm layer of mineral wool, being the system resistant to 6 bar and 120°C, with an average yield coefficient of 0.766 (Vulcano, 2015). Figure 24 illustrates a FSP.

![The WarmSun Flat Solar Panel from Vulcano](image)

**Figure 24.** The WarmSun Flat Solar Panel from Vulcano (Source: Vulcano, 2015)
Although the manufacturer claims that these panels can be placed on a vertical and horizontal position, it does not clearly specify if they can be positioned at 90° on a façade, which – being a possibility – would certainly decrease the panel’s thermal efficiency, as these tend to be placed on flat rooftops of buildings on a 45° angle facing South or on sloped rooftops in private houses with the same orientation in order to perform at the highest level. As the integration of the panel in a prefabricated module would not be a problem a priori due to the fact that the panel’s thickness (87mm) is reduced and possibly inferior to the module’s, the challenge would be to always find in the project an adequate façade with the best solar orientation to have the whole system working at its full potential, which in most cases may be a difficult task.

**Photovoltaic Panels**

Photovoltaic (PV) panels convert solar energy into electricity through semiconducting materials, such as silicon, embedded in thin semiconductor wafer also called a photovoltaic, or solar, cell (NASA, 2015). A photovoltaic module can be obtained by connecting a group of solar cells and mounting them in a support structure, which can supply electricity at a certain voltage (usually 12 volt), but depend on the amount of direct light that strikes the module. Multiple modules wired together form and array, and the larger the array, the more electricity it can produce. When connected in series and/or in parallel electrical arrangements, they can produce any required voltage and current combination (NASA, 2015). Figure 25 illustrates the main concept.

**Figure 25.** The basic layout of a solar panel, from cell and module to array (Source: NASA, 2015)
“AXITEC” and “LUXOR solar” are two companies specialized in installing PV solar systems for the domestic production of electricity selling similar PV modules featuring a hardened solar glass, 60 solar cells with 156mm x 156mm arranged in a 6 x 10 matrix, with a module dimension 1640 x 992 x 40/45 mm (L x W x H) and a total weight between 20 kg per panel (Coeptum, 2015). The basic layout is presented on Figure 26.

Figure 26. Luxor Eco Line 60/260 – 280W PV panel (Source: [http://www.luxorsolar.com](http://www.luxorsolar.com))

From the image and diagram, it is possible to visualize that PV modules tend to be smaller, thinner and lighter than the flat solar panels (FSP) required for the production of domestic hot water. As these panels only require a cable to be connected to the power system and no piping installation, the integration of these units in a prefabricated module seems to be easier when compared to FSP, with a low maintenance and a 25-year guarantee for 80% rated power (Coeptum, 2015).

PV energy has long been deemed as sustainable, as it relies exclusively on the sun – a renewable energy source – and the conversion from solar energy to electricity takes place with zero environmental emissions. After a period when solar modules were considered to be extremely expensive to produce to be economically competitive, the latest generation of solar panels – and its mass production at a global scale – has managed to significantly lower the cost of this technology, making it a viable option in certain specific situations, but not a mainstream choice for the production of electricity, as the
investment in the system is still considerable and the payback time may take too many years – or never get to happen. Today, in Portugal, selling energy to the public grid is no longer economically worth the investment, as it was in a recent past. Recent legislation has revoked all the incentives for the micro generation of electricity using PV panels lowering the price paid per MW/h to 102.9 euros, a value that is 43% lower than the one paid in 2013, no longer making this a profitable investment for the private consumer (Ambiente, 2015). As a consequence, all these investments that were made with the perspective of selling the produced electricity to the public grid, with direct financial gains, are nowadays confined to the production of electricity for self-consumption. Given the fact that at night – when people are home and the use of electricity is high - there is no production due to the lack of solar energy, installing PV panels in a home or building is an investment to be carefully pondered. Without further tax and financial incentives from the government to promote this green technology, PV panels are condemned to be an economically disadvantageous option. However, having in mind that legislation may change again in a near future to make this option a more interesting alternative, PV panels are also included as one of the energy modules that can be integrated in the layout of a façade or in a prefabricated panel, when renovating a building.

**Thermodynamic Panels**

Thermodynamic Panels (TP) are similar in appearance to solar thermal systems and consist on a type of air source heat pump that collects energy from a flat plate collector, instead of a fan, taking energy from the air and complementing it from the solar gain, if suitably oriented, using electricity for the compressors and pumps. The main advantage of this system is that it can produce heat from non-optimal collector orientations, or even at night, obtaining gains from the increase of temperature the heat pump compression cycle offers. Like any other type of heat pump, TP have a COP (coefficient of performance), which is a comparison of the energy taken to run, against the output heat energy from the system, which typically ranges from 2 to 4 in air pumps, depending on the weather conditions and season of the year, apart from the geographical location (Narec, 2015). For the thermodynamic panels, the COP values vary according to the geographical location where they are installed and solar orientation and information on the yield factor in Portugal is not easily available at the moment, but according NAREC, an independent institution part of the UK National Renewable Energy Centre focusing on reducing carbon emissions and educate energy users, in the cold UK climate and for a water temperature of 35° and ambient of 7°C, a manufacturer quotes a COP of 4.13, falling to 2.80 when the ambient is -3°C. Narec concludes that the required COP can be achieved with a suitably
designed low temperature heating system, such as underfloor in-slab, but for heating domestic hot water to 50°C it requires a much higher temperature gradient, which translates in a decreased COP value. In Portugal, where the climate conditions are much more benevolent with abundant sun even in the winter and temperatures that rarely drop below zero, it can be assumed that the COP will be much higher, making this option an interesting alternative to the more conventional solar systems.

“Energie” is a Portuguese manufacturer providing a wide range of solutions based on thermodynamic solar panels, as exemplified in Figure 27. This company describes this system as the combination of “two incomplete technologies, the heat pump and the solar thermal collector” by saying that while the heat produced from the heat pump is dependent from the changes of temperature and that thermal solar collectors are totally inefficient when there is no sun, the combination of the two systems can overcome the limitations of both solutions, resulting in a system that works even at night, “providing hot water at 55°C, day and night, hail, rain, wind or shine, unlike the traditional solar thermal system”. The company also claims that the energy consumption of the system is basically the same of a fridge compressor, only necessary to make the cooling liquid circulate between the panel and the condenser (Energie, 2015). Although this system is not completely energy independent and may not be classified as a 100% solar system, its main advantage in rehabilitation is that not only its panels are extremely

![Diagram of thermodynamic operating principle](image)
lightweight and thin, not causing any overload to the façade, but they can be positioned vertically or horizontally, in the shade or under direct sun, not requiring the specific direct sun exposure of the more conventional solar panels, making the most of all available space in any façade, despite its solar exposure, allowing for additional freedom in the design process. Each panel consists on a thin plate with an embedded circuit where the cooling fluid circulates, with a dimension of 2000x800x20 mm (LxWxT), requiring (according to the manufacturer) little or no maintenance at all.

Figure 28 illustrates the basic components of the system.

![Figure 28. Thermodynamic panel and water storage tank. (Source: Energie, 2015)](image)

Thermodynamic panels present a real alternative to flat solar panels for the production of domestic hot water and heating. Although not considered a 100% energy independent system, the combination of this solution with a backup system of PV modules to supply the necessary amount of energy (at least during the day) could help enhancing its sustainability level and lowering the electricity bill, making it an even more interesting option.

**Energy Efficient Windows**

Windows are key elements in the thermal comfort of a building and still present in most cases a high potential for improvement. This is especially evident in southern European countries – like Portugal - where the importance of an energy efficient window in renovation projects was for long overlooked in favour of the mere upgrading of the exterior walls. Windows, in fact, are responsible not only for heat losses in the winter, but also by heat gains in the summer, and as in large housing buildings a considerable part of the façades generally consist of (energy inefficient) windows, in the renovation
process special attention must be paid to choosing the most adequate model in order to reach the best possible thermal performance and ultimately save energy and money on energy bills. In that sense, ADENE, the Portuguese Agency for Energy in association with the Portuguese Association of Efficient Window Manufacturers and other national partners, has created within the SEEP energy labelling system for products ("Sistema de Etiquetagem Energética de Produtos") a special category dedicated exclusively to windows, defining a set of parameters that give the window a grade between A (most efficient) to G (less efficient), presenting the final result in a label as seen of Figure 29.

![Figure 29. The SEEP energy labelling system for windows. (Source: SEEP, 2015)](image)

This A to G classification results from the quantification of the energy performance of each window (in kWh/m²) during the coldest and hottest month of the year, reflecting its ability to reduce heat losses in winter and minimize overheating in the summer. As all this is done under the same regulatory framework, it is possible to compare windows from different manufacturers for the same conditions. The label also includes detailed technical information, such as the calculation parameters that were used to determine the energy performance, in addition to further data related to the characteristics of the glass and the sound attenuation capacity of each window. Moreover, with the large format label provided to each unit, a smaller label is also permanently embedded in the product, ensuring its traceability (SEEP, 2015).

Despite not being considered a typical energy module, an energy efficient window could help reducing significantly the energy consumption in a building by avoiding energy losses or excessive gains, as previously explained. Although in Portugal the construction market is only able to provide models within the available catalogues provided by the main window manufacturers, advanced solutions are already
Development of sandwich panels of customized functionalities for the rehabilitation of the built patrimony

a reality in Germany, having been developed a prefabricated multifunctional modular window at the Fraunhofer Institute for Building Physics IBP in Kassel especially designed for renovation projects and offering more than just good thermal and acoustic insulating levels (Figure 30).

**Figure 30.** The Fraunhofer window module with its surrounding was designed to be simply inserted in the existing window opening (Source: Fraunhofer, 2012)

The manufacturer claims that this window module is a "minimally invasive intervention" to be adopted by architects and builders in the upgrading of buildings to modern energy efficiency standards, allowing quick on-site installation times with minimum disturbance for homeowners (Fraunhofer, 2012). The window features a removable technical system box located under the window sill and provides room for installing components such as heat exchangers, ventilation ducts, air filters, internet cabling, etc. Additional installations such as electrical wiring and water pipes are installed on the outside wall, in the cavity between covered by the insulation panel and can be routed into the building through cut-outs in the technical systems box. The system allows maintenance to be done rapidly by replacing or upgrading components directly in the easily accessible box. This multifunctional modular window was developed to be used in many types of buildings, but mainly for the renovation of multi-family residential housing. Being this window for the moment a case-study prototype not available for mass production, it still illustrates all the potentialities that this important building component presents in the upgrading of the energy efficiency of most buildings.

To conclude, one could say that all the technical modules - solar and photovoltaic panels and even energy efficient windows - to be implemented in the panels could improve the overall performance of the solution but also increase final costs, so the assessment of the different possibilities would depend on the economic scale of the project, considering the final price of the "basic solution" and the various possible upgrades.
3.3 Fabrication and installation using robotization and BIM

Robotization

As previously mentioned in the state of the art, prefabrication is the future when thinking of large building renovations thanks to the many advantages it offers that compensate for the few challenges yet to be overcome. Implementing standardization in the construction process is one of them, as buildings to be rehabilitated have different features that require a certain level of detail and customization. Robotization may be the answer to this challenge as its use in the fabrication process will make possible the creation of a tailor-made solution for a specific building by integrating different levels of functionalities depending on the rehabilitation exigencies and available budget for the intervention. Robotization has been used for many years in the automobile industry, aeronautics and many other technologically advanced activities but in the construction industry it is still at an inferior level, despite recent improvements made in recent years. As main difficulties remain the subsistence of many non-repetitive processes and low levels of standardization (Pastor et al, 2005).

In a case-study conducted for the Spanish construction company DRACE concerning the benefits of converting a manual production line into an automatized process, five layout scenarios for a fully robotized production line to fabricate glass reinforced cement (GRC) façade panels were tested, having also been studied the modelling and optimization of the whole manufacturing process, considering that these consist of three main steps: panel geometry design, off-site manufacturing and on-site assembly. The main goal was to automate the manufacturing process and increase productivity, adding more quality to the final product, but the analysis was also focused on the development of a flexible manufacturing system monitored by a simulation model that could facilitate decision making both in the short and long term, helping to reduce material consumption, manual labour and the associated high costs (Pastor et al, 2005). In this case, the production of the GRC panels was still manually done in a factory and involved five different types, each with a different number of layers, being the first one common to all of them and consisting of a cement mortar without fibre with up to a total thickness of 2 mm, resulting all the different panels from the combination of the remaining layers. Concerning prefabrication, the design process of the panel geometry had to consider important constraints, such as constructive restrictions (normalisation), aesthetic criteria (limited detail options), transport and on-site assembly of the modules (avoiding oversized dimensions). Figure 31 illustrates the GRC panel variations to be produced using robotization.
The manufacturing process, now to be automatized, had to contemplate all the steps still manually performed that involved preparing and cleaning the moulds; spraying and compacting of the GRC layers; hardening and curing of the concrete and extracting the panel with cranes, preparing it to be transported and assembled on-site. All these task were still performed at the factory in fixed stations causing some limitations in productivity, manufacturing options and handling of the modules, so the main conclusion of this study was that another work philosophy had to be adopted in order to optimize all processes. The fixed workstations were then replaced by an automated line featuring robots performing the spraying operations and panels would circulate between the workstations with a set of conveyors, instead of being always limited to the same workstation. The main advantages found with this new production system were not only a greater specialization of each operator, but more importantly the possibility of increasing the size of the modules thanks to robot spraying, something not possible to achieve with the manual process, opening new possibilities to the design and manufacturing process (Pastor et al, 2005). The next step was to develop a simulation model to optimize the new layout, model the initial concepts and test new ideas, and for that purpose a simulation tool (SIMFACTORY from Caci) was used to design the model (Figure 32).

**Figure 31.** Types of GRC panels to be produced using robotization (Source: Pastor et al, 2005)
This interface permitted not only the reorganisation or elimination of the tasks, implementing automation, but more importantly to design a parametrized model featuring variables that could be easily modified according to each specific need, such as a) the number of spraying stations, b) number of workstations, c) number of teams or operators, d) the control of the conveyor system and feeding system, e) controlling the percentage of inefficiencies, f) assigning operators to different workstations or tasks; and g) monitor the sequencing of the panels. Other variables could now also be controlled, such as the productivity of the operator and the robots in an 8 hour shift, etc. From five possible manufacturing layouts, the simulation studied the best option regarding simplicity and lower cost and matching it with good results and high efficiency, resulting in the final proposal visible on Figure 33.
The conclusion from the simulation analysis was that in the end the best layout could be implemented, resulting in a robust design not only under normal operation but especially in the presence of inefficiencies, increasing by 15% the throughput over the manual manufacturing process. As a result, the whole process was considered cost-effective enough to be installed by the company in the production line. Additionally, after a year and a half it was confirmed that the use of robots at 80% of their full potential had led to a total increase of productivity of around 12%, reducing their amortization period of this equipment faster than was initially expected (Pastor et al, 2005).

Having in mind the similarities between the previous case-study and the proposed concept, as well as the positive outcome resulting from adopting robotization in prefabrication, in this work a preliminary proposed layout for a fully robotized and customized production line was also studied, having in mind the production of a panel with the characteristics initially presented on Chapter 3. The main concept for a possible production line is presented in Figure 34.

Figure 34. Proposal for a robotized line for the manufacturing of FRCC sandwich panels.

This preliminary layout can be explained in 10 different steps, sequenced from the beginning to the end of the production line:
1) **Initial table for the placement of the panel frames** - Galvanized steel frames to be used on the panels would be produced at a local metalworking facility from a parametric 3D model using a compatible software (to be explained further ahead in the BIM chapter) and brought to the factory by truck, where they would be manually placed on this initial table, according to the panel sequence to be followed by the software in the production line;

2) **“Pick and Place” structure** - This structure would consist of a computer monitored crane that could lift and position the metal frame in the casting platform, in the right position and ready to be casted;

3) **Panel frame placed on a movable casting platform in the conveyor line** - The casting platform would be movable, so that it could circulate in a conveyor line passing through all the stations, resulting on a more cost-effective solution (as explained on the previous case-study), with the possibility of increasing the size of the modules thanks to robot’s versatility concerning the casting method to be adopted (spraying, pouring, etc., depending on the density of the FRCC to be used);

4) **First robotized casting station (FRCC)** – A first 20 mm thin FRCC layer would be applied against the casting platform, previously prepared with a proper dismantling fluid; the robot would cast the mixture with precision in order to reach all the inner areas of the galvanized steel frame, but confining the layer to a thickness of 20 mm;

5) **Table for the placement of the insulation panels** - In this table the insulating panels (60 mm thick black cork agglomerate) would be placed, ready to be cut in smaller modules, according to the layout of each panel to be produced;

6) **Robotized station for the cutting of the insulating panels** - These modules would be sectioned by a robot (using high pressure water, laser or mechanical tools) from the bigger insulating panels according to the size determined by the software and placed in an intermediate table to be ready for assembling inside the panel frame, following the predetermined layout; this robot would also insert the connectors in the predefined position in the insulating panels;

7) **Robotized station for the assembling of the modules of the insulation panels** - This task would be performed by another robot, placing all the pre-cut insulating modules, following a specific order, inside the panel frame and over the first (fresh) FRCC layer;

8) **Second robotized casting station** - A final 20 mm FRCC layer would now be cast to cover the insulating panels to the edge of the panel frame; the casting speed and frequency would be programmed in order to obtain the smoothest surface possible;
9) **Panel casted and ready for curing** - Terminating the assembling phase, the panel would then be moved on the casting platform away from the assembly line, not to interrupt the ongoing process.

10) **Curing of the FRCC** - The panel would then be transported to a drying chamber under controlled temperature located in the premises - but not in the production line, due to the expected long curing times - staying there as long as necessary to fully cure the concrete, before being taken to a warehouse for storage or transported to the construction site in a lorry for on-site assembling.

As previously explained, the main advantages of robotization in the construction of concrete sandwich panels would then be a complete integration of the various layers, components and a multitude of possible assemblages. In order to further explore this concept, some consultations and meetings were conducted with the Portuguese company “Roboplan Robotics Experts” (http://www.roboplan.pt/) in Aveiro, Portugal, between July 2014 and March 2015. From these meetings an initial layout was proposed by the company for a robotized assembling line, being the one presented on Figure 34 an evolution of the initial design, adapted according to the evolution of the this work. Concerning the robots that could perform the tasks previously described, the proposed model was the Motoman DX100 from Yaskawa (illustrated on figure 35), a “manipulator robot”, consisting of the controller, the programming pendant and supply cables (Yaskawa, 2010).

**Figure 35.** The basic “4 point teaching function” performed by the Motoman DX100 and a 12 step variation based on the first 4 points (Source: Yaskawa, 2010)
The robot is based on a “4 point teaching function”, in which the task to be executed results from automatically generated rectangular shaped paths programmed by any of the four previously selected taught points, as seen on Figure 35. The precision in the casting or painting processes can be assured with this kind of equipment, as from these 4 points many other movement combinations can be programmed, generating interim routes using linear or even circular paths allowing the robot to perform a multitude of tasks, from single to double coating (painting/spraying), within a specified frequency/pitch (Yaskawa, 2010). A particularity of these robots is that a task can not only be merely programmed but also automatically generated by a pre-taught job. An example of a pattern developed with quadrangular shapes formed by 4 points in a painting sequence is represented in Figure 36.

The process starts with an original job, determining 4 predetermined points that subsequently are altered to generate a new path integrating these 4 points with a specific sequence of new ones (Paint count =1). The next job (Paint count=2) includes all the previous points, but is able to include additional ones using the previously designed routes or new ones.

The differences in directions with 4 points and with a sequence of tasks performed on the same surface (Source: Yaskawa, 2010)
In another representation, Figure 37 simulates the differences in directions of a robotic arm performing a task on a surface (e.g. a panel), from 4 predetermined points with different angles (4 taught points), showing the change in the angle of the robotic arm from position 1 to 4. With circular interpolation, the same robotic arm is able to perform a multitude of tasks on the same surface in a more complex sequence of points and with different angles. As previously seen, flexibility and adaptability make this kind of equipment the preferred choice for the manufacturing of the panels. The next step would be to integrate it with a software that could assist the project from inception to conclusion, such as BIM (Building Information Modelling).

**Building Information Modelling (BIM)**

BIM is a methodology that allows the sharing of information and communication between all stakeholders of a project, not only in the design phase, but even throughout all the stages of the building’s life, including its operation and maintenance. BIM is supported by a 3D digital model, accessible by a specific software, which contains all the information about the project (not only the architectural and structural components and installations, but even the properties and costs of all its different materials and components), enabling the virtual manipulation of a specific building to study possible scenarios and ultimately choose the best option (Azenha et al, 2014 a). The popularity of this design platform is that, unlike many other available CAD software, it no longer follows the Collaborative Process but the Integrated Project Delivery (IPD). While the Collaborative Process is the traditional methodology of sharing independent CAD files between architects and engineers - a method that often leads to disorganisation, long waiting periods and inefficient communication between all project stakeholders, originating project errors that eventually result in unexpected costs – IPD is based on the LEAN management philosophy, based on a) the optimization of utilized resources, b) reduction of the execution time, c) flexibility towards project changes, d) improvement of the quality of the final product, and finally e) cost reduction (Azenha et al, 2014 a). BIM, is then, the natural evolution of the CAD (Computer Assisted Design) process, the most common design process until now, transforming what was traditionally a 3D model - a simple geometrical representation of an object – into an object oriented model, representing it through all its components, integrating not only all its physical and functional characteristics but being able to simulate its construction process and behaviour during its entire life, including the recycling and demolition phase (Figure 38).
A BIM model of an object or building combines a 3D parametric model with an information model, storing all the information concerning the geometry and properties of its components in a common database easily accessible to all the stakeholders involved in a project (Figure 39).

A parametric model can be defined as an object oriented model where each object parametrically relates to others, defining a set of parameters that characterize the interdependency between them, interconnecting all the information and making it available in a software format that can be interpreted.
by all computers using this platform (Azenha et al, 2014a). Not only it allows the virtual construction of the building or object, automatically producing plans, elevations, sections and constructive details by virtually sectioning the model, but it can instantaneously update the model in all these design representations when a particular part or element is altered, interacting with all the other BIM tools (engineering and installations software) and optimizing productivity in all the phases of the project.

BIM can also automatically detect incompatibilities in the design phase between, for example, architecture, installations and structural elements, when the model and the corresponding information contained in the file is exchanged between all stakeholders using compatible BIM software. The sharing of information is in fact one of the main features of this methodology. Structural and energy efficiency simulations, apart from automatic verifications of building codes and management of all the building’s infrastructures in the maintenance phase, are already a reality when using BIM. For that reason, it was necessary to normalize all the many existing parameters in a single file type that could be used by all stakeholders, resulting in an open format file – the Industry Foundation Classes (IFC) – that aggregates in a single platform (the BIM model) architecture, structure and installations (Azenha et al, 2014a).

The potential of IFC files have already been studied in the parametrization of sandwich panels, with each panel file aggregating the following information within the 3D parametric model:

- Spatial location of the element;
- Description of the element’s geometry and material;
- Specification of the type of element;
- Description of possible openings in the panel surface - location and area;
- Definition of applicable IFC parameters.

By designing or upgrading the model (using one of the many available BIM softwares like ArchiCAD, AutodeskRevit, etc.) additional IFC parameters can be generated and included in the model, such as the year of manufacturing, original lot and serial number, allowing for the virtual management of all the prefabricate modules when stored in a warehouse, something important in a prefabrication environment (Silva, 2012).

In this particular project, the adoption of robotization on the manufacture of the modules would be integrated in a large scale fully industrialized pre-fabrication process, using the adequate casting technology completely integrated with BIM and based on parametric design, allowing for the full
customization and real-time ordering of the modules with enormous savings of resources. An initial on-site survey could use advanced tools such as a 3D laser scan to conceive the BIM model, allowing for a real representation of the existing geometric features of the building to be rehabilitated using a 3D point cloud that can be interpreted by the BIM software as a virtual representation of the building’s dimensions and volume (Azenha et al, 2014a). After the panels and the solution were defined and tested in virtual simulations and the modules approved for production, BIM would enable that, at each stage if necessary, further information could be added to the model, allowing for the robot to be quickly reprogrammed to execute the necessary tasks in the assembling line. This approach would help to maximize productivity, flexibility, optimising performance and reducing costs.

BIM methodologies in the construction market are soon to be mandatory in the European Union and a project like this would be implementing these technologies not only to create BIM objects for the panels but also to design the panels and the whole layout on the façades, helping to assist the project in the construction of 4D models (3D models of the solution planned in time) to allow all stakeholders to visualize the assembling of the panels in the construction phase, improving project management and the delivery of the construction project (Azenha et al, 2014a).

At the level of the panels, these would consist of BIM objects that would incorporate the geometry of the modules, as well as information regarding materials and material properties (e.g. mechanical, thermal, acoustical, etc.). For every panel typology every component's geometry would be fully parameterized (customizable) based on algorithms defined by the user to allow its direct integration into any BIM model of an existing or new building layout. Additionally, BIM would also allow several rules to be incorporated into the objects in order to function as a catalogue defining the basic principles for the whole range of panels, making it impossible for the manufacturer to produce panels that either could not be fabricated (for example, because they would exceed the maximum dimensions) or would result in poor performance levels (if the software could detect insufficient mechanical performance for the selected size) (Azenha et al, 2014b). Moreover, BIM would also detect clashes and verify if all the necessary connections between panel/ façade and panel/panel are in done according to a simulated scenario.

BIM models of the façade could incorporate not only its geometric characteristics but additional information, which associated to the parametric features of the panel objects would allow automatic analysis of the solution’s structural efficiency (using interoperability software such as Autodesk Robot, Vico, etc.), as well as the assessment of its energy performance (e.g. EnergyPlus), therefore enabling optimization processes during the design phase, ultimately allowing to determine the best solution.
Additional software (Rhinoceros, Galapagos or Grasshopper) could also be useful to help calculate these results by analysing many combinations of panels according to determined functions previously defined in the design phase (Azenha et al, 2014c).

Given the wide diversity of buildings and façade typologies to be renovated, the most appropriate solution may possibly even end up being a layout that determines that each all panels to be installed in a building are distinct. Considering that this scenario could hardly be possible in traditional style prefabrication, in which predetermined tasks are not easily adaptable to changes, by using BIM together with robotization this situation would be quite feasible, as the whole manufacturing process could be rapidly reprogrammed by updating the BIM model sent by the design team to the factory within the Open BIM framework (IFC format, according to ISO 16739:2013) (Azenha et al, 2014c). This IFC file would then be submitted to an automatic checking and filtering process to identify all the types and parameters of panels to be produced, being the information sent directly to the production planning centre to start the manufacture and storage of the modules. In the end the whole production line would be totally managed according to a BIM-based model, allowing not only the optimization and organisation of storage facilities, but also the planning of all the subsequent phases, from panel transportation to the site to its assembling in the façade according to the predetermined layout.
4 EXECUTION AND TESTING OF TWO PROTOTYPE PANELS

Following the investigation about the potentialities of the materials that can be incorporated on the proposed sandwich panels, one of the major goals of this work is to make use of the excellent physical and mechanical properties of the Fibre Reinforced Cement Composites (FRCC) testing the potential of this material in two different compositions - Fibre Reinforced Mortar (FRM) and Lightweight Fibre Reinforced Concrete (LFRC) - on two prototype panels:

- A first panel composed of a structural frame of galvanized steel with a $\Omega$ section, two outer 20 mm thick layers of mortar reinforced with polypropylene and glass fibres (FRM), insulating core in black cork agglomerate of 60 mm thickness. The FRM layers are connected with 6 steel bars of cone shape extremities and 100 mm length that cross the total panel thickness (panel 1);
- A second panel featuring the same structural frame reinforced with two inner transversal perforated still ribs, a single 100 mm thick layer of lightweight concrete (including expanded clay aggregates) reinforced with structural polypropylene fibres (LFRC) (panel 2).

The main objective of this work is to study the potential of these solutions in terms of structural and thermal performance, as well as to evaluate their cost-efficiency. In the present work, due to size constraints, the dimensions of the executed prototypes were scaled down from 300x200 to 199x133cm, keeping the same thickness considered for the standard panel (10 cm).

4.1 Panel 1

Under the study of the properties of the FRM developed for the InoTec project (Valente et al, 2014), a first prototype panel was executed measuring 199x133x10 cm and featuring two thin 20 mm FRM external layers. This formulation, included I 42.5 Portland Cem cement, class F fly ash from SGR-Ambiente, water, fine sand, viscosity controlling agent, Sika ViscoCrete 3002 HE superplasticizer, polypropylene fibres from Explorplas (with lengths of 12 and 18 mm) and finally 12 mm long glass fibres with high alkaline resistance from Owenscorning Cem-Fil 60.

Unlike the formulation used for InoTec project, where the FRM was developed to have the right consistency to be applied with a spray system onto masonry walls as a structural reinforcement technique, in this case the composition was tailored to obtain the necessary fluidity and self-
compactness to be compatible with the reduced thickness (20 mm) of the first prototype panel’s outer layers and the obstacles introduced to FRM by the connectors at the contour of the panel frame. In a large scale production of this panel solution, the casting process is expected to be carried out by robots in a fully automatized production line and not manually, as in this situation. Also important in this work was to assess the compatibility of the FRM with an inner core in black agglomerated cork. Finally, in order to assure the proper stress transfer between the two external layers of the panel, six steel connectors were also used, according to a pre-established layout. Figure 40 exemplifies the structural scheme of the first prototype panel, while figure 41 presents some constructive details.

**Figure 40.** Galvanized steel structure and layer description for the first prototype panel (dimensions in mm)
Galvanized Steel Frame

As a consequence of all the present constraints (immediate availability and high cost of the GFRP profiles), the structure for the two prototype panels consists on a frame made with galvanized steel profiles with a Ω-shaped section. Figure 42 illustrates the panel frame featuring several steel connectors on the edge of the profile already placed on the casting table prior to the execution of the first panel.

Figure 41. Details of the first prototype panel (dimensions in mm).

Figure 42. Detail of the galvanized steel (a) frame with the steel connectors (b)
Galvanized steel profiles are not only a widely available option when compared to GFRP, but present almost the same mechanical benefits with a very attractive price and higher elasticity modulus and ductility than GFRP, despite the drawback of having a high thermal conductivity. In a sandwich panel to be used as a load-bearing wall – like the one developed for the Legouse project – this high thermal conductivity would cause thermal bridges between the inner and outer layers of the panel, eventually resulting in condensations and mould that would affect the quality of the interior environment of the house and the health of its occupants. Having in mind that the proposed solution is to be exclusively used as a second skin over an existing façade, possible thermal bridges around the panel frame are not considered to be significant to affect the overall thermal performance of the solution. However, a final conclusion concerning how the use of galvanized steel frames can affect the thermal performance of the solution will only be possible to obtain when assembling and testing some panels together on a façade – a task to be done in future works.

Steel connectors
In this experiment, the main reason to use steel connectors over GFRP alternatives was their immediate availability and low price. As the panels will never be directly in contact with the interior environment of the dwelling it was also assumed that the effect of any possible thermal bridge caused by steel connectors would be negligible in the thermal performance of the proposed solution, as its use will only be necessary in the first prototype panel and in a very limited quantity (6). The proposed connectors consist on a 10 cm long threaded steel rod bar with a diameter of 6 mm and sharp endings, to connect the outer FRM layers of the panel. The conical shape of the extremities aims to decrease the probability of favoring the occurrence of corrosion. Figure 43 shows examples of the steel connector used in the first prototype panel.

Figure 43. Steel connectors used in the first prototype panel
Insulating material
In the execution of the first prototype the insulating layer consists of a 60 mm Expanded Cork Agglomerate (ECA) panel. Cork was chosen over cheaper alternatives like XPS or EPS because it is a natural, energy efficient, sustainable and recyclable insulating material. The most common insulating materials - XPS and EPS - are less expensive than cork, reaching on average half its price on the market and provide a similar thermal performance, but also have a bigger environmental impact concerning its high level of embodied energy and non-recyclability. Cork was then the natural option to provide a good insulation and to increase the level of sustainability of the solution.

Execution of panel 1
The execution of the first prototype panel took place on January 15th 2015 at Civitest, a company that has a research laboratory located in Vila Nova de Famalicão (www.civitest.com). The assembling was completely manual, as it was not viable at this stage of the investigation to set a robotized production line, as it is expected to be done in a mass scale production. The first steps involved the following procedures:

1. Placing the external structural frame of galvanized steel with a Ω section on the casting platform with the external side facing down, in order to cast the first layer of the FRM (the concrete surface to be exposed to the outside of the building, once the panel is assembled on a façade);

2. Having in mind that the insulating core would have to consist on the manual assembly of several Expanded Cork Agglomerate (ECA) panels with 1000x500x60 mm, setting the layout of all the necessary panels and placing them inside the frame was the next step (Figure 44);

![Figure 44. Manual assembling and numbering of the ECA panels](image)

3. One task that could have been performed by a robot in a mass scale production - placing the steel connectors inside the insulating core - had to be done manually and involved using an
electric driller to drill the cork panels and place each connector inside them, according to a pre-established layout, making sure that the sharp end of each connector would stand out 20 mm from the surface of the insulating core (to be later involved by the FRM on both external sides of the prototype panel) (Figure 45);

**Figure 45. Inserting the connectors in the insulating core panels**

4. After numbering all the different panels to define the final layout and removing them from the mould, a proper demould fluid was then applied to the casting platform to assure that the concrete mixture would not adhere to this surface upon removing the panel from the casting table;

5. The next step was then to start fabricating the concrete mixture, adapting the formulation used for the INOTEC project (Valente *et al.*, 2014) to obtain the necessary fluidity and self-compacting requirements for this particular situation, as previously explained. This consisted of using a concrete mixer and adding the following components in specific amounts and in this order:
   a) Granitic sand, fly ash and cement powder in the adequate proportions, making a dry mixture;
   b) Water, to start combining the mixture, adding progressively more water and a superplasticizer (Viscocrete);
   c) After this procedure, more water was added to the mixture and also a small amount of a viscosity control substance (Chryso “Acqua Beton”);
   d) The next step was to add the glass and polypropylene fibres, previously weighed and mixed, to the cement mixture, letting the mixer blend all the components for a few moments to obtain an homogenous paste (Figure 46);
6. After attaining the required aspect, the mixture was then ready to be (manually) casted into the mould and levelled with a trowel in order to obtain a 20 mm thin layer (the external layer of the panel), making sure that all the connectors around the external rim of the frame were well embedded in the FRM (Figure 47);

7. The following procedure was to carefully place the insulating cork panels on the fresh concrete mixture, having in mind the predefined layout (Figure 48);
8. After the placing of the insulating panels, it was necessary to prepare another batch of FRM to be casted over the insulating core panels (Figure 49). This process followed the exact same procedures defined on step 5. The surface of the fresh concrete was then manually levelled with a trowel in order to obtain a smooth surface and the panel was left to cure for 6 days, until the 21st of January.

![Figure 49. Second phase of the manual casting process of FRM](image)

Simultaneously, some FRM specimens were executed in order to be later tested for tensile and flexural behaviour. After the 6 days of curing time - and having in mind that the panel was executed in a large pavilion in the winter - upon lifting the panel from the casting platform it was clear that bottom concrete layer was not yet completely cured. On the exposed side (facing up) the concrete layer was cured but not uniformly, with many visible fibres and small pores at the surface level (Figure 50).

![Figure 50. Final aspect of the upper FRM layer after the curing time](image)

The lower side of the panel presented the same problems, with an uneven surface where fibres and small open pores are visible, especially around the edges (Figure 51).
Figure 51. Detail of the lower FRM layer on the corner of the panel after the expected curing time. This side would correspond to the visible part of the panel on a façade.

As this lower FRM layer would be the one visible to the exterior, the initial idea of having the finishing layer made exclusively of apparent smooth concrete will have to undergo further improvements on the rheology of the FRM in order to achieve the desired visual quality that is expected from a prefabricated element. The next step was to lift and displace the panel from the casting platform, placing it in an upright position against a wall, where it stood for an additional period of 19 days before being tested in creep load conditions.
4.2 Panel 2

The second prototype, panel 2, has the same exact dimensions of panel 1 and consists of a single layer of LFRC formulated using a lightweight concrete mixture with expanded clay aggregates reinforced with polypropylene fibres.

Figure 52 exemplifies the structural layout of the second prototype panel, while figure 53 shows some constructive details.

---

**Figure 52.** Galvanized steel structure and layer description for the second prototype panel (dimensions in mm).
This formulation, although different from the proposed FRM for panel 1, was also tested having the same three aspects in mind: high mechanical resistance, lightness and good insulating capacity. Its composition includes I 42.5 Portland Cem cement, class F fly ash from SGR-Ambiente, fine and coarse sand, water, Sika ViscoCrete 3002 HE superplasticizer, polypropylene fibres from Exporplas (with a length of 50 mm) and finally expanded clay aggregates with two different grain sizes (1-5 and 8-12.5 mm). As the specific mass of the LFRC to be used in the second prototype panel was about 17 kN/m³ - which is approximately 70% of the density of conventional concrete - this option will ensure lightness to the panel, while compressive strength is expected to be enough for this structural application, and post-cracking resistance is estimated sufficient for assuring the required out-of-plane shear strength for the panel. With this solution, thermal insulation levels are expected to be guaranteed exclusively by the expanded clay aggregates, to test if the panel can merely comply with the legal standards or present a better thermal performance. As with the first prototype panel, the mix composition of LFRC has included superplasticizers to reduce the water content without compromising the workability of the mixture. Fly ash was also used to improve the workability of the mixture and replace partially the content of cement, enhancing the sustainability of the solution.
**Galvanized Steel Frame**

Concerning the outer frame - identical for both panels - the only difference in panel 2 is that two perforated galvanized steel reinforcement bars were added at approximately 1/4 and 3/4 of the total height of the panel to help in the improvement of its mechanical behaviour (Figure 54).

![Figure 54. Galvanized steel frame for panel 2 already placed on the casting table (a); steel connectors on the edge of the profile and perforated reinforcement bars (b).](image)

**Perforated reinforcement steel connectors**

As explained before, panel 2 will not be using the steel connectors, relying exclusively on the reinforcement given by the two perforated steel plates shown in Figure 55. As this panel will be featuring a LFRC consisting on a light concrete formulation with expanded clay aggregates reinforced with polypropylene fibres, it is expected that the mixture will penetrate through the hollows on the perforated plate connector, assuring the required shear resistance to the panel.

**Execution of panel 2**

The execution of the second prototype panel took place at Civitest on March 11th 2015. Just like with the first prototype panel, and for the same reasons, the assembling was completely manual. The first steps involved the following procedures:

1. Placing the external structural frame of galvanized steel with a Ω section on the casting platform with the external side facing down, in order to prepare it for the casting.
2. The LFRC was then prepared in a high capacity mixer. This process consisted of adding the following components in specific amounts and in this order:
   a) Two types of expanded clay and river sand were combined in a dry mixture;
b) Water and part of the total quantity of cement where then progressively added to this mixture and mixed for a few minutes, followed by the remaining cement, fly ash and the superplasticizer (Viscocrete), as well as the necessary water to obtain the requested fluidity;

c) The final step was to add the polypropylene fibres to the cement mixture, letting the mixer blend all the components for a few moments in order to obtain the desired consistency.

3. The mixture was then cast to the panel frame and manually vibrated in order to help the spreading of the paste, in order to reach the edges of the panel and crossing the holes of the perforated steel connectors (Figure 55);

![Figure 55. Casting and vibrating the LFRC (a); detail of the reinforcement bar and the mixture (b).](image)

4. The panel had then to be manually levelled with a trowel in order to obtain a smooth finish, which was difficult because the expanded clay aggregates and the PP fibres had the tendency to come to the surface.

Simultaneously, six beams of LFRC were prepared in order to be tested for the characterization of the flexural behaviour of this composite, following the recommendations of CEB-FIP Model Code 2015. Cubic specimens were extracted from these beams after being tested in bending, in order to determine the compressive strength of the developed LFRC. Three beams and corresponding cubic specimens (6, two per beam) were tested at 28 days, with the remaining 3 beams and 6 cubes tested at 49 days. After 5 days, on the 16th of March, the panel was lifted from the casting platform. While on the exposed side (facing up) the concrete layer was cured but not uniformly, with visible fibres expanded clay aggregates, the bottom side, despite some apparent fibres, presented a smooth surface. As the lower LFRC layer would be the external side of the panel, the obtained surface still does not reach the desired
visual quality. The panel was then placed on an upright position against a wall, where it stood for an additional period of 16 days before being submitted to a creep test.

4.3 Mechanical properties of the cement based materials

4.3.1 Flexural behaviour of FRM

Four point bending tests (Figure 56) were executed with FRM specimens in an electro-mechanical equipment by using one LVTD (linear voltage transducer displacement) for controlling the tests at a displacement rate of 0.2 mm/min. These tests were executed when the specimens had 83 days of curing. The relevant data for the FRM specimens is indicated in Table 4.

![Figure 56. Setup for the flexural test on the FRM samples](image)

<table>
<thead>
<tr>
<th>Sample</th>
<th>Length (mm)</th>
<th>Width (mm)</th>
<th>Height (mm)</th>
<th>Weight (g)</th>
<th>Mass Density (Kg/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sample 1</td>
<td>250</td>
<td>69</td>
<td>33,9</td>
<td>1061</td>
<td>1780</td>
</tr>
<tr>
<td>Sample 2</td>
<td>252</td>
<td>66</td>
<td>32,5</td>
<td>997</td>
<td>1800</td>
</tr>
<tr>
<td>Sample 3</td>
<td>251</td>
<td>73</td>
<td>31,4</td>
<td>1040</td>
<td>1770</td>
</tr>
<tr>
<td>Sample 4</td>
<td>252</td>
<td>69</td>
<td>32,3</td>
<td>1012</td>
<td>1767</td>
</tr>
<tr>
<td>Sample 5</td>
<td>252</td>
<td>69</td>
<td>33,2</td>
<td>1047</td>
<td>1779</td>
</tr>
<tr>
<td>Sample 6</td>
<td>250</td>
<td>65</td>
<td>34,9</td>
<td>994</td>
<td>1719</td>
</tr>
</tbody>
</table>

The crack patterns observed in the tested specimens are shown in Figure 57, where it is visible that the specimens failed in bending, with the formation of a major macro-crack in the pure bending zone of the specimen, apart specimen 3, where two macro-cracks were formed one in each loaded section.
Development of sandwich panels of customized functionalities for the rehabilitation of the built patrimony

**Figure 57.** Sequence of samples (from sample 1 to 6, top to bottom) after the flexural test.

The flexural stress versus midspan deflection is represented in Figure 58, while the flexural strength is indicated in Table 5.

**Figure 58.** Flexural behaviour of the six FRM samples (after 83 days)
Table 5. Maximum Stress for the tested FRM samples and coefficient of variation

<table>
<thead>
<tr>
<th>Sample</th>
<th>Maximum Stress (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sample1</td>
<td>7.39</td>
</tr>
<tr>
<td>Sample2</td>
<td>3.77</td>
</tr>
<tr>
<td>Sample3</td>
<td>8.71</td>
</tr>
<tr>
<td>Sample4</td>
<td>5.40</td>
</tr>
<tr>
<td>Sample5</td>
<td>6.82</td>
</tr>
<tr>
<td>Sample6</td>
<td>9.39</td>
</tr>
<tr>
<td>Average Value</td>
<td>6.92</td>
</tr>
<tr>
<td>Standard Deviation</td>
<td>2.09</td>
</tr>
<tr>
<td>Coefficient of Variation</td>
<td>30%</td>
</tr>
</tbody>
</table>

It is verified a large dispersion of the flexural behaviour of the tested specimens, as well as the flexural strength (coefficient of variation of 30%) that may be caused by a quite different fibre distribution and orientation amongst the tested specimens, as well as voids and defects caused by some fibre segregation. Specimen 2 was the unique to present a flexural-shear crack, which can justify the lowest flexural strength registered in this specimen. In the opposite, the formation of two flexural cracks in specimen 3 justifies its highest post-cracking resistance (as seen on Figure 58). In any case the average flexural strength was about 7 MPa which is relatively high considering the compressive strength of this FRM (36 MPa).

4.3.2 Flexural behaviour of LFRC

Three of the six LFRC specimens were tested in accordance with the RILEM TC 162-TDF recommendations (RILEM, 2000) at the curing age of 29 days by using a high precision servo-controlled equipment and two LVTDs, one for measuring the beam’s deflection (with a stroke of 12 mm) and the other the crack mouth opening displacement (CMOD), with a stroke of 8 mm (Figure 59).
Figure 59. Setup of the three point notched beam bending tests with LFRC samples, according to the RILEM recommendations

Each one of the three samples has a prismatic shape featuring $150 \times 150 \times 600$ mm, having been executed at the mid-span of each one a 25 mm deep and a 3 mm wide notch. The tests were carried out in the same electro-mechanical machine used to test the FRM samples, by executing the tests under displacement control at a constant speed of 0.2 mm/min. The applied load was registered using a 100kN capacity load cell. Figure 60 shows the adopted test setup.

Figure 60. Flexural test performed on a LFRC sample: test setup (a) and detail (b)

Figure 61 presents the relationship between the flexural stress versus the CMOD for the 3 specimens tested at 35 days of LFRC curing. From these curves and adopting the recommendations of RILEM TC 162 TDF, the flexural strengthening parameters $f_{eq,2}$ and $f_{eq,3}$ indicated in Table 6 were obtained.
The parameters $f_{eq,2}$ and $f_{eq,3}$ are related to the material energy absorption capacity up to a deflection of $\delta_2$ and $\delta_3 (\delta_2 = \delta_L + 0.65\text{mm} \text{ and } \delta_3 = \delta_L + 2.65\text{mm}, \text{where } \delta_L \text{ is the deflection corresponding to } F_L)$ provided by fibre reinforcement mechanisms. A relatively large dispersion of the results were obtained due to the different fibre orientation and distribution, to be verified in future tests. However it is noticeable that up to the ultimate CMOD (3.5 mm) the flexural capacity has increased continuously (Figure 61), and an average value for the $f_{eq,3}$ of about 4 MPa was obtained (Table 6), when the crack width is about 10 times higher the maximum crack width limit allowed for concrete structures according to the serviceability limit state conditions imposed CEB-FIP Model Code 2010.

Table 6. Maximum Stress, $f_{eq,2}$ and $f_{eq,3}$ for the tested LFRC samples

<table>
<thead>
<tr>
<th></th>
<th>Maximum Stress (MPa)</th>
<th>$f_{eq,2}$ (MPa)</th>
<th>$f_{eq,3}$ (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sample 1</td>
<td>2.81</td>
<td>1.52</td>
<td>2.19</td>
</tr>
<tr>
<td>Sample 2</td>
<td>5.11</td>
<td>3.56</td>
<td>4.46</td>
</tr>
<tr>
<td>Sample 3</td>
<td>4.13</td>
<td>3.11</td>
<td>3.65</td>
</tr>
<tr>
<td>Average Value</td>
<td>4.02</td>
<td>2.73</td>
<td>4.05</td>
</tr>
<tr>
<td>Standard Deviation</td>
<td>1.15</td>
<td>1.07</td>
<td>0.58</td>
</tr>
<tr>
<td>Coefficient of Variation</td>
<td>29%</td>
<td>39%</td>
<td>14%</td>
</tr>
</tbody>
</table>
4.3.3 Compressive behaviour of FRM and LFRC

On the 29th of April, with a curing time of 104 days, 4 FRM cubic specimens with 4x4x4 cm were tested for compressive behaviour on a high precision servo-controlled equipment. The obtained value, 36 MPa, resulted from the average of the 4 samples, performing well above the 21.0 and 24.0 MPa obtained for the four 50x100 cylindrical specimens tested under the INOTEC experiment (Valente et al, 2014). Having in mind that the formulation used for this FRM has the same constituents from the one used on the INOTEC, this improvement might be explained not only by the large percentage of fly ash that has a significant contribution on the compressive strength of the material in the long term, since these specimens were tested at 104 days, a much longer curing time when compared to the 14 and 28 days, respectively, for the INOTEC samples, a much larger compressive strength was expected. On the same day, a similar test was performed on 3 LFRC cubic specimens with 15x15x15 cm, after a curing time of 49 days, obtaining an average result of 18 MPa, a value substantially inferior to the 48,8 MPa obtained in the compressive test performed on cylindrical Lightweight High Resistance Concrete (LHRC) samples tested under the Valente and Cruz experiment (Valente and Cruz, 2004). Having in mind that this experiment investigated the development of a LHRC to be used in structural elements where compressive resistance is of the highest importance and that the LFRC now proposed is to be used in a façade panel where good flexural behaviour and high ductility – previously demonstrated – are the most important parameters necessary to withstand the impact of the wind and other horizontal forces, the obtained results can be considered satisfactory.

4.4 Creep tests on the prototype panels

In order to assess the long term deflection of the panels when submitted to a load level simulating the expected pressure caused by the wind action on a façade, an experimental program was initiated when the curing time of the FRCC reached 20 days and 22 days, respectively for the first (FRM) and second (LFRC) prototype panels. Figure 62 shows the geometry of the panels and the layout for the test with the supporting conditions simulating the eight point connection that each module will have when mounted on a façade.
Figure 62. Geometry and supporting conditions for the load test performed on both prototype panels (dimensions in mm)

Figure 63 illustrates the test performed on the first prototype panel using a permanent load of 8 cement bags to simulate the expected wind load on the external surface of the panel (1.2 kN/m²).

Figure 63. Panel 1 subjected to a permanent load

To monitor the deformation of the central axis of the panel two mechanical displacement transducers were placed above and under the panel, as seen on figure 64.
Development of sandwich panels of customized functionalities for the rehabilitation of the built patrimony

Figure 64. Mechanical displacement transducers measuring the deformation above (a) and under (b) the prototype panel

At the curing age of 22 days, the second panel (LFRC) was submitted to the same loading and supporting conditions adopted in the first panel prototype (Figure 65). Considering that this panel consists of a single layer of LFRC, in order to monitor the deformation on the central point of the panel caused by the permanent load, only one mechanical displacement transducer was used for measuring the top surface of this panel.

Figure 65. Panel 2 subjected to a permanent load

Figure 66 illustrates the evolution on the central deflection measured on both panel surfaces (FRM) of the first prototype panel and on the top face of the second prototype panel (LFRC), measured respectively after 75 and 25 days for the same permanent load of 1.2 kN/m².
From the analysis of the chart, it is possible to notice that during the first 25 days of monitoring, the measured deflections on both FRM top and bottom panel’s surface (Panel 1) are quite similar, demonstrating that the composite system is working integrally. However, at the end 22 day the deflection values decrease from a maximum of 2.1/1.9 mm (top / bottom surface) to around 1.8/1.6 mm for the same permanent load, indicating that other external factors are influencing the obtained results. At the 30th day the deflection on this panel seemed to be stabilizing, presenting a value of 2.3 mm which was about three times the instantaneous deflection (about 0.75 mm) obtained upon loading the panel, a result consistent with preliminary results obtained from simulations performed with a FEM based program. However, after this period the deflection values kept rising until the 75th day, stabilizing at approximately 3.9 mm for both layers, indicating that probably the panel has attained a stabilized stage of creep deformation.

Regarding the behaviour of LFRC, after 25 days it is possible to observe that although the values are not yet stabilized, the central deflection caused by the permanent load on the second panel is minimal, reaching approximately 0.6 mm, nearly 1/3 of the obtained values for the FRM layers for the same period.

Apart from the permanent load and considering other external factors that may be influencing the obtained results, Figures 67 and 68 illustrate the influence of temperature and humidity on the deflection values obtained for both panels.
From the analysis of Figure 67 it is possible to verify that in the first prototype panel the oscillation in the deflection values for both FRM layers is mainly dependent on the variations of temperature, increasing the deflection proportionally with a rise in temperature. On the second panel, temperature variations did not seem to particularly affect deflection, being this phenomenon more evident with the increase of the relative humidity (Figure 68), where a rise from 20% to nearly 70% in RH shows a direct proportion with the obtained deflection values. This may be explained by the higher water content still present in the LFRC, as the second prototype panel had less time to cure that the first prototype panel before the beginning of the test. However, in the long term – and with the complete drying of the
second panel, as it seems to be occurring already with the first panel - it is likely that this trend will be reversed, with relative humidity having less impact on the deflection than temperature variations. Having in mind that the wind action that is simulated by this test is confined to a relatively short period and the maximum obtained deformation in the two tests are negligible and do not present any permanent damage to both panels, this test can validate both options in terms of creep behaviour, ultimately leaving the assessment of the best global solution to the one that presents the best overall mechanical and thermal performance.

4.5 Thermal performance of the prototype panels

In order to evaluate the thermal performance of the two panels, tests were performed on the 11th (Panel 1) and 13th of May (Panel 2) to simulate the effect of constant direct sunlight on a façade in the warmer months of the year. The setup for the tests was made according to the configuration presented in Figure 69.

![Setup for the thermal test: a) placing electrical heating resistors on the panel; b) reversing the panel and placing the test chamber against it; c) thermocouples used to measure temperature variation during the test.](image)

The test consisted on placing two electrical heating resistors (used for radiant floors) over one of the panel’s sides (a), covering them with an insulating blanket to concentrate the heat on this surface. The resistors would be heated to a maximum temperature of 65°C (obtained on the surface of the
panel) to simulate a façade exposed to strong direct sunlight during a hot summer day and results would be registered during this period. The simulation of the interior environment of a dwelling was achieved by using a thermally insulated test chamber, with an opening on one of its sides, placed against the panel (b). Simultaneously, the monitoring of the temperature variations was done using 4 thermocouples (c) strategically placed in different locations: the first thermocouple (T1) was placed at the panel’s midpoint between the two heating resistors to measure the rise in temperature on this surface (exterior side), while the second thermocouple (T2) was positioned on the opposite side of the panel, also at its midpoint, to measure the difference of temperature between the two sides during the test. The two remaining thermocouples (T3 and T4) were placed inside of the test chamber, respectively at a distance of 45 and 70 cm from the panel to monitor the temperature variation in an interior atmosphere. Figure 70 shows temperature variations registered by thermocouple (sensor) T2 during the thermal tests on both panels.

![Temperature variation in thermocouple T2](image)

**Figure 70.** Temperature variation in thermocouple T2 (placed in the test chamber, over the panel’s midpoint) during the thermal test performed on the first and second prototype panels

It is visible that for the same exterior temperature of 65°C, while the T2 sensor placed at the opposite side of the heat source on the FRM and cork panel (Panel 1) recorded a minor increase from 22°C to 24,4°C (+2,4°C), the same sensor placed under the same conditions on the LFRC panel (Panel 2) registered 38°C (an increase of 16°C). Simultaneously, the remaining two sensors, T3 and T4, were recording the temperature increase inside the test chamber at different distances from the panel, (Figure 71 and 72), with the following results:
Figure 71. Temperature variation in thermocouple T3 (placed in the test chamber, at 45 cm from the panel) during the thermal test performed on the first and second prototype panels.

Figure 72. Temperature variation in thermocouple T4 (placed in the test chamber, at 70 cm from the panel) during the thermal test performed on the first and second prototype panels.

From the analysis of Figures 71 and 72, it can be observed that while inside the test chamber and under the same exterior temperature of 65°C the obtained values for Panel 1 almost remained constant from the initial interior temperature of 22°C (22.6°C and 22.4°C respectively for T3 and T4), the registered values for the same sensors in the second test with the LFRC panel had recorded 32.8°C (T3) and 32.5 (T4), a difference of more than 10°C under the same conditions.
Considering that the values that define thermal comfort in a house are situated between 18°C and 26°C (Silva, 2009), it can then be concluded that while the obtained results for the first panel complied with these values, maintaining a comfortable interior atmosphere, the opposite occurred on the second test performed on the LFRC, resulting in an overheated environment. It is then possible to assume that while in Panel 1 the insulating effect of the cork panel and its low thermal conductivity (0.045 W/m °C) acted as an efficient barrier against the high thermal conductivity (between 1.65 and 2.00 W/m °C) of the 2 FRM external layers, regarding Panel 2, the disappointing results may be explained by the high porosity and thermal conductivity of the LFRC (between 0.36 and 0.46 W/m °C), making this composite more permeable to the passage of heat from the outer to the inner surface of the panel (Santos and Matias, 2006).

To better understand the heat transmission on the panels, a thermographic camera was also used to monitor the experiment. Figure 73 shows a thermographic image of the first prototype panel taken approximately 80 minutes after the beginning of the test.

![Figure 73. Photo of panel 1 taken approximately 80 minutes after the beginning of the test (a); corresponding thermal image showing temperature variation on the panel surface (b).](image)

Despite of the 43.1°C already registered on the panel’s heated surface (by sensor T1), the temperature measured on the opposite side by T2 remained unchanged (22°C), demonstrating the thermal efficiency of the insulating layer. However, a more detailed analysis of the image can detect two orange dots on the panel that are actually thermal bridges induced by the steel connectors (A).

The same procedure was followed in the second test, having been registered the thermal transmission on the LFRC panel after 120 minutes (Figure 74).
Figure 74. Photo of panel 2 taken approximately 120 minutes after the beginning of the test (a); corresponding thermal image showing temperature variation on the panel surface (b).

In this case, the image demonstrates that during the 120 minute period, despite a registered temperature of 46.5°C on the external surface of the panel (T1), the thermographic pattern on the visible side clearly displays an uneven thermal distribution, with a large area (in red) already above the 23.9°C registered at the centre of the panel by the camera. In this image it is also visible a horizontal area where the reinforcement bar used on the panel frame is creating a thermal bridge (B). Being a thermal bridge a significant problem if the panels were to be used as a single wall – as it would create condensations and mould in the indoor environment - in this particular case this phenomenon can be considered of relative importance, as the panels are to be used only as a second skin over existing façades and the occurrence of thermal bridges would merely take place between the outside environment and the air chamber located between the façade and the panel, never reaching the interior of the dwelling. Nonetheless, the obtained results suggest exploring in future tests other alternatives to steel - such as the GFRP connectors already mentioned on chapter 3.1.3 - to prevent this situation from occurring altogether.

From the obtained results it is possible to conclude that the solution proposed for the first prototype panel (20mm FRM + 60mm cork panel + 20mm FRM) is the one that thermally has the potential to be part of a comprehensive façade system that effectively upgrades the energy performance of underperforming buildings. Despite its mechanical efficiency, the solution proposed for the second prototype panel (100mm LFRC) will always tend to underperform in terms of thermal behaviour due to the high thermal conductivity of the lightweight concrete.
4.6 Cost assessment of the two proposed solutions

Apart from the assessment of the mechanical and thermal performance, the estimated cost for the manufacturing of each panel is also an important variable to be taken into account in the final comparison of the two solutions. Table 7 presents a preliminary comparison concerning exclusively the cost for the execution of the prototype panels (and not other variables of difficult quantification at this stage, like the cost of the assembling system, necessary manpower or transportation of the panels to the site), comparing the obtained values with the cost for a similar panel alternative available on the Portuguese market.

Table 7. Cost comparison between the two prototype panels

<table>
<thead>
<tr>
<th>FIRST PROTOTYPE PANEL - PANEL 1</th>
<th>Quantity Kg/ m³</th>
<th>Price €/kg</th>
<th>Cost €/ m²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fibre Reinforced Mortar (FRM)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cement</td>
<td>547</td>
<td>0,092</td>
<td>50,32</td>
</tr>
<tr>
<td>Fly ash</td>
<td>669</td>
<td>0,055</td>
<td>36,80</td>
</tr>
<tr>
<td>Filler</td>
<td>0</td>
<td>0,048</td>
<td>0,00</td>
</tr>
<tr>
<td>Water</td>
<td>318</td>
<td>0,001</td>
<td>0,32</td>
</tr>
<tr>
<td>Fine sand</td>
<td>437</td>
<td>0,004</td>
<td>1,75</td>
</tr>
<tr>
<td>Superplasticizer</td>
<td>21</td>
<td>2,258</td>
<td>47,42</td>
</tr>
<tr>
<td>Glass fibres, 4% Volume</td>
<td>96</td>
<td>4,000</td>
<td>384,00</td>
</tr>
<tr>
<td>Polypropylene fibres, 1% Volume</td>
<td>11,9</td>
<td>2,600</td>
<td>30,94</td>
</tr>
<tr>
<td>Cost / m²</td>
<td></td>
<td></td>
<td>551,54</td>
</tr>
</tbody>
</table>

Cost for the quantity used on the first Prototype panel (60+60 litres=0,12m³) **66,19**

<table>
<thead>
<tr>
<th>Other panel components</th>
<th>Price €/m²</th>
<th>Quantity (panel) m²</th>
<th>Cost €/m²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cork agglomerate 60 mm (Source: Sotecnisol, 2015)</td>
<td>15</td>
<td>2,6467</td>
<td>39,70</td>
</tr>
<tr>
<td>Galvanized Steel Frame</td>
<td>-</td>
<td>-</td>
<td>132,50</td>
</tr>
<tr>
<td>6 panel connectors (included in the frame cost)</td>
<td>-</td>
<td>-</td>
<td>0,00</td>
</tr>
<tr>
<td>Total cost for the first prototype panel</td>
<td></td>
<td></td>
<td>238,39</td>
</tr>
<tr>
<td>Panel area (199 x 133 cm)</td>
<td></td>
<td>2,6467</td>
<td></td>
</tr>
</tbody>
</table>

**Cost /m² for the first prototype panel** **90,07**
SECOND PROTOTYPE PANEL - PANEL 2

<table>
<thead>
<tr>
<th>Lightweight Fibre Reinforced Concrete (LFRC)</th>
<th>Quantity</th>
<th>Price</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cement</td>
<td>380</td>
<td>0,092</td>
<td>34,96</td>
</tr>
<tr>
<td>Fly ash</td>
<td>350</td>
<td>0,055</td>
<td>19,25</td>
</tr>
<tr>
<td>River sand</td>
<td>676</td>
<td>0,003</td>
<td>2,03</td>
</tr>
<tr>
<td>Expanded clay 1-5 mm</td>
<td>220</td>
<td>0,08</td>
<td>17,60</td>
</tr>
<tr>
<td>Expanded clay 8-12,5 mm</td>
<td>85</td>
<td>0,197</td>
<td>16,75</td>
</tr>
<tr>
<td>Water</td>
<td>202</td>
<td>0,001</td>
<td>0,20</td>
</tr>
<tr>
<td>Superplasticizer</td>
<td>9,5</td>
<td>2,258</td>
<td>21,45</td>
</tr>
<tr>
<td>Polypropylene fibres, 1% Volume</td>
<td>14,64</td>
<td>2,600</td>
<td>38,06</td>
</tr>
</tbody>
</table>

Cost / m³ | 150,30

Cost for the quantity used on the second Prototype panel (264 litres=0,264m³) | 39,68

<table>
<thead>
<tr>
<th>Other panel components</th>
<th>Price (£/m²)</th>
<th>Quantity (panel)</th>
<th>Cost (£/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Galvanized Steel Frame (Source:</td>
<td>-</td>
<td>-</td>
<td>132,50</td>
</tr>
<tr>
<td>2 reinforcement bars (included in the frame cost)</td>
<td>-</td>
<td>-</td>
<td>0,00</td>
</tr>
<tr>
<td>Total cost for the second prototype panel</td>
<td></td>
<td></td>
<td>172,18</td>
</tr>
</tbody>
</table>

Panel area (199 x 133 cm) | 2,6467

Cost / m² for the second prototype panel | 65,05

With a price per m² of 65€, the production of the second prototype panel costs on average 72% of the cost of producing the first prototype panel (90€/m²), making it a prori a more interesting proposal.

It must be noted that, at this stage, it is not possible to assess the cost of the whole assembling system to fully compare these results to existing panel solutions, but having in mind the cost of similar solutions available at an online price generator website for the Portuguese market, it was possible to obtain a market price of 106 €/m² (above the cost per m² estimated for the two prototypes) for a similar sandwich panel solution – a “façade wall sandwich panel formed by GRC (Glass Fibre Reinforced Concrete), 12 cm thick, 3.3 m wide with a maximum surface of 12 m²; smooth finish white, formed by two blades of GRC with selected graded silica sand and fiberglass, and a polystyrene core” (Gerador, 2015). Having in mind that the cost estimate obtained for the two proposed solutions is the one effectively obtained from the manual low scale process used in this experiment – it would be certainly lower in a mass scale production – and that the necessary profit margin is also not considered, it can still be assumed that the final market price to be asked for both solutions could compete with similar concrete sandwich panel solutions already available in Portugal.
4.7 Conclusions

In this work, a concept for two different solutions regarding sandwich panels based on the use of FRCC for the renovation of the existing building stock was presented. The basic concept relies on the testing of two different panel solutions:

- Panel 1, featuring the use of two thin layers of FRM of ultra-high ductility, a core of sustainable and recyclable insulating material, steel connectors and a structural galvanized steel frame;
- Panel 2, consisting on a single layer of Lightweight Fibre Reinforced Concrete (LFRC) formulated using a light concrete mixture with expanded clay aggregates reinforced with polypropylene fibres, with a structural galvanized steel frame and two perforated reinforcement bars for additional structural performance;

During this work two prototypes were built and the experimental program started, having been performed a series of tests to evaluate the structural behaviour and energy efficiency of both solutions to assess which presented the best solution regarding these parameters and also cost-efficiency. In terms of mechanical performance, it can be assumed that for both prototypes the maximum deformation values obtained from the creep test are negligible and do not present any permanent damage for both panels, validating the formulations used for LFRC and FRM as possible materials for the panels when assembled on a façade.

Concerning the thermal performance, it was verified that the solution tested on the first prototype panel (FRM+cork+FRM) is the one that presents the best results, by far exceeding the thermal performance of panel 2 (LFRC), deemed unsatisfying. Having in mind the estimated cost for each solution, still competitive with a similar alternatives already available in the market, it can be concluded that the solution proposed in Panel 1 is the one that presents the best global performance to be used as a second skin in the rehabilitation of underperforming buildings.
5 RELEVANT RESULTS AND FUTURE DEVELOPMENTS

Concerning the mechanical behaviour of FRM, the average flexural strength obtained in the bending tests was about 7 MPa, a relatively high value considering the compressive strength obtained in the corresponding test (36 MPa), with the post-cracking resistance of the tested samples confirming the high ductility of this composite. With regard to LFRC, its flexural behaviour tested in accordance with the RILEM TC 162-TDF recommendations confirmed that up to the ultimate CMOD (3.5 mm) the flexural capacity of all tested samples had increased continuously and an average value for the $f_{cr}$ of about 4 MPa was obtained when the crack width was about 10 times higher the maximum crack width limit allowed for concrete structures, according to the serviceability limit state conditions imposed CEB-FIP Model Code 2010.

As for the compressive behaviour of LFRC, the obtained average value (18.3 MPa) can be considered relatively modest when compared to the values already obtained for other lightweight high resistance concretes (Valente and Cruz, 2004), but satisfactory for the intended purpose (façade panels).

The creep tests performed on both panels attested that a permanent load of 1.2 kN/m² simulating the expected pressure caused by the wind action on a façade caused minor deformations and no permanent damage to both panels, validating these solutions in terms of structural behaviour.

Concerning the expected cost, as both solutions show potential to compete with similar existing alternatives, the ultimate differentiating factor lies in their thermal behaviour, where Panel 1 stands out as the best alternative and Panel 2 fails to present a good performance due to the high thermal conductivity of the lightweight concrete.

To conclude this work, on the Annexes a preliminary proposal for a possible assembling of the panels in two different façades of a case study building is presented, simulating the modulation of the panels according to maximum dimension determined for a mass produced prefabrication system using robotization. More than a definitive layout, the aim was to present the functional and aesthetical potential of this solution, leaving the precise definition of the assembling solution for another stage of development of the module, to be studied in a subsequent phase. Concerning future developments, some additional tasks that could complement the investigation already completed are now presented:

- Optimize the mechanical and rheological behaviour of the proposed Fibre Reinforced Cement Composites having in mind their compatibility with a fully robotized manufacturing process;
P. Sá Costa, Painéis Sandwich Customizados para a Reabilitação do Património Edificado

- Test the viability of incorporating self-cleaning materials (e.g. TiO₂) to improve the panel performance and explore the use of FRP profiles instead of galvanized steel on the panel frames to increase the panel performance;
- Simulate, using BIM, and test the assembling and optimization of the panel layout on a given building and study the integration of robotics and BIM in the production of customized cement composite sandwich panels;
- Perform structural and thermal tests on real scale prototypes assembled on a façade and further study the mechanical performance of the panels and relative susceptibility to humidity and temperature, evaluating their behaviour during "wet / dry" cycles;
6 POSSIBLE ASSEMBLING OF THE PANELS IN A CASE STUDY BUILDING

As previously mentioned, the use of BIM software and parametric design, preferably associating it with a laser scan to carry out the building survey, would be the preferential tool to develop this work focusing on the assembling of the panel solution on a given building. As this study would be in itself a new investigation that cannot be carried out under this work due to time limitations, chapter 5 presents a preliminary concept - using photos of two buildings and a 2D CAD program - to simulate the assembling of the panels on two different façades (A and B), as well as some technical details explaining the constructive solution studied at this point of the investigation.

The building under study is part of a social housing complex – the Bairro de Vilar - built possibly in the 70’s (unavailable data) in the city Porto. It is located in the city centre, not far from the Palácio de Cristal gardens, between the streets Rua Abade de Baçal / Rua de Vilar / Rua Abade de Faria and Rua Arcediago Vanzeler. The two façades, A and B, were merely chosen as two examples out of many others in this housing complex, and while Façade B is facing Northwest instead of Southwest or South – the best orientation concerning the installation of solar panels integrated in the proposed panel layout – it was chosen because it was the one that could be more easily photographed from a focal point with the minimum distortion. In reality, Façade B represents most of the façades at the top of the housing blocks visible in Figure 75.

![Figure 75 – Bairro de Vilar in Porto, with the two façades under study (Source: Google Maps)](image-url)
As the social housing blocks were build decades ago to cater to the urgent housing needs of a low income population and at that time no thermal, constructive or aesthetical concerns were a priority, the constructive and aesthetic solution is poor, causing people today live in clear discomfort. This makes this housing complex a clear example of a building typology destined for this renovation solution, as it lacks the necessary requirements not only to comply with the demanding EU regulations concerning energy efficiency in buildings to be implemented until 2020 but also presents a high number of construction related problems, not to mention the completely uninteresting visual aspect of the buildings now calling for a much needed update. The main pathologies to be found in several buildings from this housing complex show the crucial problems that this intervention would have to address, from thermal bridges and poor interior environment to concrete detachments, poor framing, delamination of materials from the façade, etc., as pictured in the following images 76 and 77.

![Concrete detachment on structural elements of the façade: columns (a) and wall (b)](image)

**Figures 76.** Concrete detachment on structural elements of the façade: columns (a) and wall (b)

![Corrosion on a window sill (a) and extensive material delamination on a façade (b).](image)

**Figure 77.** Corrosion on a window sill (a) and extensive material delamination on a façade (b).
The previous images illustrate the need for a complete retrofit of the whole social housing complex, but in order to illustrate the proposed solution, two façades in two different buildings were chosen, as pictured on Figure 78.

Concerning Façades A and B, a possible layout of the panel solution is now presented based on an analysis carried out using a photographic survey and measurements taken on the site. For both façades the methodology was to modulate the layout of the panels having in mind the maximum dimensions already determined for a mass produced prefabrication system using robotization, trying to not exceed 300x200cm. However, it was considered that for some smaller modules (namely the corner panels), the length of each could surpass the 300 cm as these units still would be easily manipulated. A proposal for the layout for Façade A is presented on Figure 79 and the final aspect of the solution featuring a composition with coloured panels on Figure 80.
Figure 79. Proposed study for the modulation of façade A (dimensions in cm)

Figure 80. Proposed layout for façade A with a composition featuring coloured panels (dimensions in cm) and highlighting an area to be further detailed (Detail 1)
Through this simulation it is possible to visualize how the retrofit of the building with the proposed prefabricated solution would benefit its visual aspect, apart from the intended improvement in energy efficiency and the correction of constructive pathologies, radically improving the living standards of its inhabitants. While façade A represents the main elevation of the building, Façade B, located at the top of the housing blocks, is an example of a closed wall punctuated by small windows presenting a good opportunity to integrate solar modules in the panel layout, as seen on Figures 81 and 82.

**Figure 81.** Proposed study for the modulation of façade B (dimensions in cm)
Figure 82. Proposed layout for façade B with a composition featuring coloured panels (dimensions in cm) and highlighting an area to be further detailed (Detail 3)

Preliminary concept for the assembling of the panels on a façade

In the proposed assembling of the panels on a façade – presented here in a preliminary concept in a detailed area of Façade A to be further studied and perfected in future works - the panels are supported by horizontal and vertical galvanized steel profiles which, in turn, are also connected to the façade of the building, ultimately supporting the weight of the whole system. However, the development of the design during the course of this work determined that using the same support profile for vertical and horizontal situations, as well as around the windows, would not be feasible as these elements need to
address different requirements. Figure 83 represents part of the façade A (Detail 1) to illustrate the placement of the three different solutions found for the panel supporting profiles (S1a, S1b and S2).

**Figure 83.** Detail 1 – Distribution of the panel connectors S1a, S1b and S2 on façade A highlighting an area to be further detailed around the window (dimensions in cm).
For this reason, while the vertical (S1a) and horizontal profiles (S1b) are similar in dimensions and section and guarantee panel-to-panel and panel-to-façade connections, a different profile had to be created around the windows (S2) to assure the panel-to-window connection.

Figure 84 shows in more detail an area around the window (Detail 2).

![Figure 84. Area around a window - Detail 2 (dimensions in cm)](image)

Regarding the vertical and horizontal standard profiles (S1a and S1b), the main difference between the two is that while the first can be directly attached to the wall as the panels can slide down between them, the horizontal profiles can only be put in place after the panel under the profile is in its final position. As panels will be juxtaposed from bottom to top, attaching previously all the S1b profiles to the existing wall would not allow the system to be assembled on the façade. For this reason, after each panel is put in place, these horizontal profiles can then be inserted in a plate that is previously attached to the wall in the right position, being ready to support the next panel to be juxtaposed.

Figures 85 and 86 present the horizontal and vertical sections (H1/H2 and V1/V2) featuring the initial situation (without panels) and the proposed solution.
**Figure 85.** Detail 2: Horizontal Sections H1 and H2 with detail PH1, PH2 and PH3 (dim. in cm)

**Figure 86.** Detail 2: Vertical Sections V1 and V2 with detail PV1, PV2 and PV3 (dimensions in cm)
Figures 87, 88, 89 and 90 illustrate the proposed solution for the profiles S1a, S1b and S2, as well as vertical (PV1, PV2 and PV3) and horizontal (PH1, PH2 and PH3) details of the panels on the façade.

**Figure 87.** Details of the vertical profile S1a, with connections panel-to-panel and panel-to-façade; Detail PH1 (dimensions in mm)
Figure 88. Details of the vertical profile S1b, with connections panel-to-panel and panel-to-façade;
Detail PV1 (dimensions in mm)
Figure 89. Details of the window profile S2; PH2/PH3 horizontal section (dimensions in mm)
S1 a/b and S2 galvanized steel profiles will not only insure all the necessary panel-panel, panel-façade and panel-window connections, but also play a decisive role in the structural stability of the sandwich panel system. All the tubular profiles to be inserted between the panels will be thermally insulated in
the cavity to reduce as much as possible the thermal bridging on the inner side of the panel that could result in energy losses for the building. As these profiles are not continuous, it will be also necessary to insulate the space between the panel supports with pre-cut agglomerate 55x55mm cork profiles to be inserted between the panel supports. The whole new façade system will be sealed with a bead of mastic filling the gap between panels to guarantee that the façade is airtight and waterproof, avoiding any water leaks to the interior air chamber located between the existing wall and the panel.

The same constructive solution is to be applied to façade B, as it presents the same panel-to-panel, panel-to-façade and panel-to-window situations. Figure 91 presents a detail (area in detail 3, visible on Figure 82) to illustrate how a solar panel could be integrated into a prefabricated panel.

![Diagram](image)

**Figure 91.** Study for the integration of solar panels in the module - Detail 3 (dimensions in cm)

Considering that each solar panel has a dimension of 206x113x9 cm this study proposes to integrate two solar panels in one large prefabricated module (H1b, with 250x265x10 cm). This would imply that the prefabricated module would have to be tailor-made to accommodate the two modules, something that can be attained using a robotized production line, as previously explained. Figures 92
and 93 feature the horizontal (PH4/PH5) and vertical (PV4/PV5) details illustrating the insertion of the solar panels in the prefabricated module.

Figure 92. PH4 and PH5 horizontal details featuring the insertion of the solar panel in the module (dimensions in mm)
Finally, figure 94 illustrates a horizontal detail (PH6) with a possible solution for the panel connections around the corner of the building. In this situation, as the vertical support structures (profiles S1a) need to be attached to the existing façade and the panel is in contact with each vertical support only on the frame, it was necessary to create a L-shaped element (Corner A2 – 22x265 cm) that could overcome the 22 cm from the outer face of the panel to the vertical support, closing the new façade around the corners of the building.
Development of sandwich panels of customized functionalities for the rehabilitation of the built patrimony

Figure 94. PH6 detail featuring a possible solution for the connection of the corner panels
(dimensions in mm)

Final remarks

It must be noted that the solutions proposed in this work for the assembling of the panels on a building are merely conceptual and still present some challenges to be overcome, such as studying another kind of the panel connection at the corners, as visually these panels should be large elements avoiding the corner pieces, and redesigning an alternative horizontal profile to simplify the proposed solution (S1b) and speed up the assembling process on site.

Although the proposed assembling solution at this stage of the investigation is not the ideal, the overall layout studied for the assembling of the panels aims at demonstrating that the panel system is feasible, leaving the perfecting of the solution for future works.

The development of this concept in a subsequent phase using BIM software and all the available mechanical and thermal simulating software tools will most certainly revise and adjust many details presented in this proposal, taking it to the next level.
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