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SPECIAL ISSUE – ICAE 2018

THE INTERNATIONAL CONGRESS ON ARCHITECTURAL ENVELOPES

EDITORS IN CHIEF ULRICH KNAACK AND TILLMANN KLEIN
GUEST EDITORS JULEN ASTUDILLLO LARRAZ AND JOSE ANTONIO CHICA
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SPECIAL ISSUE

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JFDE Journal of Facade Design and Engineering

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JFDE Special ICAE2018 – Envelope 4.0

Dear Scientists, Engineers, and Designers,

With this new edition we continue the collaboration with our funding member Tecnalia and the International Congress on Architectural Envelopes (www.icae2018.eu), which they organise every 3 years in San Sebastian (Basque Country, Spain).

The eleven articles found in this new issue were carefully selected from 50 abstracts that will be presented during the scientific section of the congress. The final selected papers were subjected to the regular double-blind review process of the journal.

With this selection of papers, we want to give an overview of the traditional technologies that are normally discussed in the context of façades, while also making some mention of new technologies, which, some time ago, existed only in the realm of the laboratory but which have begun to appear in real buildings and construction in recent years. In fact, the main topic of the conference this year is the Envelope 4.0, and consequently the aim of the magazine. Under this title, the aim is to unify two elements: the architectural envelope, due to it being the main reason for holding the conference, and the term "Industry 4.0" as a representation of the need to improve the manufacturing, assembly, distribution, and installation processes of many of the products included in today's envelopes in order to be competitive in the market.

We hope that with this selection we can provide you with new ideas and possibilities.

An interesting set of approaches to new technologies is demonstrated (using robotics systems to install façades), new materials for the envelope (biocomposites, smart and multifunctional materials, and new types of membranes), use of BIM from design to manufacturing, 3D printed façades for thermal regulation, solar heating and cooling technologies in the envelope, characterisation of the thermal performance in roof solutions, and numerical and experimental performance assessment of structural thermal bridges.

In conclusion, we want to thank our special editors, Julen Astudillo and Jose Antonio Chica from Tecnalia, for their effort in making this partnership happen.

The editors of this special edition,

Julen Astudillo
Jose Antonio Chica
Ulrich Knaack
Tillmann Klein

Development of a Modular End Effector for the installation of Curtain Walls with cable-robots

Meysam Taghavi[1], Homero Heredia[2], Kepa Iturralde[1], Håvard Halvorsen[2], Thomas Bock[1]

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2 nLink AS, Norway

Abstract
The installation of façade enclosures is a manual, dangerous, and time-consuming construction task. However, thanks to the capability of automated systems, the application of automation in construction is increasing, and therefore, manual work and risky situations can be avoided. Despite this, only a few robotic systems are capable of spanning such a vast work space, i.e. the façade of a building. Among these systems is the cable driven parallel robot (CDPR). Furthermore, the CDPR could carry heavy loads such as unitised curtain wall modules (CWM). Nevertheless, the tools and devices required for installing the CWM need to be innovated. Firstly, in order to cover that research gap, the current manual procedure was analysed in detail. After that, the development team evaluated several options for performing the tasks. Finally, an optimal solution was chosen: the so-called modular end-effector (MEE). The MEE comprises several tools in order to achieve various tasks. Mainly, these tasks are: drilling the concrete slab, bracket installation, and CWM handling and positioning. In addition to the aforementioned tasks, the MEE should accurately fix all elements with a desired tolerance less than 1 mm. Meanwhile, the MEE should compensate for the perturbation movement due to external forces such as wind that affect the system. As part of the study, a detailed workflow for the automated installation of CWMs was elaborated. The drilling step of the work-flow was tested and the result is presented in this paper.

Keywords
Modular end effector, Cable robot, Construction robotics

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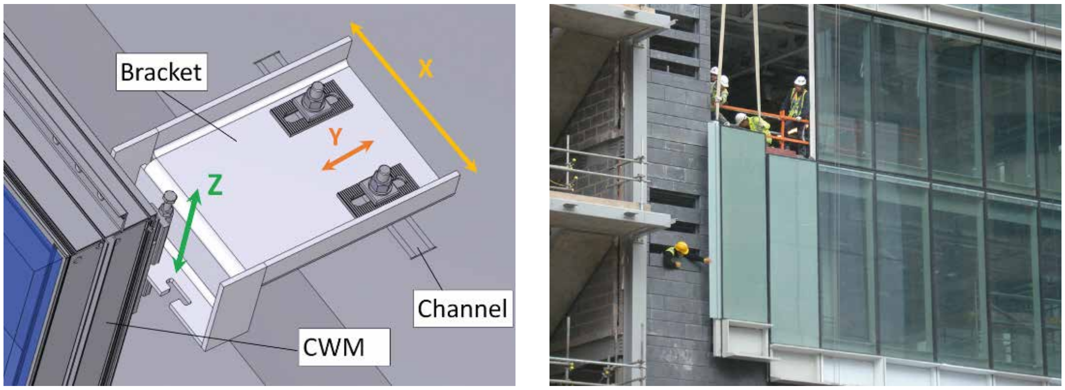

FIG. 1 Left: Bracket and CWM level adjustment. Two possible directions of bracket adjustment (X & Y) and one direction of CWM adjustment (Z). Right: Conventional installation of a CWM, possible dangers for labourers (e.g. falling) and the number of workers involved in the installation process. (Images by FOCCHI SPA-2017)

1 INTRODUCTION

The existing conventional CWM installation is a manual procedure that is based on two major steps: bracket fixation and installation of the CWM. Installing a CWM on a building requires the prior installation of an interface, or bracket. As of now, these brackets get anchored to the edge of the concrete slabs, thanks to cast-in channels. Apart from hosting and holding the CWM load, these elements are designed to cope with deviations between theoretical and actual construction geometries. The groove in these channels, in combination with the slotted cuts in the bracket plate, allow the manual adjustment of the location and orientation of the bracket itself. See Fig. 1 (Left).

However, when considering their use by automated systems, it not only becomes cumbersome, but redundant, as automated systems can eliminate or reduce the variation between actual and theoretical states in previous CWM installation stages. This can be achieved by using another correct, but less popular, method for CWM interface installation: slab drilling and setting of expansion anchors. This method allows for the preparation of the structure and work in the correct location right before the installation of a CWM without the need for further adjustments. Aside from the ease of automation, a relevant advantage of drilling (over cast-in channels) is the reduction of complexity during the design, planning, and concrete casting of slabs. Furthermore, using expansion anchors allows the installation of CWM on new construction sites as well as on existing ones that require renovation work.

Once all brackets are installed, and adjusted in their locations with a tolerance of 1 mm, the CWMs are transported to the desired building level with aid of a crane or elevator and, finally, are manually located, mounted, and fixed in the planned position. Fig. 1 (right) shows the CWM being lifted up using a crane, and several workers, who are working in a dangerous situation. The amount of labour work, danger, and required time is considerable. Workers could use the adjustment screw to level the CWM in the Z-direction (Fig. 1 (Left)). Automating the CWM lift and installation will increase the safety of labour. In foresight, the higher installation speed could be reached, while maintaining the required accuracy.

1.1 PREVIOUS ROBOTIC EXPERIENCES FOR INSTALLING ELEMENTS AND MODULES IN CONSTRUCTION

The automation level of different industries has been increased notably in the last decades. Although the construction sector has been demanding the use of automation and robotics in recent times (Bock T. , 2015), the presence of proper automatic systems is rare (Hastak, 1998) (Vähä, Heikkil, Kilpelinen, Jrviluoma, & Gambao, 2013). As an example of robotics working in the construction industry, a prototype of a moving platform hosting a modular end effector for an overhead (ceiling) nailing system was developed by the company Lindner and the Technical University of Munich (Bock & Linner, 2016). Another commercial robot for drilling the ceiling was produced by the company nLink in Norway (nLink, 2018). The corresponding required features of the robot, such as flexibility, heavy duty, reliability, and big workspace should be deeply considered when developing automation systems in the construction sector (Moreira, et al., 2015). For instance, the installation of the automatic Curtain Wall Module (CWM) requires a large work space (the façade of the building), heavy payload (The CWM weight is about 300 kg), and it happens in an outdoor environment. Several automatic systems for CWM installation have already been proposed. For instance, the patented technology from Brunkeberg Systems AB (USA Patent No. US8695308, 2014) is in use. It brings the railing system into action just for their dedicated CWM. Alternatively, a mobile robot that installs the CWM from inside the building is used by Yu et al. (Yu, Lee, Han, Lee, & Lee, 2007). This method automates only the CWM installation and not the bracket installation. A telescopic, tele-operated hydraulic system was designed and tested to nail the sandwich panels from outside the building by (Cinkelj, Kamnik, Cepon, Mihelj, & Munih, 2010). The system is also designed to work only with specialised panels. As previously mentioned, these systems have their own limitations. The CDPR provides the big workspace and high payloads. This makes the CDPR a proper solution for construction automation and especially for CWM installation. Therefore, within the call ICT-25-2016-2017 (EU, 2017) from the European Union, the HEPHAESTUS project (HEPHAESTUS, 2018) was founded. The project, as well as the subject of this paper, focuses on CWM installation using Cable Driven Parallel Robot (CDPR).

1.2 SUB-SYSTEMS AND TASKS FOR CWM INSTALLATION

To automate the CWM installation, the system in the HEPHAESTUS project is divided into three subsystems: 1) CDPR, 2) MEE, and 3) controlling system. This paper addresses the challenges of the MEE design in detail. The requirements for the MEE were carefully analysed and considered as:

- Drilling the concrete
- Installing the bracket (the interface between the CWM and building)
- Positioning and mounting the CWM on the installed brackets

Moreover, the MEE should be able to work outdoors and provide required accuracy for the system. It means that the system should be stable in case of environmental loads and vibration caused by, for example, wind, and that the bracket should be installed with a tolerance of 1 mm.

2 DEVELOPMENT OF THE MODULAR END EFFECTOR

The end-effectors are tools that are attached to the robotic manipulator, and interact with the environment. In the case of the HEPHAESTUS project, this end-effector operates within the platform of the cable robot and it is modular, meaning it contains several devices including the end-effectors. In this project the main task is to install a Curtain Wall Module (CWM). Within the task, there are four main requirements. First, the MEE should perform tasks such as drilling, fixing a bracket and handling the CWM. Second, the MEE should fulfil the tasks accurately. The issue is that the cable robot does not provide the required accuracy. Therefore, the MEE must re-adjust to the location. A secondary robotic device will be necessary for the completion of this subtask. The third requirement is that the MEE needs to be stable while performing these tasks and the outdoor hazards, including their forces, need to be neutralised. A fourth and final requirement is that the CWM module needs to be lifted and fixed into its correct position.

For each of the requirements of the MEE, several possible options were considered. These options were analysed carefully and evaluated. In the selection method, careful considerations occurred for the following indicators:

- The preferred option should fulfil the requirements of the system completely with smallest risk of failure.
- It should be safe.
- Its design and manufacturing should be possible within the available resources of the HEPHAESTUS project.

Once the analysis was carried out, an optimal solution for each of the requirements was selected. The evaluation process and the selected solutions are explained in the next sub-chapters.

2.1 SECONDARY ROBOTIC SYSTEM

The cable robot is expected to have an accuracy of about 40 mm, thus a secondary robotic system is required to achieve the 1 mm positioning need for the different tasks, from the structural preparation of the building to the installation of necessary mounting hardware. That is, the cable robot will achieve a 'macro' positioning throughout the building façade plane, and the secondary robotic system will do the 'micro' positioning of tools and components at the required locations. Once the coordinates for the CWM and the anchors' design locations are known, it is possible to locate the cable robot frame in a nearby position, where the anchor points are accessible to the tooltip of the robotic arm.

A thorough consideration of options for this secondary system included: Cartesian system, Pyramid based movement, Hexapod, and finally, a serial arm robot. To evaluate these options, sub-tasks and useful end-effector tools were analysed for completing the tasks. For example, a drill with a rotary hammer was considered. Given the tasks, tool availability, and project resources, it was defined that the most appropriate option for a secondary system is a 10 kg payload serial robotic arm. This system will then manipulate off-the-shelf tools that are adapted and mounted at the robot head via pneumatic or electric tool changers, which allow for fast and automated swapping throughout the CWM installation process. Universal Robots UR-10 is tentatively the system to be integrated.

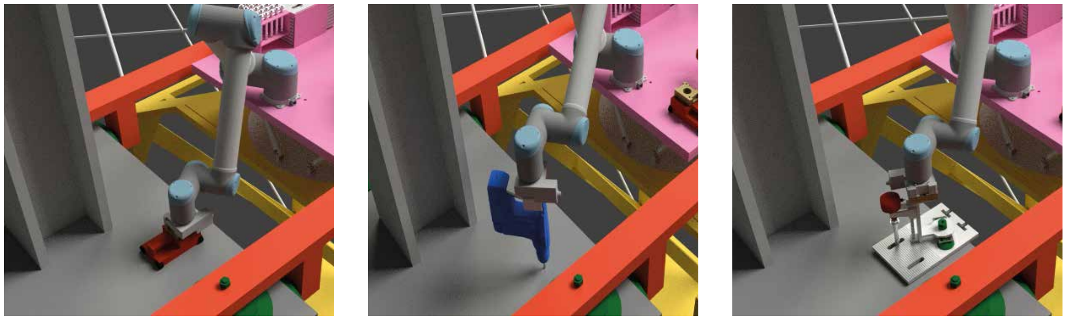

FIG. 2 Robotised Bracket installation process. Left: Rebar scanning, rebar scanner in red colour is handled by serial arm robot and scan a specific area to check if there exist a rebar or not. Centre: Drilling, the driller in blue colour is handled by serial arm robot to do the drilling. Right: Bracket adjustment and installation, a gripping tool is handled by serial arm robot.

2.2 STABILISING THE MEE

It is considered that the HEPHAESTUS robot works under wind conditions with a maximum speed of 15 m/s; this point initially brings the stiffness characteristic of the cable robot into consideration. The stiffness of the cable robot could be translated as the relation of the applied external force and the resulting movement. It is a parameter that can be considered during design of the cable robot. However, there are some limitations, since higher stiffness needs higher cable tension, while the other factors remain constant. For higher tension in the cables, there are cost and technical constraints. The stiffness of the cable robot influences the accuracy of the performance of the MEE, since external loads imposed on the cable robot and its platform (e.g. wind) will cause the cable robot to move, which consequently means the movement of the MEE. The MEE is the final performer of the task on the building and it should be stable during the performance. A driller is an example of a final tool performing the task on the building, which should not move due to external loads while drilling. For filling the gap between the stability of MEE and the stiffness of the cable robot, the stabilising system was designed in this project. In the system, the MEE will grip the building in order to be stabilised during the performance of the task.

2.3 PERFORMING TASKS ON THE BUILDING

In order to mount CWMs, the first requirement is to install the CWM mounting bracket on the edge of the slabs at each level of the building. The sequence for this interface installation can be defined by three main phases: Structural Preparation (steps 1 and 2), Bracket Installation (steps 3-5), and Quality Assurance (step 6), which consists of 6 steps in total:

1. Rebar Scanning: To avoid structural damage or potential drill bit jamming, it is imperative to scan the slab surface to detect embedded reinforcement bars. This task will be performed by adapting and manipulating an off-the-shelf manual rebar scanner. Fig. 2 (left) shows the concept of the automated method of rebar scanning in this project.

2. Drilling: Following the identification of optimal drilling locations, the actual drilling takes place using a rotary hammer tool. This operation needs to be followed by, or include, an integrated dust management system to leave the hole ready for further steps. Fig. 2 (centre) shows the concept of automated drilling in this project.

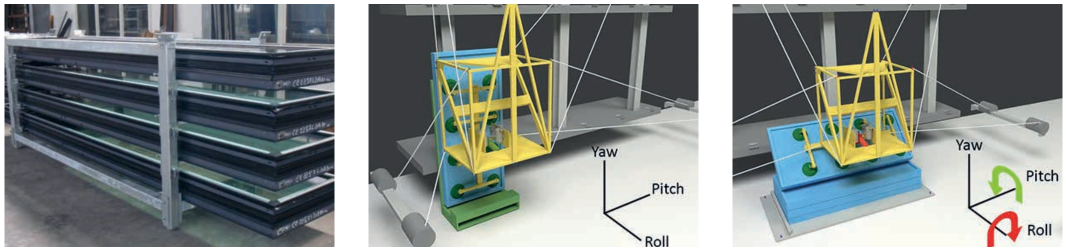

FIG. 3 CWM handling. Left: CWM crates [Picture rights: courtesy of FOCCHI SPA]. Centre: Picking up the CWM vertically with no rotation, green is the reference bed and blue is the curtain wall module. Yellow is the cable robot frame. Right: Picking up the CWM horizontally, two degree of rotation in roll and pitch direction is implemented.

3. Expansion Anchor setting: Setting an anchor requires a gripping mechanism to manipulate the anchor from a magazine onto the drilled hole. Once the location is locked, a hammering device (e.g. rotary hammer with hammering-only function) inserts the element down into the hole. This operation is done for two anchors: the first anchor with the bracket plate (see next step), and the second anchor alone to secure bracket plate rotation about the Z-axis.

4. Bracket plate setting: The bracket plate, which will create the interface between the building and the CWM, will be gripped, manipulated, and positioned on the slab at the correct location. Here, it will be locked by the 1st installed expansion anchor (from previous step). Fig. 2 (right) shows the robotic procedure of the bracket adjustment and installation

5. Nut tightening: To fully secure the interface hardware, the nuts from both previous anchors must be tightened to the right torque. For this operation an impact driver is used.

6. Installation quality: Prior to installing the CWM using the installed bracket, the correct installation of components needs to be verified. For this a 3D camera is utilised to remotely verify all components are in place and ready to take the panel load.

The six steps above describe the installation of bracket plates and required hardware. The combination of a robotic arm manipulator, tool changer, and off-the-shelf components conveniently allows the change or addition of tools. This feature benefits the utilisation of the same configuration for other applications such as façade washing or painting. e.g. mounting a spray paint nozzle onto the robot arm and moving it across the building exterior walls for painting complex surfaces.

2.4 HANDLING THE CWM

The transportation and arrival of the CWM is achieved using racks, with which the CWMs are transported horizontally to the construction site, as shown in Fig. 3 (left). For the CDPR, the necessary manoeuvres could be minimised if the CWMs were transported vertically (Fig. 3 (centre)), but that would decrease the optimisation of the transportation of the modules. At this point, it was decided that the CDPR needs to pick up the CWMs from the horizontally stacked position, and must then mount them in a vertical position parallel to the building façade. For solving this issue, a two-directional rotary handling system with suction cups has been preconceived as a preliminary solution (Fig. 3 (right)).

FIG. 4 Drilling test. Left: Serial arm robot UR10 mounted hosting a driller with integrated dust suctioning system. Centre: Drilling with a 16 mm drill bit into sample concrete. Right: Showing the quality of a drilled hole.

2.5 INITIAL PROOF OF CONCEPT

In order to initiate the validation of the developed MEE, the secondary robotic system, the process, and the tools to be used, an initial test experiment was set up. A rotary hammer with a 16 mm diameter drill-bit installed was mounted on the serial arm UR-10 and driven into a concrete box that simulated the structure found in the slabs of a building. In parallel, the tool was equipped with a vacuum cleaner hose to remove dust during the drilling process. The test was successful and the resulting hole proved to be ready and useful for the installation of an expansion anchor, by following the procedure in the workflow defined in Chapter 2.3 of this paper. Fig. 4 shows the process and result.

3 CONCLUSION

Current practices for the installation of curtain wall modules imply several adversities, including the safety of workers. In order to achieve a more automated process, ongoing research based on an adaptation of a cable driven parallel robot will focus on this topic. This paper describes the elaboration process of a novel robotic modular end-effector or tool system that, in the near future, should perform the tasks for installing a curtain wall. First, several options were gathered and evaluated. Then a final solution was selected based on achievability criteria. The chosen modular end-effector integrates and makes use of market-ready solutions that can sufficiently perform the set of tasks involved in the installation of CWM. This development approach enabled the accessibility to a high feasibility-rate scenario, where it is possible to validate the concept in small and progressive steps without the need to develop completely new concepts and technology. Validating the system solution as a whole will enable further refinement of the solution itself. It will also enable continual abundance of automation solutions to the construction industry, which can address its most recurrent issues, such as inefficiency and safety.

For progressive movement towards the full construction and use of the CWM installation system, the different sub-tasks and tools will be tested individually in a similar way to the experiment described in Chapter 2.5. Some of these experiments will comprise mounting tools on the serial arm UR-10 to prove the effectiveness of the workflow defined in Chapter 2.3. In order to refine the design, and validate the function of the bigger MEE elements (e.g. building gripping damping system), digital simulations and physical experiments will follow. Finally, after designing and validating the MEE, it will be manufactured and the system will be tested on the real building together with cable robot.

Acknowledgements

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On the development of a façade-integrated solar water storage

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Abstract

The integration of active solar thermal technologies into building envelopes has recently been receiving greater attention, and has been promoted within international projects such as IEA Task 56 and Cost Action 1403. Although the façade integration of solar thermal collectors is a topic that has been debated at length, little attention has been paid to the building integration of solar water storage.

The scope of this paper is to highlight the main barriers that are experienced in the development of façade-integrated solar water storage. This activity is a part of the SunRise project that aims to develop a new unitised curtain wall element for tertiary office buildings. The façade element integrates a complete solar thermal system consisting of a solar collector, hot water storage, a radiant panel, and all the required operation components. A mock-up of the solar façade is manufactured to identify practical constructional issues. The thermal behaviour of the tank is analysed through FEM simulations and laboratory tests.

Keywords

solar active envelope systems, building integration, product development, heat storage

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1 INTRODUCTION

In recent years, the attention given to the building-integration of active solar thermal systems (BISTs) has risen. The market penetration of BISTs, however, is still low, and a greater number of market-available solutions is desired to improve the acceptability of solar envelopes and increase the amount of building loads covered by solar energy. International efforts like IEA SHC Task 56 (IEA, 2016) and Cost Action 1403 (Cost Action TU, 2013) are investigating this topic from market, technological, and energy perspectives with the aim of studying and promoting solar envelope systems.

Scientific literature highlights that BISTs suffer from technological and economical barriers (IEA, 2009) such as high investment costs and mistakes during installation that can be effectively tackled with the development of turnkey solutions and the application of prefabrication techniques (Soppelsa et al., 2016). From this perspective, R&D projects together with industry become fundamental.

As a concrete example for overcoming such limitations, the integration of a complete solar thermal system in a curtain wall element is studied within the framework of the SunRise project. This R&D collaboration with a façade manufacturer aims to design a new turnkey plug-and-play façade element that is suitable for new and retrofitted tertiary buildings. Whenever solar radiation is considered as a means to cover thermal building loads, a a Thermal Energy Storage (TES) is required for making collected heat available at times when the solar resource is not present. The heat harvested by solar façades is typically stored in the building's thermal mass or in water-based TESs.

Low-tech passive design strategies recommend exposing the building's thermal mass in order to collect solar radiation during the day and slowly release the collected heat overnight. As in the case of Trombe walls (Givoni, 1998), air-based solar concepts can be assisted by fans and dampers or can be operated on natural convection principles. The thermal capacity of building materials can be further enhanced with phase change materials (PCM) incorporated in the wall structure or mixed with the construction materials (De Gracia & Cabeza, 2015; Kolaitis et al., 2015). The thermal mass of the envelope is also exploited by Massive Solar Thermal Collectors (MSTCs) (D'Antoni & Saro, 2012), which are capacitive building envelope structures capable of removing the absorbed heat through an embedded pipe loop. MSTCs can serve water-based active solar systems for a direct or indirect use of collected heat in covering building loads.

In existing façade-integrated solar thermal systems, the collected heat can be stored in conventional water TESs that are detached from the building façade (Risholt et al., 2015; WAF, 2018). Alternatively, solar collectors and water thermal storage can be combined into a single unit, so that neither external storage nor connection pipes are needed. This energy concept has a long tradition in hot climates but continuous research (Singh, Lazarus, & Souliotis, 2016) has resulted in improved designs, such as the installation of water storage as a separate layer behind the solar collector (Sopian, Syahri, Abdullah, Othman, & Yatim, 2004), the combination of water and PCM storage (Reddy, 2007) or the merging of water storage and absorber plate in a unique tubular structure (Khalifa & Jabbar, 2010).

From this literature review, it emerges that only a limited number of concepts and solutions of building-integrated solar water storage have been developed. As a contribution for future BIST concepts, this paper aims to share the experience acquired in the development of a building-integrated water TES, considering both technological and thermal aspects. In the framework of the SunRise project, a mock-up of the solar façade that integrates such compact water TES is manufactured to identify practical constructional issues. In addition, the thermal behaviour of the TES is analysed through FEM simulations and performance tests carried out in the laboratory facilities at the Institute for Renewable Energy of Eurac Research.

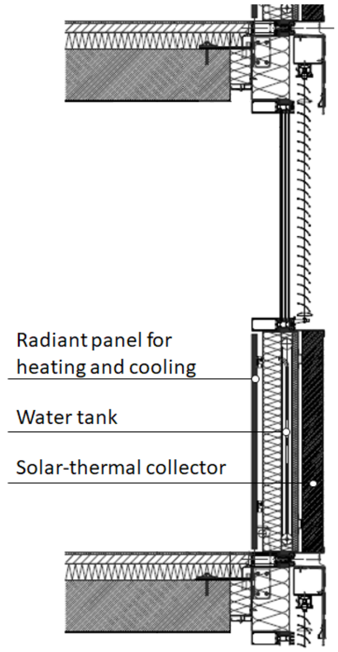

FIG. 1 Building-integration of the solar thermal system into the façade.

2 FAÇADE CONCEPT

2.1 CONCEPT OVERVIEW

The energy concept consists of a solar thermal system integrated in the opaque part of a unitised curtain wall element (Fig. 1). Such a system is composed of a flat-plate solar thermal collector installed on the external side of the façade element, a compact water TES incorporated in the parapet, and a radiant panel fixed to the inside as the finishing layer (Fig. 2). The solar system includes a hydraulic module containing the required hydronic components (i.e. circulating pump, tempering valves, expansion vessel, safety valves, fill and drain ports, deaerator, manometer, and thermometer) and an electronic board. From a construction perspective, these components are embedded within two metal semi-shells, which, once joined, guarantee air and water tightness of the spandrel panel. The solar thermal collector is hung on the external metal shell and a 3 cm air gap is left in between to facilitate installation operations.

The façade-integrated system can harvest solar radiation through the solar collector, store the collected heat in the water TES and either deliver it to the thermal zone or to a centralised DHW tank. Each façade element is equipped with two water circuits that are independent and hydraulically separated: the solar loop (SC) transfers the heat collected by the solar collector to the façade-integrated tank or to a centralised DHW tank, whereas the heating and cooling loop (HC) delivers heating/cooling power to the occupied space through the radiant panel. The heating water can be either drawn from the façade-integrated water storage or supplied by an external back-up system (i.e. gas boiler), depending on the availability of stored solar heat. The cooling water is instead produced at central system level with an auxiliary chiller and directed to the radiant panel, bypassing the TES.

FIG. 2 View from inside (left) and outside (right) of façade prototype taken during the tests in the climatic chamber.

Obviously, the development of a robust control strategy is of key importance in the effective management of heat fluxes from/to the façade, the achievement of high final energy savings, and to avoid stagnation in the solar loop. The control developed for the SunRise façade is based on an irradiance detector and a number of temperature sensors placed in the water loops and in the TES.

2.2 DRIVERS FOR THE FAÇADE CONCEPT

The development of new energy concepts should consider not only energy performance targets but all issues connected to the design, manufacture, installation, and operation of the system.
From the energy perspective, the SunRise façade concept aims:

- to cover part of heating and DHW loads through solar energy available on the external façade;
- to maximise the local exploitation of solar energy in order to reduce parasitic heat losses in distribution pipework (quantified in 20% of the collected heat (DGS, 2005));
- to share the excess collected heat at building level.

The key technological driver is the prefabrication of the hydronic circuit in order to (1) reduce construction and installation costs and (2) achieve higher quality workmanship. Prefabrication principles such as modularity and standardisation of components are prerequisites in this activity.

The façade-integration of a solar thermal system influences the layout of generation, transmission, and emission systems. The manufacturing of a façade element integrating a heating/cooling terminal allows for to savings in material costs and costs incurred during installation phases.
At building level, the installation of a decentralised TES in the building façade allows for resizing or elimination of the volume of the centralised tank and, therefore, the reduction of technical spaces. Furthermore, the thermal insulation required in the façade element could be replaced in part by the rear-side insulation of the solar collector, which could be also exploited by the tank.

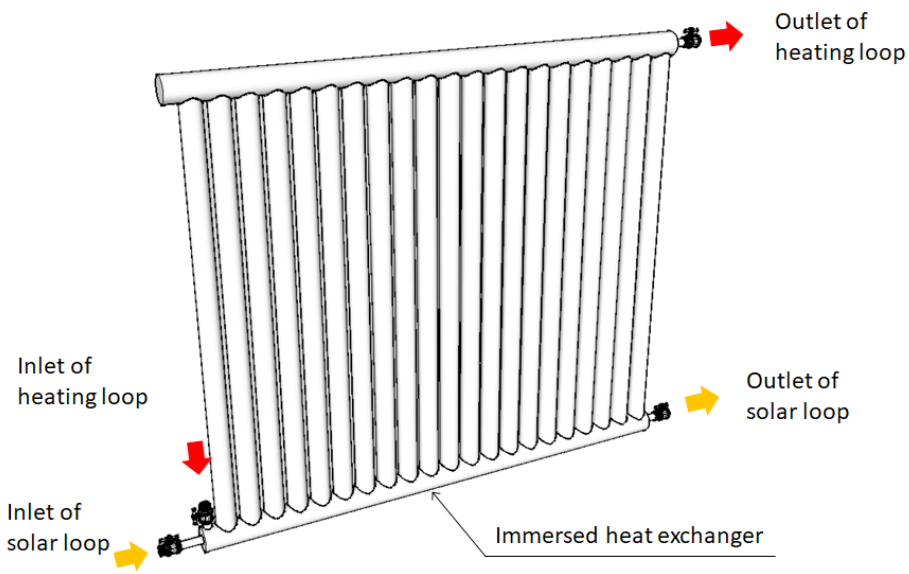

FIG. 3 Design of the TES integrated in the building façade.

2.3 SUNRISE SOLAR WATER STORAGE

The design of the TES installed in the SunRise façade is developed with consideration given to the following technological requirements:

- It has to include two independent and hydraulically separated loops.
- It must handle the thermal and mechanical stress induced by the solar system operation.
- It cannot cause detrimental conditions for the façade element.
- It has to have a minimum weight and thickness.

The SunRise storage is custom-made and consists of a series of steel cylinders connected by two headers at both ends, as shown in Fig. 3. The overall dimensions of the tank are about 1.2 m high, 1.3 m wide and 0.06 m thick for a total water capacity of about 46 litres.

An immersed heat exchanger is installed in the lower header to allow the heat transfer between SC loop and water storage. The connection with the HC loop is realised via two openings in the upper header (water outlet) and lower header (water inlet). The thermal insulation of the tank consists of a 10cm thick mineral wool layer on the inside and a 4cm thick layer on the outside.

3 CHARACTERISATION OF THE FAÇADE-INTEGRATED WATER STORAGE

The experiences gained during the product development are reported here. With respect to the façade-integration of a water TES, the analysis has a two-fold perspective: a focus on the individual component (TES) and a focus on the façade.

3.1 COMPONENT LEVEL

3.1.1 Geometry

The integration of any new component into a façade element must deal with dimensional restrictions. The overall dimensions of the tank are limited to the height of the spandrel panel, the width of the façade element, and the maximum acceptable thickness. Moreover, the building-integration of a water storage element suggests a parallelepipedal tank shape conceived as a slim flat layer inserted in the spandrel panel's multi-layer structure. The common cylindrical shape of water storage elements is hardly an option in this case because of its excessive thickness.

Another limit to the tank geometry is posed by the mechanical stress induced by the water operating pressure (in the range of 4-6 bars), which can cause structural deformations in the tank's walls and decrease its lifespan. In the SunRise façade, the tank shape is designed as the junction of more vertical cylinders so that the pressure distribution on the tank walls is homogeneous. The resistance to mechanical stress is enhanced at the price of a lower water capacity and compactness of the TES.

The energy efficiency of water storages is affected by the compactness of the tank expressed with the surface-to-volume ratio or S/V. Given a certain tank capacity, larger external surfaces mean indeed larger dispersing areas and higher heat losses. Table 1 compares the S/V ration for different shapes of TES with equal water volume. The external surface area of the SunRise TES design is about 2 and 6 times larger than for full parallelepipedal and cylindrical water storages, respectively.

The heat capacity of the TES is the result of a trade-off between tank size and the target amount of solar coverage of building loads. Insufficient heat capacity can easily worsen the performance of the whole energy system as higher heat losses through the tank walls and lower solar collector efficiencies can be expected. In the case of residential solar combi-systems, the typical design ration between TES volume and solar field area is between 40-100 L/m^2, whereas here it is limited to 18 L/m^2. In fact, geometrical constraints limit the overall dimensions of the TES and its shape further reduces the water volume to only 52% of the occupied gross volume.

Although these calculations testify a sub-optimal behaviour of the SunRise TES in terms of both heat retention and thermal capacity, thermal performance requirements were revealed to be of secondary importance with respect to geometry limitations.

TES GEOMETRY	VOLUME [L]	EXTERNAL SURFACE [m^2]	COMPACTNESS S/V [1/m]
SunRise TES	46	4.15	90
Parallelepiped		2.22	48
Cylinder		0.76	16

TABLE 1 Comparison of compactness ratio between different TES geometries.

3.1.2 Thermal insulation

Proper thermal insulation is essential for any water storage in order to reduce the heat losses through the mantle and improve the storage efficiency. When the TES is integrated in the façade, the insulating material must not only guarantee satisfying thermal performances, but also respect technological specifications such as fire resistance class and permeability to water vapour.
As already pointed out, the insulation layer installed in the spandrel panel of traditional façade elements or on the back of rear-insulated solar thermal collectors can synergistically reduce the thickness of the tank insulation layer.

Different insulation thicknesses and materials (mineral wool and VIP vacuum insulation panel) are considered during the design process of the SunRise TES. In spite of the excellent thermal behaviour of VIP, its use in the SunRise mock-up is discarded because of its susceptibility to mechanical damages, the complexity of application, and the high cost of the materials used in the panel's core. Instead, the chosen insulation material is mineral wool because of its good thermal insulation proprieties, its excellent behaviour in fire, and the ease of its application.

In light of these considerations, two insulation layers of 10cm and 4cm are installed on the internal and external sides of the SunRise TES, respectively. A thicker insulation layer (10cm) is applied on the internal side in order to embed the water pipes, whereas the external layer can benefit from the insulation in the rear side of the solar thermal collector.

The heat transfer coefficients (U^{2D}) calculated with COMSOL simulations under the hypothesis of stationary conditions and bi-dimensional heat transfer are shown below (Fig. 4 and Fig. 5).
The total heat losses correspond to 1.9 W/K (or 85 W for a ΔT = 45K) for the chosen configuration, that is equivalent to a class E efficiency hot-water storage according to the Commission Delegated Regulation (EU) No 812/2013. The main cause of such poor energy performance is undoubtedly the shape of the tank, which is characterised by a large heat dispersing surface per unit of volume.

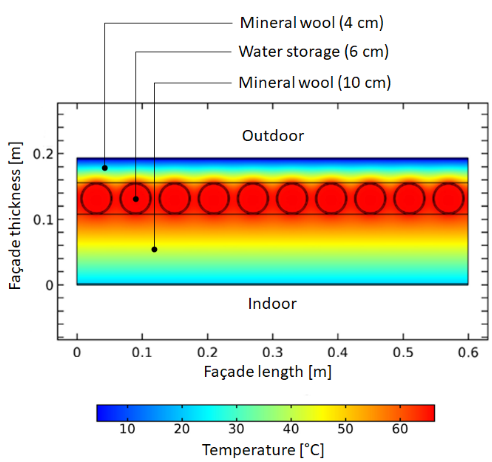

FIG. 4 FEM simulation of the TES assuming T_{water} = 65°C, T_{indoor} = 20°C, $T_{outdoor}$ = 4°C.

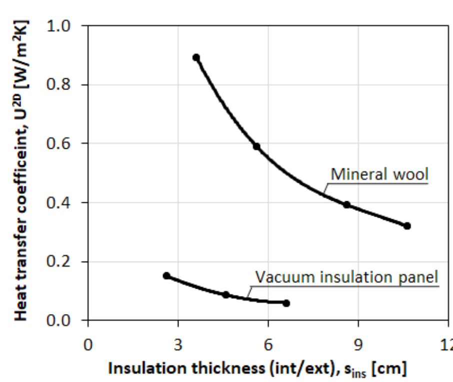

FIG. 5 Heat transfer coefficient calculated from FEM analysis for different insulation thicknesses.

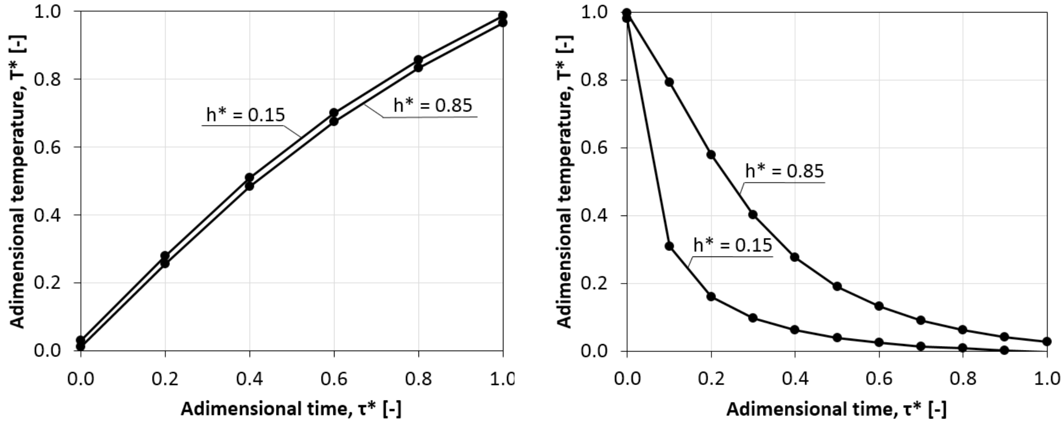

FIG. 6 Adimensional temperature in the TES during charging phase on the left (T_{min}=23.5 °C, T_{max}=76.1 °C, Δτ=5 h, H=1.2 m) and discharging phase on the right (T_{min}=21.1 °C, T_{max}=76.1 °C, Δτ=72 h, H=1.2 m).

3.1.3 Thermal stratification

The thermal stratification in TESs is beneficial to the performance of solar systems as higher solar collector efficiencies are achieved, the heat losses from equipment are reduced, and the set point temperatures for heat delivery can be more easily reached. In this perspective, a key factor in TES design is the definition of the height-to-diameter ratio of the tank. The typical recommended ratio for TES with optimum stratification is at least 2.5:1, whereas the ratio in the developed TES concept is about 20:1 and thus a good thermal stratification is expected.

Fig. 6 shows the temperature profiles of the charging (left) and discharging (right) phases measured during the experimental activities carried out in a climatic chamber. The hot and the cold chambers are kept at a constant temperature of 20°C and a sun simulator is used to provide a constant irradiance of 1000 W/m^2 on a solar collector surface during the charging test. The temperature stratification is expressed with the notion of adimensional temperature T* (=$\Delta T/\Delta T_{max}$), calculated using minimum and maximum temperature measured during the test. Temperature sensors are installed at different heights of the TES and, in particular, at a relative height h* of 0.15 and 0.85. The transient variation of temperature is expressed as function of adimensional time τ*.

The charging phase starts when the TES is at fully-mixed conditions and in thermal equilibrium with hot and cold chambers. It can be observed in Fig. 6 that fully-mixed conditions are maintained during the whole charging process as the solar heat exchanger is installed in the lower header of the SunRise TES. The test is interrupted after 5 hours when the maximum temperature of about 76°C is reached. At this point, the charging phase test is interrupted and the artificial sun is switched off. The discharging phase test consists of the monitoring of the TES temperature variation due to the sole thermal losses across storage mantle. This process is much slower than the previous one and it takes 72 hours before initial temperature conditions are restored.

3.1.4 Product availability and cost

The façade-integration of the water tank must deal with shape and technological constraints that go beyond the range of products that are commercially available, so tailored solutions have to be designed. The price per unit of volume of the tank is expected to be significantly higher with respect to the solar TES available on the market. This is due to three factors: the small size, the high rate of consumption of raw material per unit of volume, and the customisation of the product. Assuming a specific list price of €2/L that can be achieved for standard solar tanks, the target price for the SunRise storage should be less than €100, which is unrealistic at the current stage.

3.2 FAÇADE-INTEGRATION LEVEL

3.2.1 Weight and thickness of the façade

The integration of water storage into the spandrel panel undoubtedly increases the complexity of the façade in several aspects, but the most visible and straightforward effect is an increase in the weight and thickness of the façade. In the manufactured mock-up, the integration of the water storage causes an increase of the façade weight of about one quintal, of which around half is due to the weight of the steel and half is due to the weight of the water. The use of plastic materials in place of steel could reduce the overall weight, but it is not recommended because of the lower resistance to thermal and mechanical stresses. The primary and secondary load bearing structures of the façade shall be appropriately sized to account for the additional weight and prevent deformations overtime.

The thickness of the façade element is increased by the integration of the TES in the layered structure of the spandrel panel. Such effect, however, is relatively limited when a slim parallelepipedal tank is installed, as in the case of the SunRise TES that is only 6 cm thick. The need for thermal insulation in addition to that already installed also increases the weight and the overall thickness of the façade.

3.2.2 Heat fluxes

When the façade-integrated tank is charged, a fraction of the stored heat is progressively lost over time through the tank walls. The heat losses can be reduced improving the insulation quality, increasing the insulation thickness, decreasing the external surfaces and minimising thermal bridges. A fraction of heat losses is directed to the inside and can affect the indoor microclimate. In particular, parasitic losses from TES can be considered a beneficial side effect during the heating season: the temperature of the zone slightly rises, the user comfort is improved and the active heat transfer from space heating terminals can be reduced. If this phenomenon is beneficial during the winter season, in summer it represents an undesirable event that shall be avoided as much as possible since it might cause an increase of space cooling energy demand. The magnitude of heat losses is affected by the water temperature in the storage element and thus also by the heat capacity of the water storage and the typology of solar thermal collector (unglazed, glazed, or evacuated tube).

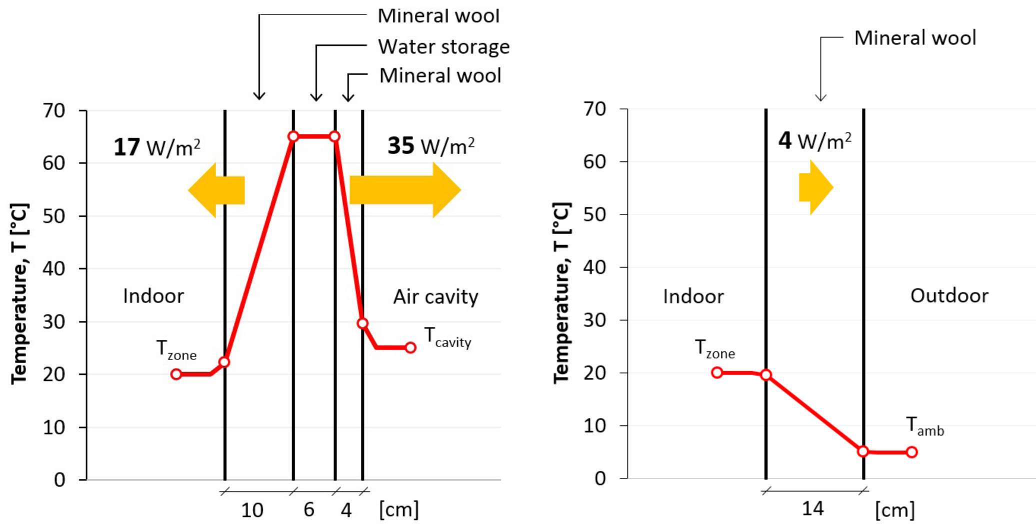

FIG. 7 Comparison of temperature gradient and heat fluxes under between the façade-integrated TES (left) and an insulated assembly (right) during the winter season (T_{zone}=20°C, T_{amb}=5°C, T_{cavity}=25°C).

The heat losses from the front and rear sides of the charged tank are compared in Fig. 7 against a traditional façade construction with the same insulation thickness (14cm of mineral wool) and identical boundary temperatures (indoor: T_{zone}=20°C, outdoor: T_{amb}=5°C). The calculation is performed considering a mono-dimensional heat transfer model and stationary conditions. The façade-integrated solution is assumed to be adjacent to an air cavity at 25°C (average temperature measured during solar collector operation). As can be observed, the heat flux is directed outwards in case of the traditional façade assembly, whereas the thermal losses of the TES represent a heat gain for the thermal zone for the solar active façade.

3.2.3 Hydraulic layout of the façade element

The installation of the TES in the façade element increases the complexity of the façade and, therefore, the requirement for inspections and maintenance as well as the risk of failure. Hydronic components such as an expansion vessel, valves, and charging and discharging points might be required depending on the design of the hydraulic system. The SunRise solar façade is designed so that the solar field can be enlarged by connecting multiple façade elements to each other with limited design efforts since a single hydraulic module can serve up to 10 solar façade elements. This is possible through a number of water pipes embedded in the façade thickness that pass through the mullion and a set of throttles that ease the connection between adjacent façade elements.

3.2.4 Accessibility to the stored solar heat

The exploitation of the stored solar heat can be limited in case of façade-integrated tanks, as some services such as DHW preparation are centralised. Viewed from a broader perspective, the interaction between façade-integrated solar thermal collectors and heating distribution networks can be easily realised if a central water storage is installed. In this case, the solar thermal collectors might cover not only the space heating demand of the zone nearby the installation site, but also other thermal loads of the building (i.e. DHW).

4 CONCLUSIONS

The paper reviews the development process of a façade-integrated solar water storage. This activity is carried out within the framework of an R&D project where the scope is the development of a new solar envelope system for the tertiary building sector. During the project, a mock-up of the façade concept is manufactured, simulated, and tested in the climatic chamber of the Institute for Renewable Energy of Eurac Research (Bolzano, Italy).

From the project activites, it emerges that the integration of a solar water storages is not an easy task. Looking at the SunRise façade development, the respect of the technological requirements and the achievement of high thermal performances are difficult goals to attain at the same time. Moreover, as the solution is building-integrated, geometrical requirements (i.e. thickness, compactness) drive the development of the façade concept and play a much more relevant role than energy efficiency criteria.

More specifically, the façade-integration of the TES binds its design to geometrical limits that are unfavourable to the purpose of heat storing. The overall dimensions are constrained and the high surface-to-volume ratio is responsible for higher thermal losses compared to traditional shapes. The design of the thermal insulation of the tank is also restricted in terms of thickness and material properties by the façade structure. In addition, such tanks are not available on the market and therefore must be customised at higher costs. Focusing instead on the façade-integration, the overall thickness and weight of the façade elements are increased by the addition of the water tank. Parasitic heat fluxes toward the interior are expected to occur, with a positive fallout during the heating season and a negative one during the cooling season. Finally, the accessibility of the stored solar heat is limited by the delocalisation of the stored heat and integration of central services or thermal loads could be difficult without an additional central tank.

Although the results are not so encouraging, the experience gained is considered highly valuable and can set new design drivers and incentives for future developments on solar envelope systems.

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Characterisation of the thermal performance of a novel roof ridge solar hot water system

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Abstract

The demand for the development of novel systems for the on-site integration of renewable energy in buildings is increasing, in order to reduce the energy consumption resulting from domestic hot water, heating, and cooling usages. Within this context, the development of efficient solar collectors for domestic hot water production that can benefit from being integrated in the architecture of buildings is highly relevant.In this study, a novel solar collector device with a tube-in-tube concept, which integrates domestic hot water storage and an absorber in a single unit, is tested under the standard ISO 9459-5. The thermal performance of the collector is evaluated by means of the so-called DST (Dynamic System Testing) method that allows its annual energy efficiency to be predicted under different climate condition scenarios. The study concluded that three collector modules in series can provide a high annual DHW energy coverage of 62-70 % for Southern European climates and in the range of 30-40% for Central and Northern European climates. Along with its compactness and efficient design, which allow easier architectural integration on roof ridges, an additional advantage of the system is that its cylindrical geometry makes it possible to rely on a significant surface for full diurnal radiation absorption, independently of solar orientation. With the objective for this new development to be technically and economically competitive compared to available solar domestic hot water systems (SDHW), it is currently in pre-production phase and ready to enter the market in 2018.

Keywords

domestic hot water, solar collector, ISO 9459-5, dynamic testing, SDHW, roof ridge

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1 INTRODUCTION

New policies and mandates are being increasingly introduced to implement renewable energy technologies for reducing the carbon footprint derived from energy use, including the introduction of solar thermal systems to meet demands for domestic hot water (CTE-HE4). However, the design of current solar systems is yet to be improved in order to enhance their efficiency and integration in the architectural design of buildings (Munari & Roecker, 2007).

Some of the limitations of current solar thermal cells are that they require a southern orientation on tilted roofs and that they compete for space with photovoltaic (PV) cell installations and areas of roof windows. On the other hand, novel solar systems technologies are needed that are more easily integrated within the architectural design of buildings and that provide higher thermal performance.

This study describes a new design that addresses some of the limitations indicated above. The solar system presented is a ridge-integrated cylindrical solar water heater that is independent of the space orientation, and is therefore suited to both tilted and flat roofs. It is based on a tube-in-tube concept that integrates the solar collector absorber and the water storage tank within the same design. Specially designed for single family houses, the collector has minimal visual impact due to its integration on roof ridges, it does not compete for space with PV cells due to its compact design, and it does not require extra space for water storage.

The current work presents the results from testing the energy performance of a single solar collector module using the DST (Dynamic System Testing) method for rating solar systems as described in the ISO 9459-5 standard (ISO 9459-5). Estimations of annual energy performance were extrapolated to 3 module units, and evaluated under different climatic conditions and DHW tapping profiles using a simulation model in TRNSYS calibrated with the collector model parameters determined from the DST method. According to the results of the present study, the energy provided by 3 modules can meet more than 50% of the energy consumption for a single-family home. The system performance was evaluated with typical profiles, in terms of volumes and draw-off duration, as defined in standards for testing DHW production devices (EN16147). The performance is dependent on the climate, the number of modules, and the tapping profile. High contributions of DHW energy coverage of 62-70% were found for Southern European climates, with lower contributions of 30-40% for Central and Northern European climates.

2 SOLAR SYSTEM DESCRIPTION

The module that was tested is a solar collector in which the absorber and the water storage tank are integrated within the same unit (see Figs. 1 & 2). The system consists of a tube-in-tube design in which one tube is assembled inside the other. The inner tube stores the hot water while the outer tube is provided with a special layer thanks to which the absorbed solar energy is efficiently converted into heat. The space between the tubes is under very low pressure, enabling the water to evaporate and condense in the inner tube, which is filled with tap water. When the outer tube is heated by the solar energy, the water evaporates. The evaporated water condenses and, in this way, transfers the heat from the outer tube to the inner one, where the hot water is stored. The system is installed on the ridge of the dwelling roof, as modules in series (Fig. 2). Depending of the number of modules connected, the storage can reach as much as 130L. Due to the tubular design of the modules, the system performance is almost independent of the orientation of the dwelling. Another advantage of this system is that an additional hot water storage volume in the dwelling is not needed.

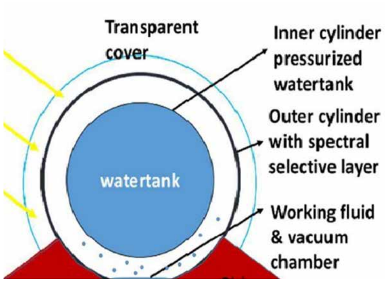

FIG. 1 Cross section schematic of solar collector module

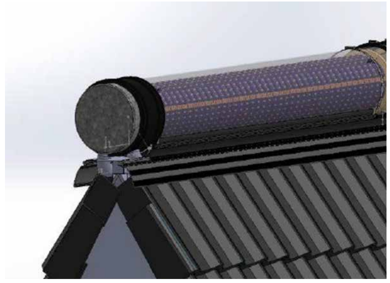

FIG. 2 CAD representation of the installation of solar collector module on a ridge rooftop

FIG. 3 Outdoor installation of the Sunridge module used during testing

The system has been developed within an InnoEnergy innovation project (Knowledge Innovation Community of European Institute of Technology), which supports the developments of products with a relative high TRL (technology readiness level), from about TRL=6. This product has been in development since the end of 2014 and will be introduced to the market in 2018 as a competitive product.

3 SET UP FOR SYSTEM TESTING

The first prototype of the system (so-called Econok system) and the final improved prototype (Sunridge module) were tested following procedures in the ISO 9459-5 standard (ISO 9459-9). Performance test methods for solar domestic hot water (SDHW) systems provide designers, manufacturers, installers, and users the necessary information to compare thermal performance among solar systems. The DST method is used to predict the long-term annual performance from a set of short-term measurements described in the ISO standard. In this study, two prototype versions of the module were tested at the Semi-virtual Energy Integration Laboratory (SEILAB) at the Catalonia Institute for Energy Research (IREC). This laboratory is equipped with facilities that are suitable for testing the dynamic performance of energy components and their optimal integration within the building environment.

A single module of the Econok and Sunridge prototypes with a length of 1.4m and internal water volume of 35L, were tested in Tarragona (North Eastern Spain), in March, 2016 and July, 2017, respectively. These months were chosen for the reason that, at the latitude at which the tests were performed, the requirement for total daily solar radiation levels is met from March to October. Among other improvements related to easier installation and integration, the Sunridge system differs from the first prototype version, Econok, in design characteristics that enhance solar absorption and reduce the overall heat losses.

The collector module (Fig. 3) was attached to a roof test bench that allowed the thermal characterisation of the system by means of the following elements:

- Flowmeter: used to characterise the flow rate through the collector (Cflow)
- 2 PT100 temperature sensors: placed at the inlet of the collector (Tin) and outlet of the collector (Tout), respectively. An additional PT100 sensor was placed on the cold water by-pass line.
- Meteorological information: outdoor temperature (Tamb) and global horizontal solar radiation were measured during the experiments.

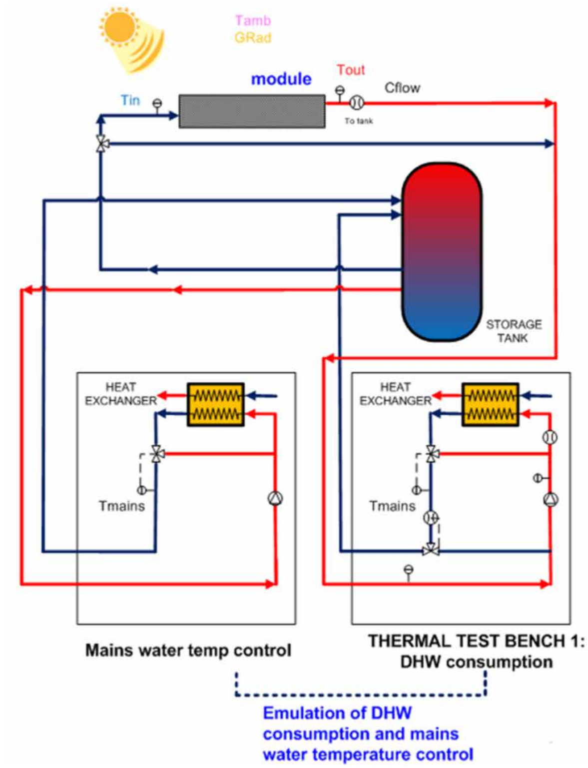

FIG. 4 Laboratory schematic for testing the solar collectors

The inlet and outlet pipes of the collector were connected to the laboratory hydraulic circuits as indicated in the schematic in Fig. 4. The outlet of the collector was connected to a laboratory thermal test bench that controls the flow rate during DHW extractions. A water tank of 1000L was kept at the desired mains water temperature conditions (10°C) by means of the continuous recirculation of cold water provided by an external cooling circuit. A by-pass system was connected to the collector so that the cold water could be diverted to the test bench when there was no need for hot water extraction from the collector. Cold water is circulated through the by-pass line before an extraction event to ensure that the inlet cold water was kept at the required set point temperature at the beginning of each water draw-off.

In the DST method, a mathematical SDHW model is used to predict energy performance from the available experimental data. The measuring data are obtained from a series of short outdoor tests on the SDHW system. The data obtained is used together with the SDHW mathematical model in order to identify model parameters, which characterise the behaviour of the SDHW system tested.

In order to predict the annual thermal performance for a selected climate condition and daily tapping profile, a SDHW computer model configured with the identified parameters was used. Three types of measurement sets comprise the DST testing method: the so-called S-sol tests (A and B sequences) and the S-Store test. The aim of tests A is to obtain information about collector performance at high efficiencies. The aim of tests B is to acquire information about the store heat losses and collector array performance at low efficiencies. The S-store test sequence is intended to identify the overall store losses. Test sequences had to comply with a set of conditions for the test days to be valid. The following table summarises the deviations of the variables to be controlled during the tests, which comply with requirements defined in the ISO standard.

Besides the above, the requirement of a minimum of 12 MJ/m^2 solar radiation per day for a test day was met for the experiments conducted.

MAINS WATER TEMPERATURE		WATER FLOW (2 LPM)		WATER FLOW (10 LPM)	
Standard	Tests	Standard	Tests	Standard	Tests
±3K	-1.5 K/+2.4 K	±0.5	±0.3	±1	±0.35

TABLE 1 Mean deviation of control variables during laboratory tests in comparison with the ISO standard requirements

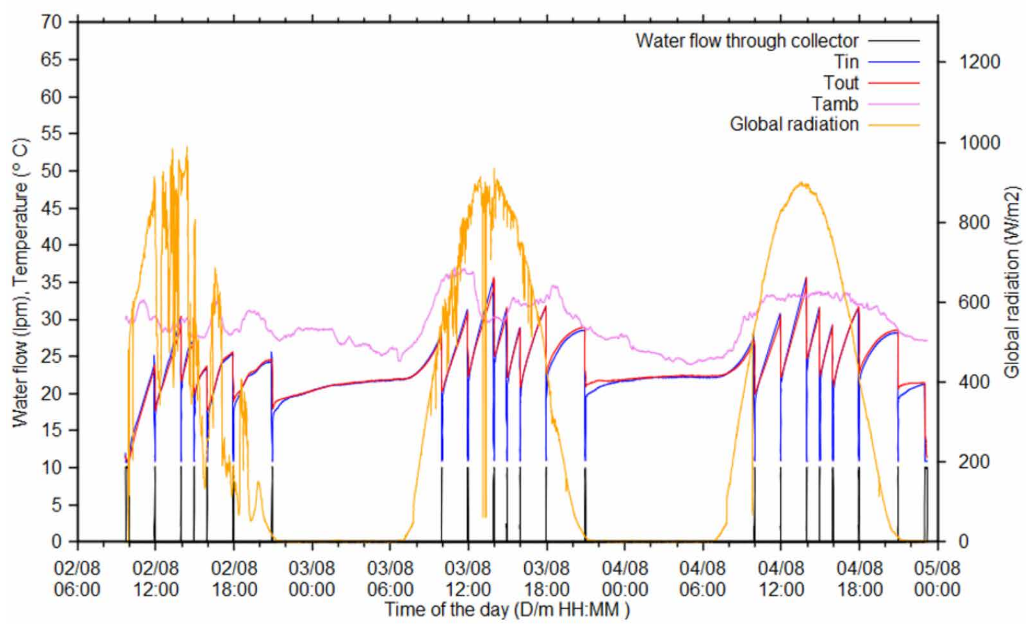

FIG. 5 Evolution of inlet temperature (Tin), outlet temperature (Tout), ambient temperature (Tamb), global radiation and volume flow rate through collector during the A test sequence.

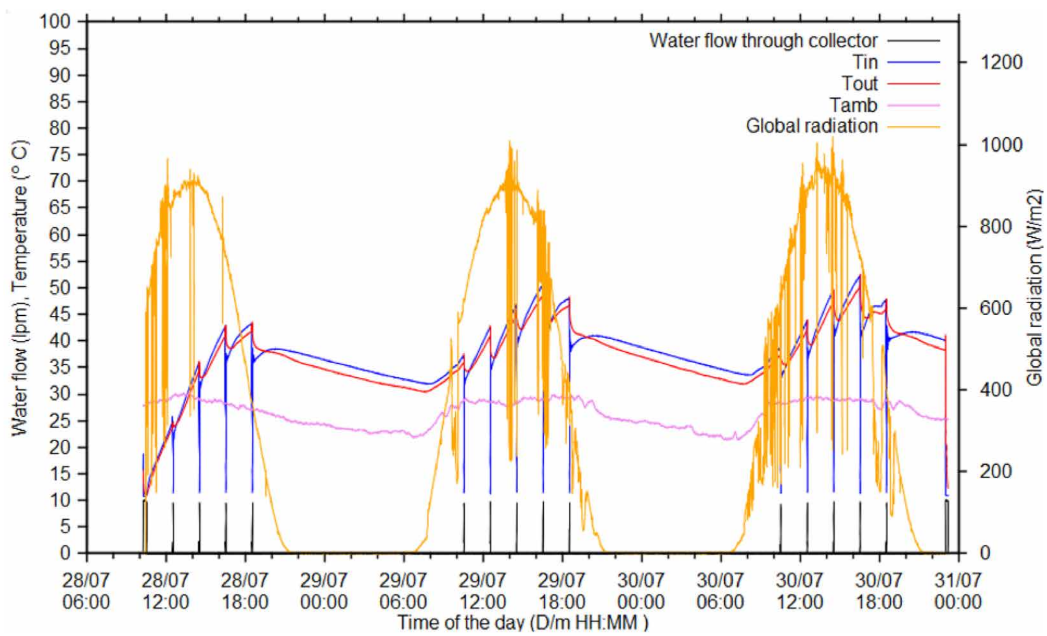

FIG. 6 Evolution of inlet temperature (Tin), outlet temperature (Tout), ambient temperature (Tamb), global radiation and volume flow rate through collector during the B test sequence.

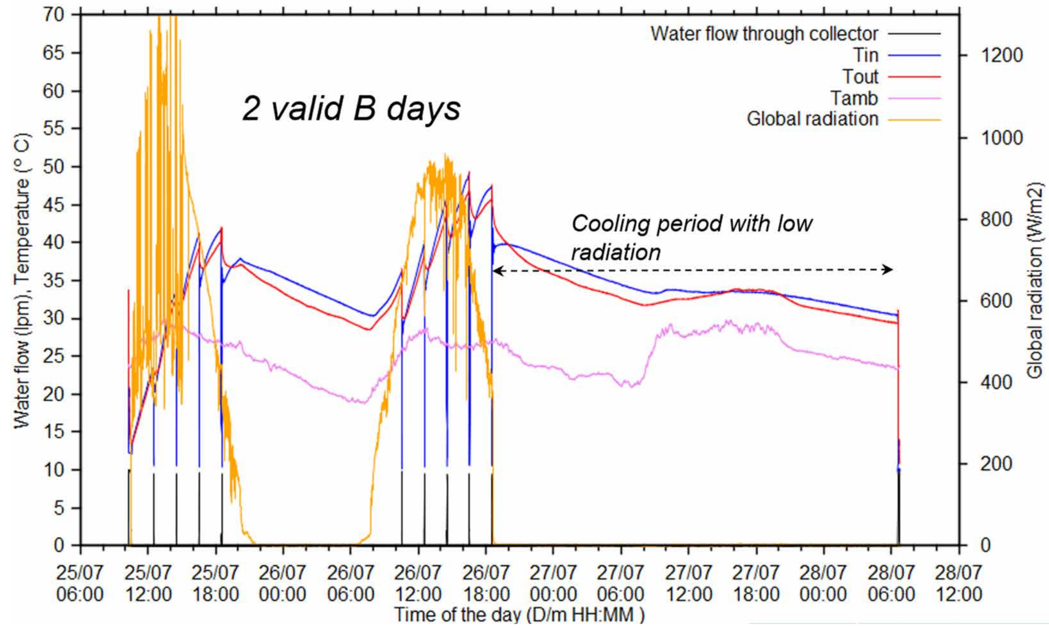

FIG. 7 Evolution of inlet temperature (Tin), outlet temperature (Tout), ambient temperature (Tamb), global radiation and volume flow rate through collector during the S-Store sequence.

4 RESULTS

Figs. 5 and 6 show the evolution of the inlet (Tin) and outlet (Tout) temperatures of the collector, the water flow rate (Cflow), the ambient temperature (Tamb), and the global solar radiation during three valid test A and test B days for the Sunridge prototype. During a water draw-off, a sharp drop in the inlet temperature was observed as a result of the activation of the by-pass and the circulation of cold water through the collector. On the other hand, at the start of each extraction, the outlet temperature increased slightly and then dropped as the cold water circulated through the tubing. Maximum temperatures achieved during water extractions for A type experiments were in the order of 35°C. The highest thermal power obtained correlated with the peak of solar radiation, with a maximum of 14kW. For the B sequence (three valid days), similar behaviour was seen, with higher temperatures achieved than for the A days (maximum of 50°C). Regarding the released heat, a maximum of 25kW at peak radiation conditions was obtained. The test sequence S-Store is illustrated in Fig. 7. This test consisted of two valid B days, after which the collector was covered to cool down for 36 hours. Similar to the B test days above, in the S-store test, the maximum temperatures were close to 50°C. The DST model parameters obtained from the testing were used as inputs for a simulation model that was built in the software TRNSYS in order to evaluate the performance of a set of collectors in different climates and under different tapping profiles. This allowed for estimations of yearly energy production for several modules for both prototypes to be provided. Calculations were done for cycles S (36L), M (100L), L (199L), XL (325L), and XXL (420L) for different European climates. The names S, M, etc. of the cycles represent tapping profiles as defined in testing standards for water heaters and heat pumps, depending on the total daily consumption of standard buildings (EN16147:2011). The climatic conditions used for the calculations were De Bilde, Athens, Stockholm, Wurzburg, and Barcelona, as shown in Fig. 8 (left). As expected, better performance is obtained for the southern latitude countries, where the solar radiation is higher throughout the year.

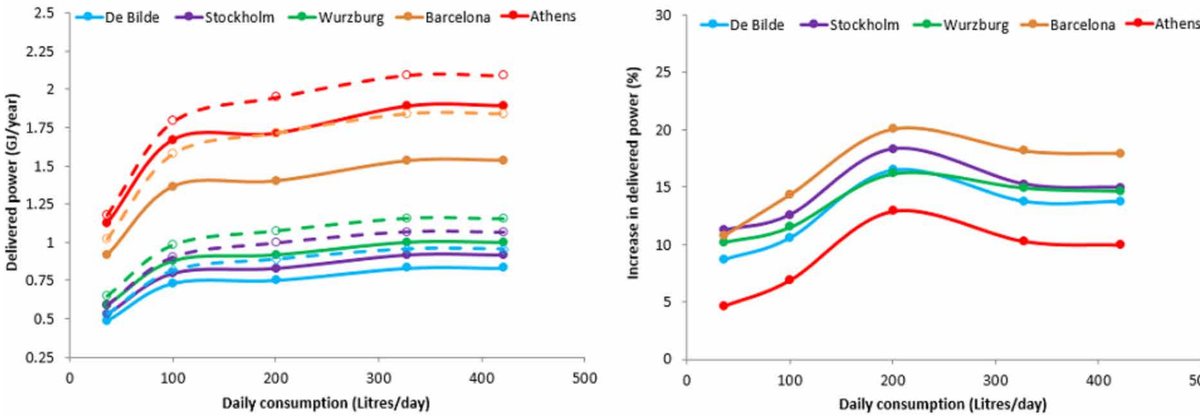

FIG. 8 Left: Annual delivered power for different daily consumption profiles for Econok and Sunridge modules. Right: Increase in the delivered power by the Sunridge prototype with respect to the Econok prototype. Increase in power (%) = (Power Sunridge-Power Econok) x100/((Power Sunridge-Power Econok)/2)

This last figure also illustrates the improvements achieved with the second prototype with respect to the first version, thanks to the lower energy losses achieved in the new prototype. The Sunridge prototype showed an increase in the energy delivered, from 5 – 22%, depending on the climatic conditions and water consumption profile. The design differences between the Econok and the Sunridge module are based on a change in the water circulation design inside the collector and the material of the absorber. In the Econok module, the inlets and outlets for water circulation are on the same side of the tube while in the Sunridge module the inlet and outlet are placed on the opposite edges of the tubing. In addition, the absorption material in the Sunridge module has a spectral selective coating material that was not used in the first prototype.

Table 2 summarises the predictions of the fraction of annual energy that would be covered by 3 solar collectors in series for a single-family home with DHW demand of 100L/day (cycle M), which corresponds to an annual energy demand of 7.62 GJ/year. A significant improvement is achieved with the second prototype in terms of energy coverage thanks to the reduction in the heat losses. For warm climates, the energy coverage can reach values up to 70%, while in higher latitudes the energy coverage can be as high as 39%. The table also includes values of collector performance calculated as the ratio between the annual DHW energy produced and the annual solar radiation in % (parameter Prototype name-Collect). This value of collector performance ranges from 21.7 to 29% for the Sunridge collector, with an improvement of up to 3% with respect to the first prototype version. The results of the study indicate that this novel system can provide significant energy savings, however, an auxiliary heater will still be necessary in order to meet the annual energy requirements and raise the water temperature to the levels required for avoiding legionella issues. No additional water storage will be required with several modules since 3 units provide a storage volume of nearly 100L. The system has successfully passed stagnation tests (with empty and filled storage), demonstrating that it meets the required standards to guarantee good performance under a variety of environmental and usage conditions.

PARAMETER	DE BILDE	STOCKHOLM	WURZBUG	BARCELONA	ATHENS
Econok-DHW	28.9	31.4	34.5	53.8	65.8
Sunridge-DHW	32.2	35.6	38.7	62.1	70.5
Econok-Collect	20.7	19.2	19.8	23.9	27.0
Sunridge-Collect	23.0	21.7	22.2	27.7	29.0

TABLE 2 Fraction of DHW annual energy coverage (%) (Prototype-DHW) and solar collector efficiency (%) (Prototype-Collect) provided by 3 collector modules for a single family home consumption profile (100 L/day, cycle M) at different European climate zones.

5 SUMMARY AND CONCLUSIONS

A new type of solar collector prototype has been tested for energy performance according to guidelines in the standard ISO 9459-5. Long term prediction performance has been compared for 2 prototype versions of the system for different climatic conditions using European standards tapping profiles. The evaluation of the performance of the second version of the prototype indicates an improvement in the thermal energy efficiency of 5-22%, depending on the climatic conditions and water consumption profile. The improved performance is a consequence of lower heat storage losses achieved with design modifications compared to the first prototype version. An annual coverage of the DHW energy demand of 62-70% was found for Southern Europe climates and between 30-40% for Central and Northern European climates. The compactness and the high performance of this system makes it highly competitive as a novel renewable energy technology when compared to other SDHW products on the market, since with a similar cost to current designs it provides good performance and easier integration than standard solar panels.

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- RTB de Beijer, innovative SME company
- ArtEnergy, SME company

Development and prototyping of an integrated 3D-printed façade for thermal regulation in complex geometries

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Abstract

Currently, several research projects investigate Additive Manufacturing (AM) technology as a possible construction method for future buildings. AM methods have some advantages over other production processes, such as great freedom of form, shape complexity, scale, and material use. These characteristics are relevant for façade applications, which demand the integration of several functions. Given the established capacity of AM to generate complex geometries, most existing research focuses on mechanical material properties and mainly in relation to the load-bearing capacity and the construction system. The integration of additional aspects is often achieved with post processing and the use of multiple materials. Research is needed to investigate properties for insulation, thermal storage, and energy harvesting, combined in one component and one production technology.

To this end, the research project "SPONG3D" aimed at developing a 3D-printed façade panel that integrates insulating properties with heat storage in a complex, mono-material geometry. This paper gives an overview of the panel development process, including aspects of material selection, printing process, structural properties, energy performance, and thermal heat storage. The development process was guided by experiments and simulations and resulted in the design and manufacturing of a full-scale façade element prototype using FDM printing with PETG. The project proved the possibility of the integration of functions in 3D-printed façades, but also highlighted the limitations and the need for further developments.

Keywords

additive manufacturing, 3d-printing, PETG, heat storage, thermal insulation, façade module

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1 INTRODUCTION

Additive manufacturing methods provide great freedom of form compared to traditional methods (Strauss & Knaack, 2016). Nowadays, designers and engineers can freely create complex designs in shapes that traditional production processes could not provide. Furthermore, additive processes allow access to the inner part of the product, thus enabling integration of multiple design domains to realise multi-functionalities (Yang & Zhao, 2015), with no additional cost for the increased complexity (Gao et al., 2015). In additive manufacturing, regardless of their degree of complexity, objects are fabricated following the same procedure. This capability provides the design with very large geometric design freedom (Quan et al., 2015).

Complexity in form is observed in the façade, which is one of the most challenging parts of a building. This complexity can be attributed to the multifunctional nature of the component that controls the indoor environment of a building (Strauss & Knaack, 2016). Moreover, the growing demand for low energy consumption and comfort have given the façade an important role in the overall building concept. It must not only be extremely well insulated but also adaptive in order to positively modulate the interior climate. This ultimately has a positive effect on the use of energy. The façade becomes an integral part of the climate concept and building services components can be integrated into it (Klein, 2013). An increasing interest in the application of advanced building envelope solutions can be seen both in research activities and in industrial developments (Favoino, Goia, Perino, & Serra, 2016; Loonen, Trčka, Cóstola, & Hensen, 2013). The potential of 3d printing technology to generate complex geometries for integrating multiple materials and functions should be investigated in this respect.

The potentials of 3d printing technology for façade construction has been investigated by a few studies, such as the one from Peters (2016), Paoletti (2017) and de Witte et al. (2017). However, there is still research to be done to define the performance limits, especially for insulation and building physics to be combined in one component and one production technology. The focus of most research has been on the mechanical material properties, and mainly in the relation to the load-bearing capacity (Labonnote, Rønnquist, Manum, & Rüther, 2016). It is necessary to explore and determine the boundaries of those functions that can be integrated within a façade component.

In this context, the present research focuses on the potential and limits of integrating multiple functions in one façade component with 3d printing production technology. The main objective of this research is to demonstrate that with 3d printing technology it is possible to create mono-material façade components that integrate multiple functions. This hypothesis is tested by creating a façade panel that regulates the temperature inside the building with the use of its thermal insulation and heat storage properties. This paper presents the design and evaluation of the façade panel. Four research phases are presented. In the first one, samples were designed and 3D printed based on symmetrical cellular structures. In the second phase, samples were designed and 3D printed based on elongated and asymmetrical structures; and a broad range of heat flux and temperature measurements were conducted. In the third phase, channels for water circulation were designed, 3D-printed and tested for water tightness. Finally, the most promising design principles were scaled up into larger prototypes.

2 METHODOLOGY

The proposed façade panel has two main functions: thermal insulation and adaptable heat storage. The heat storage consists of the two external layers that are 3D printed: the water based liquid and the water tank. According to the different seasons and time of the day, the water is placed on the inside or outside of the façade to absorb or release heat, as shown in Fig. 1. To circulate the water, two reversible pumps are used, connecting the two external layers with the water tank. The façade thus acts as a cooling device in summer and as a heating device in winter. Along with the heat storage function, the panel needs to provide thermal insulation as part of the external envelope.

A *research through design* methodology was used to test if the above façade concept can be manufactured as a 3D-printed mono-material panel. Research through design is a methodology in which design alternatives, samples and prototypes are being developed in an iterative process, in which evaluations (e.g. simulations and measurements) lead to input for the development of the next generation of design alternatives, samples, and prototypes. The main tools used for these evaluations were theoretical models and literature, physical experiments, heat transfer simulations and structural optimisation. Multiple samples were produced for the different parts of the façade with variation in different parameters such as: layer height, infill percentage, speed, extrusion width, and temperature.

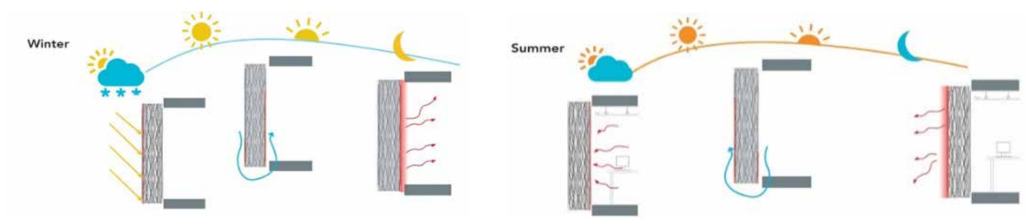
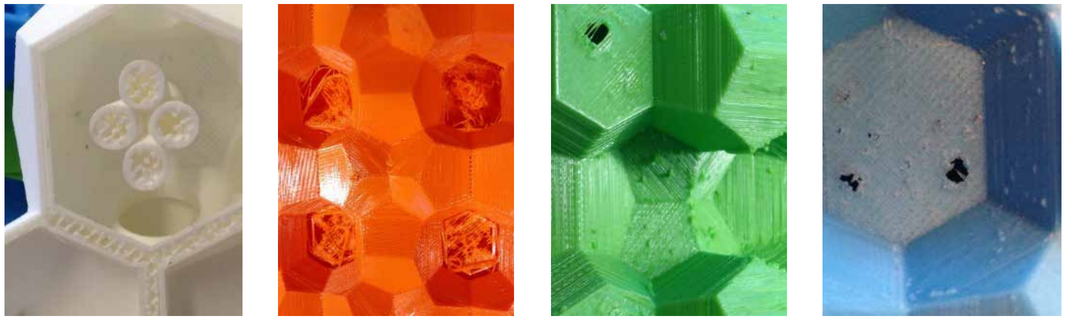


FIG. 1 Façade panel principle: Water circulation in a cooling season (a) in a heating season (b)

The designs of the first samples were created using software called Rhinoceros 3D and Grasshopper, in order to produce the geometry of the thermal insulation and the heat storage system. The 3D printing process that was selected was Fused Deposition Modelling. FDM technology and polymer filament is easily accessible to anyone who wants to 3D print. In addition, thermoplastics are relatively lightweight, have low thermal conductivity, and some of them are recyclable. Transparent PETG was chosen due to its higher solar transmittance for the external layer. Moreover, PETG has higher stiffness and strength than PLA for instance, and it is 100% recyclable.

3 PHASE 1: POLYHEDRA CONFIGURATION

In the first phase, the preliminary research of polyhedra structures and their potentials in thermal insulation were considered. The part that was designed and tested first was the external layer that will integrate water for heat storage. The main parameters used to evaluate the specific configuration were the ability to 3D print this configuration, the 3D printing time, the water tightness, the ability to design and print larger components in short timeframes, and the structural performance.
The material that was used was PLA.



a b c d

FIG. 2 Printing samples of the polyhedral configuration, showing problems of the printed surfaces.

Closed cellular structures are known to have relatively good thermal performance (Ashby, 2006). The cells are designed to have a low surface area, like a foam structure, which creates potential for cellular structures that have a relatively low ratio of solid to gas. Previous investigation into the 10mm cells showed that small panels made with these cells have relatively low effective thermal conductivity, 0.044 W/mK (Sarakinioti, 2016). The limiting factor in reducing the effective thermal conductivity is the minimal wall thickness needed from the manufacturing technique.

The process that followed was to 3D print the first samples of this configuration using FDM production technology. The objective was to test the properties of the 3D printed surface in terms of water tightness and surface quality. The samples were 3D printed with a nozzle of 0.4 mm. The length of time taken for printing was an issue and a solution needed to be investigated to produce the larger components. Furthermore, the specific configuration of polyhedral structures resulted in some surfaces being horizontal and collapsing during the printing process, as shown in Fig. 2.

4 PHASE 2: ELONGATED CELLS CONFIGURATION

Based on the conclusions drawn during Phase 1, the next phase of the research was set, aiming to improve the use of material, printing speed, and total production time. In particular, the approach based on two layers was revised, leading to re-thinking and re-designing the façade panel with different configurations.

4.1 CELLS DESIGN CONSIDERATIONS

The results received from the investigation of the Phase 1 helped to design further configurations that require less material, shorter printing time, and have good thermal performance. Considering the two different functions of the façade component (heat storage and thermal insulation), the two parts of the façade were investigated separately. The inner core needed air cavities to act as insulation, whereas the external layer needed channels that integrate water for heat storage and circulation. The air cavities were stretched in all directions except the direction of the heat transfer which was kept between 10-20mm, while the water channels were re-designed based on structures driven by fluid dynamics, using streams and channels that would circulate the water faster and with lower pressure drop from the bottom of the layer to the top (Fig. 3).

a b

FIG. 3 Cross section of the panels, showing the elongated cells in the insulation core and the channels in the external water layer.

In addition, the cells were initially designed with surfaces that are connected to enclose air inside them. The sides of the cells were regular and created sharp edges at the points at which they are connected. In the final design, the configurations have curved edges and sides. As a result, the extruder follows a continuous path while extruding material, the travelling time of the extruder is reduced, the printing speed could be increased as vibrations were lowered, and, therefore, the total printing time was reduced.

4.2 THERMAL CONDUCTIVITY PROPERTIES

First, the possible options for the insulation layer were designed, 3D printed, and tested for their thermal conductivity. For the thermal tests, a 1 m^3 box made of polystyrene was built and a hole of 20cm X 20cm in which to place the samples was created in one side. A lamp was placed inside the box to heat up the environment. The tests of the heat flux that is transferred from one side of the sample to the other took place during the summer months. In one typical summer day the mean temperature of the office was 28.7°C. On that day the temperature inside the box was 54°C, while outside was 28.7°C. This means that the difference was 25.3°C. A similar difference in temperature was also measured in the temperatures of the surfaces.

The thermal resistance of the sample was determined by measuring the temperature inside the box, on the surface of both sides of the sample, and of the external environment using thermocouples, and by measuring the heat flux through the sample with a heat flux plate (Hukseflux HFP01) on each side of the sample. Only the long-term average results were used once a steady-state situation had been reached.

The results for the different samples, as shown in Table 1, showed a relatively high thermal conductivity. The reason for this is the amount of material needed due to the production process; the porosity of the samples is rather low. The values of the thermal conductivity of the samples were similar and therefore the configuration with the shortest printing time was selected. The selected configuration was flexible and not stiff for a façade panel. Therefore, the configuration was deformed by keeping the main principle of the smooth curves and inserting connection points in some parts of the surfaces to increase the structural stiffness.

DESIGN	1	2	3	4
				
Nozzle size mm	0.4	0.4	0.4	0.4
Wall thickness	1.2mm	0.8 mm	1.2mm	1.2mm
Material	PETG colour	PETG transparent	PETG transparent	PETG transparent
Mass kg	0.533	0.286	0.417	0.693
Volume ratio solid /gas	0.2	0.08	0.23	0.23
thermal conductivity λ	0.101W/mK	0.094W/mK	0.104W/mK	0.109W/mK

TABLE 1 Different configurations that were tested for thermal conductivity

5 PHASE 3: EXTERNAL LAYER CONFIGURATION AND FIRST LARGE-SCALE PRINTING

In the third phase, the focus was on the external layer but also on the design of the large components. The design with the most promising performance, highest printing speed, potentials for uniform water flow, and lowest pressure drop was selected and further 3D printed. Several tests for water tightness were undertaken. Moreover, for the larger component, the two layers were designed in one object and the final design was 3D printed for the first time.

5.1 EXTERNAL LAYER

The configuration of the external layer is inspired by natural configurations that transfer fluids such as blood vessels, veins in leaves, and 3D bionic structures. The external layer, where the liquid flows, requires water-tightness and the channels in this layer require a hydrodynamic shape to allow for minimal pressure drop and uniform flow. Based on this concept, channels of different diameter were incorporated in the external layer (Fig. 4).

FIG. 4 Printed segment of the external layer

a *b*

FIG. 5 Water circulation test in the external layer

Several samples with different configurations were tested for flow resistance and water tightness, using a water pump and a hose that connects the input of the sample with the output of the pump (Fig. 5). Preliminary testing of the samples showed that the surface had micro-holes between the layers, caused by discontinuities and high speeds in the printing process. An epoxy coating (EpoxAcast 690) was applied both on the inside of the channels and on the external surface of the component to ensure water tightness.

5.2 THERMAL PERFORMANCE

In parallel to the design and manufacturing process, the potential for energy saving was investigated for different climates. The potential in the heating season was assessed by analysing correlations between solar irradiance and ambient temperature in TMY weather files for 14 cities. Similarly, the potential in the cooling season was investigated by comparing the difference between daytime air temperature and night-time sky temperature. From this study, it was found that Spong3D has more potential for cooling than for heating, because there are several warm climates in which the night-time sky temperature drops significantly below the thermal comfort zone, and can thus be used as a heat sink for nocturnal cooling. The added value of Spong3D is most pronounced in composite climates with at least a moderate need for both heating and cooling. Madrid, Los Angeles, and Cape Town are examples of such cities. The climate analysis showed that, in these cities, there is potential for natural heating or cooling with Spong3D on 75% to 80% of the days in a year. In all three climates, Spong3D has potential throughout almost the entire cooling season and for around half of the heating season (sunny days). This result indicates that Spong3D can have a significant impact on reducing heating and cooling energy demand, provided that its operation is tuned to the resources that are available in the ambient climate.

A dynamic simulation study was carried out to further quantify the performance potential of Spong3D. To this end, a Trnsys model of a reference office zone was developed with hydronic systems in the exterior (solar collector) as well as interior (radiant system) layers of the façade. These heat-exchanging surfaces were coupled with a storage tank with controlled fluid flow to represent the daily and seasonal behaviour of Spong3D. The Spong3D system was only modelled on the south facing façade – it was assumed that the office space was part of a bigger building, and that other

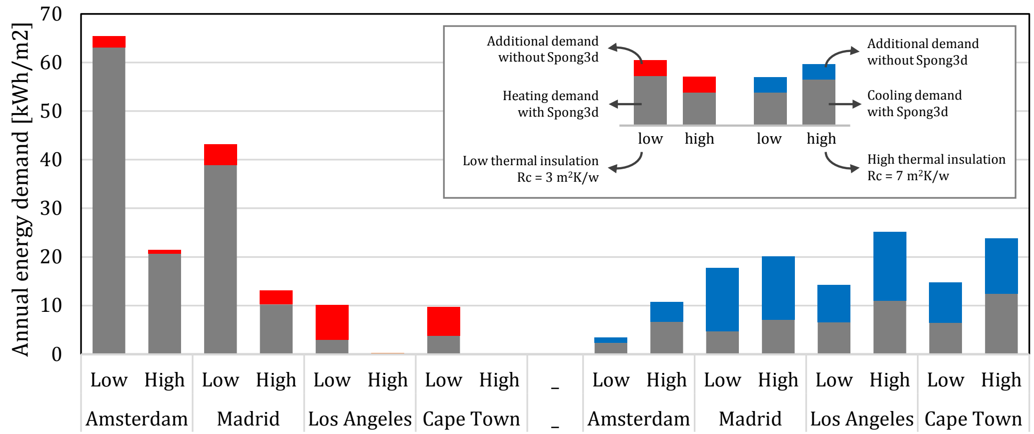


FIG. 6 Predicted energy demand for a reference office space in four different cities.

walls, floor, and ceiling are adjacent to rooms with similar thermal conditions. Among the many design variables that were studied, it turned out that tank volume, solar absorptance, and fluid flow rates have the greatest influence on the resulting performance of Spong3D. The case study results (Fig. 6) show that application of Spong3D can lead to significant reductions in energy demand, particularly for cooling. Percentage-wise, the energy-saving effect is similar for both a moderate and a highly insulated building envelope system. This is an encouraging finding for the viability of the Spong3D concept, as it shows that the thickness of the insulating middle layer can be kept at modest values and still lead to satisfactory performance.

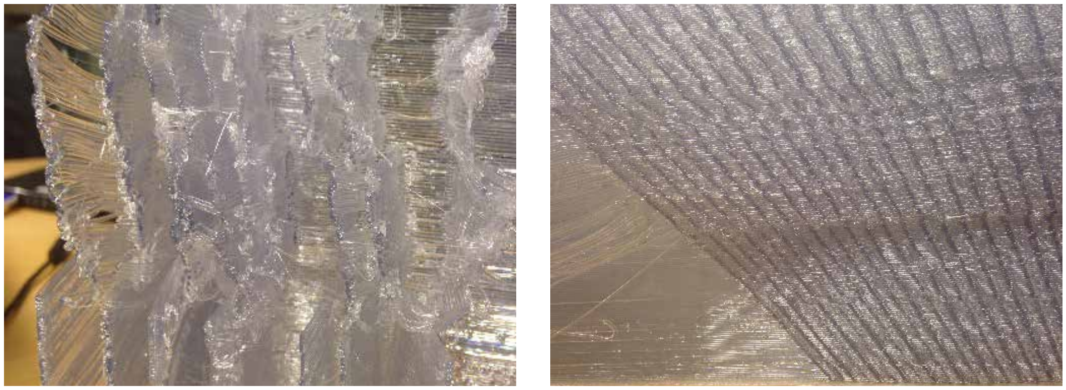
6 PHASE 4: LARGE SCALE PROTOTYPES

The project aimed not only to design the panel but also to produce a 1:1 scale prototype for a proof of concept. Two different prototypes were designed for the final production. The first one was a double-curved panel. The second one was a straight panel. Both prototypes faced several challenges, of which two are the most relevant.

6.1 LARGE SCALE 3D PRINTING

The first challenge regarded the identification of a proper number of layers for the large-scale prototype, based on achieving a balance between printing time and stiffness of the printed surfaces during printing. The second challenge regarded the stabilisation of the prototype during printing, to avoid warping during the cooling process of the extruded material, and to avoid any shifting of the prototype on the print bed. Firstly, a double-curved panel with water channel sizes of 5mm-15mm was prototyped. The printing process stopped at a lower height than expected. The final size of the produced panel was (55x30x30cm). The process of prototyping the double-curved panel allowed for the drastic improvement of the production of the straight panel with regard to both of these main challenges.

Regarding the number of layers, for the double-curved panel, the external channels were designed to be printed with one layer only, to minimise the use of material and time. Because the channels were not stiff and not thick enough, the extruder could put pressure on the channels and therefore could easily cause a displacement of the channels and deformation of those parts. Regarding the



a *b*

FIG. 7 The double-curved prototype, showing the displacement of the printed layers; cross section (a) and frond view (b).

stabilisation of the prototype during printing, every surface adhered to the print bed with a narrow base (a large thin printed surface). The surface that connected the model to the print bed was minimised and each surface would act independently during the printing process causing vibrations of the model and higher possibilities to deform (Figs. 7a and 7b). Based on this experience, decisions were taken to print the straight prototype with multiple layers for the external channels. Moreover, the decision was taken to sufficiently enlarge the surface that connected the model to the print bed.

6.2 FINAL PROTOTYPE

The final product is a large-scale prototype, which basically constitutes the proof of concept.
The design was adjusted to address the problems identified in printing during the previous phase. The diameter of the channels was increased from 5mm to 20mm for the small channels and from 15mm to 40mm for the big channels. Moreover, a second wall in the channels was inserted to make them stiffer. A single base for all the parts of the component was designed. These settings and some irregular parts of the design caused the creation of small surface cavities in the transitional areas between the large and smaller channels. The large panel had a rectangular shape.
The internal layer, which provides the thermal insulation properties, was designed according to the elongated cells principle (Fig. 8a) developed and measured in Phase 2. The thermal conductivity λ was measured to be 0.1 W/(m·K), which means that the panel with a thickness of 33cm insulation, has a thermal transmittance coefficient U value of 0.30W/(m2·K).

The overall prototype dimensions are 1500x500x360mm. Due to limitations of the printed size, the panel was printed as two components. The two models interlocked vertically and consisted of a free-standing component (Fig. 8b). The purpose of this model was to demonstrate the feasibility of printing such a panel, and it is not a fully functioning system. The water circulation system was not incorporated at this stage. Nevertheless, the possibility of water circulation in the 3d-printed channels was tested in the previous development phase, with a working prototype.
The printing process of the large component was successful except for some small cavities in the surface. The total printing time for the panel was 512 hours.

7 DISCUSSION

The manufacturing of the multifunctional façade panel was proven to be feasible, as the production of a 1:1 scale prototype indicates. Such a development, although still experimental, provides a positive outlook of the possibilities of additive manufacturing to integrate functions and improve the energy efficiency of buildings. The steps of the development process provided insights into the issues that may be encountered during the manufacturing of larger building components and how they can be addressed, as well as the opportunities offered by complex geometries, not only for appearance but also for performance of the building.

However, it needs to be clarified that considerable further developments are required to lead it towards a marketable façade system, which are, on the one hand, related to the manufacturing process, the function, and the performance of the system and, on the other hand, to the system implementation. Regarding the manufacturing process, which is the main innovation of the study, a number of issues need to be addressed. Firstly, the water circulation system should be integrated and tested in the panel and the design of the channels should be improved for better water circulation and heat storage. Most importantly, the 3D printing time is long for complex geometries and multiple integration of performances, despite trying to reduce the time through proper design. However, there is a continuous development of larger scale printers/chambers and techniques that can shorten the 3d printing time. Finally, further investigation needs to be done in relation to the feasibility of the production of large scale components in terms of time and costs.

a *b*

FIG. 8 The final full-size prototype: side view of the bottom part (a) and the full, freestanding prototype (b)

Furthermore, an in-depth analysis and testing on the structural behaviour of the 3D printed material are required, especially when considering extreme thermal conditions and durability, as well as long term testing on creep. The testing is also related to the investigation in 3d printed polymers and the selection of the most efficient polymer. 3d printing technology provides the designer with an opportunity to create elements that are tailored to the overall shape of the façade and the placement on the building, which allows the design of the façade to adapt according to customised requirements. Further investigation needs to be done to find the correct direction for implementing this customisation potential. Moreover, the component should be investigated in terms of its potential to be part of a façade that can integrate areas with transparency, translucency, and opacity.

To further develop the proof of concept into a façade product, investigation needs to be done on the potentials for compatibility with existing façade systems and components, such as gaskets sealants, infills, connectors etc., in addition to the 3d printed product's assembly and connection to the main structure and other building components. Finally, compliance with building regulations, such as structural load, building physics, daylight, fire safety etc. needs to be proven and ensured, before the façade panel can be considered as a product.

8 CONCLUSION

This paper discusses the development process of a mono-material, multifunctional, adaptive façade panel, which controls the heat exchange between the indoor and the outdoor environment, while testing the potential of additive manufacturing for its production. The panel concept is based on an inner core with highest possible thermal resistance and two outer layers where water accumulates heat from solar gain or indoor sources, circulates, and releases it on the other side. The intention was to create a component that is relatively lightweight and is recyclable. The plastic filament is a material that can be easily accessible to anyone who wants to 3D print.

The research work was structured in four phases. During the first phase, samples were designed and 3D printed based on symmetrical cellular structures; structural performances were measured on specimens and simulated. In the second phase, samples were designed and 3D printed based on elongated and asymmetrical structures; a broad range of thermal measurements for heat-flux were conducted under different thermal conditions. In the third phase, channels and tanks for water circulation were designed, 3D printed, and tested for water tightness. Finally, in the fourth phase, the most promising design principles were further implemented in the design and manufacturing of a one-to-one scale prototype.

The construction of the prototype constitutes the proof of the concept, as it demonstrated that it is possible to print a façade panel with complex geometry, which incorporates a heat storage system and thermal insulation properties. Moreover, the thermal simulations showed that, even though the system is not capable of replacing conventional heating and cooling systems entirely, it still shows promising predictions in reducing the heating and cooling demand of buildings and thereby reducing the costs for heating and cooling energy as well as associated greenhouse gas emissions, especially when implemented in a location with a composite climate requiring a moderate need for both heating and cooling.

The described façade panel is an experimental approach to prove that integrating functions in additively manufactured building components is possible. Such approaches have the potential to provide the needed energy efficiency, while accommodating design requirements for complex geometries. Nevertheless, several developments, investigations, and tests should be performed in terms of a marketable façade system, including structural, construction, and safety requirements, along with expanding design and performance possibilities. As additive manufacturing technologies rapidly advance, the design and production of integrated products will be, on one hand, facilitated and, on the other hand, will set the requirements for those technologies.

Acknowledgements

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How to analyse the performances of innovative variable diffusivity membranes integrated within prefabricated timber facades: Computer-based modelling and experimental analysis

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Abstract

Vapour barriers and retarders are often needed to improve the hygro-thermal performance of the building envelope. Their use is particularly important in prefabricated timber façades, especially when critical boundary conditions occur. In the literature, very little is known about the actual performance of complete envelope packages that integrate these membranes, since most previous studies focused on the analysis of single components. However, considering the growing interest and use of such timber facade elements, an analysis of the performance of integrated membranes is needed in order to improve the material function curves available in the datasheets to enable the correct design of the whole wall structure. Thus, the novelty of this work lies in the validated analysis of a building envelope sample that integrates membranes with a variable vapour diffusivity.

The focus of the paper is more related to the experimental set-up and particular attention has been paid to the development of a relatively simple testing procedure to analyse the behaviour of such integrated membranes. The study seeks to investigate the behaviour of an envelope component integrating a hygro-variable membrane and a breathable membrane by using computer simulation and experimental facilities.

A thermo-hygrometric analysis of the element has been performed in Delphin, and an experimental methodology is presented, aiming to validate the numerical model, measuring the temperature and relative humidity in different layers. Two sets of boundary conditions have been accurately chosen as they are critical for the building component in terms of thermal and humidity transmission.

Results show very good agreement for one test condition. For the second condition, the measurement uncertainty was greater. One possible reason for this was the presence of condensate in the measurement box frame caused by the first test run. The experimental set-up developed is a relatively easy-to-replicate layout for the validation of similar complex packages. Compared to previous studies, the experimental set-up used in this research is simpler and less expensive.

Keywords

hygro-variable membrane, hygro-thermal analysis, delphin, timber façade, relative humidity measurement

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1 INTRODUCTION

Humidity can enter buildings in different ways: infiltration (caused by rain drainage or due to problems in wall-integrated supply ducts), capillary action (due to rising water from the ground), water vapour stored in materials during the building construction phase, and vapour generated by the occupants.

High levels of humidity combined with low interstitial temperature within the building envelope can cause problems such as superficial and internal condensation, reduction of the insulation capacity of materials, aesthetic degradation, and mildew growth (Lucas, Adelard, Garde, & Boyer, 2001). Hence, humidity levels not only influence the performance of materials, but can also become a problem for the comfort and health of occupants.

Therefore, it is crucial to carefully analyse the vapour diffusion within a building envelope in order to avoid these inconveniences and to preserve both the building integrity and the wellbeing of the occupants.

In cold climates, and during wintertime, problems with excessive humidity are usually caused by the poor ventilation of indoor spaces. The vapour produced within the building moves through the building envelope and condenses near colder layers. In order to prevent this behaviour, the humidity level near the wall surface should be reduced, for instance using a vapour retarder membrane on the warm side of the wall.

On the other hand, in hot and humid climates, the main source of vapour can be the outdoor air. In these conditions, condensation problems may occur near the inner layers of the wall, especially if the indoor environment is cooled. A possible solution to this issue is the use of breathable materials within the envelope, in order to let the humidity flow through the wall build-up, avoiding moisture being trapped in the material.

Vapour barriers and retarders are fundamental to control vapour diffusion through the building walls and therefore to regulate the hygrometric behaviour of the whole structure.

Previous research on in-situ existing wall and small single-material specimens have already been done (Litti, Khoshdel, Audenaert, & Braet, 2015) (Guizzardi, Derome, Vonbank, & Carmeliet, 2014) (Campbell, McGrath, Nanukuttan, & Brown, 2017), but few examples on more realistic multi-layer building samples that integrate variable permeability membranes have not been found in the literature.

Thus, this study aimed at investigating the behaviour of an envelope component that integrates a hygro-variable (“smart” vapour barrier) membrane named Clima Control 80 (Rothoblaas, 2017) and a breathable membrane named Traspir75 (Rothoblaas, 2017), by using computer simulation and experimental facilities.

The experimental set-up developed is a relatively easy-to-replicate layout for the validation of similar complex packages.

2 METHODOLOGY

2.1 EXPERIMENTAL SET-UP

In this work, the behaviour of a building envelope sample (0.5m x 0.5m), composed of the layers listed in Table 1, has been analysed through numerical modelling and experimental investigation. The layout was defined in collaboration with a local supplier of components for timber constructions to ensure the selection of a realistic configuration.

Hence, the choice of testing the layer composition that is reported in Table 1 has been agreed together with the company, in order to fulfil the requirements of the most hot and humid regions around the world, such as Asia or South America.

The Traspir75 membrane is commonly adopted in façade packages similar to the one analysed in this study because of its air and water tightness combined with a high vapour permeability, allowing the drying out of the humidity stored within the wall.

Moreover, instead of using a vapour barrier in the inner layers to reduce the amount of humidity entering the façade from the inside, it has been decided to adopt the Clima Control 80. In fact, if this membrane is exposed to high humidity levels, it transforms from a vapour barrier into a breathable product, guaranteeing that the structure remains dry.

	Material name	Thickness	Density	Specific heat	Thermal conductivity	Vapour diffusion resistance	Equivalent air layer thickness (SD)	Total U- value
INDOOR		[mm]	[kg/m^3]	[J/(kg*K)]	[W/(m*K)]	-	[mm]	[W/(m^2*K)]
Layer 1	Gypsum fibre board	12.5	1133.35	1228.37	0.34	16.83	0.21	0.23
Layer 2	Wood fibre insulation board	60	150	2000	0.04	3	0.18	
Layer 3	Clima Control 80 membrane	0.2	400	1700	0.20	1000÷25000	0.2÷5	
Layer 4	Wood fibre insulation board	100	150	2000	0.04	3	0.3	
Layer 5	OSB board	18	630	1880	0.13	280	5.04	
Layer 6	Traspir75 membrane	0.3	250	1800	0.30	67	0.02	
OUTDOOR								

TABLE 1 Layer composition and characteristics

The Clima Control 80 is a particular type of vapour barrier that can adapt its vapour diffusion resistance based on the surrounding relative humidity. In particular, the more it increases, the lower membrane SD is obtained (Table 2).

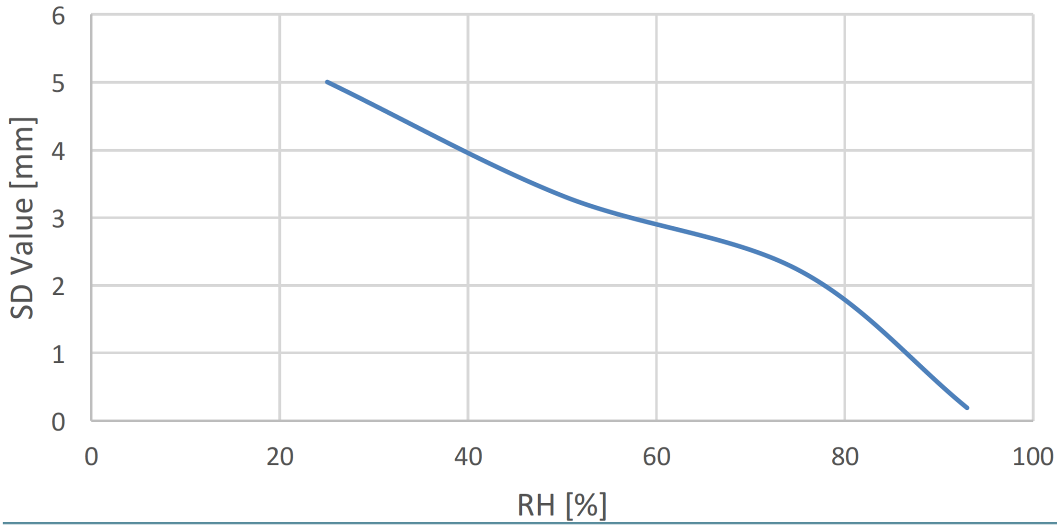

TABLE 2 Clima Control 80 membrane relation between surrounding RH and SD-value

EE08 by E+E sensors (RH→0÷100% ± 2%; T→-40÷80°C ± 0.2°C) have been placed between specimen layers for temperature and relative humidity monitoring. Fig. 1 shows the sensors' position within the materials. In particular, four internal sensors have been embedded into small cavities inside the wood fibre insulation boards: position 1 is at gypsum – insulation (60mm) interface; position 2 is at insulation (100mm) – Clima Control 80 interface; position 3 is at OSB – insulation (100mm) interface; position 4 is at Clima Control 80– insulation (60mm) interface.

Two different boundary conditions were created on the different sides of the specimen during the analyses. On one side, the temperature and relative humidity level were maintained by a mono-zonal climatic chamber. On the other side, it was decided to use a dummy climatic chamber made from wood, which is very well insulated for both thermal and vapour diffusion purposes. This box was made of OSB panels (18mm thick), covered internally with pressed insulation material (Styrodur 2500C, 60mm thick).

During the two performed tests, the box was plugged by the specimen on one side, as shown in Fig.2, and the whole block was inserted into the main climatic chamber. The desired temperature inside the box was set using a thermostat connected to a heating coil, while the relative humidity of the air was set using salt solutions.

In this way, it was possible to impose a thermal and vapour flux from one side of the tested component to the other.

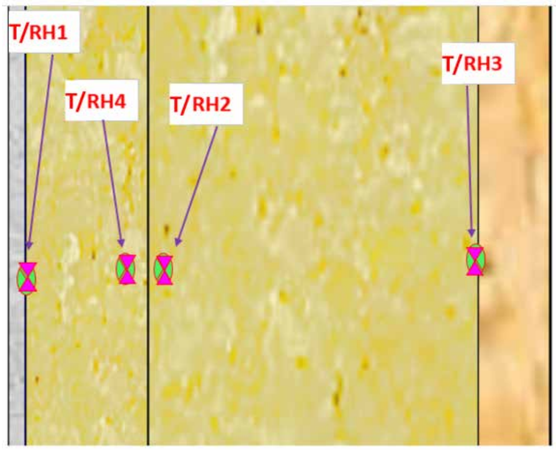

FIG. 1 Sensors' position inside the specimen

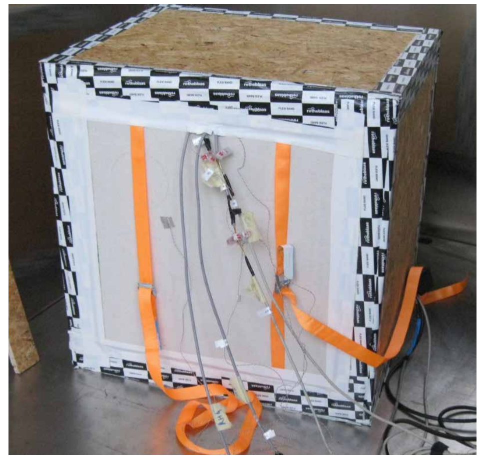

FIG. 2 Specimen closing the box

2.2 BOUNDARY CONDITIONS

In order to analyse the behaviour of the component under critical temperature and high humidity conditions, two tests were undertaken. In the first one, typical hot and humid conditions for the outdoor environment were used. In particular, the temperature was set to such a high value (Fig. 3) to take into account the possible effect of direct sun irradiation on the façade.

In the second test, typical cold and very humid winter conditions were used (Fig. 4).

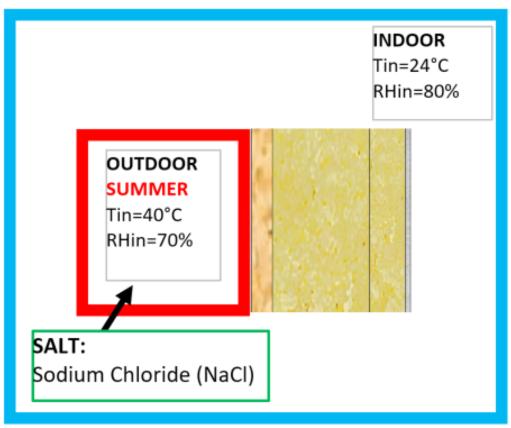

FIG. 3 Boundary conditions TEST 1 (hot/humid summer outdoor conditions)

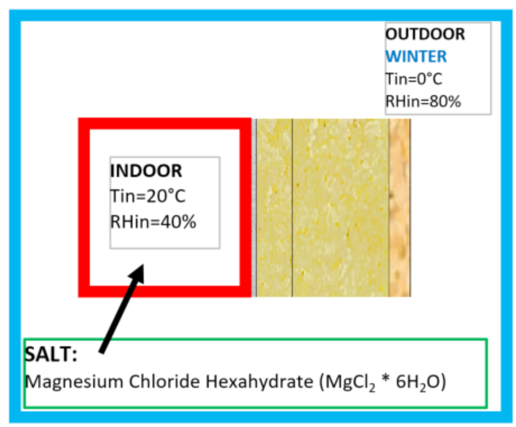

FIG. 4 Boundary conditions TEST 2 (cold/humid winter outdoor conditions)

The duration of each test was determined after considering the necessary time it would take to reach the thermal and humidity flux steady-state conditions in the specimen, accepting a difference of 0.1 W/m^2 (heat flux) and 0.1 g/m^2h (humidity flux) between entering and exiting fluxes, respectively. These values were assessed through a preliminary simulated numerical model. Finally, it was decided to let each test run for almost 15 days.

In the following figures (Fig. 5, Fig. 6), the monitored boundary conditions for the second test are reported. Conditions for TEST 1 are not shown because no relevant differences with designed conditions were present.

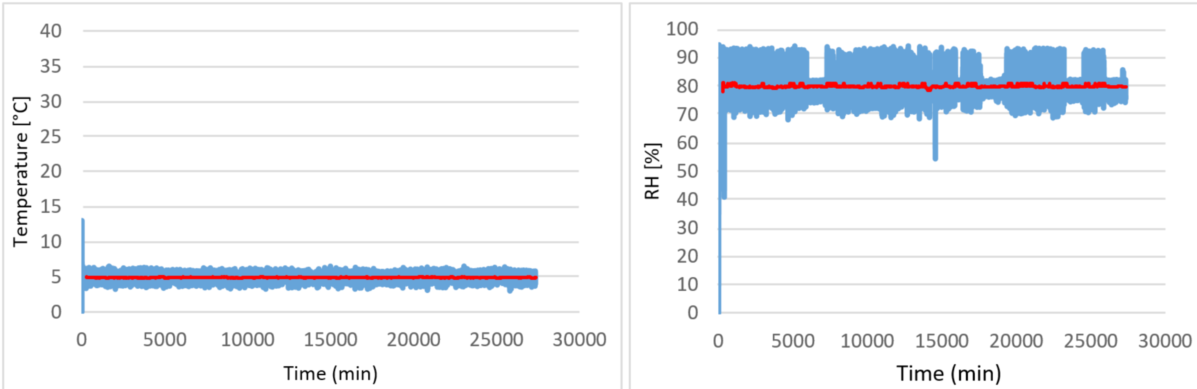

FIG. 5 Climatic Chamber Temperature (left) & RH (right) - TEST 2

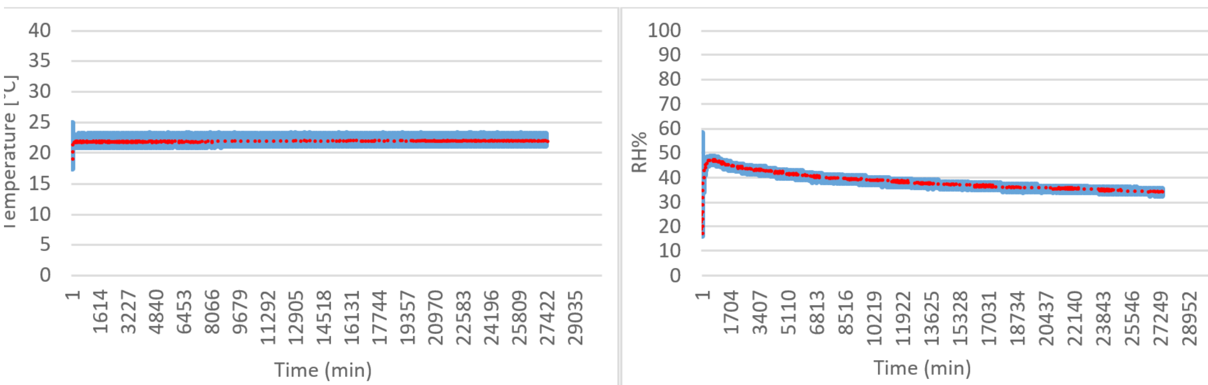

FIG. 6 BOX Temperature (left) & RH (right) - TEST 2

3 RESULTS

In this section, the results of the monitoring campaign are compared with those calculated by the numerical model built in Delphin 5.

All the results for temperature and relative humidity are referred to specific positions (namely 1, 2, 3, and 4) within the specimen. These positions are presented in Fig. 1.

The presented values obtained with the model were reached following a calibration process on some uncertain parameters, mainly related to the humidity transfer function of those materials whose technical sheet was not available.

3.1 TEST 1 – HOT/HUMID OUTDOOR CONDITIONS

In this test, NaCl solution has been used within the BOX to generate the desired humidity rate (RH=70%).
In Fig. 7 and Fig. 8, the monitored and measured trends for temperature and relative humidity at each material interface are presented.

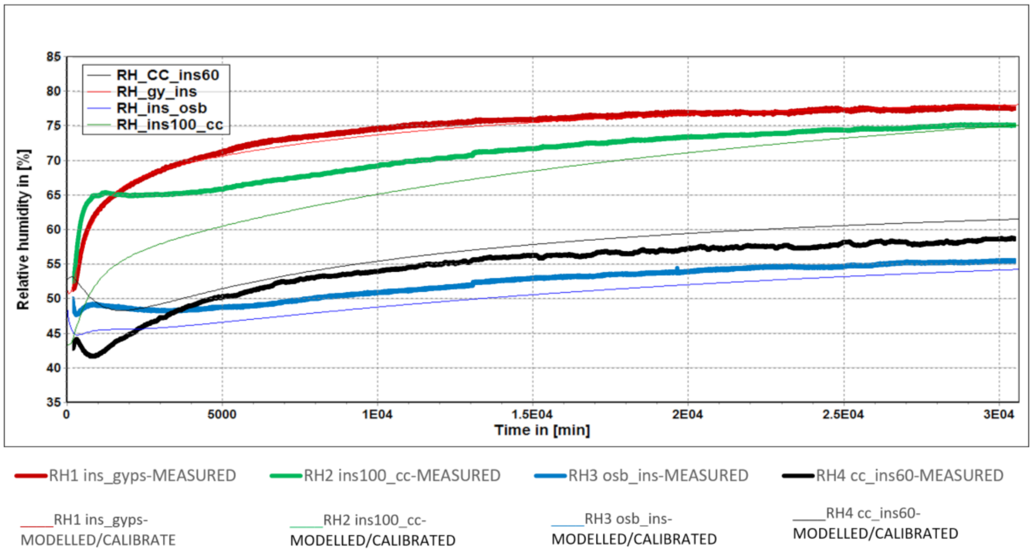

FIG. 7 Relative humidity trends – measured data (thick line) & modelled data (thin line) – TEST 1

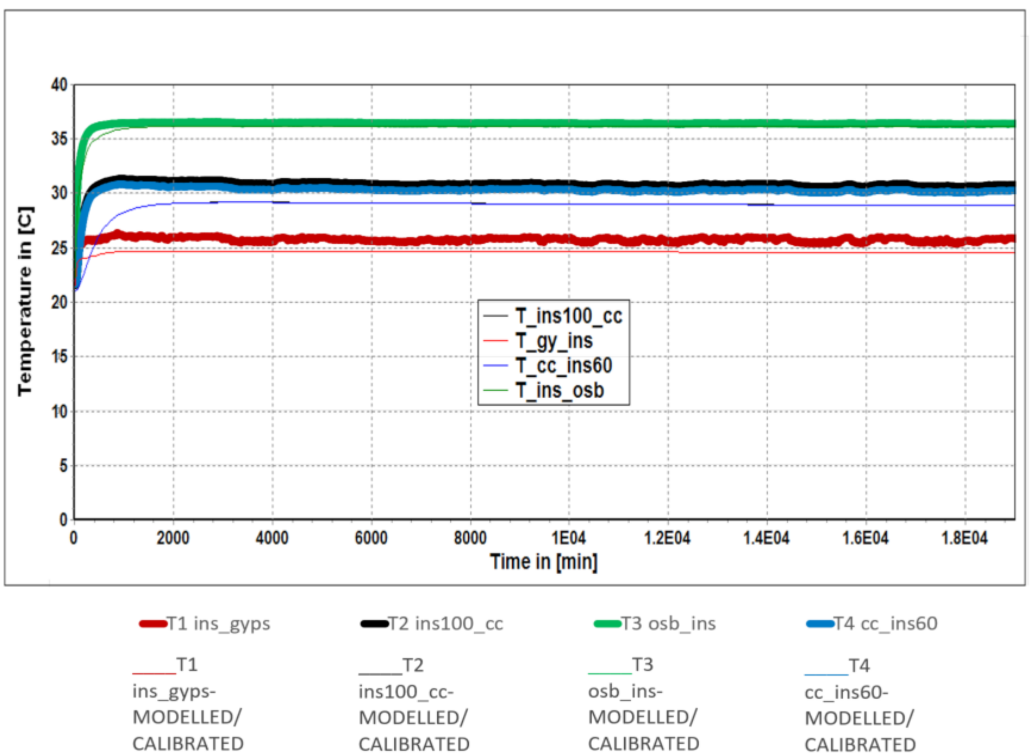

FIG. 8 Temperature – measured data (thick line) & modelled data (thin line) – TEST 1

Fig. 9 presents the comparison between measured (both calibrated and not) and calculated relative humidity, after having reached stationary conditions for vapour flux across the specimen.

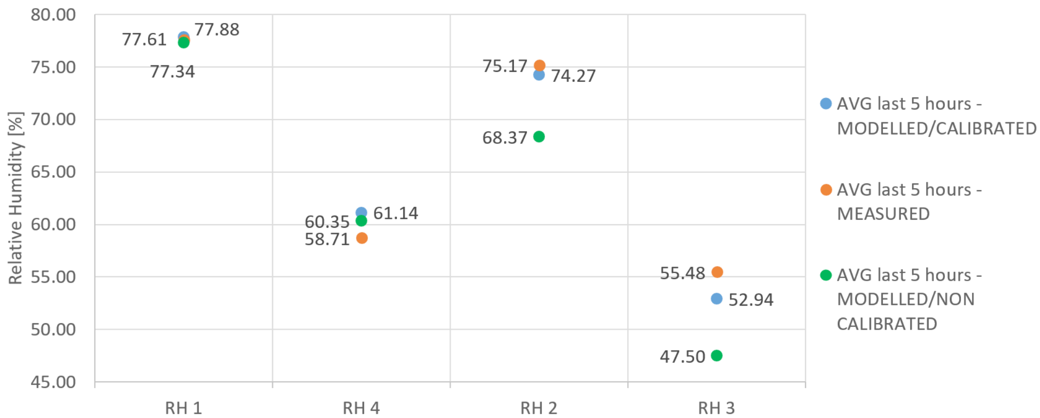

FIG. 9 Comparison between RH values measured & modelled, after stationary conditions (averaged on last 5 hours) – TEST 1

Table 3 and Table 4 present the standard deviation and the absolute value between calculated and monitored values for each sensor in the final hours of the simulation (after stationary conditions occurred).

RMSE(RH1)	RMSE(RH2)	RMSE(RH3)	RMSE(RH4)
0.18	1.11	2.56	2.38

TABLE 3 Root mean square error RH values - TEST 1

MAE(RH1)	MAE(RH2)	MAE(RH3)	MAE(RH4)
0.17	1.11	2.56	2.38

TABLE 4 Mean absolute error RH values – TEST 1

3.2 TEST 2 – COLD/HUMID OUTDOOR CONDITIONS

In the second test, $MgCl_2$ solution was used in order to create the desired humidity conditions within the BOX (RH=40%).

In Fig. 10, Fig. 11, Fig. 12, and Table 5, the results of the comparison between monitored and calculated data are reported for TEST 2. It can be noticed that complete steady state conditions have not yet been reached.

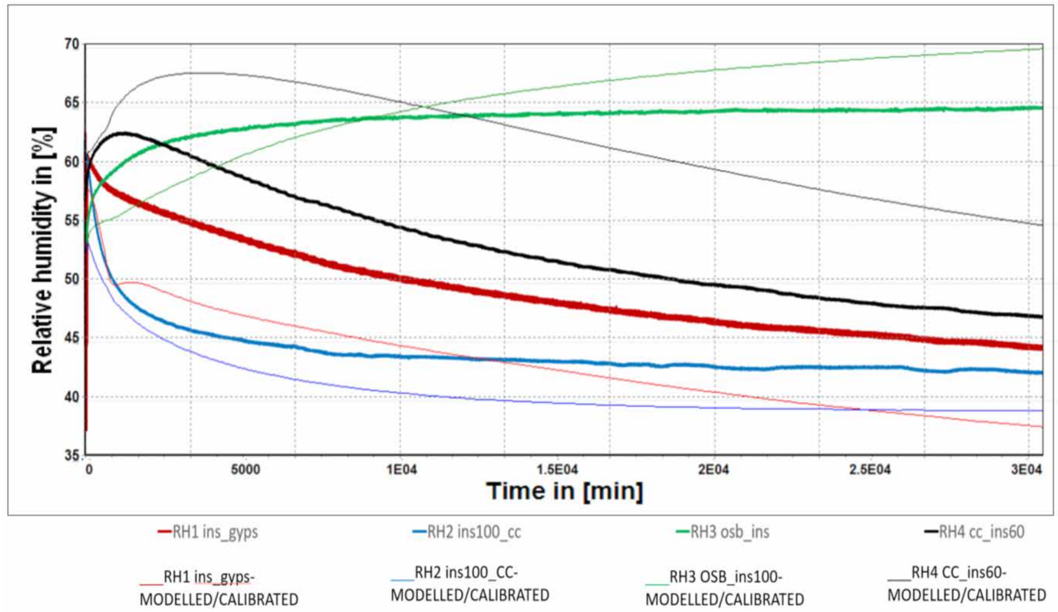

FIG. 10 Relative humidity trends – measured data (thick line) & modelled data (thin line) – TEST 2

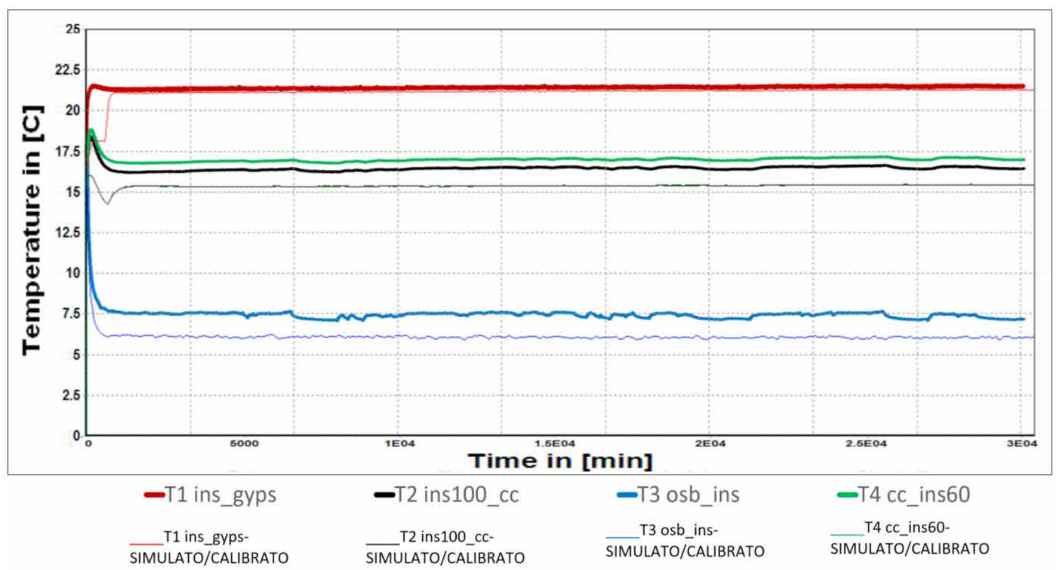

FIG. 11 Temperature – measured data (thick line) & modelled data (thin line) – TEST 2

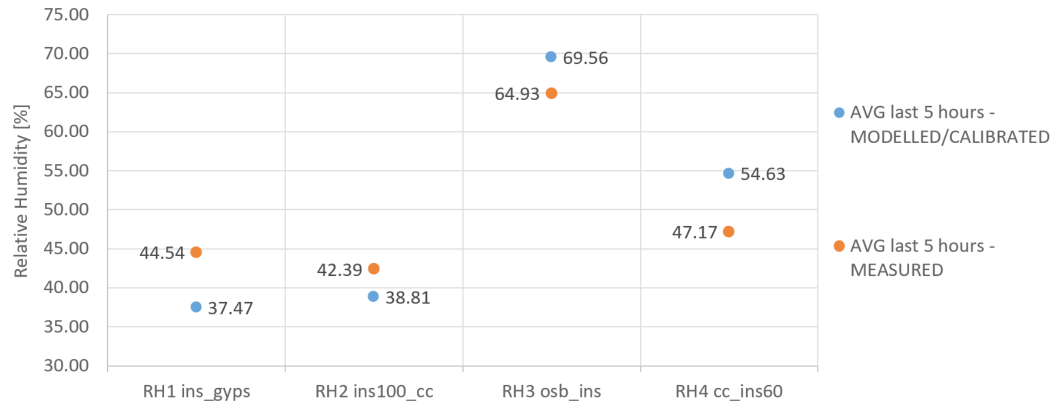

FIG. 12 Comparison between RH values measured & modelled, after stationary conditions (averaged on last 5 hours) – TEST 2

RMSE, MAE (RH1)	RMSE, MAE (RH2)	RMSE, MAE (RH3)	RMSE, MAE (RH4)
10.1	4.89	4.61	8.39

TABLE 5 Root mean square error & Mean absolute error RH values - TEST 2

4 DISCUSSION

In both tests, the measured temperature values are in agreement with the model results. This is due to minor uncertainties relating to the heat transfer process. The only small issues regarding the temperature are caused by the climatic chamber`s difficulty in maintaining conditions around 0°C in a stable way during TEST 2.

On the other hand, the relative humidity results (especially in TEST 2) show more discrepancies between the model and the reality. Possible explanations for this are as follows.

Firstly, it is noticeable from Fig. 5 and Fig. 6 that the relative humidity boundary conditions, both in the box and in the climatic chamber, have quite low stability: for the box, this can be due to a non-optimal dosage of the salt solution. Regarding the instability of RH level in the climatic chamber, the main problem is related with the too low operative temperature set in the machine (~ 0°C).

Although the results of the first test are in good agreement with the simulation, another source of errors in the tests can be related to the sensor positioning inside the specimen. In fact, while RH simulation results from Delphin represent the moisture contained in material`s pores, the E+E sensors that have been used in this experimental activity measure the humidity level in the small air cavity in the material in which they are inserted.

Another cause of uncertainty that is likely to have affected the second test is the inadequate estimation of drying time. Some humidity, trapped in the sample from the previous test, may have slightly influenced the results of the second test.

Finally, it should be taken into account that the physical properties' functions of all the materials used in the model, in particular those of less known materials within our specimen (e.g. OSB layer and vapour retarders), can themselves present small uncertainties.

In the future, this kind of study and experimental setup would allow for the reduction of uncertainties related to the material function by undertaking a step-by-step test and calibration of each layer.

5 CONCLUSIONS

It can be concluded that, in the first test, there is a good match between simulation and calculated data, with a maximum difference in stationary condition (value assumed as the average in the last 5 simulation hours) of 4% for RH and 1°C for temperature.

The less conclusive agreement of the second test is likely to have been caused by the above-mentioned possible reasons. Thus, considering the overall results of the performed analyses, it can be concluded that the modelling of the smart vapour barrier was successful. Overall, the methodology applied to this study, albeit with a limited budget, revealed itself to be a solid approach for the investigation of thermal and hygrometric phenomena in a building envelope sample.

Further analyses could investigate the hygro-thermal behaviour of the samples, using a double climatic chamber in order to set more stable boundary conditions across the specimen. Moreover, a comparison between different sensor typologies could be done (e.g. dimension, accuracy, output typology), in order to consolidate this approach to measuring within envelope components. Future studies should extend these analyses to more complex façade systems to investigate eventual problems related to the integration of components such as ventilation machines, PV modules, or solar thermal panels.

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BIM from Concept Design to Fabrication: A Customised Methodology for Façade Consultancies

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Abstract
When an architect ideates a complex building envelope, they often rely on a façade consultancy to develop the final detailed solution of their design. The purpose of this paper is to describe a customised BIM methodology to develop complex building envelopes, evaluating the process followed to convert an architectural concept design to a fabrication reality.

Over recent years, building information modelling has developed greatly in terms of architectural, structural and MEP disciplines. It conveniently advances and analyse the variables of a concept design, and furthermore, coordinates disciplines during the detailed design phases. However, when a technical approach to the envelope's design must be implemented, we need detailed engineering tools to simulate the environmental data, and to analyse and develop the system's fabrication features and assemblies, which are tedious to incorporate on BIM basis.

This paper describes the process followed to develop and execute a building envelope project, starting with a concept design and incorporating virtual simulation processes for the solution to meet its structural and thermal requirements. The final aim is to have detailed drawings and documents of the envelope's elements, with coordinated information for construction and fabrication purposes.

Keywords
Building Information Modelling (BIM), Prototyping, Digital manufacturing

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1 INTRODUCTION

The architecture, engineering, and construction industry (AEC) is facing an era in which technology is improving the way we develop projects, as well as the techniques and the materials used for those projects. Blanco, Mullin, Pandya, and Sridhar (2017), from the McKinsey Institute, explain how new applications and tools are changing the way companies design, plan, and execute construction projects. Since such designs are becoming increasingly complex and expensive, managers must take into consideration solutions for cost improvements, the timelines of projects, and the overall efficiency of the construction process.

The construction industry is one of the largest in the world economy, despite having the dubious honour of being at the tail-end of labour productivity in most countries. Fig.1 shows how the construction sector labour-productivity growth averaged 1% per year over the past two decades, compared with 2.8% for the total world economy, and 3.6% for manufacturing. The complete study is found in the McKinsey report (Barbosa et al., 2017).

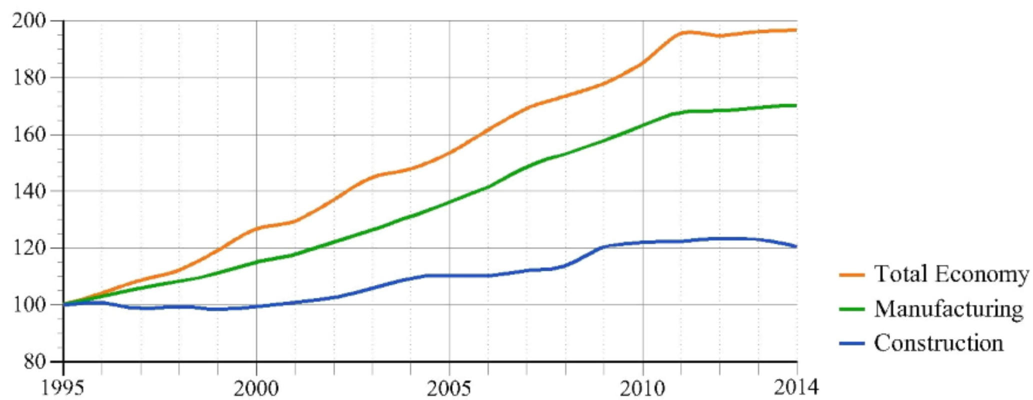

FIG. 1 Global productivity growth trends. Source: McKinsey Global Institute

The McKinsey report outlines how productivity can be improved in the sector and suggests seven actions that the construction industry should adopt: (1) reshape regulation and increase transparency; (2) rewire the contractual framework; (3) rethink design and engineering processes; (4) improve procurements and supply-chain management; (5) improve on-site execution; (6) infuse digital technologies, new materials and advanced automation; and (7) reskill the workforce.

This report also profiles how productivity in the construction sector will increase if some parts of the industry move to a manufacturing-style production system, such as the projects developed by Barcelona Housing Systems or the Osirys Research Project: Forest Based Composites for Façades and Interior Partitions to Improve Indoor Air Quality in New Builds and Restorations.

The AEC industry needs to adopt an integrated advanced platform that spans project-planning, design, construction, operations, and maintenance. Companies can start by making 3D building information modelling (BIM) universal within the company's workflows along with digital collaboration platforms to establish transparency in the design, costing, and progress visualisation of a project. Frontrunners in the construction industry are embracing the BIM methodology, as they have with other new technologies such as 3D printing, cloud computing and Big Data. The need for synchronised information throughout the project life cycle is beneficial not only for project owners and for contractors, but for the efficiency of every design team involved in the construction sector. In addition, the advanced analytics enabled by the Internet of Things improves on-site monitoring of materials, labour, and equipment productivity.

When the BIM methodology is adopted correctly, it facilitates an integrated design and construction process, and enables an improved on-site execution. This is verified in the McKinsey report by means of case studies that have been developed in different countries around the world, where the use of new technologies, along with Building Information Modelling, allows them to achieve greater productivity.

2 BUILDING INFORMATION MODELLING OF ARCHITECTURAL ENVELOPES

Building Information Modelling (BIM) is a very broad term that describes the process of creating and managing information about a built asset through one or more virtual models that are digitally constructed. BIM technology supports design through its phases, allowing better analysis and control than with manual processes. When completed, these computer-generated models contain precise geometry and data needed to support the construction, fabrication, and procurement activities through which the building is realised.

In 2014, the European Union urged member countries to adopt BIM on public projects to improve the productivity of the AEC industry. The efficiency outcomes are realised in viewing the design, construction, and operation as a whole: the life cycle of the asset. Traditional construction relies on 2D drawings for information sharing, while BIM provides an added dimension to design, communication, and strategic planning. 3D digital models allow clients and project teams to view a design with more accuracy than any flat image can provide. In 2017, the British Standards Institution published the new ISO 19650, describing the international standards that must be followed for information management using BIM. This standard gives recommendations for a structured framework to manage, exchange, and organise information through the whole life cycle of a built asset, and guidance for organisations to develop the right commercial and collaborative environment so that information is produced in an effective and efficient manner during the project's delivery phases, reducing wasteful activities.

All of these standards are also applicable for the envelope models, where information exchange amongst the architectural and structural teams is crucial. The correct organisation of the information required to develop the project within the team is also a key factor. The following points outline the basis of the BIM methodology and provide specific guidance for the development of the envelope information models.

2.1 DIMENSIONS WITHIN THE DIGITAL MODELS

Everybody familiar with the BIM methodology knows about the dimensions of the models, which comprise the basic difference - as well as the benefit - of using this technology. Building elements have geometrical and classification standards as basic information, which lead to automated

FIG. 2 The new dimensions of BIM models. (Image by Gammon Construction Ltd, 2015)

measurements and billing of the components in the model. We can also associate timeline information to the elements that compose the envelope for planning construction, procurement, and logistics. The sixth dimension of the virtual models is particularly relevant for building envelopes because the solar and thermal simulations will determine a sustainable solution for the performance of the building. Finally, strategic decisions regarding the maintenance and operation of the asset can be made prior to the construction, making the project 7D. This is important in technological envelopes, where the building maintenance unit (BMU) is often needed in the project, and therefore the consideration of the maintenance of the glass elements of the façade is essential in the design phase. By using BIM to develop design options during a project, we can see in a matter of hours the consequences that will result from decisions made in all dimensions of the project.

We can see in Fig.2 how new dimensions are being introduced in the construction scheme to integrate new fabrication methods, such as the use of robots in the process of assembling façade components, or the introduction of the IoT (Internet of Things) in the entire construction process. What is referred to here as BIM 8D is especially interesting in terms of the optimisation of the design process of the envelope, having an automated analysis and a calculation of the façade's external condition, and integrating the standards with which the envelope needs to comply in the same process will provide us with a satisfying design basis.

2.2 COORDINATION WITH OTHER DESIGN DISCIPLINES. INFORMATION EXCHANGE.

The building envelope is currently considered as an independent design discipline in the construction schema, and this is a new departure, since it was always part of the architectural model. This is undeniable when we consider the definition of the discipline provided by the American Nation Institute of Building Sciences: "each design discipline has a different set of skills, professional standards and issues that drive how they operate in the building process".

The building envelope must be fully coordinated with the structural engineers' information, but also with architectural finishes, HVAC, plumbing, and electrical systems. An integrated design of a building requires the various stakeholders and disciplines to interact as early as possible in the process, and making available the clear information that is required at each stage of the project for the resolution of design objectives.

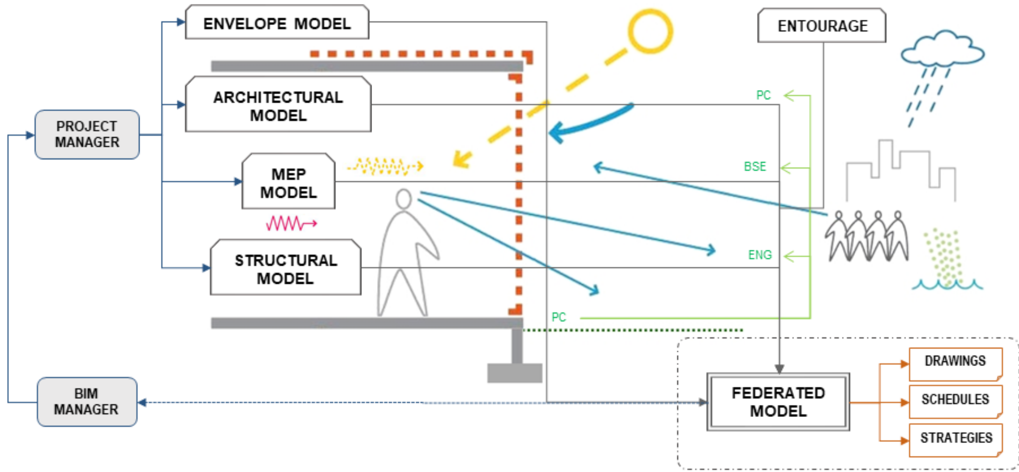

FIG. 3 Diagram of a BIM design collaboration team.

"A building envelope must reconcile many requirements –ventilation, solar heat gain, glare control, daylight levels, thermal insulation, water management, materials, assembly, sound and pollution control– making the design a complicated balancing act." (Lovel, 2013).

The integration of environmental systems in the solution of the envelope must be a synthesised and integral part of the design process. For this to be accomplished there must be a comprehensive and clear information exchange between all the disciplines involved in the design of the asset, which is achieved more easily using BIM models.

DESIGN DISCIPLINE	REQUIRED INFORMATION	INFORMATION DELIVERED
ARCHITECTURE	Geometry, materials, aesthetics	Surface perimeter lines
	Space characteristics, occupancy	Accesses, comfort quality
STRUCTURE	Supporting elements	Façade system loads
	Characteristics, resistance	Anchorages & stiffeners
MEP SYSTEMS	Ventilation, heating and cooling	Thermal gains
	Drainage strategy, electric support	Façade transmittance

TABLE 1 Basic information exchange for envelope's development.

2.3 MANUFACTURED OBJECTS FOR BIM

Many platforms facilitate façade components for virtual models, where thousands of objects and construction systems can be downloaded with all the accompanying information to cover all the levels of development (LOD) needed in the project. This data is useful when the aim is to create an as-built model for operations and we need to incorporate all the characteristics of the building components for their future replacement or maintenance (LOD 400). However, all this information is unnecessary in the project phase, when we need to define the solution clearly in order to develop shop drawings.

FIG. 4 Level of development of a curtain wall system. (Image by BIM forum)

The problem that many designers face when downloading these elements is the size of the files, due to all the associated information and the custom variables that the elements present. As façade consultants, we often work with customised solutions or non-commercial building components made for a specific project, and therefore, we must create new specific components for each project. Following the project progress timeline, which can be associated with the different LOD of the building components, we start by defining the 3D geometry and introduce the information and details needed to define the element. The detailed development of these bespoke assemblies is one of the frameworks of this optimisation.

Part of the engineering proposals given by the façade company is the provision of an extremely detailed solution, which is in contrast with a typical architecture detail. Experience has taught us that we cannot associate every detail of the building elements in order for them to appear when making a section or a plan view of the model. Maintaining the same level of detail of components on a BIM model as if it were a CAD drawing will simply cause the model to crash. The aim of the 3D model is to coordinate the façade solution with other disciplines and share information with them. Most of these 2D details are unnecessary for this purpose, but are required for drawings produced for fabrication purposes and for detailed specifications. Being able to discern what information is necessary for the specific purpose in each phase of the project is the first step of the optimisation process.

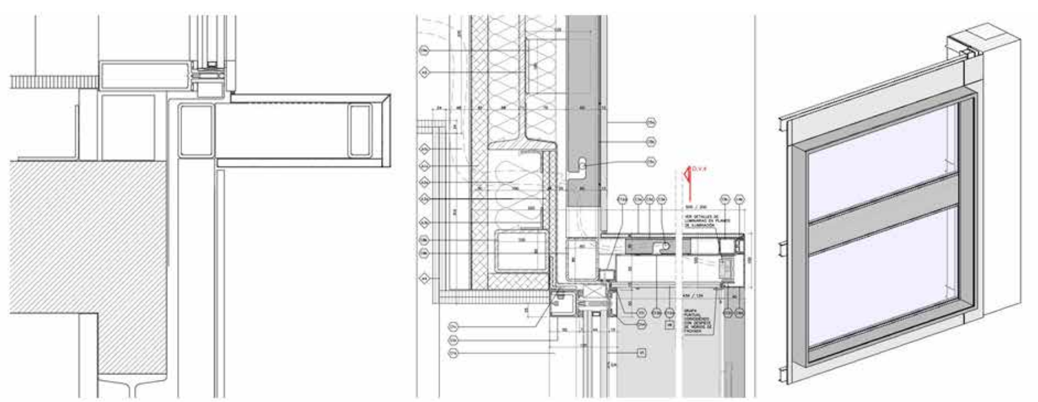

FIG. 5 A detailed envelope drawing versus the BIM model.

2.4 FRAGMENTED DELIVERY PROCESS VERSUS INTEGRATED STRATEGIES

One reason for the industry's poor productivity record is that it still relies mainly on paper to manage its processes and deliverables such as blueprints, design drawings, procurement and supply-chain orders, equipment logs, daily progress reports, and punch lists. Due to the lack of digitisation, information sharing is delayed and may not be universal.

Fig. 6 represents the different design approaches taken by the consultancy when delivering a project. The first diagram represents the traditional workflow and technical roles, while the second shows an integrated BIM methodology with the software simulations tools within the project.

Most of the BIM protocols focus on collaboration techniques and the various disciplines involved in a project, as well as the information exchange between them, which is key to developing a comprehensive and well-coordinated project. These fundamentals are also applicable to the work developed by the team of consultants when creating and executing a building project. It is necessary to move over to integrated strategies and collaboration platforms for sharing information within the companies to increase productivity, and avoid the loss of information and lack of coordination. Incorporating BIM into the design workflow of the envelope project allows us to evaluate it as a whole and comprises a unique database for all the information associated with the components of the building. The benefits of BIM for subcontractors and fabricators are widely analysed in the BIM handbook (Eastman, Teicholz, & Sacks, 2011).

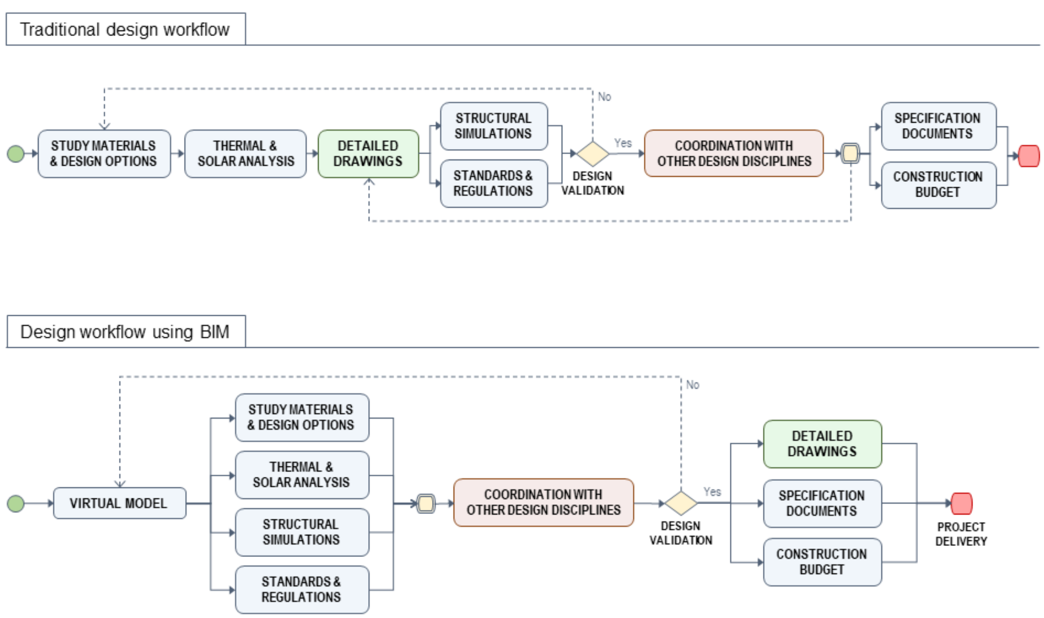

FIG. 6 Traditional design workflow versus a BIM integrated workflow.

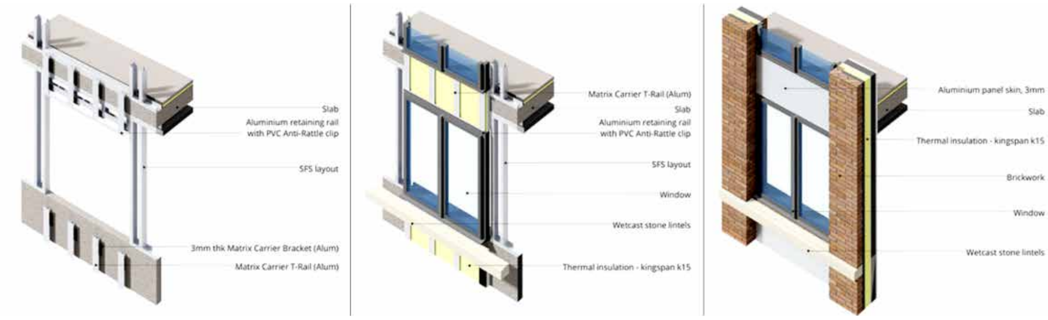

FIG. 7 Detailed fabrication model. (Image by F+A+T Facades, U.K)

3 OPTIMISATION OF THE DETAILED DESIGN METHODOLOGY

As a consultancy, we must adapt our workflow to the criteria established by our clients, and each one has a different way of handling the information they give to the design disciplines involved in the construction project. We work with the BIM software Revit, from Autodesk®, but our clients may not work with the same platform or even with BIM at all. Therefore, the first step for our design team is to translate the basic architectural and structural information received -when they are not Revit models - in order to define a common starting point from which to develop the project and follow the same BIM methodology regardless of what the incoming source is. We also have to define an exchange procedure to coordinate the design process, and this depends on the software used by our clients.

The type of building determines the objectives and the main characteristics that need to be obeyed by the envelope. We develop a wide variety of projects, such as offices, hotels, greater complexes such as shopping malls or refurbishment of existing buildings. Whatever the type of building, it is important to establish how our team will use the model, as well as determining the uses our client needs for the efficiency of the design process.

In multiple phases of a building project, the envelope designers need to interact with various simulation tools to predict the performance of the model, which makes interoperability among different programs a necessity (Chi, Wang, & Jiao, 2015). We use mainly Autodesk® tools, which implies that they have a priori good interoperability between each other, although this is not always directly achieved. For example, within the Autodesk® tools, there is a gap between the software used in architecture and software intended for fabrication: architecture, engineering, and construction (AEC) is a different collection than the one intended for product design & manufacturing (PDM).

Every façade solution is preceded by the geometry and the materials ideated by the architect. The design of the building envelope takes into consideration the form, size, and type of the glazing elements in order to create an energy efficient model with a maximum level of acceptable daylight. The BIM-based performance optimisation described in the BPOpt article (Asl, Zarrinmehr, Bergin, & Yan, 2015) can be used to evaluate the variables and search for an optimal solution at an early stage of the design, which is frequently done prior to the detailed development of the project that supports the architect in the design of the façade.

The consultancy has to find the best technical solution to satisfy the design intent of the architect, while also considering the structural stability of the façade, the thermal conditions required in the building, and the compliance of international construction standards without disregarding the aesthetic of the envelope.

TASK DEVELOPED	INPUT	PROCESS - SOFTWARE	OUTPUT
Architectural and structural base for the façade design	2D .dwg Files 3D .sat Models	AutoCAD Dynamo	Coordination model
Envelope geometry	Coordination model	Revit	Base model
Basic solar analysis	Façade base model	Revit sun path / Insight	Design criteria
Structural constructability	Façade base model	Dynamo / Excell	Structural criteria
Detailed development	Detailed drawings	Inventor / Revit	Fabrication module
Detailed sun analysis	Geometry model	Dynamo / Ecotect	Performance
Detailed structural solution	Façade model	Revit / Dynamo / Robot	Structure model
Execution project	Envelope models	Revit / Dynamo / Inventor / AutoCAD	Drawing production

TABLE 2 Software integration and automation processes considered.

We usually start the detailed project from 2D CAD drawings or 3D rhino files received from our clients, where the geometry of the building is defined and the structure outlined. Using the BIM platform along with its open source visual programming tool Dynamo allows this process to be automated and have a reliable construction model with which to start the process of detailed design of the envelope. BIM represents the building as an integrated database of coordinated information, and enables sharing this data for interoperability between prevalent software tools for specific simulations.

Once we start to develop the solution, we have to analyse the characteristics of the structure, and the geometry of the project as a whole, to consider an optimal technical solution. The size and form of the building elements have already been defined on a 3D coordination basic model. Performing a basic analysis of the solar path and the radiation reaching the façade within the BIM model will establish the design criteria we need to consider. Having an initial estimation of the wind loads and the stability of the structural components is also necessary at this stage to have reliable dimensions of the components that will be assembled in the solution. This process can be optimised using Dynamo to extract the geometrical information needed from the model and automatically introduce it into calculation sheets.

Once these analyses have been completed we have the technical criteria to do a first sketch of the typical detailed solution of the façade that needs to be validated by the architect in order to establish the coordination dimensions with the structure and the rest of the disciplines.

We can then start to develop the detailed envelope model with the typical solutions considered. Using BIM coordinated models with other disciplines allows us to detect and analyse different encounters that need to be solved on the project being executed. Performing clash detection with structure, interior finishes, and MEP systems is a key process for automating this task.

When the structural elements of the façade are complex, we introduce specific analysis tools like Autodesk Robot® to our workflow. Finally, when the assemblies of the components are especially challenging we also use fabrication software to develop a detailed 3D model of a façade module. Autodesk Inventor® allows us to assemble the components of a module and have a detailed analysis of the element's structural performance. This software will also allow us to generate drawings showing the assembly instructions of the components on a timeline basis.

Whichever software is used throughout the envelope's development, the final goal of the detailing process is to have all the documents needed for the construction of the building. The implementation plans and technical documentation of the systems must be clear, coordinated, and comprehensive.

FIG. 8 Digital construction organization. Source: McKinsey Global Institute

4 EVALUATION OF THE PROCESS

The knowledge generated with each project that we develop in the consultancy with the BIM methodology differs, in part because we never work on the same building types or with the same materials, and partially because our workflow must be adaptable to the one our clients follow.

Fig. 8 illustrates the five trends that will shape the digital construction organisation of the near future, developing the next generation of digital-native leaders to deliver projects of the future: (1) higher definition surveying and geolocation, with rapid digital mapping and estimating; (2) next-generation of 5D building information modelling; (3) digital collaboration and mobility, moving to paperless projects; (4) the Internet of Things and advanced analytics, that will enable intelligent asset management and decision-making; and (5) future-proof design and construction, by integrating materials and methods of the future into our designs.

Every project becomes an opportunity to test and refine our workflow, optimise the interoperability and coordination processes within our team and discover new digital solutions that can be tested on future projects. For this to be accomplished, there needs to be not only a commitment to invest on innovation, but also continuous training of team members -as well as the leaders- who need to use the latest equipment and digital tools.

5 CONCLUSIONS

In the Spanish construction system, there are several phases of the design project to undertake before we can obtain the construction permits given by the appropriate authorities, and once these permissions are obtained and the design is finalised, the builders are chosen to materialise the project.

Using Building Information Models allows fewer errors during the on-site construction process. Developing and executing a project solely of the façade does not save time in the construction process. Quite the contrary, we must develop a virtual coordinated construction model of the entire envelope, instead of developing the typical details of the façade components needed for the subsequent fabrication process. Not only should the time spent in developing a façade engineering project increase, but the owner's budget for the design phase should also increase accordingly, since, with the use of BIM, savings are realised in the construction phase and the management of the asset.

The process of digital collaboration and mobility means moving away from paper toward online, real-time sharing of information to ensure transparency and collaboration within a project. For this to be accomplished, there needs to be a change of mentality in many fields within the construction industry, and this goal is, unfortunately, a remote one today.

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New Biocomposites for Innovative Construction Façades and Interior Partitions

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Abstract

Osirys is a European Research Project where a holistic solution for façades and interior partitions ready to be applied in building retrofitting and new construction has been developed. The project uses biocomposites as the base material to define different products: a multilayer façade, a curtain wall, a window, and an interior partition. The biocomposites developed have different functionalities able to meet the strictest requisites of the European Building Codes in relation to fire and structural performance, improve indoor air quality through the elimination of VOCs (volatile organic compounds) and microorganisms, increase thermal insulation, and increase the durability of construction elements. The new systems are lighter than traditional ones, leading to reductions in overall weight, thereby reducing implementation costs during both manufacturing and assembly processes, thanks to an industrialised concept that utilises modular elements.

The project was developed with the collaboration of 18 European partners (5 research centres, 9 SMEs, 2 large industries, and 2 public bodies). The main activities were devoted to the establishment of requirements, the development of materials, the design of products, the integration of materials into products, the verification of properties by simulation and testing according to EU standards, the integration of products into real buildings, and economic and environmental assessment.

The scope of this paper is to provide a general overview of the entire project work and results to demonstrate the feasibility of using biocomposites in envelope solutions with the aim of solving some of the main problems that exist in façade traditional solutions. The project finishes with the implementation of the developments in real buildings as prototypes; further research is required before industrial scale manufacturing of the systems can be launched into the market.

Keywords

façades, curtain wall, biocomposite, multilayer façade, interior partition, windows.

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1 INTRODUCTION

Nowadays, several types of façade systems are used (traditional systems like brick façades, and steel and aluminium curtain walls). However, various problems are associated with these façades, as listed below:

- The use of steel and aluminium, materials with high thermal conductivity, demand the use of a different material to avoid thermal bridging. This requires the use of geometrically complex profiles and is therefore problematic for manufacture. New materials with better thermal attributes can improve this behaviour, with less complexity in geometry and manufacturability.
- The use of fossil resources and high energy consumption in the manufacturing process must be reduced. New materials from natural resources, such as bio-based materials, can accomplish a more sustainable production process and a better use of natural resources (eventually achieving a better result in relation to a circular economy in which all the materials and processes are connected during their entire life cycle).
- Many materials that are now on the market have problems in relation to the generation of contaminants (like VOCs, formaldehyde, fibres, and particulates). New materials that do not generate such contaminants are needed. Moreover, active materials that can eliminate this type of hazardous components and other elements, like microorganisms emitted by other sources, are required. This requirement is produced by an increased concern for indoor air quality in buildings, a requirement that will soon become more stringent due to new standards and regulations that are in the process of being approved in Europe.
- It is necessary to avoid the use of water on construction sites and to reduce the amount of sub-standard work normally involved in the construction of a building. It is essential to explore new solutions that have a high component of industrialisation and a modular approach, that avoid the use of water on-site and improve the quality of the final work by increasing work completed in the factory and reducing these works during the installation process. This also leads to higher skills amongst the workers that participate in the entire process.

Additionally, new possibilities related to design in the envelope should be explored. The use of new materials with different manufacturing processes can lead to new solutions that work better for building envelopes, avoiding the constrains of the current materials.

With the aim of solving the above-mentioned constraints, the Osirys project was developed. The aim of the project was to design a holistic biocomposite façade solution with better performance than traditional solutions. The selection of the biocomposite materials was done according to their performance with regard to thermal conductivity, design possibilities, absence of hazardous materials, industrialisation capacity, and reduction of use of fossil fuel resources, in comparison to metals, the current most widely used material. However, the use of a new material with different characteristics involves a complete redesign of the product geometries and construction process. Thus, the Osirys project starts with the development of different biocomposite materials, progressing through the design and manufacture of biocomposite products, and finishes with the testing and installation of these products in real conditions.

The project has been running for 4 years with the collaboration of 18 partners, of which there are 5 research centres, 9 SMEs, 2 industries, and 2 public bodies, from 11 EU countries. The consortium combines scientific and technological knowledge on materials and design to reach the goal of the Osirys project.

- The RTOs (Research and Technology organisations) focused on the development of materials, the improvement of their characteristics, environmental assessment, and validation of performance through standardised testing.
- The SMEs and industries up-scaled the laboratory-scale processes to semi-industrial processes to produce real-scale products, and developed the engineering and architecture to allow them to be installed in the demo buildings.
- The public bodies were in charge of the demo activities by using the products in real buildings.]

The methodology followed to obtain the final results during the execution of the project is explained below:

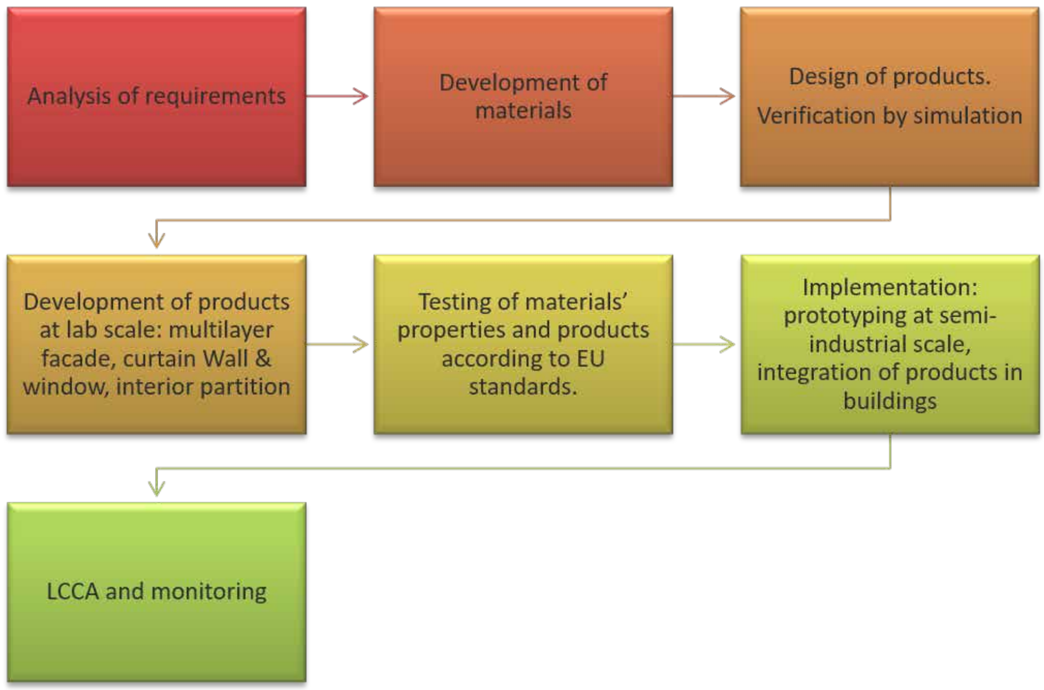

FIG. 1 Methodology to design and develop Osirys products

Taking into account these requirements, the following materials and products were developed in the project:

Materials developed for use as components of the final products:

- **Light foam biocomposite**: to be used as a base material for the internal layer of the different components developed. With improved thermal characteristics and less weight. Complying with building codes requirements.
- **Natural insulator**: to be used as an insulation component in the different systems. Improving fire behaviour without losing thermal characteristics.
- **Biocomposites with improved mechanical and fire performance**: one of the problems of the composites is their poor mechanical performance when compared to steel and aluminium solutions. New developments using different types of resins and fibres must be explored to avoid this problem. Moreover, the fire performance of these materials must be improved to reach the requirements of the European regulations.

- **Biocomposites with good outdoor durability performance**: to improve the outdoor performance of these materials to make them comparable with the existing systems on the market such as cladding elements for ventilated façades.
- **Indoor multifunctional coating**: to avoid the generation of contaminants and to improve active characteristics to eliminate the problematic components that are present indoors after construction.

Final components and systems, utilising characteristics of the new materials developed:

- **Multilayer façade**: an industrialised system with the aim of substituting traditional opaque façades (brick and concrete) for a lighter option, with better thermal, acoustic, and fire performance and with enough flexibility to be adapted to different building solutions. Mainly built in the factory, with a kit concept to avoid works on site.
- **Curtain wall and window**: a biocomposite curtain wall and window, with less complex profiles, better thermal performance, and high aesthetic flexibility. Moreover, this uses a modular and industrialised concept.
- **Interior partition**: a system to construct all the internal walls of a building with the new eco-materials, without losing the beneficial qualities of traditional systems.

With these new developments, the project offers a complete solution to be used in both envelopes and interior partitions, in many different types of buildings (mainly residential, as well as tertiary buildings such as commercial, administrative, and offices), overcoming the problems associated with current systems.

The aim of this paper is to provide a general overview of the Osirys project, to make readers aware of the innovations that can be achieved by using novel materials such as biocomposites for façades and interior partitions. So, the information provided in this article is not an exhaustive detail of each development and test, but intends to give general information and results about new possibilities when using materials other than steel and aluminium.

2 OBJECTIVES FOR THE DEVELOPMENT OF THE NEW MATERIALS AND SYSTEMS

The development of such novel systems requires the fulfilment of several objectives. The most relevant ones are detailed below:

- Development of a new photocatalytic coating to be active under indoor illumination, with protection against fire, and coloured. It was estimated that a VOC concentration reduction to <1mg/m3 and mould generation is can be reduced by a reduction factor of 5-6 logarithmic units in 12 hours.
- Development of a lighter system with weight savings of 70% compared to traditional brick and precast concrete walls.
- Development of an industrialised system to reduce implementation costs. Assembly works were expected to be reduced significantly.
- Fulfilment of the main requirements from the European Building Codes related to mechanical resistance, thermal behaviour, fire, and acoustic performance, etc. (see tables in the article)
- Biomass feedstock was above 60% in the multilayer façade and almost 70% without including fastening devices.
- Assumed price increase of the system over traditional products: comparable price for the curtain wall, 32% increase for the multilayer façade, and 15-20% increase for the interior partition.

3 WORK PERFORMED

In order to achieve these results, the Osirys project was divided into different research activities that are explained as follows:

3.1 ANALYSIS OF REQUIREMENTS

The main objective of this work is to establish and quantify the requirements to be met by the developed materials and products as a basis for further developments to be achieved in the following works. In this regard, the following requirements have been considered and analysed:

- Characteristics that the materials must fulfil
- Design requirements for products to facilitate construction
- Regulatory requirements affecting the materials and products
- Market requirements focused on market drive forces
- Definition of the most common types of buildings where the new developments can be implemented

Results from LCA studies most commonly show that raw material production has the greatest importance in the total environmental impact of a product. Thus, in order to keep the environmental impact of a product as low as possible, the impact from raw material production should be minimised. Materials based on biomass feedstock were considered for the replacement of existing petrochemical and other traditional materials. Natural fibres such as wood, cork, flax, and jute, and bio-based biopolymers were considered for the development of new materials and products.

A first set of guidelines to design the four products defined in the project (interior partition system, multi-layered wall system, window, and curtain wall) were established. This process considered both a prefabricated system combining all Osirys elements and a site assembled hybrid system where the elements can be combined with commercial systems. Each product is made by combining the different materials that were developed in the project according to their final function (i.e. the curtain wall comprises profiles, the interior partition includes profiles, insulation, and coating, etc.). Each element that comprised the four novel products was defined, along with its function. In addition, reuse and recycling concepts were also considered in the design process.

In accordance with Construction Product Regulation (EU) N° 305/2011 (CPR), six Basic Requirements (BR) for construction works were checked to ensure that they are designed and executed so as not to endanger the safety of persons, domestic animals, or property, nor damage the environment. After analysing the requirements for the four products in various European countries, very demanding Osirys targets were set up. There is no specific regulation for indoor air quality, but various recommendations have been considered to minimise VOCs emissions and the growth of microorganisms.

Osirys products can be used in different types of buildings. Therefore, they were analysed for different building typologies (offices, residential, commercial, and culture/public), and were also related to building envelope types (multi-layered wall and curtain wall), while also considering the optimum U-value for each city/region of Europe.

3.2 DEVELOPMENT OF HIGHLY BIO-BASED MULTIFUNCTIONAL MATERIALS (TO BE USED AS THE BASIS FOR THE PRODUCTS DEVELOPMENT)

Within this work, several materials were developed, each one for a specific purpose.

Indoor multifunctional coating: The aim of this material was to decompose VOCs and introduce antimicrobial properties on indoor surfaces. First of all, a suitable method was developed, based on methylene blue to evaluate the photocatalytic activity of pigment powders and coatings under indoor lighting conditions. The developed coating showed good photocatalytic performance based on the methylene blue method; activity performance was higher than other commercial products. A testing setup to analyse antimicrobial properties was optimised. Results indicated that the new paints show very good antimicrobial activity against two selected microorganisms: Aspergillus niger (mould) and Sarcina lutea. To evaluate the fire performance of the coatings, cone calorimeter testing was carried out. The coatings did not ignite on aluminium substrates and did not contribute to the release of heat. When applied on organic substrates, the adhesion was good but it was necessary to add a fire retardant to the coating to reduce heat emission. Customers and architects are interested in having a coating with a range of colours, and so the coloration capacity of the coating was evaluated along with the stability of the colour after three months in both standard indoor conditions and extreme humidity conditions. Results showed that every colour is available in bright shades and remains stable over time.

Light foam biocomposite: The aim of this material was to develop a light foam biocomposite sandwich panel with good mechanical, thermal, and acoustic performance for use in interior walls. The surface panels that best promote mechanical and sound absorption properties were found to be porous wood fibre webs produced by a foam-laid forming technique. The core layer was formed by expanded biopolymer foam produced by extrusion to improve thermal and sound insulation properties. Initially, fibre material, additives, process parameters of foam forming, pressing and drying processes, and manufacturing procedures for fibre web production was tested and optimised. The formulations with the best performances were optimised and several tests were conducted and compared to traditional gypsum board. Lignin-based biopolymer foaming was possible at lab-scale, but up-scaling the process was unsuccessful. Therefore, PLA based biopolymer foam was optimised. PLA foam layers of 10-15mm thickness were obtained with a density of 60 kg/m3 and thermal conductivity in the range of polystyrene. Pilot scale layers were obtained. The thermal performance of PLA foam was better than commercial XPS.

SAMPLE ID	THERMAL CONDUCTIVITY [W/MK]	THERMAL DIFFUSIVITY [mm^2/s]	SPECIFIC HEAT PER VOLUME [MJ/M^3K]
PLA FOAM 05/15	0.037	0.449	0.083
XPS (Reference)	0.033	0.573	0.057

TABLE 1 PLA foam thermal performance

Natural insulator: Cork materials were used as part of the sandwich panels to improve the thermal and acoustic performance of the final systems. Although cork is a natural material with fire resistance properties, agglomerated cork with different binders could affect the fire performance of the material. The main objective was to improve the fire performance of the cork materials. To do so, different fire retardants were included in the agglomerated materials. Samples were produced by block technology, cylinders, and double belt press. A small flame test was used as a screen process and the best formulations were tested in a cone-calorimeter to analyse the ignitability, the fire propagation, and smoke density. In general, the production line products showed worse fire reaction performance than laboratory ones. However, all the fire analysed retardants improved the fire-retardant properties of the samples.

Biocomposites with good outdoor durability performance: following research on different coatings, six commercial coatings have been selected (four colour coatings and two transparent coatings) for evaluation in terms of their suitability for improving the outdoor durability of the biocomposites in their use as ventilated façade cladding. Durability was assessed by testing the samples for 1000h in a QUV device. In addition, the mechanical performance of the coatings was also evaluated.

Biocomposites with improved mechanical performance: To increase the mechanical performance of the biocomposites to be used as profiles, graphene functionalisation was tested. A roll mill was selected as the optimum dispersion method of graphene in bioepoxy resin. It was possible to include a minimum percentage of nanofiller in the system without a substantial increase in viscosity. Afterwards, the pultrusion process at lab-scale was optimised as follows:

- Modifications to the pultrusion equipment to adapt to the curing cycle of the bioepoxy resin
- Processability evaluation of the bioepoxy resin with glass fibre and graphene
- Impregnation of the flax fibres by combining them with glass fibres, graphene, and a standard polyester resin
- Rebars with different formulations were obtained for mechanical testing
- Tensile tests of the biocomposites indicated that graphene does not improve mechanical performance of the materials and flax fibres did not reinforce as successfully as glass fibres. However, hybrid systems composed of flax fibres and glass fibres provided similar mechanical performance as glass fibres.

Biocomposites with good fire performance: Thermoset biocomposites were protected by three methods: coatings, the use of mats impregnated in a liquid flame retardant, the use of graphene. However, dispersion problems in infusion type bioepoxy hindered the use of graphene as a fire retardant. In pultrusion bioepoxy, the graphene contributed somewhat positively to the fire-retardant effect. In terms of protective coatings, all of the coatings tested for improved fire performance were tested by single flame test. The best candidates were tested in the cone-calorimeter. The intumescent coating showed the best results. In the case of thermoplastic biocomposites, different fire retardants and natural fibres were tested.

FIG. 2 Osirys products under testing (from top left, clockwise): fire resistance test for multilayer façade, acoustic test preparation, wind load test for the ventilated façade (external layer of the multilayer façade), Kubik testing for thermal properties,)

3.3 INTEGRATION OF MATERIALS INTO COMPONENTS

The overall objective of this part of the work is to combine the different materials developed previously into the final components.

Manufacture of sandwich structures: The different materials developed by Osirys partners were characterised with respect to their thermal, mechanical, and viscoelastic properties, and combined to produce multilayer sandwich panels. Overall, these multilayer sandwich panels performed well, indicating their potential for use as partition walls, interior separation panels, and cladding panels in buildings. Their low density and the known properties of thermal insulation, acoustic insulation, and low hygroscopicity given by the configurations tested contribute to the value of these sandwich panels for the planned project demo cases in construction.

Evaluation of assembly properties: The aim was to develop an adhesive that can improve indoor air quality by achieving low VOC emissions while offering a good bonding solution for the sandwich structure. Adhesives provide some benefits over mechanical fasteners, like lower structural weight, lower fabrication cost, and improved damage tolerance.

Manufacturing and testing of lab-scale prototypes: Different configurations were produced with a variety of previously developed sheets, core materials, profiles, coatings, and adhesives, and were assembled to provide a wide range of solutions for the case studies proposed: internal partition and multilayer façade. The multilayer façade was divided in 3 sections: interior finish, multi-layered core module, and exterior finish panel. In order to choose the most suitable configurations, the thermal conductivity of the internal partition and interior finish was tested. Results indicated that the range of thermal insulation of the interior partition was similar to mineral wool and EPS, and that of the interior partition was similar to the use of natural fibres. With these results and the design results, the final configurations for lab-scale prototypes were set up.

PERFORMANCE	TEST	STANDARD	RESULT	COMMENT
Structural safety	Impact resistance to soft body	EOTA Technical report TR001, section 2	E= 500J, 1200J Permanent denting of the outer layer. No breakage or release of elements	OK No breakage
	Impact resistance to hard body	EOTA Technical report TR001, section 3	E= 5J, 10J No damage	
Protection against noise	Acoustic insulation	EN ISO 10140-2	R_w= 54 dB	OK Average with commer-cial products
Thermal insulation	Thermal Transmittance	Theoretical calculus	U=0.127 W/m^{2}K for the complete system U=0.193 W/m^{2}K with-out XPS	OK to targets defined by demo owners U_{tartu}=0.14 U_{spain}=0.25
Air permeability	Air permeability	EN 12114	Class 3 0.034 m^3/hm^2 at (+/-) 55 Pa	OK Values according to low energetic consumption buildings
Water tightness	Water vapour trans-mission	EN ISO 12572 and theo-retical calculus	μ_{cork}= 40 μ_{WPC}=1,700 $S_{d,total}$= 40m (3)	OK Breathable and non-breathable layers
Fire safety	Fire resistance	EN 1363	EI90	OK to target EI60 defined in the project
	Reaction to fire	EN ISO 11925-2	Bs2d0	OK to the target defined

TABLE 2 Resume of the obtained test results on lab-scale sandwich systems

3.4 DESIGN OF CONSTRUCTION SYSTEMS FOR FAÇADES AND INTERIOR PARTITIONS

Building typologies scenarios: Several façade typologies of buildings in Europe were studied and classified to set up a guideline to assist in the design of the new products. Two façade groups were defined according to the main uses of buildings (residential or office buildings), and within each group several typologies were defined according to the construction method. Thus, the main features and characteristics of each constructional solution have been studied, taking into account the climatic zone, the year of construction, and other parameters. Conclusions drawn from the study are summarised below:

- Residential building conclusions:
  - The 67% of the European residential building stock that was built before 2005 comprises a heavy resistant wall (such as concrete or cored brick), often covered with an exterior overlay and an interior plaster, but with no air chamber and with no insulation.
  - Almost 50% were constructed between 1946 and 1990 (post-war buildings) in Southern Europe (31.7 %) and in Central Europe (15%) and 15% are classified as old buildings
  - 28% of the residential buildings are composed of a heavy resistant wall with an unventilated air chamber filled with insulation.
  - Most of these were constructed between 1946 and 1990, mainly in Central Europe
  - Among the current building construction trends in South Europe, 50% of the façade typologies are ventilated façades, which comprise a resistant wall, a discontinuous overlay, a ventilated air chamber, and insulation to the outside.
  - Almost 40% of current residential buildings are composed of a heavy resistant wall with an unventilated air chamber that is filled with insulation.
- Office buildings conclusions:
  - Among the current office building construction trends, 35% of the typologies constructed are stick-system curtain wall façades, which are the most commonly used construction solution in South Europe and Central Europe.
  - This prevalence of this system is followed closely by the unitised curtain wall system.
  - Double skin systems are becoming more common on the market due to the higher importance of energy efficiency and reduction in energy consumption (zero-energy buildings).
- Conclusions drawn from the study of the residential buildings have been taken into account in the design of the multi-layered façade solution and the biocomposites window design, while the conclusions obtained from the analysis of office buildings have been used for the design of the curtain wall product.

CONCLUSIONS FOR THE OSIRYS MULTI-LAYERED FAÇADE		
GEOMETRIC FEATURES	Floor to floor height (m)	3.0
	Free floor height (m)	2.5 – 2.6
	% Window / Façade Ratio	30%
FAÇADE DESCRIPTION	Thickness (cm)	35 - 40 cm (up to 2005) 23 - 29 cm (new trend)
CONCLUSIONS FOR THE OSIRYS CURTAIN WALL		
GEOMETRIC FEATURES	Floor to floor height (m)	3.8 – 3.9
	Free floor height (m)	3.0
	Façade modulation (m)	1.8
FAÇADE DESCRIPTION	Thickness (cm)	20
	% With solar protection	20 %

TABLE 3 Conclusions to be used in the design of Osirys products

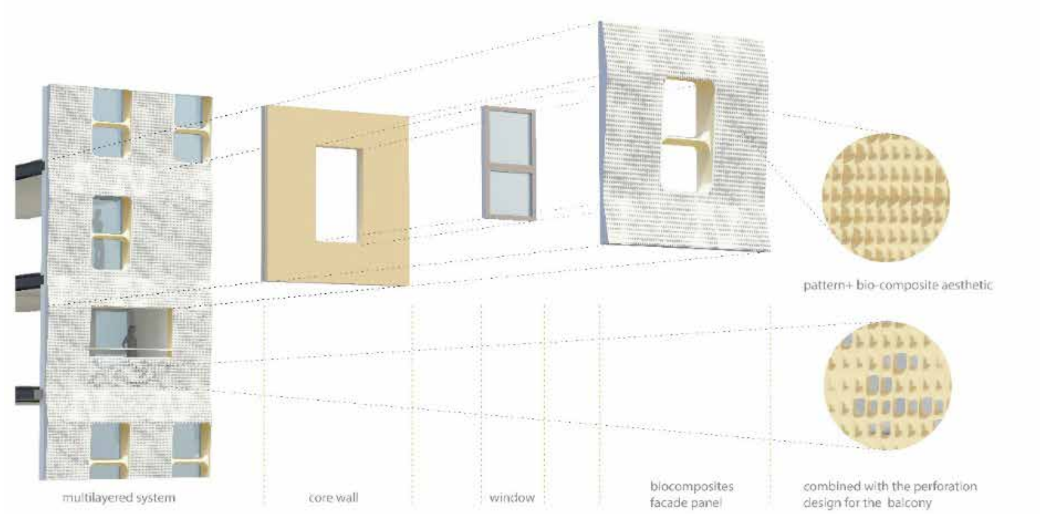

FIG. 3 Multilayer façade system components

Multilayer façade design: The developed multilayer façade system combines three main sections: internal finishing, core of the wall (multi-layered module), and external cladding. Each section consists of several elements developed within Osirys and combined together to create a fully functional building envelope.

- The assessment process used to verify the different products of the Osirys project comprises the following steps:
  - Initial design of the system
  - Structural and thermal simulations
  - Laboratory prototype construction and testing
  - Breathability, moisture, and presence of fungus and micro-organism simulations
  - Final design of the product
- Computer simulations provided important information showing that the design of the multilayer façade system comprising novel elements developed within the Osirys project fulfils necessary and crucial requirements like structural stability and proper thermal performance. Hygrothermal performance analysis of the multilayer façade panel under northern climate conditions was also assessed and results indicated that a vapour resistant membrane (moisture barrier) in cold (northern climate) was necessary to avoid moisture accumulation in the structure.
- With these results, the final design for the multilayer façade was provided element by element and also per system. The final designs also included the design of the connections between the Osirys elements, and between Osirys elements and non-Osirys elements, to integrate the new products in the demo buildings.

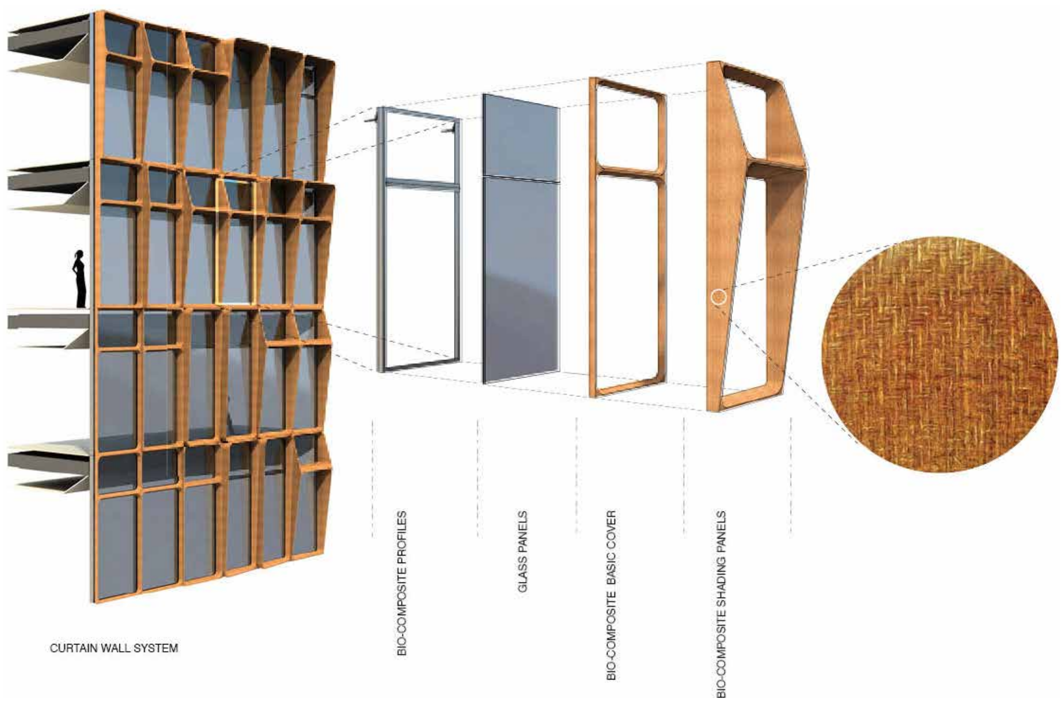

FIG. 4 Curtain wall façade system components

Curtain wall and window design: Different possibilities have been evaluated to find the best solution. The dimensions for prototyping are 3.8m high x 1.2m wide. The preliminary system design included the configuration and schematic definition of components, the study of the interactions of system components, and building systems and modularity. Like the multilayer façade design, structural and thermal simulations were performed to validate the final design according to the defined requirements. For the final design the following aspects were considered:

- The complexity of the profiles was reduced to avoid problems in manufacturing. A total of 3 profiles were designed for the curtain wall.
- For the window frame, a pultrusion profile with an operable part was designed.
- The final glass types were selected for the curtain wall and the window, and outdoor features for the Tartu Demo were decided.

Partition system design: After analysing the types of partition walls, it was decided to focus on a stud wall hybrid system, which is a fusion of a system assembled on-site and a prefabricated sandwich partition panel, which provides particular construction advantages. The partition wall is divided into two main components: structural profile and sandwich wall board.

- Structural biocomposite profiles are designed based on a standard, C-profile: aluminium structure with a width of 50mm, height of 60mm, and wall thickness of 5mm.
- The second component of the partition wall is the sandwich wall board. Different partition layers are combined together into one prefabricated panel mounted directly on to pultruded studs. The panel will ensure that all necessary properties that are to be fulfilled by partition walls are met. It will comprise bio-based acoustic and thermal insulation as well as a wall board that works as a wall lining. The width and cut edges of the panel are adjusted to the correct shape, and the distance between pultruded profiles is 400mm.

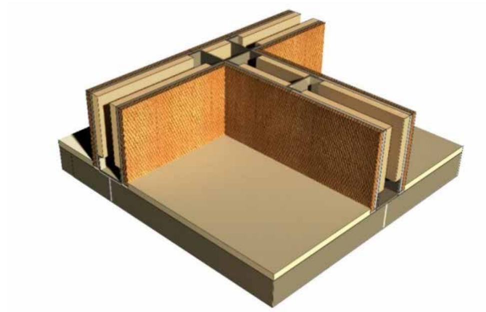

FIG. 5 Detail of the interior partition system

Laboratory prototype construction and testing: Full size prototypes were manufactured and validated under European Standards to verify that the Osirys products can be used in the demo buildings without legal problems regarding their final behaviour onsite.

A resume of the final results for the fourth systems can be found in the following tables.

ESSENTIAL CHARACTER-ISTIC	STANDARD	EUROPEAN STANDARDS MINIMUM REQUIREMENT	OSIRYS FINAL RESULT
Reaction to fire	EN 13501-1 and Test under EN 13823	B-s2-d2	B-s2-d0
Fire resistance	1364-3 and EN 1364-4. Classification by EN 13501	EI60	EI90
Watertightness	EN 12865	150A	300A
Wind load resistance (services loads)	ETAG 034	Depending of the building (façade classified)	1800Pa (P) 1400 (S)
Mechanical resistance	ETAG 034	Category IV	Category I
Horizontal point loads	ETAG 034		
Impact resistance	ETAG 034		
Airborne sound insulation	EN ISO 140-3	Depending of the building and the situation (33 dB in some cases)	53 dB
Thermal resistance	EN ISO 10077-2	0,25-0,35 W/m^{2}K	0,139 W/m^{2}K

TABLE 4 Multilayer façade results

ESSENTIAL CHARACTER-ISTIC	STANDARD	EUROPEAN STANDARDS MINIMUM REQUIREMENT	OSIRYS FINAL RESULT
Water permeability	EN 12155	R4	R7
Wind resistance (Service loads)	EN 12179	Depending of the building (façade classified)	1200 Pa (P) 1200 Pa (S)
Self-Weight		L/500 or 3mm	L/500 or 3mm
Airborne sound insulation	EN ISO 140-3	Depending of the building and the situation (33 dB in some cases) (*)	40 dBA
Thermal transmittance	EN 13947	Depending of the building and the situation (2 W/m^{2}K in some cases) (*)	1,04 W/m^{2}K
Air permeability	EN 12153	A1	A2

TABLE 5 Curtain wall results

ESSENTIAL CHARACTERISTIC	STANDARD	EUROPEAN STANDARDS MINIMUM REQUIREMENT	OSIRYS FINAL RESULT
Water permeability	EN 1027	1A	3A
Wind resistance	EN 12211	600 (Pa)	3000 (Pa)
Self-Weight		L/500 or 3mm	L/500 or 3mm
Airborne sound insulation	EN ISO 140-3	Depending of the building and the situation (33 dB in some cases) (*)	40 dBA
Thermal transmittance	EN ISO 10077-2	Depending of the building and the situation (1,2 to 2 W/m^2K in some cases) (*)	1,15 W/m^2K
Air permeability	EN 1026	Class 1	Class 3

TABLE 6 Window results

ESSENTIAL CHARACTERISTIC	STANDARD	EUROPEAN STANDARDS MINIMUM REQUIREMENT	OSIRYS FINAL RESULT
Reaction to fire	EN 13501-1 and Test under EN 13823	C-s2-d0	B-s2-d0
Fire resistance	1364-3 and EN 1364-4. Classification by EN 13501	EI60	EI90
Resistance to dynamic loads	ETAG 003	Category 2A (Residential) Category 2B (Offices)	Category 2A (Residential) Category 2B (Offices)
Resistance to eccentric vertical loads	ETAG 003		
Resistance to point loads	ETAG 003		
Airborne sound insulation	EN ISO 140-3	Depending of the building and the situation (33 dB in some cases)	47 dB

TABLE 7 Interior partition results

3.5 DEMONSTRATION ACTIVITIES

Different activities were performed during the project to verify the final behaviour, in real conditions, of the developed products. These activities were divided into three main demos:

Demonstrator in KUBIK test building: The KUBIK facility (from Tecnalia) is a three-storey high building with a basement floor in which HVAC systems are located. An enclosed east-facing room on the ground floor is dedicated to the Osirys project. A prototype of the Osirys multi-layer façade was successfully prefabricated (wall core) and erected on site (wall core, external cladding, and internal part of wall), validating the construction process of the wall. Together with the on-site assembly process, a number of sensors were installed, allowing an experimental campaign for the measurement of the thermal performance of the multi-layered wall.

FIG. 6 Multilayer façade installed in Kubik test cell

Demonstrator in a real building: Case study 1: Public building in Northern Europe: The Tartu demo building is a 250m^2 stadium building located at Mart Reinik High School in the central area of Tartu (Estonia). The demo building consists of 4 dressing rooms, 2 shower rooms, 2 saunas, office space for teachers or referees, and a dressing room for the referees. The building will serve around 1200 students from 3 nearby schools. It will also be used by around 300 recreational users every week throughout the year.

— Firstly, the architectural design on Tartu demo building was carried out. The technical design of the Tartu demo building was finished after all details and joints between Osirys products and the other building materials were agreed. The HVAC design was also accomplished.

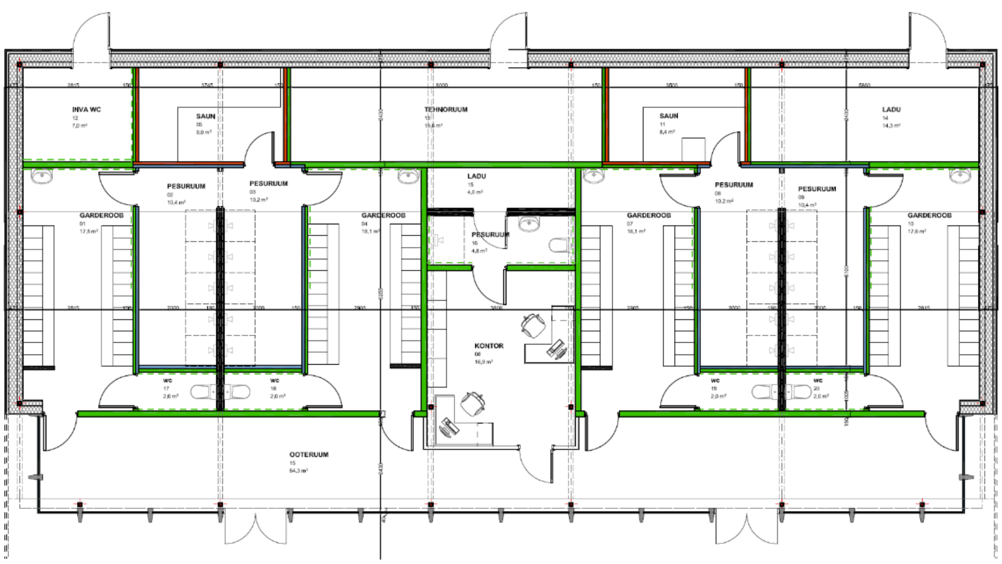

FIG. 7 Floor plan of the Tartu building

— Osirys systems (multilayer panel, interior panels, and curtain wall) were successfully installed quickly and simply, despite some on-site works being required due to the handcrafted nature of the products. Thus, the feasibility of using Osirys products in buildings was demonstrated, although optimisation of the industrialisation process and aesthetics is required for further commercialisation.

FIG. 8 External view of the Tartu demo building. The front curtain wall was developed through the Osirys project like the rest of the façades (which use the multilayer façade solution). The partitions inside the building also use the Osirys developments.

— Demonstrator in a real building: Case study 2: Residential building in Southern Europe, promoted by the partner VISESA (Basque Government): The demo building is located in a social housing block in San Sebastian (north of Spain). The construction plot is rectangular in shape (69 x 12m), with a slope of 4%, it consists of 2 underground floors + ground floor + 7 floors + attic and has 10 apartments per floor (total of 70 apartments). The apartment in which the Osirys products would be installed was selected on the south-east corner, at second floor level. It comprises two bedrooms, bathroom, kitchen and living room.

FIG. 9 Second floor of the San Sebastian demo building with the Osirys apartment highlighted

— The installation of Osirys products had to overcome barriers related to the inexperience of the construction team handling and working with this type of materials. So, to help the working teams with the installation of the systems, a guide for design and maintenance was prepared.

FIG. 10 Render of the final solution for the San Sebastian demo

3.6 MONITORING RESULTS FOR ALL DEMO BUILDINGS

Indoor air quality: Concentration of nitrogen dioxide and ozone were below the recommended guideline values for indoor air in the 3 demo sites and the indoor-to-outdoor ratios were < 1, indicating efficient removal of these compounds from outdoor to indoor air. TVOC measurements indicated that without ventilation it takes 7 weeks to reach a safe concentration of 300 µg/m3 as recommended in the guidelines. However, when slight ventilation of 23 m^3/h (corresponding to approx. 0.77 air exchanges per hour) is applied, even the initial TVOC concentration decreases to 500 µg/m3 and the time required to reach the safe level is reduced to 5 weeks, approximately half of the time required by a commercial coating to reach the same safe level. According to the TVOC guidelines issued by the German Federal Environmental Agency, painters will be exposed to indoor air of moderate quality. Thus, ventilation is adequate to provide a safe workplace. On the other hand, it was also observed that without lighting TVOC concentration increased, showing the photocatalytic effect of the coating upon indoor lighting.

Thermal performance: A thermal transmittance U-value of 0.160 W/m^2K was estimated for the plane areas of the multi-layer wall. The measured U-value keeps within the same range as expectations from numerical calculations, with a slight increase of 0.021 W/m^2K, which is commonly found in physical measurements and can be attributed to workmanship issues or measurement errors, among others. The measured thermal performance confirms that the Osirys multi-layer wall is a well-insulated assembly that can work in any European climate and complies with requirements of all national regulations. Infrared images, together with the constant temperatures measured, showed that the multi-layer wall keeps a uniform temperature across its area, and the thermal bridging effect of the biocomposite profiles is very low. Relative humidity measurements indicate no moisture accumulation. Localised moisture spots dried out during this period, which is an indication of good drying capacity.

Life cycle assessment: The environmental performance of the multilayer façade, curtain wall, and interior partition was assessed. Each product was defined according to its elements and materials, and the weight per m^2 of wall and bio-content were quantified. Despite there being no similar products to

Osirys on the market, the following benchmark products were used for comparison because of their extended use or similarity to Osirys developments:

- Multilayer façade: brick wall façade. Traditional façade system used throughout Europe.
- Curtain wall: Glass façades of Fiberline composites. A product that could be comparable to Osirys products due to the use of composite materials.
- Interior partition: Knauf Aquapanel indoor panels. Gypsum panels with metal profiling.

The environmental assessment included the analysis of these parameters:

- Biomass feedstock: The bio-content of the products increased from around 1% of benchmark products to above 30% and 40% in the curtain wall and interior partition, respectively, and to almost 70% in the multilayer façade with 0.14 W/m2K, corresponding to the materials developed in Osirys (without glass or fastening devices). These results indicate the high value of the Osirys products in relation to their use of natural materials.
- Embodied energy: Because no multilayer façade comprising similar materials exists on the market, the wood-plastic fire-retardant panel included in the multilayer façade (that can be also found as fossil-based/traditional materials in the market) was chosen for comparison. Results indicated that the embodied energy in the fire-retardant wood plastic composite (WPC) panel was 161 MJ/m2, while in the conventional WPC it was 232 MJ/m2. The Osirys product was thus 31% lower in the content of embodied energy than the WPC.
- The weight of the new systems has been significantly reduced in comparison to commercial benchmark products: 78% for the multilayer façade, 50% for the interior partition, and 10% for the curtain wall.

4 FINAL CONCLUSIONS

The project is a first step to introduce new materials in the envelope sector, trying to solve some of the problems found in the traditional solutions or that are solved with more complex systems. The technical viability of using biocomposite materials on constructional elements to be applied in different European climates, assuring more comfortable buildings regarding energy efficiency and indoor environmental performance, has been assessed. The main result shows that new materials can be used in façades without major problems and that they can provide new characteristics and possibilities to the envelopes sector. Three real examples of their good behaviour can be shown in the demos of the project. Therefore, the demo buildings are a showcase for the developed novel products.

The best results are obtained in terms of the thermal characteristics of the systems. The solutions developed are simpler than the traditional ones (easier for manufacture), with better thermal behaviour, with more flexibility to be adapted to different climate conditions without major changes, and with fewer problems related to condensation and corrosion. Fire performance results are also in line with European requirements. Moreover, the creation of a façade identity by using biocomposite materials allow differentiation of the building works.

The environmental results are very promising as defined in the monitoring results.

The project is now finished. Some additional research is needed to improve both the mechanical characteristics of the materials and design to increase performance such as acoustic, air permeability, watertightness, and wind resistance. However, these problems can be easily overcome due to the good behaviour of the materials. The consortium is willing to continue working on improving the performance of the products in a further research project.

As soon as industrialisation of manufacturing processes is completed, these novel products can be launched into the market. Furthermore, the design process has considered the possibility of combining the different new elements with traditional systems to facilitate market penetration.

Likewise, some materials like the photocatalytic coating, the low-VOC adhesive, and the insulation cork have already been commercialised. Other products are under a patent process to be marketed.

Future publication will include a detailed explanation of the different activities developed in the project.

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An analysis of the potential of envelope-integrated solar heating and cooling technologies for reducing energy consumption in European climates

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Abstract

There is a clear trend towards the increased contribution of renewable energy at European level, and EU policies are oriented in this direction. The building sector is no exception and presents an urgent need for increasing the share of renewable energy sources (RES) to reduce the impact on the environment.

The aim of this paper is to examine the potential of solar heating and cooling technologies in reducing energy consumption by incorporating solar thermal and PV collectors within the building's envelope. Although generally envisaged as being integrated into the roof, preferably oriented to the south, this study explores their potential for integration into building façades.

External climate influences both the demand for space heating and cooling (influenced by temperature) and the potential of solar renewable energy (incident global irradiation). However, a time lag exists since supply and demand peak at different times within the day as well as during the year.

This study assesses the interplay of solar energy supply with heating and cooling energy demand. An analysis is performed over climate data files for five European locations, based on daily weather data. Besides the extent of incident solar irradiation, its seasonal usability is assessed with regard to the thermal demand. The impact of the inclination of solar collector devices is assessed by comparing their placement on a horizontal plane, on the inclination of maximum exposure for each climate, and on vertical planes for the four cardinal directions.

As a conclusion, the utilisation of solar energy in different scenarios is assessed and a discussion on the integration of solar thermal and PV collectors on façades is presented, building on the potential of these technologies for developing innovative solutions that could significantly upgrade the buildings' energy performance in the near future.

Keywords

façade integrated solar technologies, solar heating, solar cooling, solar collectors

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1 INTRODUCTION

The poor state of the building sector in relation to energy consumption, efficiency, and associated impacts such as CO_2 emissions is a well-known problem (UNEP - SBCI, 2009). The challenge posed by the EU's ambitious goals for 2020, 2030, and 2050 (European Commission, 2017) has stated a clear position looking to correct this course and achieve a significant improvement over the current situation. In such a scenario the necessity for a higher contribution to come from renewables is undisputable. This is clearly stated by the EU in the Nearly Zero Energy Building (NZEB) definition (European Commission, 2010), in which, in addition to the maximum admissible primary energy consumption in buildings, a minimum contribution from Renewable Energy Sources (RES) is demanded. The Directive also specifies that this energy must be produced "on-site or nearby". Due to the complex development of the NZEB concept within different member states with varied interpretations of that definition, the Commission has also published some recommendations (European Commission, 2016), to provide quantifiable references that could help to better explain what is expected. Specifically, it distinguishes four major climatic zones in Europe (Mediterranean, Oceanic, Continental, and Nordic) and sets the minimum renewable contribution in relation to each of these zones, within a range of 28-77% for new single-family houses and 30-70% for the case of office buildings. This represents an effective yearly coverage over the primary energy of 25-50 kWh/m^2 and 30-60 kWh/m^2 respectively. The path described for these cases should be the main goal to be achieved by all buildings in any future scenario, and places significant focus on renovation works. This is a critical point as, according to the International Energy Agency, approximately 60% of the current building stocks will still be in use in 2050 in the European Union, United States, and Russia (IEA, 2013).

Once the requirement to incorporate RES in buildings is accepted, there are various ways to execute these technologies in buildings, from independent devices attached to buildings to solutions that look for a higher integration, taking into consideration that this concept accepts different interpretations. Given the complexity of the processes of energy harvesting, storage, and distribution, the method for combining renewable systems and bringing them into buildings is a major challenge. At present, there is a set of systems and technologies that, taking benefit from the energy provided by the sun, can significantly contribute to the reduction of energy consumption in buildings. These systems, which are labelled as renewable, are already commercially available in some cases, while others are still in development. Solar thermal collectors, PV collectors, heat pumps over a certain performance, thermal storages, batteries, and management systems are the key components that have been identified as the means to achieve solar heating and solar cooling transformation. On the other hand, there seems to be no single measure that can solve the whole problem, but combinations and systems brought together can provide various solutions under holistic approaches.

Although existing technologies and solutions do have great potential under optimum conditions, when these are brought into buildings, the impact and effect of different configurations is not fully obvious. Solar collectors are very rarely, if ever, displayed in a fully horizontal position. Discarding sun-following panels and assuming a fixed position, collectors are commonly oriented to the south (as far as possible) and with a certain slope that seeks to maximise solar gains over the complete year, this angle being a function of the latitude and the sun declination (Stanciu & Stanciu, 2014).

In the search for better architectural integration, specific and unique design solutions for solar collector devices are devised to suit individual buildings, considering the aesthetic benefits of integrating flush mounted panels in the roof, in the façade, or in any other angled plane limited by the constraints of the construction and type of the building. The integration of collectors on building façades can be especially appealing when installing them as seamless solutions. In addition to this, their placement on vertical planes offers additional benefits in terms of a more stable energy production when oriented to south (Munari Probst & Roecker, 2012). This approach foregoes the orientation and/or tilt that receives the highest overall annual irradiation, getting less energy in absolute terms. Nevertheless, a more regular production is obtained throughout the whole year, allowing a better management and distribution of energy and, additionally, avoiding or minimising problems in summer conditions, such as overheating and stagnation for thermal collectors, and efficiency losses in PV panels. In summary, many different possibilities are feasible for the integration of solar panels within the building envelope, but at present there is no clear strategy or guidelines in the bibliography to help in the definition of such integrated solutions and their suitability to specific European climates.

The main aim of this study is to address the potential of solar systems incorporated into the building envelope (O'Hegarty, Kinnane, & McCormack, 2016) for space heating and cooling, taking into consideration different climates and orientations, under a general scope that seeks to balance solar production and demand. As a result of the assessment, some recommendations and criteria for designing solar façades are provided, and a number of currently available technological solutions for the integration of solar collection devices are presented.

2 METHODOLOGY

An analysis of climatic data for five European locations is performed to determine the theoretical potential of solar collection technologies. The selected approach is based on the correlation between solar potential, expressed as global irradiance, and thermal demand, expressed in Heating Degree Days (HDD) and Cooling Degree Days (CDD). Given the variety in performance for different solar collection technologies, and the greatly varying insulation levels for different EU regions and construction periods (Elguezabal et al., 2018), this method has been selected to represent the generic solar potential of each climate, without restricting it to specific technologies or building types.

The adopted methodology is explained through the following steps:

1. The starting point is the data obtained from a statistical weather database (Meteonorm 6.0) (Meteotest, n.d.), providing the external ambient temperature as well as the incident solar irradiation over a horizontal plane with hourly resolution during a representative year.
2. Taking external temperatures as a reference, the necessity for heating is assumed to be activated once the external temperature goes below 15 °C, and correspondingly, there is cooling requirement once ambient air exceeds 20 °C. These base temperatures have been selected to allow comparison among different cases; actual base temperatures are dependent upon the specific case considered, influenced by the type of construction, insulation properties, etc. (Schoenau & Kehrig, 1990). The temperature difference from these base values, integrated over a whole year, will give an indication of the demand for heating and cooling, expressed as (HDD) and (CDD).

$$\text{Heating Degree Days} = \text{HDD} = \sum_{i}^{365} \text{hdd}_i , \quad \text{hdd}_i = \begin{cases} \left(288 - \overline{T_{amb_i}}\right), & \overline{T_{amb_i}} < 288\text{ K} \\ 0, & \overline{T_{amb_i}} \geq 288\text{ K} \end{cases} \tag{1}$$

$$\text{Cooling Degree Days} = \text{CDD} = \sum_{i}^{365} \text{cdd}_i , \quad \text{cdd}_i = \begin{cases} \left(\overline{T_{amb_i}} - 293\right), & \overline{T_{amb_i}} > 293\text{ K} \\ 0, & \overline{T_{amb_i}} \leq 293\text{ K} \end{cases} \tag{2}$$

3 The next step is to determine the available irradiation to cover these needs. As the database only provides hourly values for global irradiation over horizontal surfaces, the anisotropic sky model (Perez, Stewart, Seals, & Guertin, 1998) has been used to estimate the incident radiation over surfaces at different orientations and tilts.

4 A daily resolution has been adopted to uncouple the calculation from the specific storage system chosen. This assumes a thermal storage than can make use of the solar energy received at any moment over a given day, but cannot store the excess energy for longer than that 24-hour period. Seasonal energy storage is therefore not considered.

5 The usable solar irradiation has been defined as the irradiation received when a heating or cooling demand exists. Taking into consideration the average daily external temperature and comparing it with the thresholds (base temperatures) stated above, the irradiation received for a given day is assigned for heating or cooling. In the same line, the irradiation is considered unusable if a daily demand does not exist.

6 Once the heating/cooling demand and the solar production are combined, the possibilities of the solar energy to respond to these demands can be appreciated for each location and orientation.

7 Following the above method, the theoretical potential of the solar energy has been determined for different orientations and inclinations. In practice, due to different constraints, the optimal surface may not be always available or provide the sufficient area, and the solar potential might be affected by local conditions such as exposure to wind or shadowing from neighbouring buildings or objects.

8 Finally, practical recommendations are provided in terms of possibilities and interest for integrating different systems in building envelopes.

3 ASSESSMENT OF POTENTIAL FOR DIFFERENT EUROPEAN CLIMATES

Five locations have been selected as representative situations for a variety of conditions within Europe. Large cities with some of the highest heating and cooling demands are studied, as well as some more balanced scenarios. The selected cities were Stockholm, Dublin, Budapest, Madrid, and Athens.

For these cities, Fig. 1 provides information represented at three different levels:

- In the upper row, total global irradiation, expressed monthly, for a set of different planes: horizontal plane (commonly used in irradiation atlases), tilt of maximum incidence depending on the location, and vertical south, west, north, and east planes.
- In the middle row, monthly accumulated heating and cooling demand, expressed in HDD and CDD.
- In the bottom row, the share of usable overall irradiation that is exploitable for heating and cooling purposes, depending on the adopted plane (horizontal, maximum irradiation, south or west, assuming that west and east are practically equivalent).

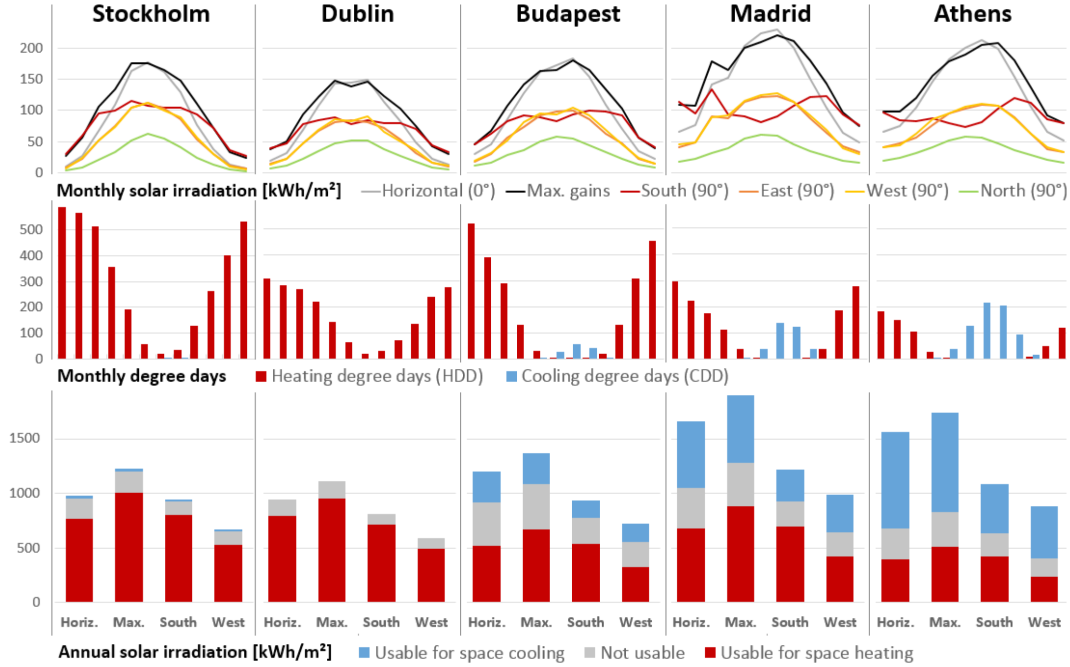

FIG. 11 Monthly global irradiation over different planes: horizontal, maximum incidence depending on the location, and vertical south, west, north, and east (top). Monthly accumulated heating and cooling demand (middle). Exploitable irradiation for heating and cooling purposes depending on plane (bottom).

4 RESULTS AND DISCUSSION

Besides the total available irradiation, it is crucial to consider what that energy is destined for, as well as the period when production and consumption are able to be combined. As expected, the predominance of the heating demand in most of the cases is clear, with more intensive demands at northern latitudes such as Stockholm, but also in severe continental climates, as for Budapest. Cooling demand is insignificant for Stockholm and Dublin, starts to appear at more southern latitudes with a very small requirement for Budapest, becomes higher in Madrid, and is the predominant demand in Athens.

The non-usable energy (grey in Fig. 1 bottom) relates to the solar irradiation received in those days where the space heating or cooling demand is null. For both Stockholm and Dublin, this portion is small, as some heating demand exists even during the months with maximum irradiance in summer (middle row in Fig. 1). In contrast, for the case of Budapest, the demand is quite low for those months, thus the solar energy is not conveniently exploited, making the non-usable proportion more significant. On the other hand, in Madrid and Athens, the energy harvested during the summer has a strong potential to be used for solar cooling.

When considering the usable solar energy in its maximum amplitude, Dublin presents an interesting result: while being the city with lowest irradiation (even below Stockholm which is at a higher latitude), most of this irradiation is potentially usable for heating purposes as described in Fig. 1 bottom.

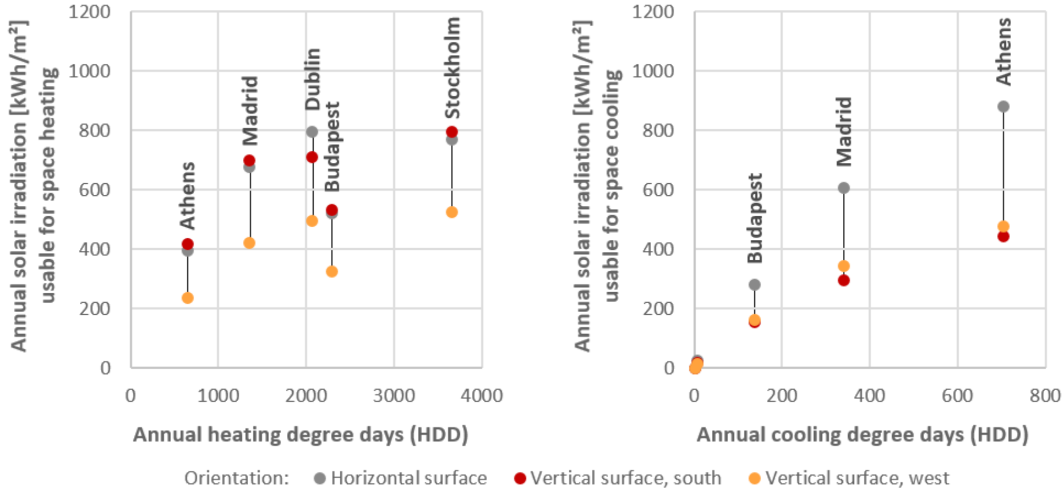

FIG. 12 Relationship between usable annual solar irradiation for heating (left) and cooling (right) in relation to the total demand expressed as annual HDD and CDD, respectively.

LOCATION	ORIENTATION	USABLE FOR HEATING	USABLE FOR COOLING
Madrid	Horizontal	77%	99%
	Vertical south	80%	48%
	Vertical east	48%	56%
Athens	Horizontal	78%	97%
	Vertical south	83%	49%
	Vertical east	47%	53%
Budapest	Horizontal	78%	99%
	Vertical south	79%	55%
	Vertical east	49%	57%
Stockholm	Horizontal	76%	95%
	Vertical south	79%	65%
	Vertical east	53%	59%
Dublin	Horizontal	83%	–
	Vertical south	75%	–
	Vertical east	52%	–

TABLE 1 Percentage of solar energy usable for space heating and cooling, for each city and plane orientation, in comparison with the optimal angle for solar collection.

Fig. 2 and Table 1 assess the usability of solar gains for space heating and cooling, depending on the specific climate and orientation. Taking as a reference the maximum angle where the total solar collection is maximised, there is always a reduction of the collected energy when a horizontal, south, or west/east plane is adopted, aiming to integrate these solutions within the envelope. Looking at the share of expected gains that is exploitable for heating and cooling purposes, some general recommendations can be appreciated and considerations given.

For solar heating production, the southern façade is the most interesting orientation as it provides a regular profile throughout the whole year, smoothing the summer profile and reducing peaks in that season when heating is not requested (top row in Fig. 1). It represents an interesting option for heating, providing 75% - 83% of the energy that would have been collected at the maximum orientation among the cases studied (Table 1). It is worth noting that, in all cities assessed except Dublin, the irradiation usable for heating in a south-facing plane is higher than for a horizontal plane, which is the commonly used source of information in weather databases.

For solar cooling production, the more interesting angles are those that maximise absolute gains, because the most intensive cooling needs are coupled with the period of highest solar production. Even horizontal surfaces can harvest 95% - 99% compared to the orientation of maximum gains (Table 1). However, if roof surfaces are limited or unusable, especially when retrofitting, west and east façades replicate the distribution of solar gains over the duration of the year (top row in Fig. 1), although this results in a significant reduction and meets around 53% - 57% of energy demand for those cases with relevant cooling requirements.

5 EXAMPLES OF INTEGRATED SOLAR TECHNOLOGIES

The results presented above have demonstrated that a significant quantity of solar energy reaches the different planes of buildings. This energy, which can be employed to produce heating and cooling, represents an interesting opportunity to integrate solar technologies within buildings.

	VACUUM PIPE	FLAT PLATE	UNGLAZED
Temperature (°C)	100 – 140	50 – 100	25 – 50
Power (kW/m²)	1.6 – 2.2	1.5 – 2	1 – 1.2
Average production (kWh/m²a)	480 – 650	400 – 600	300 – 350
Average cost (€/m²)	800	370	220

TABLE 2 Characteristics of the three main technologies for solar thermal panels.

An overview of currently available solar technologies for thermal collectors is presented in Table 2, based on research for panels installed in Switzerland (Munari Probst & Roecker, 2012). With regard to photovoltaic technologies, the wide range of currently available systems and recent developments have boosted the efficiency of such systems, while the cost is continuously decreasing. In any case, values ranging between 0.15 – 0.3 kW/m² for an annual production of 100 - 300 kWh/m² and a cost of 1500 - 4000 €/m² are representative of such solutions (IRENA, 2012; IRENA, 2017).

When combining the available solar energy with the characteristics of each technology, the potential for integrating these into the envelope can be appreciated. Considering mainly thermal solutions due to their higher efficiency, the possibilities for solar heating are wide and all the technologies can contribute to reducing the demand for non-renewable energy sources. On the other hand, solar cooling requires high temperature levels achievable only by vacuum tube collectors and some flat plate systems. The exploitation of electricity from PV panels is more straightforward for both heating and cooling, reducing the electricity consumption of energy provision devices such as heat pumps.

LOCATION	PRIORITY PRODUCTION	HIGHEST POTENTIAL FOR SOLAR INTEGRATION	
		ORIENTATIONS	TECHNOLOGIES
Stockholm	Heating (100%)	South vertical	Unglazed, flat plate, vacuum, PV
Dublin	Heating (100%)	South vertical	Unglazed, flat plate, vacuum, PV
Budapest	Heating (94%)	South vertical	Unglazed, flat plate, vacuum, PV
Madrid	Heating (80%)	South vertical	Unglazed, flat plate, vacuum, PV
Athens	Cooling (52%)	Max. exposure (30°), west, east	Flat plate, vacuum, PV

TABLE 3 Assessment of the interest for integrating solar technologies as a function of location and of most beneficial orientation for each case.

Discarding the horizontal plane and taking into consideration the predominant demand in each climate, Table 3 assesses the interest for integrating a number of solar technologies in the specific locations and orientations assessed in this study, considered to be representative of many locations within Europe. The choice of systems to integrate is quite varied, except for unglazed panels in locations where cooling is pursued. This limitation is not so important in climates with a predominant demand for heating, where such solutions are very interesting due to their lowest investment required. On the other hand, the consideration of which orientation has the highest interest is critical for an effective integration process and ultimately for achieving a cost-effective payback of the intervention.

As exemplar applications of such solutions, flat plate, unglazed, and PV panels provide a high level of integration for opaque areas, while vacuum pipe panels offer interesting possibilities for glazed areas as well as for opaque zones. The external glass of PV and flat plate technologies also allows certain combinations and interactions with glazed areas, although the collectors will not allow natural light to get inside the building.

Fig. 3 shows flat plate and unglazed panels covering opaque areas, providing good efficiencies for heating in south vertical façades. An application for glazed areas where vacuum pipe panels are integrated is portrayed in Fig. 4. For a case such as the one in Athens, where cooling and heating loads are quite similar, such panels can be employed in a south orientation for heating and in east or west orientation for cooling production. In addition, these solutions are also applicable for heating generation in other locations and in the south façade, although the effect of solar gains will require a detailed assessment to avoid overheating during summer, probably requiring filtered glasses within the solution.

FIG. 1 Left. Glazed flat plate collector integrated into a modular façade system (Winkler Solar, n.d.), Right. Prototype of unglazed collector integrated into a metal cladding panel (Elguezabal, Garay & Martin, 2017).

FIG. 2 Left. Vacuum pipe collectors integrated into a modular curtain wall providing a glazed façade. Right. Detail of the prototype (University of Stuttgart, n.d.)

6 CONCLUSIONS

The potential for the exploitation of solar energy is very significant, since it is a renewable resource available in the environment in high quantities. This challenge supposes that, in addition to conventional measures such as increasing insulation levels and equipment efficiency, it is necessary to seek to integrate renewables in buildings through their envelope, turning them into a key element in the transformation of buildings in relation to energy exploitation. It is very important to consider the coupling of production and consumption to improve system performance and avoid inefficiencies in management and distribution. Endeavouring to meet the NZEB requirements, buildings will increasingly be required to be more and more self-sufficient, while their connection to the main supply networks should decrease until they eventually become negligible. This will imply the introduction of solar collecting devices comprising a significant surface area. The available surface in the optimal orientations varies depending on the demand that is expected to be covered, but limitations are common especially when retrofitting is pursued. In such situations, alternatives to the optimal orientations need to be considered.

The present study has investigated different scenarios regarding the integration of solar collecting devices into the building envelope and their potential to be exploited for space heating and cooling, resulting in some interesting key findings.

It is important to consider the dominant demand for each climate since this has a significant impact on the maximum usable energy. In many cases, the placement of solar collectors in vertical façades instead of on the roof could provide benefits, especially for solar heating, as collection and demand achieve a better coupling on south-facing orientations. To cover space heating demand with solar energy, the south vertical orientation is very promising in all five cities studied. Although some energy is not used, the benefits of getting a regular production profile could represent a general improvement compared to the maximum angle orientation. As an additional reason to consider vertical façades for the incorporation of energy harvesting systems, the available surface of the façades is usually greater than that of the roof, and increases more for slender and block buildings.

If the cooling demand is greater than the heating demand, or in a similar range of magnitude, the advantage of the south orientation is not so obvious, since the east and west cases can maximise cooling production in summer, but their production goes below the south case in winter. For such applications, more detailed studies would be needed, making comparative designs between different orientations and combinations and taking into account the cost and return on investment associated with energy savings.

Finally, some currently available and recently developed thermal and PV solutions have been shown as examples of the applicability for integrating solar technologies. Taking into consideration their performance, efficiencies, and costs, as well as the main interest for placing them in specific envelope orientations, the potential of these solutions has been highlighted, providing general recommendations about the convenience of their integration, aiming to contribute to a higher penetration of RES within buildings.

Future research could build on the findings from these studies, by considering the impact of the efficiency curves for different solar technologies, on the one hand, and the influence of building shape and insulation levels on the energy demand, on the other hand. This would allow a direct comparison of on-site energy production and consumption, as well as their distribution over time and the usage of common metrics (Cao, Hasan, & Sirén, 2013) for assessing the correlation between supply and demand.

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Hybrid numerical and experimental performance assessment of structural thermal bridge retrofits

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Abstract

A methodological approach to the multi-dimensional heat transfer assessment of building envelopes is performed. The proposed method focuses on thermally weak points in envelope-structure junctions and the assessment of envelope retrofit alternatives. Thermal performance in these spots is seldom assessed in energy audit processes, although it is one of the main heat loss paths in many insulated façade solutions. An envelope-slab junction case is presented, where multi-dimensional heat transfer occurs. This paper proposes a methodology that allows for a hybrid experimental and numerical performance assessment in such circumstances. A numerical model is calibrated against experimental data, which is then modified to reflect various envelope retrofit solutions. Several possible analysis procedures are proposed, based on the capacities of transient thermal models.

Key words

Building envelope; Experimental assessment; Thermal bridge; Finite Element; Envelope retrofitting

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1 INTRODUCTION

1.1 HEAT TRANSFER IN BUILDING ENVELOPES & ENVELOPE RETROFITTING

According to the Sustainable Building and Climate Initiative of the UN (UNEP, 2016), and other sources (DOE, 2008; Pérez-Lombard, Ortiz, & Pout, 2008; EU, 2002; EU, 2010), buildings are responsible for 40% of the global primary energy consumption. Within buildings, envelopes – roofs, façades, and glazed areas - represent the main heat transfer path from a building to its environment. ECOFYS (2007) studied the techno-economical optimum insulation level for building envelopes. In this study, optimal thermal transmittance levels were found to be substantially below the current insulation levels in building envelopes. Thus, there is great potential for heat flux reduction by incorporating additional insulation to building envelopes.

Once the decision to renovate a building is taken, incorporating additional thermal insulation is a robust solution, as it increases the overall thermal resistance of the building envelope. Commonly, this measure is the first energy efficiency measure taken in most buildings, and combined with other energy efficiency measures, provides for a medium to long-term return of investment (ROI).

There are various technical solutions such as external thermal insulation composite systems (ETIC), ventilated façades, cavity wall insulation, and internal insulation systems. The basic approach of all these systems is to improve the thermal transmittance of the wall, by means of the addition of insulation materials. In this context, the thickness of the insulation material and its insulation capacity are key variables (Elguezabal & Garay, 2015).

1.2 THERMAL BRIDGES. RELEVANCE & CALCULATION PROCEDURES

Commonly, retrofitting design decisions are made based on one-dimensional performance of insulation systems. Multi-dimensional heat transfer paths such as window sills, slab-façade junctions, balconies, etc. are disregarded. These items account for a relevant share of the heat loss coefficient of a building envelope.

Several sources, such as ASIEPI (2010), show that the relevance of thermal bridges within the heat balance of a building is up to 30% of heating energy loads due to these elements. This ratio is considered to increase for highly insulated buildings. The correct design and improvement of junction details is estimated to reduce the same ratio to 15%. For this reason, adequate thermal bridge calculation methods for highly insulated buildings are needed (Kuusk, Kurnitski & Kalamees, 2017).

One of the reasons to avoid multi-dimensional heat transfer in the assessment procedure of a building envelope retrofit lies in the complexities of numerical models and the lack of robust experimental procedures to conduct such assessments.

Regarding numerical models, multi-dimensional heat transfer codes such as Therm (LBNL, 2018) are freely available to designers, but, to the authors knowledge, these are seldom applied in construction projects. When related to the on-site experimental assessment of the thermal performance of architectural junctions, standard methods such as EN ISO 9869-1:2014 cannot be applied and only qualitative assessments can be made by means of methods like infrared imaging.

In Garay, Uriarte, and Apraiz (2014), numerical and experimental works were conducted over a 2-dimensional thermal bridge. In this work, it was observed that steady-state numerical models did not correctly match the dynamics of the thermal bridge. This same source showed that for cases with unknown thermal properties, models failed to correctly identify the steady-state and transient aspects of thermal bridges.

In recent dates, works including that by O'Grady, Lechowska, and Harte (2017) have studied the possibility of integrating thermal imaging as a quantitative source of information for thermal bridge assessment. However, their applicability is yet to be further demonstrated.

1.3 EXPERIMENTAL PROCESSES FOR BUILDING ENVELOPE ASSESSMENT

Experimental heat transfer assessment procedures in building envelopes have traditionally been focused on one-dimensional heat transfer assessment. In fact, it is common to find instructions to avoid the influence of thermal bridges in experimental setups within standardised assessment procedures.

Experimental procedures for on-site assessment heat transfer in buildings are standardised under EN ISO 6946:2007 and ASTM C1155 – 95 (2013). Although these standards integrate transient assessment methods, they are primarily focused on steady-state performance metrics. Their most common implementation is performed by means of averaging processes, which filter out the dynamics of building envelopes.

Within the research community, there is an increasing awareness of the need for transient assessment methods, which has led to specific transient methods (Gutschker, 2008, Strachan & Vandaele, 2008, Naveros, Bacher, Ruiz, Jiménez, & Madsen, 2014). In any case, all of this experience remains in the one-dimensional domain.

Atsonios, Mandilaras, Kontogeorgos, and Founti (2017) apply EN ISO 9869-1:2014 and ASTM C1155 – 95 (2013) procedures over datasets from field experiments on building envelopes with various levels of insulation, at different times of the year. For each case, the required campaign length is identified. In some cases, it is impossible to obtain satisfactory results from steady-state methods, while in others, campaign lengths up to 20 days are required. Transient methods perform substantially better, delivering robust results in 5 to 10 days.

The methodology presented in this paper does not intend to be a substitute for experimental methods to assess one-dimensional heat transfer. It will complement existing procedures with a novel system for the assessment of multi-dimensional heat transfer, which, to date, is outside the scope of experimental procedures.

1.4 GOAL AND LIMITATIONS OF THE PROPOSED METHODOLOGY

In this paper, a hybrid numerical and experimental procedure is proposed to assess the present thermal performance of an architectural junction. The procedure allows building envelope retrofit systems to be assessed. Ultimately, this allows for a more detailed assessment of the thermal performance of a retrofitting intervention.

The methodology is illustrated by means of a 2-dimensional façade-slab junction. The presented calculation method is also suitable for 3-dimensional heat transfer. The 2-dimensional heat transfer case is presented as it gives a greater representation of the performance gap illustrated in this section.

Singular 3-dimensional thermal bridges are known to be less relevant in terms of heat transfer, but critical in terms of cold spots, and potential locations for mould growth. Users trying to replicate this methodology for repetitive 3-dimensional thermal bridges such as cladding anchors may experience difficulties in doing so. For these cases, users are encouraged to deal with this phenomena by means of pseudo-2D models. Specific adaptations of the present methodology may need to be developed. Reference to multi-dimensional heat transfer in architectural junctions may be found in Atsonios, Mandilaras, Kontogeorgos, and Founti (2017).

2 THERMAL ASSESSMENT METHODOLOGY

Thermal bridges are construction details in which multi-dimensional heat transfer occurs. As such, heat flux in these locations cannot be measured directly by means of heat flow meters.

The proposed assessment method bases its assessment of the heat flow across architectural junctions on several localised temperature and heat flow measurements. Point measurements are used to calibrate a transient numerical thermal model. Once calibrated, the model can be used to provide an accurate assessment of the heat transfer of the architectural junction under examination. The impact of envelope retrofit alternatives on the heat transfer across the junction can be calculated with the calibrated model. In Table 1, the method is presented as a stepped approach.

STEP	ACTIVITY
1. Monitoring of present state	Define the location of sensors
	Monitorisation campaign, ~1month
2. Calibration of thermal model	Construction of a numerical model
	Optimisation of thermal properties of materials
3. Evaluation of retrofitting alternatives	Parametric study of retrofit possibilities vs performance indicators

TABLE 1 Thermal assessment sequence.

The goal of this methodology lies in the identification of thermal and geometrical properties of an already constructed architectural junction based on insufficient data. Although geometrical details are commonly known in buildings constructed in the last 60 years, many thermal properties remain unknown and their determination is commonly performed by means of bibliographical research.

This method allows for the determination of critical information in the assessment of thermal bridges such as the effective thermal conductivity of insulation layers and air cavities, specific heat and density of concrete and brick constructions, etc.

This proposed hybrid methodology is complemented by state of the art one-dimensional heat transfer assessment techniques as shown in Fig. 1.

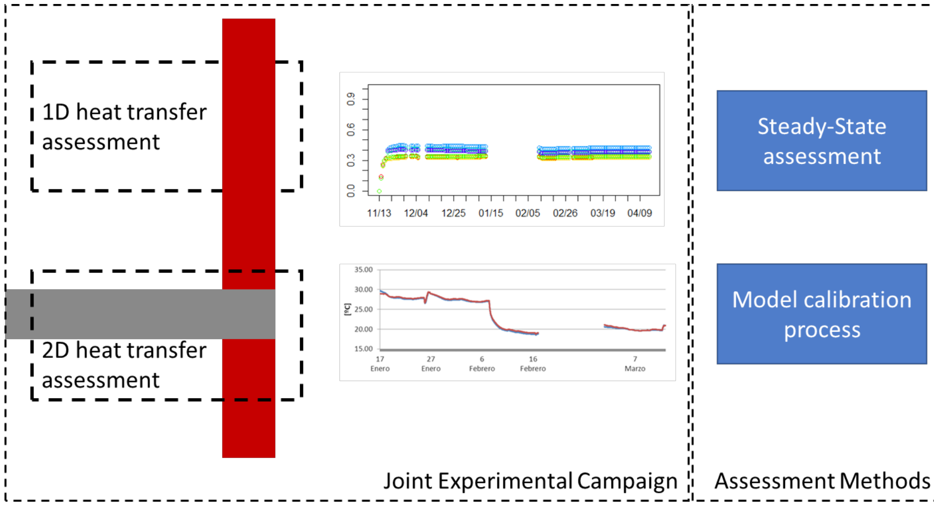

FIG. 1 Integration of assessment methods in a joint experimental campaign for on-site works

3 STEP 1: MONITORING

In this step, the geometrical detail is defined, and several spots are selected for the installation of sensors. Commonly, 3-4 sensors are sufficient to provide a detailed thermal map of the architectural junction. In the selection of the sensor location, sensors should be located in such a way as to allow the mapping of the architectural detail in all its relevant internal surfaces.

The particular location of sensors will depend on each architectural junction, and the feasibility of integrating sensors in some of the locations. Garay, Uriarte and Apraiz (2014) used steady-state thermal models to identify suitable locations for sensor placement. By doing so, better experimental conditions are achieved. Alternative processes such as thermal imaging are also possible means of identifying suitable sensor locations. The goal is to achieve spatial and transient representation of the measurement scheme:

- Spatial representation is achieved by means of sensor placement across the architectural junction, some of them mostly exposed to the external ambience, others in contact with indoor environment, and some of them in between.
- Transient representation implies that sensors are positioned in such a way that they are exposed to different dynamics. Sensors in contact with insulation materials will deliver faster responses than those in contact with concrete and other capacitive materials.

The number of sensors to be placed needs to be defined based on the scope of the selected assessment. Considering that standardised one-dimensional heat transfer assessment procedures (EN ISO 9869-1:2014) incorporate ambient and surface temperature sensors and at least one heat flow sensor, this amount should be increased to achieve good representation. Good practice should incorporate the following sensors:

- 1 ambient temperature sensor for each of the boundary conditions of the thermal bridge
- 1 surface temperature sensor for the coldest spot on each of the boundary conditions

- 1 heat flux on each of the internal boundary conditions
- 1 additional surface temperature sensor for planar systems not instrumented for EN ISO 6946:2007
- External weather conditions need to be measured, and comprise outdoor ambient temperature, wind speed & direction, and solar radiation over the façade.

For the application presented, Pt100 temperature sensors and PHYMEAS heat flux sensors are identified as suitable devices.

In Fig. 2, a monitorisation scheme is proposed for a slab-façade junction. In this figure, meteorological sensors are not shown.

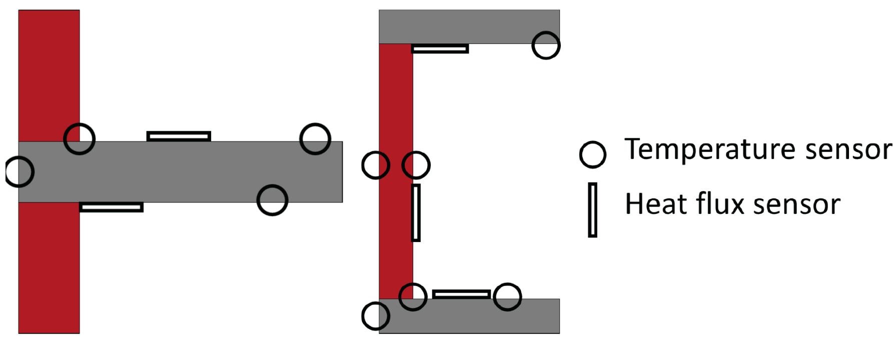

FIG. 2 Monitorisation scheme of a slab-façade junction (left), distribution of sensors in a multi-storey setup (right)

To facilitate the experimental process, the experimental campaign should be coordinated with the installation of other sensors for the one-dimensional assessment of the thermal performance of walls. This would allow for the common utilisation of data loggers. In the same figure, the monitorisation spots are redistributed, to allow for the installation of the data acquisition system within one floor of a multi-storey building. The presented experimental setup would only be valid in a multi-storey building in which boundary effects caused by foundations and roof can be neglected (i.e. central floor in a 7-storey building).

In Fig. 3, the detailed location of sensors in an architectural junction can be seen.

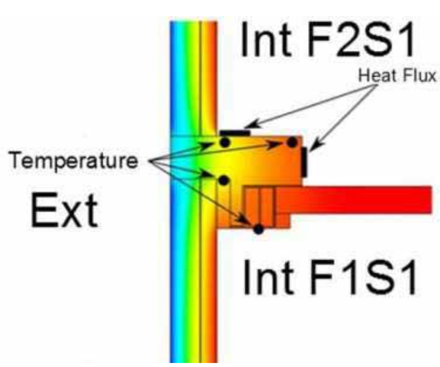

FIG. 3 Location of temperature and heat flux sensors in an experimental assessment of the heat transfer in a façade-slab junction (model height: 2.77m) (Garay Martinez, Uriarte Arrien & Apraiz Egaña, 2015)

Depending on the existing boundary conditions (i.e. indoor-outdoor temperature gradient), the insulation level of the construction etc., the length of the monitorisation campaign may divert. However, it is reasonable to assume that a proper result can be achieved with experimental campaign lengths in the range of 3 to 5 weeks.

In Atsonios, Mandilaras, Kontogeorgos, and Founti (2017), one-dimensional heat transfer assessment was performed by means of identification processes over various wall assemblies. Different climatic conditions, envelope compositions, and assessment methods resulted in variable campaign length requirements to deliver a result. When transient methods were applied, campaign lengths in the range of 10-20 days were required to achieve good identification of the system. In the proposed methodology, longer experimental campaigns are required to properly address heat dynamics in massive elements, such as concrete slabs. In any case, the prescribed campaign length is still inductive.

4 STEP 2: CALIBRATION

A thermal model of the architectural detail is constructed based on the available information relating to the junction. Commonly tabulated data from sources such as EN ISO 6946:2007 and Ministerio de Fomento (2013) are taken to complete project-specific data. It should be considered that, in most cases, retrofitting projects are performed over relatively old buildings, with non-professional owners (e.g. individual owners/dwellers, not involved in the construction process), with only minimal architectural data available.

The definition of architectural dimensions needs to cover the influence area where multi-dimensional heat transfer occurs. General criteria established in EN ISO 10211:2007 suggest that 1m of one-dimensionally homogeneous wall/slab length shall be modelled. The readers should consider that secondary criteria such as symmetry planes and wall thickness may modify this length.

Fig. 4 shows a thermal model of a façade-slab architectural junction.

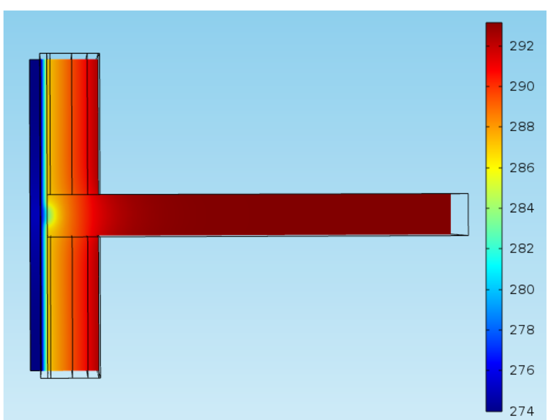

FIG. 4 Thermal model of an architectural junction. (Garay Marinez, 2017)

Boundary condition data from the monitorisation campaign is introduced in this model, and a transient thermal simulation is performed over the monitored period. The boundary conditions incorporated into the model are ambient temperature (on all surfaces) and solar radiation (for external surfaces only).

Thermal properties of materials and modelling assumptions are varied to minimise the observed error in output variables when compared with monitored spots in the physical junction within the monitored campaign.

In Fig. 5, output data from a calibrated model in VOLTRA (PHYSIBEL, 2009) is compared to experimental data taken from a façade-slab junction constructed in the KUBIK experimental building (Garay, Chica, Apraiz, Campos, Tellado, Uriarte, & Sanchez, 2015).

Error minimisation needs to be achieved simultaneously in all point measurements.
The comparison of the calibrated model against experimental data for all sensors installed in the junction can be found in Garay, Uriarte and Apraiz (2014) and Garay Martinez, Uriarte Arrien, and Apraiz Egaña (2015).

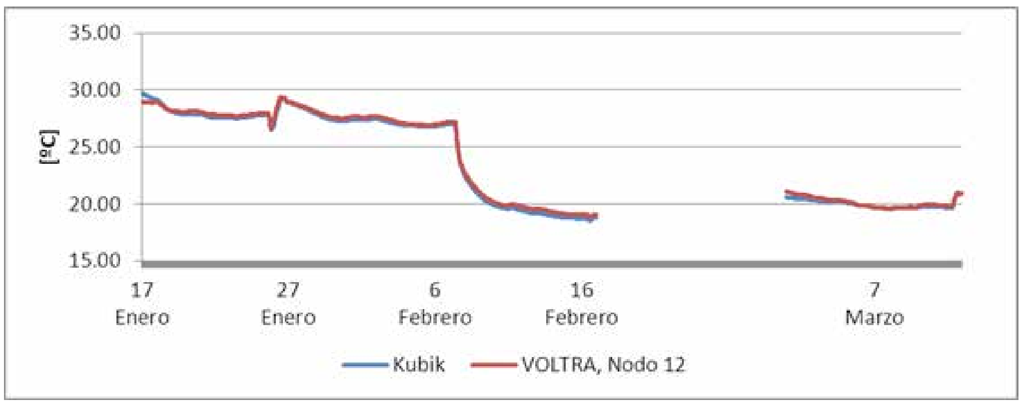

FIG. 5 Calibrated output signal on a thermal model. (Garay, Uriarte, & Apraiz, 2014) (Garay Martinez, Uriarte Arrien & Apraiz Egaña, 2015)

In Garay, Uriarte, and Apraiz (2014) and Garay Martinez, Uriarte Arrien, and Apraiz Egaña (2015), the model was parametrised to incorporate thermal capacity and conductivity of materials (concrete, steel, polyurethane, and XPS). It was found that minor tuning was required to identify the parameters of concrete. Concrete density and conductivity were varied in a range of 2000-2400kg/m3, and 2-2.6 W/mK respectively. The model best fit to experimental data was achieved with 2300kg/m3 and 2.2W/mK.

This same model was found to be more sensitive to internal convective heat transfer phenomena. Separate heat transfer coefficients were required for horizontal, vertical upward, and vertical downward heat transfer. Additional coefficients were required for corner areas. Each of these resulted in surface heat transfer coefficients in the range of 2.5-4 W/m2K, substantially lower than reference values in EN ISO 6946:2007. Full details on the calibration process can be found in Garay, Uriarte, and Apraiz (2014).

At the end of this process, the thermal model is classified as "Calibrated", and can be used for later assessment of retrofitting alternatives. In TECNALIA (2013), a visual inspection was used to identify the model that best fit the experimental data, but this process can be improved by using error minimisation techniques simultaneously over all measurement spots. From experimental data, the model was able to predict surface temperature within +- 0.2 °C, as can be seen in Fig. 4.

The calibration is performed based on punctual sensor locations, none of which are sufficiently reliable as to fully represent the thermal performance of the architectural junction. However, considering the accordance of the calibrated model with experimental data, it is reasonable to accept that the calibrated thermal model can be used to predict the thermal performance of the full architectural junction.

5 STEP3: EVALUATION OF RETROFIT ALTERNATIVES

The calibrated model from the previous section can be used to predict the thermal performance of architectural junctions targeted at various performance figures. The model itself is a transient thermal model, which can be used to perform both transient and steady-state calculations of the architectural junction for various purposes such as the following:

- Calculate thermal bridge coefficients and temperature factors of various alternative designs, based on calculation criteria and boundary conditions in EN ISO 10211:2007, but with calibrated thermal parameters for the baseline junction
- Calculate the overall coupling coefficient of the building envelope under standard EN ISO 13790:2008
- Calculate the transient thermal response of the architectural junction under harmonic boundary conditions similar to EN ISO 13786:2007 and that described in Garay Martinez, Riverola, and Chemisana (2017).
- Obtain transfer functions and response factors of the architectural junction by procedures, as described by Martín, Flores, Escudero, Apaolaza, and Sala (2010).
- Obtain equivalent one-dimensional thermal models for its integration into energy simulation programs by means of system identification techniques, stochastic procedures, etc. as proposed by Gacía Gil (2008).
- Perform heat transfer analysis of the architectural junctions for the verification of energy savings in energy performance contracts by means of IPMVP (EVO, 2012) or equivalent methods.

Overall, the proposed models allow for a detailed assessment of the architectural junction, with many relevant output parameters, which should be defined on a case-by-case basis, along with the particularities of each project from its many perspectives (architectural constraints, expected performance levels, engagement of contractors in the final performance, etc.).

In the following paragraphs, a case study on the assessment process for building energy retrofits is presented. The model for the façade-slab section presented in Fig. 3 is taken as baseline, and façade retrofit is performed by means of a ventilated façade system. This system is a closed joint ventilated façade cladding system (ULMA Architectural, 2018) based on vertical profiles and point anchors to the edge of concrete slabs (Garay Martinez, 2017).

The presented study was performed by means of multi-dimensional modelling of the junction. The ventilated façade model is parametrised to incorporate insulation thickness as the main variable. Anchor thickness is a dependent variable, as this parameter is required to be increased when the cladding is separated from the façade to meet mechanical criteria. The suitability of each alternative is assessed by means of surface, linear, and point heat transfer, and temperature factor is obtained. Fig. 6 shows the architectural detail and temperature field of the studied junction.

FIG. 6 Architectural detail and thermal field in the cross-section of the slab-façade junction

The U-value of the façade changes from 1.05 W/m^{2}K (Uninsulated) to 0.13 W/m^{2}K (20 cm of insulation). The achieved insulation levels are compared with normative requirements in Spain (Ministerio de Fomento, 2013).

In Fig. 7, the evolution of thermal transmittance and temperature factors is shown for varying thermal insulation levels. For the uninsulated case, there is a 12% surplus heat transfer due to the 2D heat transfer over the 1D study. When adding insulation over this junction, the 2D surplus heat is substantially mitigated. However, 3D heat transfer introduced by mechanical anchors becomes a relevant part of the heat transfer across the façade. This surplus heat increases from 16% (5cm) to 48% (20cm) when the façade is insulated externally. The surplus 3D heat transfer is stable in absolute terms for all cases, but its relative relevance increases substantially.

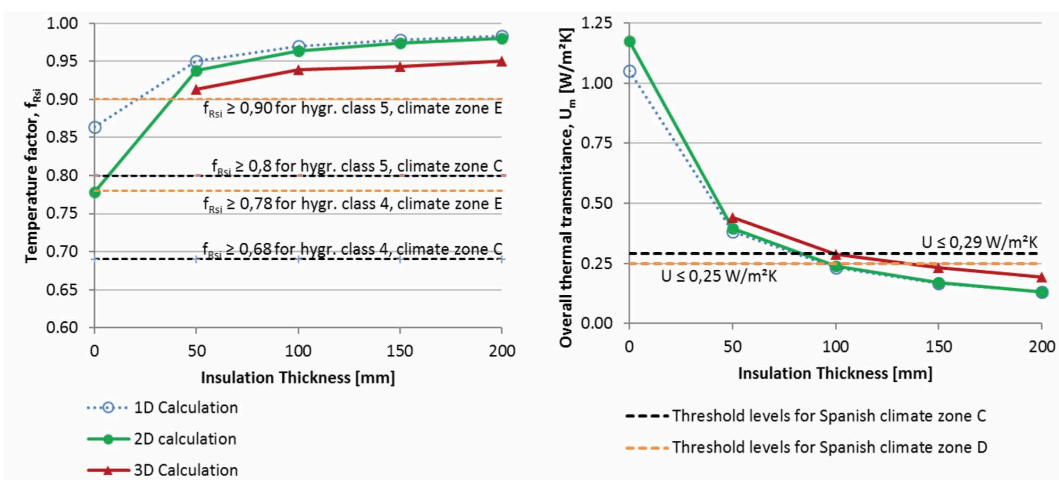

FIG. 7 Temperature factors and thermal transmittance values. (Arregi Goikolea, Garay Martinez, Riverola Lacasta & Chemisana Villegas, 2016)

The method results in a more precise assessment, where calculation errors due to 3D heat transfer are detected and corrected. As a result, the façade system is selected for compliance with the Spanish requirement of overall façade U-value (0.25 W/m^2K). In this correction, insulation thickness is increased from 10cm to 15cm of mineral wool.

6 CONCLUSIONS

With the increasing thermal performance levels required by national building codes in developed societies, steady-state thermal performance of one-dimensional sections of envelopes are not sufficient to guarantee the thermal performance of architectural envelopes. The need for detailed assessment is increasingly relevant in retrofitting projects, where architectural information and design alternatives face relevant constraints. Under such schemes, advances in design and assessment procedures are necessary, particularly considering that thermal bridges in these junctions are major heat loss paths, and cold spots exist in which surface condensation and mould growth are more likely to occur.

The proposed methodology provides a minimally intrusive methodology for the robust assessment of thermal performance of architectural junctions with many possible outcomes, which could be defined based on the requirements of each case. Considering the rapid adoption of wireless technologies in the sensor and monitorisation market, it could be expected that the intrusiveness of the methodology could be further reduced by removing wires in the monitorisation process.

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Exploring the Potential of Smart and Multifunctional Materials in Adaptive Opaque Façade Systems

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Abstract

Climate adaptive façades are considered promising breakthroughs for the reduction of energy consumption, as energy exchange is enabled when the weather conditions offer benefits instead of threats. So far, conventional building envelopes enhance thermal performance through opaque façade components and static insulations. Therefore, natural resources from the building environment remain untapped. Little research has been done in adaptive opaque façades, even if their dynamic behaviour shows a strong potential to exploit environmental resources. For the successful development of these innovative façade systems, a balance between sophistication and benefit is necessary. To manage this objective, the implementation of smart and multifunctional materials in the envelopes seems promising, as they are able to repeatedly and reversibly change some of its functions, features, or behaviour over time in response to environmental condition. Consequently, to trigger the response of the envelope, no external actuator or complex software management would be necessary. Nevertheless, these materials do not fulfil all of the façade requirements by themselves. Thus, they need to be combined with other adaptive technologies and building elements. This paper shows an initial definition of different façade configurations that include reactive materials, which enable the adaptiveness of opaque façade systems. The desired results are new façade roles suitable for a temperate climate, according to the potential of these multi-performance materials in the external layer of the envelope: the dynamic temperature change of the external cladding through the solar reflectance change and the enhancement or prevention of thermal losses through shape-changing ventilated façades. To achieve these new high performances, an ideal approach to the thermal behaviour of each façade layer was taken, and the required physical properties of each element was highlighted. As a result, we propose a mapping of a potentially suitable combination of reactive materials with other building elements that might enable holistic adaptive thermal performance.

Keywords

Climate response, environmental resources, temperate climate, thermal performance, adaptive technologies, innovative systems

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1 INTRODUCTION

Traditionally, the main objective when designing building envelopes was to balance the optimal performance for average climatic situations with their reasonable behaviour under adverse conditions. Most of the time, this meant that the envelope was not optimised from the point of view of construction design and performance. However, nowadays, adaptive or smart technologies can provide suitable and more efficient outputs under diverse climatic conditions. Smart and multifunctional materials belong to these kinds of technologies, as they are engineered materials that respond automatically and reversibly to environmental stimuli. Some Smart Materials (SMs) can change one or more of their properties as direct responses, whilst other SMs transform one energy form into another (Addington & Schodek, 2005). multifunctional materials (MM), also known as information materials, are less sophisticated raw materials whose "multi-properties" were designed by manipulating their structure by computational techniques (Kretzer, 2017). These advanced materials are applied in different fields, such as robotics or biomedicine, and some researchers have already pointed out their potential to develop successfully climate adaptive building envelopes (Loonen, Trčka, Cóstola, & Hensen, 2013)due to a growing demand to satisfy more ambitious environmental, societal and economical performance requirements. The application of climate adaptive building shells (CABS. Even if there are some conceptual proposals for their application in the façade industry (Badarnah & Knaack, 2005; Lelieveld, 2013)by adapting the material properties. Thus, smart materials have both sensory and actuation characteristics.
By introducing smart materials in the building system immediate adaptive environments can be realized. The purpose of this research is to study the application and performance of smart materials for the realization of a shape morphing adaptive building component (ABC, they are still at an early research stage. This could be due to their technical limitations, as will be discussed in section 3.2, but may also be due to the fact that their application and potential performances haven't yet been proposed in a defined, holistic way. To address the above-mentioned challenges, we propose two new roles of opaque adaptive façades and we follow a holistic first-stage design strategy, based on a literature review about reactive materials and responsive building elements. The objective of the proposed adaptive opaque façade systems is to enhance their thermal performance due to the dynamic response of smart and multifunctional materials, even when they are combined with other façade components. These roles are specially proposed for temperate climates with small day-night oscillations, characterised by their diverse climatic conditions changing in short time periods, as well as by their rich environmental resources that could contribute in the reduction of energy demand.

2 NEW ROLES OF THE OPAQUE FAÇADES: OUTLINING THE IDEAL THERMAL PERFORMANCE

2.1 THE POTENTIAL OF EXTERIOR CLADDINGS WHICH ADAPT THEIR SOLAR REFLECTANCE

Vernacular architecture makes use of different colour coatings in façades depending on the thermal behaviour that is required for each location. However, when we need to define the finishing for a temperate climate, a conflict exists and we must make a choice that won't always be ideal, especially if the temperate climate doesn't have any dominant climatic condition. In these climates, when ambient temperatures are below the comfort temperature range, the transmission of solar heat gains through façades are effective in the reduction of energy demand. High absorptance and emittance materials, which are usually dark in colour, are the perfect choice to enhance these gains (Table 1). Meanwhile, if the exterior temperatures are above the comfort temperatures, the use of cladding materials with low absorptance and emittance (clear or light coloured materials) is advisable to prevent overheating (Ibañez-Puy, Vidaurre-Arbizu, Sacristán-Fernández, & Martín-Gómez, 2017; Sánchez-Ostiz Gutiérrez, 2011). Therefore, the ideal material is an adaptive one that could change its reflection coefficient. Smart materials called thermochromics have the ability to reversibly change these properties upon reaching a specific temperature. In fact, the experiments undertaken by Ma and Zhu (2009) and Karlessi, Santamouris, Apostolakis, Synnefa, and Livada (2008) reveal that the reflectance of these materials increases towards long wavelengths, which provokes a reduction in the temperature of the coating. Furthermore, exterior cladding material also influences the intensity of thermal flux depending on their thermal diffusivity and conductivity. In this sense, we couldn´t find any multifunctional materials that could dynamically adapt their diffusivity and conductivity, so the heat transferring to the inner façade layer will depend on the "static" material that we choose, as shown in Table 1.

Thermal performance	Physical properties	a) Enhance solar gain	b) Thermal dissipation	Technology	
Heat gain	Absorptance	High	Low	Thermochromic finish	
	Reflectance	Low	High		
Heat transfer to the inner façade layers	Emittance	High	Low	Thermochromic finish	
	Thermal diffusivity	High	Low	a) Metallic cladding	b) Ceramic, stony cladding
	Thermal conductivity	High	Low	a) Metallic cladding	b) Ceramic, stony cladding

TABLE 1 Relevant physical properties of exterior cladding materials to obtain adaptive thermal control.

Thermal performance	Physical properties	a) Enhance solar gain	b) Thermal dissipation	Technology	
Thermal conservation	Thermal conductivity	High	Low	Adaptive Air Cavities Dynamic Insulations Adaptive Insulations	
	Thermal diffusivity	High	Low		
Thermal storage	Time-lag	Low	High	a) Lightweight	a) Heavyweight
	Thermal diffusivity	High	Low	a) Air, metal	b) Ceramic, stony material
	Sensible heat content	High	Low	a) Stone, concrete, ceramic, clay, water	b) Air, light wood, thermal insulation material
	Latent heat content	High	Low	PCM	
Heat transfer to the interior space	Thermal diffusivity	High	Low	a) Metallic cladding	b) Ceramic, stony cladding
	Thermal conductivity	High	Low	a) Metallic cladding	b) Light woods, Synthetic cladding

TABLE 2 Relevant physical properties of interior façade materials to obtain adaptive thermal behaviour.

Possible adaptive control of solar thermal radiation through the cladding needs to be properly understood in terms of the overall thermal flux of the system. For instance, it would be useless to foster solar heat gains under certain climatic conditions if the internal layers of the façade component were blocking that thermal flux. Therefore, to meet all the environmental boundary conditions, they must also include a dynamic behaviour to afford suitable heat transfer, thermal conservation and storage. Table 2 summarises the determining physical properties in each stage of the thermal flux, and promising technologies and building materials that could provide the target performance, are detected.

2.2 SHAPE-CHANGING CLADDINGS TO SEEK HIGH PERFORMING VENTILATED FAÇADES

Opaque ventilated façades enhance thermal performance under mild and warm climatic conditions. These façade systems consist of two opaque layers with an air cavity between. The convective movements in the cavity cause heat dissipation and decrease the surface temperature of the second opaque layer (Ibañez-Puy et al., 2017; Sánchez-Ostiz Gutiérrez, 2011). Nonetheless, in cold periods this behaviour is detrimental as it increases thermal losses, especially if the convective movements reach high velocities. Ibañez-Puy et al. point out that the appropriated outer skin, as well as joints configuration, change depending whether conditions are hot or cold and windy (Ibañez-Puy et al., 2017). Transferring that to a temperate climate, where sequences of threatening climatic scenarios coexist with mild scenarios (even in the same season), it is impossible to choose an optimal, static solution. Adaptive configuration of the outer skin seems like a promising solution to meeting all climatic scenarios, and smart and multifunctional materials may play a role. There are two material families that look favourable: Shape memory alloys (SM) and thermobimetals (MM). The former, such as Ni-Ti alloys, are capable of returning to their original shape from a deformed state, when a certain temperature is reached. Thermobimetals, like Ni-Fe alloys, are two different sheets of differing metal alloys that, laminated together, expand at different rates within a few seconds, causing the bending of the piece (Fig. 1). When the heat source is gone, they can return to their original shape (López, Rubio, Martín, Croxford, & Jackson, 2015).

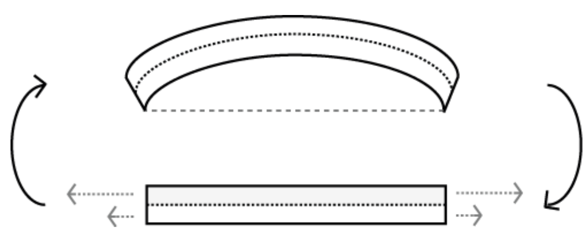

FIG. 1 Thermobimetals bend when they are exposed to the operational temperature, as they are composed of two different metal alloys that expand at different rates.

However, shape changes in the exterior cladding, which aim to control convective heat transfer, would only be effective if physical events are analysed in a holistic way. Firstly, we need to understand that convective movements inside the cavity can happen because of two phenomena: a temperature gradient due to solar gains or wind pressure. Both phenomena can enhance thermal dissipation if physical parameters are considered in the design. If the exterior cladding controls thermal dissipation triggered by solar radiation, then cladding material is a critical factor. For instance, materials with high absorptance and emittance would be suitable to boost convective insulation. Otherwise, when playing with wind action to promote thermal dissipation, material choice has little relevance (Table 3).

Thermal performance	Physical properties	Thermal dissipation		Convective insulation	Promising Responsive material
		Solar gain	Wind action		
Heat gain	Absorptance	Low	Little relevance	High	Thermochromic finish
	Reflectance	High	Little relevance	Low	
Heat transfer	Emittance	Low	Little relevance	High	Thermochromic finish
	Thermal diffusivity	*	Little relevance	Low	*
	Thermal conductivity	*	Little relevance	Low	*

**Further numerical and experimental assessments are needed to discover required physical property*

TABLE 3 Physical property requirements of exterior cladding materials to shift from thermal dissipation to convective insulation

In addition, the morphology and dimensions of the air cavity are important for thermal performance (Table 4). Ventilated façades with significant height and low roughness, will more easily prevent overheating. When this dissipation is due to solar heat gains, it is more appropriate to have a ventilated cavity and a cladding element with closed joints, as the stack effect is boosted, whereas to prevent overheating by making use of the wind, it is better that joints are open (Ibañez-Puy et al., 2017). On the other hand, if we want to avoid the thermal losses that wind would create, the air cavity should be 1-5cm thick, unventilated, and with the lowest height possible (Sánchez-Ostiz Gutiérrez, 2011).

Thermal performance	Ideal morphology	Thermal dissipation		Convective insulation	Promising Responsive material
		Solar gain	Wind action		
Heat transfer	Opening degree (Ibañez-Puy et al., 2017)	Ventilated, closed-joint	Ventilated, open-joint	No ventilated	SMA thermobimetals
	Thickness	7-35cm(Balocco, 2002)	*	1-5cm(Sánchez-Ostiz Gutiérrez, 2011)	
	Roughness	Low	Low	High	
	Height	Higher, better	Higher, better	Higher, better	

** Further numerical and experimental assessments are needed to discover required physical property*

TABLE 4 Morphological requirements of the air cavity to shift from thermal dissipation to convective insulation

Thermal dissipation by both wind and solar action broadens the scenarios in which the façade would perform in an optimal way. It must be considered that dissipation by solar heat gains becomes less effective as wind velocity increases, and is negligible over 2.5m/s. Besides, convective thermal dissipation overnight can occur in windy conditions, or in situations in which there is not enough solar radiation (Ibañez-Puy et al., 2017).

3 POSSIBLE IMPLEMENTATIONS OF SM & MM IN ADAPTIVE OPAQUE FAÇADES: A PROPOSITION OF PROMISING FAÇADE CONFIGURATIONS AND THEIR CHALLENGES

3.1 SUITABLE COMBINATION OF SM OR MM WITH OTHER FAÇADE TECHNOLOGIES

Adaptive solar control façades result from the adequate combination of thermochromic-coated claddings with other façade components. It can be concluded from the information shown in Table 1 that when the façade aims to gain thermal energy from solar radiation, heat transfer needs to be as fast and effective as possible in the cladding, in such a way that it can be stored in the internal layer or transferred to the interior environment (Fig. 2). Heat gained in the outer skin is transferred to the internal layers, where it should be stored by thermal mass, sensible heat, or latent heat. Finally, it is transferred to the interior environment through convection and radiation. When solar gains are detrimental to thermal comfort, the radiant heat that can't be reflected by the exterior cladding is dissipated by convective movements (if there is an air cavity placed just behind the outer skin). This, coupled with thermal conservation layers, minimises thermal gains by conduction in the indoor environment.

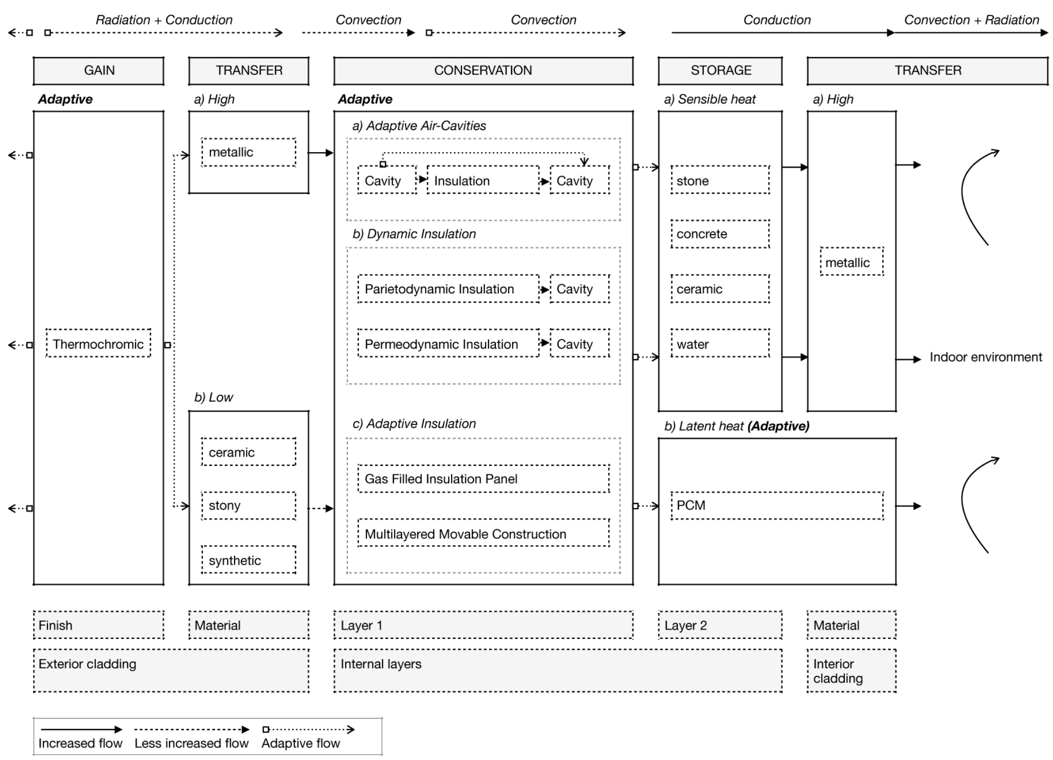

FIG. 2 Possible combination of thermochromics with other technologies.

The thermal behaviour shown in Fig. 2 might be achieved through a different configuration of thermochromics with other building elements. This can be illustrated briefly by the cladding material, which modifies the intensity of the thermal flux depending on the material type that is chosen. When applying a thermochromic finish in a metallic cladding, thermal flux is more intense than if ceramic, stony, or synthetic materials were chosen. Regarding thermal conservation, as energy exchange is profitable at certain climatic conditions, it would be inadequate to use regular insulation materials. Indeed, an adaptive conservation layer should be placed in the internal layers. A possible solution is to place an adaptive air cavity behind the external cladding, which could include an autoreactive damper (made by SM/MM or an electro-mechanical actuator). To open this damper, heat would be transferred to the intermediate layer by introducing pre-heated air, and a second air cavity would, by necessity, be in contact with the storage façade element (Fig. 3).

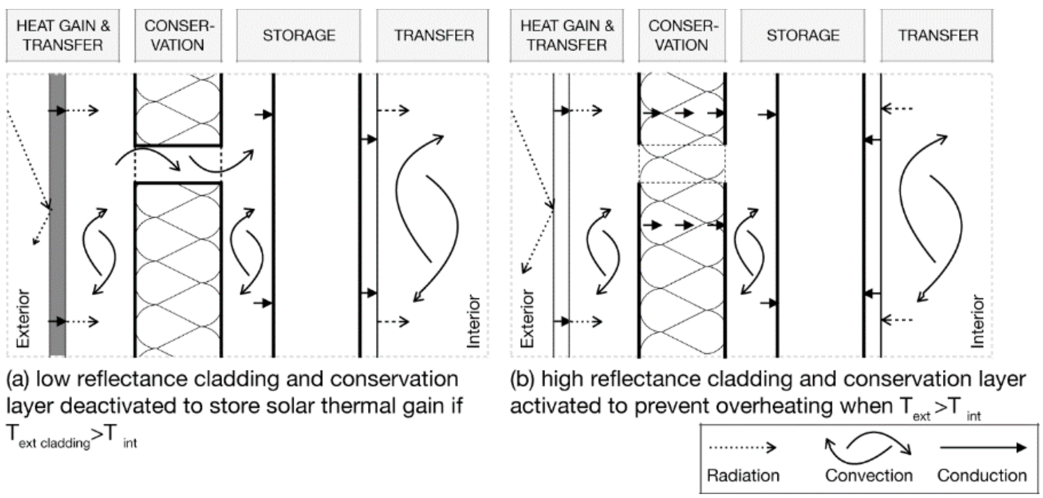

FIG. 3 Possible configuration combining thermochromic finish applied in exterior cladding and adaptive air cavities to achieve adaptive thermal performance in an opaque façade system.

Another option is to replace the traditional insulation material with a dynamic insulation element, which changes its behaviour to enhance or block thermal conduction (Fig. 4), or adaptive insulations (Favoino, Jin, & Overend, 2017), which adapt their features to change their thermal performance (Fig. 5). Finally, thermal storage could be achieved by combining the aforementioned elements with an internal layer of high sensible heat content, such as concrete, ceramic, or water, or high latent heat, such as phase change materials (Fig. 2).

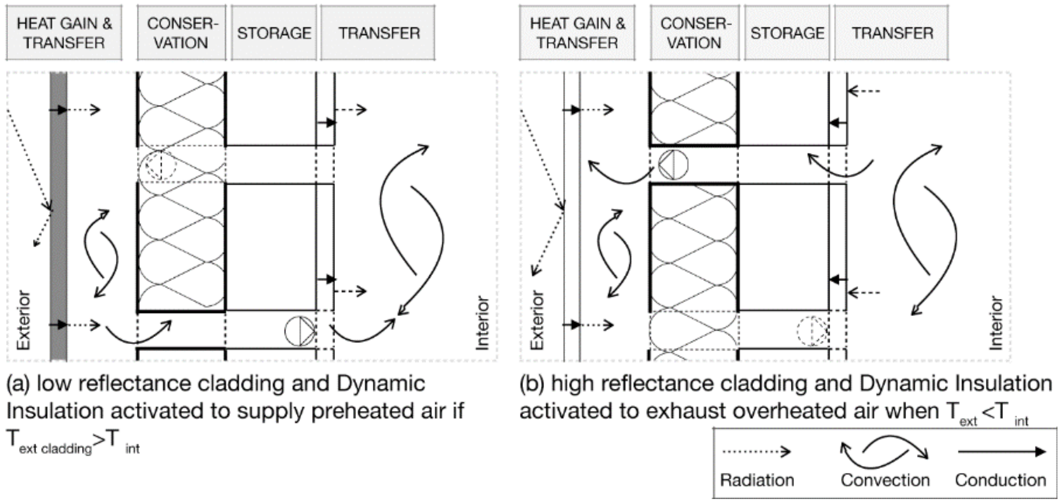

FIG. 4 Possible configuration combining a thermochromic finish applied in exterior cladding and a dynamic insulation element to achieve adaptive thermal performance in an opaque façade system.

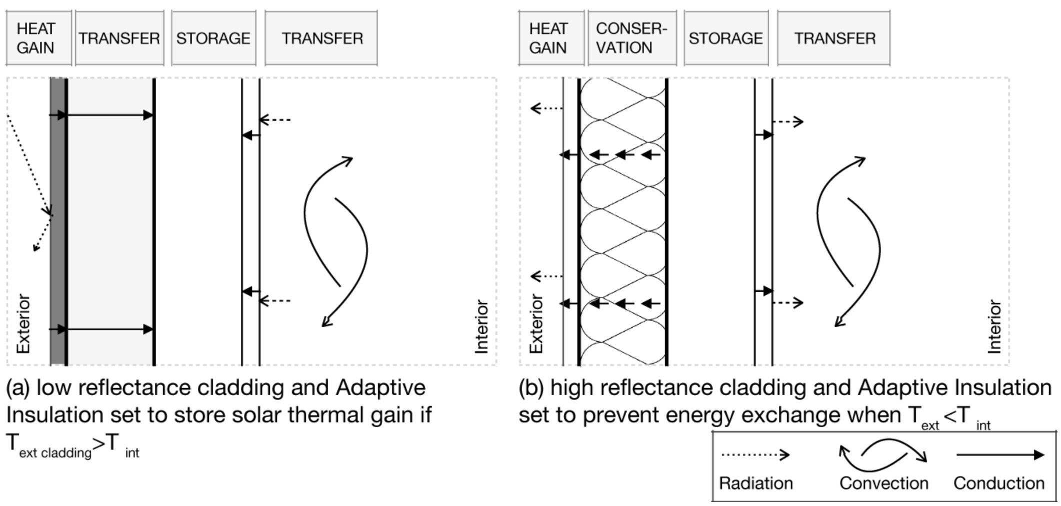

FIG. 5 Possible configuration combining thermochromic finish applied in exterior cladding and adaptive insulation element to achieve adaptive thermal performance in an opaque façade system.

With respect to shape-changing ventilated façades, morphology variations of the outer cladding must be set properly within the system to enhance or reversibly block thermal flux. In order to meet all the possible requirements in each climatic condition, three possible morphological configurations are proposed for a ventilated façade system. The first shape configuration provides a ventilated façade with a closed air cavity, as the external cladding geometry has a closed-joint arrangement and furthermore, the upper and lower dampers of the cavities are closed. The second configuration enables heat dissipation by solar radiation, as the outer skin has a closed-joint geometry but the dampers of the cavities are opened, which enhances the stack effect due to the temperature gradient. The third and final configuration makes thermal dissipation possible by wind action, as both cavity and cladding joints are opened.

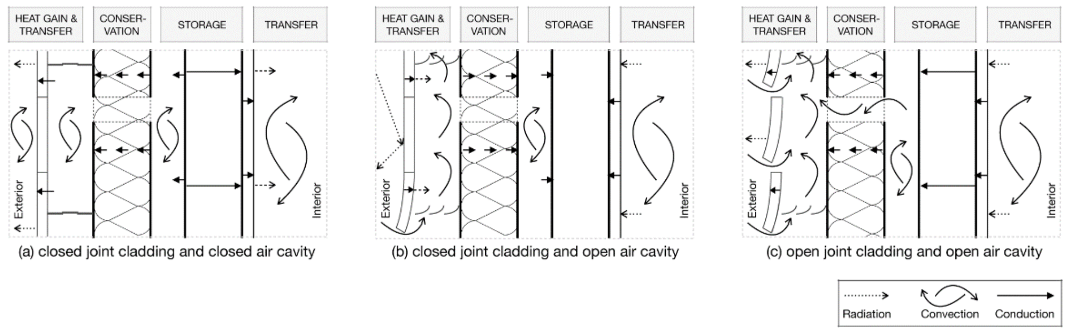

FIG. 6 Possible configurations of a shape-changing ventilated façade using SM or MM as actuators embedded in the cladding and in the dampers. Different morphologies would allow the control of thermal losses due to convective movements. Configuration (a) would allow a convective insulation, (b) would enable thermal dissipation triggered by solar thermal radiation, and (c) would prevent overheating in the interior space, enhancing thermal losses by wind action.

SM and MM would be the actuators of the kinetic behaviour and they would react automatically and reversibly to a set operational temperature. This would prevent or allow ventilation of the air cavity. Besides, the opening degree of the outer skin would be controlled by opening or closing the joints of the cladding and/or by partitioning the air cavity at specific temperatures.

When thermal dissipation is intended, the direction of energy exchange would be from indoor to outdoor (Fig. 7). In order to reduce the temperature of the interior environment, different strategies could be provided by a single façade system. On one side, internal heat loads could be minimised by the storage layers, to redistribute that energy by conduction when it is needed. Furthermore, disabling conservation layers could improve thermal comfort when the exterior conditions are more suitable than the interior ones, as heat could be transferred from the interior to the cavity by conductive and convective fluxes. Finally, as previously discussed, convective movements in the air cavity could cause significant thermal losses. On the contrary, to use the exterior cavity as a convective insulation element, it should be fully closed, and the conservation layer should be activated, impeding convective flows and blocking thermal flux by conduction. In this case, material combinations fit with the ones that were exposed in Fig. 2. Once more, adaptive flow from the internal layers to the exterior cavity would only be possible if the conservation layers performed in a dynamic way according to different boundary conditions.

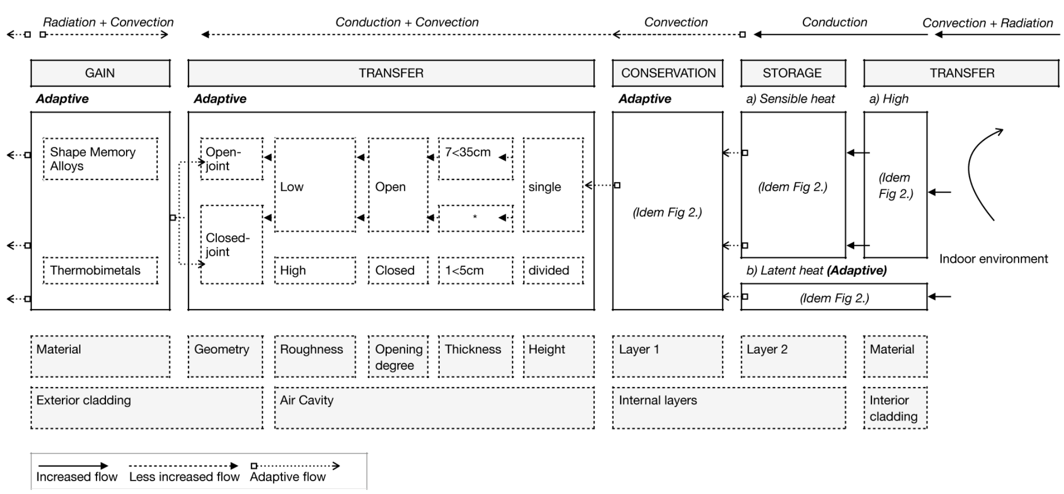

FIG. 7 Possible combination of shape-changing materials with other technologies

3.2 TECHNICAL LIMITATIONS

Technical limitations delay the success of some smart and multifunctional materials in the building industry. Their drawbacks need to be properly understood to overcome this challenge, in such a way that they could be addressed by finding suitable combinations with other building technologies. For instance, according to the literature reviewed, thermochromic materials have a serious problem with degradation, especially when they are exposed to ultraviolet radiation (Addington & Schodek, 2005) and their mechanical properties decay (Ma & Zhu, 2009). This is the reason why the number of reversible adaptation cycles are considered too short for façade application. However, we can find commercialised products containing thermochromics in the glass industry, which ensure optimal fatigue life. In fact, they are usually applied as thin films between glass panels; the glass prevents UV radiation. When applying SMAs or thermobimetals, we must combine these materials in a multi-layered façade system to face thermal, hygrothermal, and acoustic requirements. In addition, these alloys are oxidised when they are in contact with aggressive environments (marine or industrial). But while the oxide layer of some SMAs, such as Ni-Ti alloys, is compact, thin, and passive, and it acts as a protection layer, the oxide layer of thermobimetals (Ni-Fe alloys) is porous and, therefore, destructive. As these materials act kinetically, a hypothetical protection layer would be useless, as it could be broken by the repetitive deformation of the piece. Consequently, thermobimetals shouldn't be used in marine or industrial atmospheres.

4 CONCLUSIONS AND FUTURE DEVELOPMENTS

This paper has shown different possible façade configurations in which to apply smart and multifunctional materials in adaptive opaque façades. To reach this stage, it was necessary to consider the physical events in a conceptual way, so that the ideal thermal behaviours in the overall systems were designed. This analysis allowed for the anticipation of the most appropriate physical properties for each layer of the systems, according to the pursued dynamic roles. Based on the literature review, we highlighted promising materials and technologies that could meet these requirements and we explained briefly how they could work in a holistic way.

To more accurately scope the potential of these new systems and to find out which configurations are the most suitable ones, further research is still needed, starting with numerical assessments. They would allow for the optimisation of the adaptability range, the velocity of adaptation, and the operational scenario (operational temperature setting) of these materials. Moreover, they would allow for the determination of whether the proposed combinations with other building materials would enable a holistic responsive performance. Lastly, these new façades must be validated through experimental assessments to prove that current technologies can offer suitable adaptive responses over an adequate lifespan.

Acknowledgements

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Unglazed Solar Thermal Systems for Building Integration, coupled with District Heating Systems. Conceptual Definition, Cost and Performance Assessment

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Abstract
In this paper, the energy performance of a solar thermal (ST) façade system is studied in relation to its connection to a district heating system. This concept allows for the direct use of ST heat in the building, while taking profit from the network for delivery/selling of excess heat and purchase of heat during periods of underproduction. The use of unglazed collectors for low-intrusive architectural interaction in façades is discussed.

Studies are carried out on the heat production of the system and its capacity to cope with local demands. Economic studies are carried out in order to balance the investment and operational costs/profits of the system.

Keywords
solar systems, thermal energy, building integration, energy systems

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1 INTRODUCTION

In developed countries, there is a clear need, and political impulse, to achieve an energetic transition from fossil fuels to renewable sources. Within renewable energy sources, the potential of solar power and associated technologies is well known. In particular, solar thermal systems are a proven renewable heating technology. Although the exergy of this energy source is quite low, the potential of solar energy is still one of the greatest on the planet (Ehsanul, Kumar, Kumar, Adelodun, & Kim, 2018).

In this context, solar energy must be one of the main pillars of a renewable energy strategy. A clear example of the drive towards this transition is the minimum solar contribution required by national building codes in developed countries, such as the Spanish CTE (2013).

In most traditional heating system designs, Solar Thermal (ST) systems are sized to meet only a fraction of the entire demand for thermal energy. Solar production and heat loads in buildings have daily and seasonal variations due to transient and variable weather conditions. In most climates, space heating (SH) load is interrupted in summer periods, but domestic hot water (DHW) loads are stable all year round. In winter, the available ST heat is not sufficient to cover heat loads in buildings, while in summer, solar heat production clearly exceeds the demand of the building. ST systems are commonly sized not to exceed heat loads over the spring-autumn period.

Most ST systems are incorporated in roofs. In order to meet the increased requirements for ST installation, larger surfaces will need to be activated for ST installations. For this, building façades need to be considered as candidate areas due to their large available surface, although challenges of overshadowing in high urban building densities must still be resolved.

With the steady incorporation of nZEB (nearly Zero Energy Buildings) in cities, relevant reductions in heat loads can be foreseen in the near future. The utilisation of renewable energies in these same buildings will reach a point where the directionality in the production-consumption role will be altered. The increase in ST installation with the reduction of heat loads in buildings modifies traditional ST sizing criteria. As a result, excess heat may be available from these ST systems. In this paper, the connection to district heating (DH) is explored in order to allow this excess production to be used in adjacent buildings.

DH systems are one of the most efficient ways to cover heat loads in urban areas. Traditionally, DH systems have been based on large boilers or CHP (combined heat & power) systems. Nowadays, it is increasingly common to find DH networks that incorporate distributed energy sources (Monsalvete Álvarez de Uribarri, Eicker, & Robinson, 2017), commonly with lower exergy in comparison with traditional high temperature power plants.

This includes the exploitation of industrial waste heat and solar thermal systems, among others. All this results in a reduction of fossil fuel dependence and contributes to a de-carbonised environment.

Heat losses in the DH system are proportional to the temperature gradient between supply temperature and environment temperature. With lower operational temperatures and distributed energy sources, there is a substantial improvement in system performance.

In this paper, the potentialities, constraints, and performance levels of façade-integrated solar thermal systems coupled with low temperature district heating (LTDH) are studied, comprising their thermal and economic performance. The techno-economic viability of unglazed façade-integrated solar thermal systems when combined with low temperature district heating systems.

1.1 UNGLAZED SOLAR THERMAL COLLECTORS

In general, ST systems are composed of solar thermal collectors, where a heat transfer fluid is circulated in a pressurised circuit. Solar heat is absorbed and transferred to the fluid, resulting in an increment of the temperature. Depending on external conditions and collectors` characteristics, the performance of each collector is different. Their performance definition is described in detail in (Duffie and Beckman, 1980).

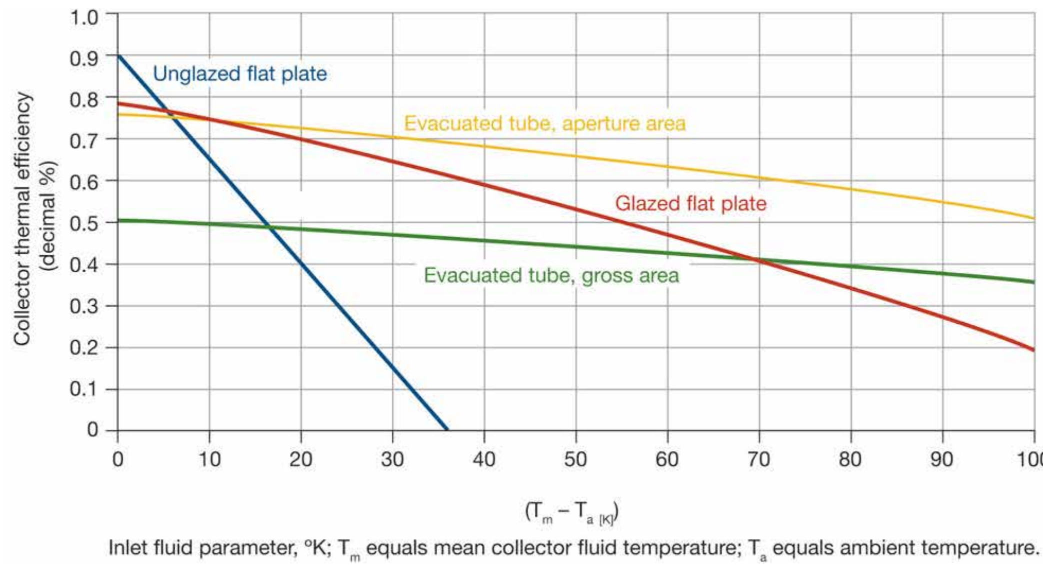

FIG. 1 Collector efficiency vs (T_m-T_a). G_T = 800W/m^2. Source: Stickney, B. & Soifer, B, (2009).

Fig. 1 shows that with a low temperature difference, unglazed collectors present better efficiency levels than other systems. The possibility to incorporate unglazed systems in buildings has been studied in diverse investigations such as (A. Giovanardi, 2016) but only a few companies propose integration into the façade, and the technology is still under-exploited.

1.2 ARCHITECTURAL INTEGRATION OF ST SYSTEMS

Building integration of ST systems has been historically limited due to the need to accommodate glazed areas and tubular assembles in the architectural composition of buildings. Despite this, smart but marginal integration solutions for vacuum tubes have been achieved in balconies or transparent areas (O'Hegarty, Kinnane, and McCormack, 2016)

As for the unglazed collectors, the method for their integration in façades is explained in (Garay Martinez, R., Arregi Goikolea, B., Bonnamy, P. & Lopez, J., 2017). Having no glass or tubular covers, the unglazed collectors are the only ones that can be integrated without modifying the aesthetics of the building. Specifically, the unglazed solar collector enables varied forms (shape, size, and typology) and materials (colour, texture, transparency etc.).

In broad terms, it must be considered that façades are the prominent image of the building. In the selection of ST technologies and their integration with solar thermal façades (STF), this aspect needs to be taken into account. The existence of a wide range of architectural façades requires delivery of a wide range of STF products, to ensure freedom of design intent. In (Garay Martinez, Arregi Goikolea, Bonnamy, and Lopez, 2017), an experimental study is performed on unglazed ST collectors and their potential to deliver heat to HVAC systems in buildings. In this work, it is identified that façades are the biggest area on to which collectors can be installed, and that unglazed collectors are one of the most sensible alternatives to achieve ST production and architectural integration.

1.3 ST CONNECTION TO DH NETWORKS

With the trend to incorporate decentralised and decarbonised heat, ST is an increasingly common alternative heat source being incorporated in DH. There are two integration alternatives for ST in DH: centralised and distributed ST systems. To date, most ST installations have consisted of centralised ST plants outside cities. This paper explores the possibility to integrate distributed ST systems in buildings, by means of their integration in building façades. This allows for the moving of energy sources closer to consumption points to reduce the transmission losses associated with the aforementioned centralised plant. DH connection of ST systems can be performed in different ways, with different functionalities. (Sanchez Zabala and Garay Martinez, 2017) describe several types of connections. Fig. 2. shows different types of ST integration schemes into a DH network.

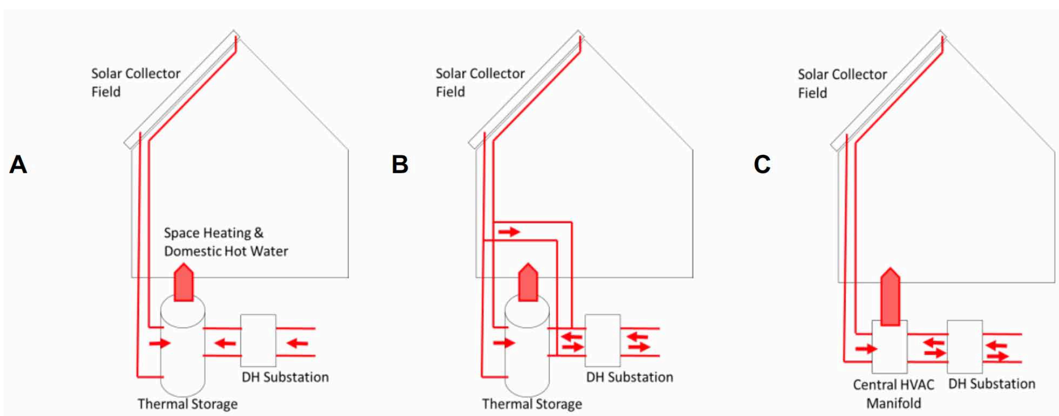

FIG. 2 ST integration into DH networks. A. ST & DH in parallel. B. Delivery of excess heat to DH. C. Hybrid system without storage (Sanchez Zabala & Garay Martinez, 2017)

This paper explores a direct ST and DH connection to central HVAC manifolds in building, allowing bi-directional heat transfer to the DH. In this concept, local storage is avoided.

2 METHODOLOGY

In this paper, simulations are performed in order to assess the technical and economic viability of unglazed ST systems connected to DH networks in order to deliver decarbonised heat within reasonable economic metrics.

For this purpose, simulation studies are performed for a multi-storey building in the region of Bordeaux (France). According to the Koppen-Geiger climate definition, described by (Kottek, M., Grieser, J., Beck, C., Rudolph, B., & Rubel, F., 2006), Bordeaux is classified as having a C_{fb} climate, which covers most climates in Western Europe, from the north of Spain to central EU latitudes such as UK, The Netherlands, etc... For this reason, Bordeaux is considered to be a representative location for West-EU climates.

The heat load, for DHW and space heating is calculated by means of dynamic simulation methods with an hourly resolution. Heat production of a south-oriented ST façade is simulated for the same climate with the same resolution.

The economic viability of DH-connected ST systems is evaluated by means of a comparative study against fossil-fuel alternatives. Various ST connection & heat pricing schemes are studied.

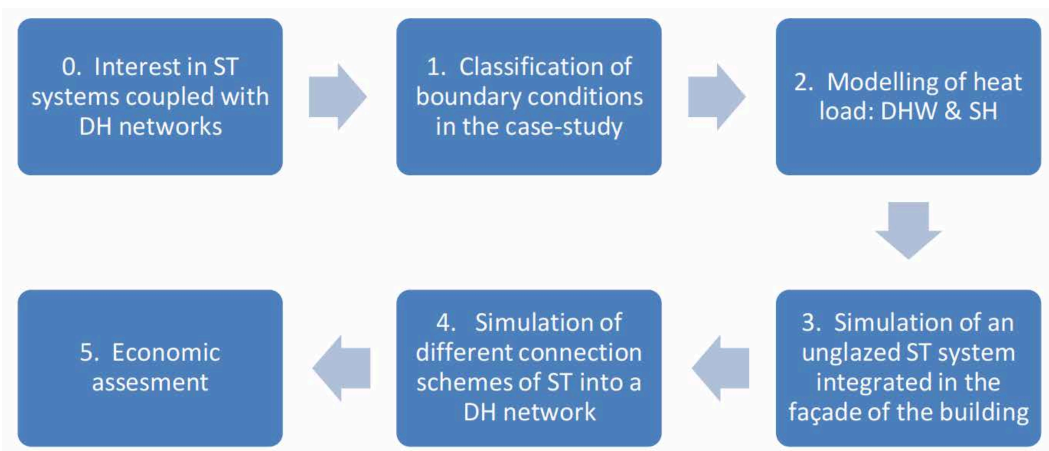

FIG. 3 Methodology description

2.1 HEAT LOAD MODELLING

The first step in this study is developing the building model and defining its main characteristics, depending on which the heat loads vary considerably. The selected case study comprises a 5-storey building, with a façade surface area of 1250 m^2. In Fig. 4, a general view of the building and its basic connection scheme to DH is shown. The U-value of the walls is 0.8 W/m^2. The window-to-wall ratio is 40% with a U-value of 1.4 W/m^2. Fig. 4 shows general prototypes for ST integration in the building and its connection to DH substation.

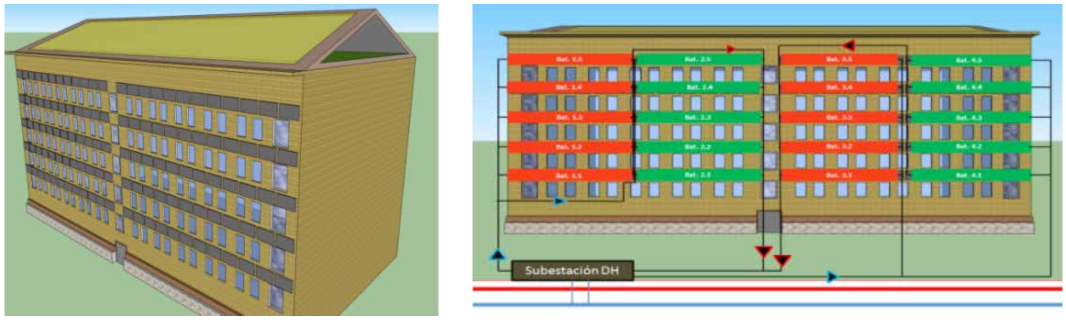

FIG. 4 3D model of the building geometry & ST system on the south façade (left); Connection scheme within the collector field and connection to DH (right)

DHW heat load has been calculated according to (Código Técnico de la Edificación [Technical Building Code], 2013), considering a total floor area of 5000m^2 divided in 80m^2 apartments inhabited by families comprising 3 people. According to the calculation procedure, 22 litres of DHW (60°C) are consumed per person per day.

For SH, a pseudo dynamic calculation has been used, with a self-developed procedure that is compliant with UNE-EN ISO 13790:2011.

2.2 MODELING OF THE UNGLAZED ST SYSTEM

For the modelling of the ST façade, a self-developed model in the software R has been used for thermal calculations. This software tool allows big databases to be worked with as vectors, thereby reducing calculation times. Within this model, specific collector Energie Solaire Kollektor AS (2012) data has been used in order to calculate efficiency and other parameters used in the model.

As for the working temperatures, the inlet temperature has been fixed in order to be the same as the DH return line temperature (± 30 °C) and the outlet temperature from the collector field has been set according to each of the simulation cases, which are further defined later in the text. Moreover, load losses have been estimated to be 10%.

2.3 CONSIDERATIONS FOR ECONOMIC METRICS

The economic assessment is based on general economic metrics which can be found in general purpose economic literature such as (Harris, 2018). For their calculation, the investment necessary for the installation and exploitation of each technology has been calculated, leading to the calculation of the yearly revenues and operational costs. This will include the consumption of primary energy sources and the heat purchase and delivery. As it is a theoretical study, the maintenance costs have been avoided for being much lower in comparison with other cash flows.

Specifically, the metrics used for this economic assessment are as follows: return on investment (ROI), which is the time taken to recover the investment; cash flow, the net amount of cash moving in and out of each technology; and net present value (NPV), which is the difference between the present value of cash inflows and the present value of cash outflows over a period of time.

3 THERMAL PERFORMANCE OF UNGLAZED ST SYSTEM

A ST collector system is studied in a high-rise building. This collector field comprises 240m^2 of south-oriented unglazed ST. The field is arranged in 20 parallel circuits, comprising 6 collectors in a serial arrangement, with each collector covering and area of 2m^2. Data relating to the specific collector used for this installation can be found in Energie Solaire Kollektor AS (2012).

In general, collectors achieve better efficiency when the temperature difference between the collector (average) and environment is low. In order to limit the average is the solar field, a sensitivity analysis is carried out to ensure that the inlet-outlet temperature difference is limited to 10 °C. That temperature difference is defined by difference between the average temperature in the collector battery and the ambient temperature. This results in the aforementioned configuration.

In an isolated system, the service temperature needs to be met by solar thermal collectors. In these systems, it is common to use the lowest possible service temperature to increase the overall performance of ST. In the case of considering ST systems coupled with DH, there is no need to configure ST systems to raise fluid temperature to the overall flow temperature in the DH network. There is a minimum temperature difference (normally 3-5°C) that the system must achieve before it is worth activating the pumps to circulate the fluid. If the heat output is delivered in the return pipe of the DH, greater performance is achieved due to the lower service temperature compared to insulated ST systems. In Fig. 5, the results from the simulation of unglazed ST when reacting to different situations are shown.

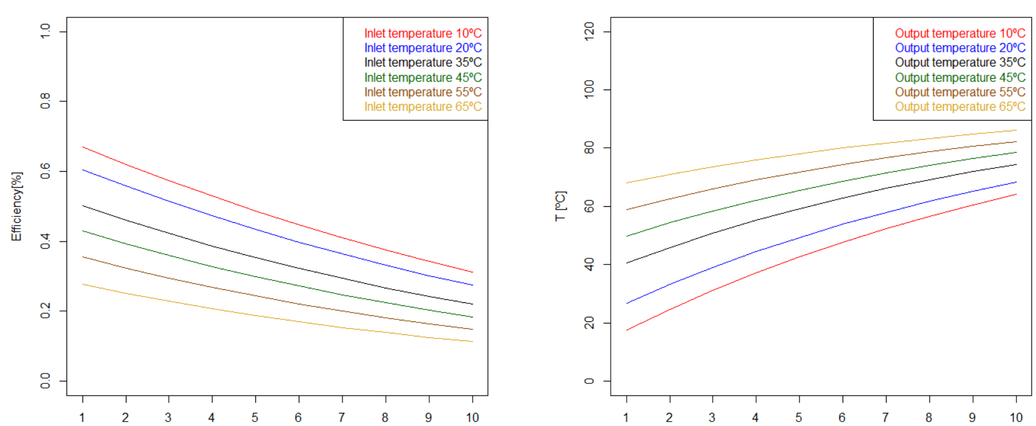

FIG. 5 Collector in serial arrangement performance for different situations

Depending on the service temperature required, the number of collectors arranged in series increases, so that the surface needed increases proportionally. Taking into account the fact that the inlet-outlet temperature difference is limited, the number of collectors is also limited.

Nowadays, LTDH (low temperature district heating) is considered as an alternative to conventional DH, and the working temperatures of this system are much lower, reducing heat losses in supply temperatures. In this case, the best solution for installing integrated ST is to install the ST system to the return pipe of LTDH system.

4 RESULTS

4.1 HEAT PRODUCTION

Solar production is simulated for the climate of Bordeaux for various operational conditions. These conditions consider various inlet temperatures, among which low temperatures are incorporated and used in line with LTDH. Temperatures in the range of 50-60°C are representative of flow temperatures, while temperatures of 20-30°C are representative of DH return lines. In Fig. 6, the total heat production of a solar unglazed collector (Energie Solaire Kollektor AS, 2012) and the total efficiency defined by the production, divided by the total solar radiation, are shown. The bar plot refers to the total solar production by the unglazed collector; the lines refer to the total efficiency. The results indicate that better results are achieved for the cases in which the inlet-outlet temperature difference is limited to 10°C, no matter what the inlet temperature is.

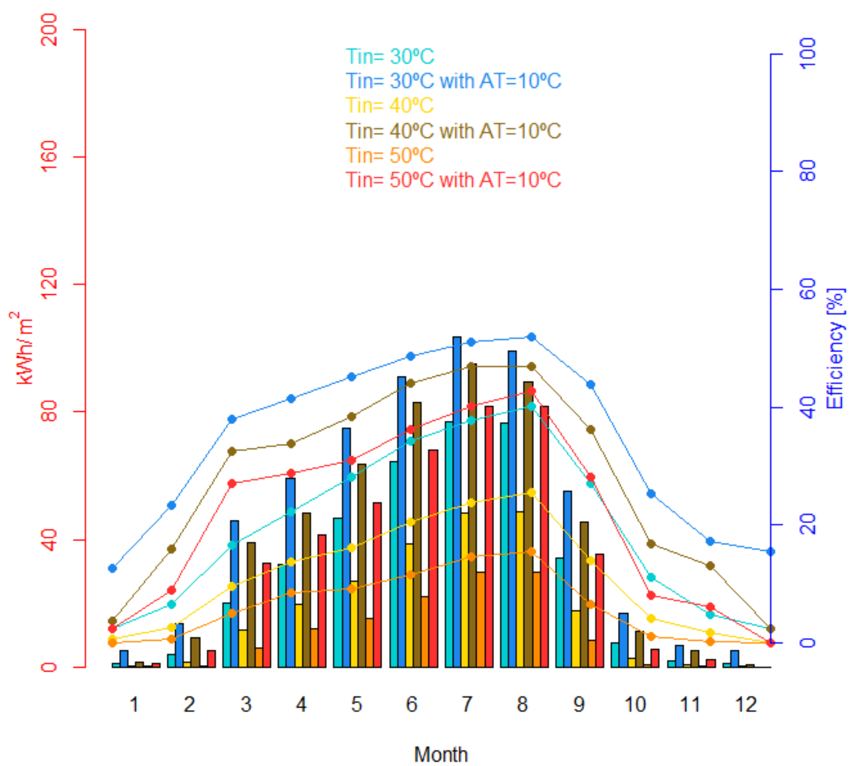

FIG. 6 Solar production and total solar efficiency for different inlet temperatures

Temperature differences in the range of 10°C can be used to inject heat to the return line of the DH system.

4.2 ECONOMIC VIABILITY

The economical assessment of DH connected ST system is studied against several benchmark cases (natural gas boilers, electric heaters etc.). Investment and operational costs are calculated and the economic performance of the system is calculated over the service life of the system.

Investment and operational costs have been calculated for the cases under review. Investment costs cover the equipment and installation costs of each system. Representative HVAC systems for multi-storey buildings have been used and their cost normalised per kW. Data has been taken from (Precio centro Guadalajara, 2018) and from (Tarifa de precios solar térmica Salvador Escoda, 2018).

Technology	Material installation costs (€/kW)
Natural gas boiler	85
Joule heater	5
Ground source heat pump	692
Unglazed collector without DH	915
Unglazed collector with DH	608

TABLE 1 Installation cost per unit of power for different technologies.

In Table 2, the breakdown of the investment costs is presented.

Concept	Unitary cost (€/unit)	Quantity	Total €
Solar Collector RK // ALPIN RKM 2001 2m^2	305	120	36630 €
Support assembly for façades // SFV-AR	120	120	14400 €
Valves and other installation materials	---	---	4041 €
Workforce costs	---	---	7251€
Total	---	---	62023 €

TABLE 2 Cost estimation for ST installation. Source: Tarifa de precios solar térmica Salvador Escoda [Salvador Escoda solar thermal price list] (2018).

Operational costs incorporate the primary energy consumed by heating systems. The cost of primary energy sources are shown in Table 3.

Primary energy	Price (€/kWh)
Natural gas	0.05
Electricity	0.14
ST	0
DH heat (UNE-EN ISO 13790:2011)	0.0685
Heat purchase (estimated 70% of DH heat cost) (UNE-EN ISO 13790:2011)	0.04795

TABLE 3 Prices for primary sources (2016).

The cost of DH has been obtained from the commercial price of heat in the DH network in Paris, specifically; data has been obtained from (Tarifs de Vente CPCU, 2016), which is one of the largest networks in EU. As for the DH cases, it has been assumed that the heat produced by ST system could be sold to DH network at two price points: 100% of heat price produced in DH and 70% of the heat price produced in DH. This is simply a consideration in order to simulate an ideal case, as well as a more realistic one.

Investment and operational costs of all alternative systems studied are recorded in Fig. 7.

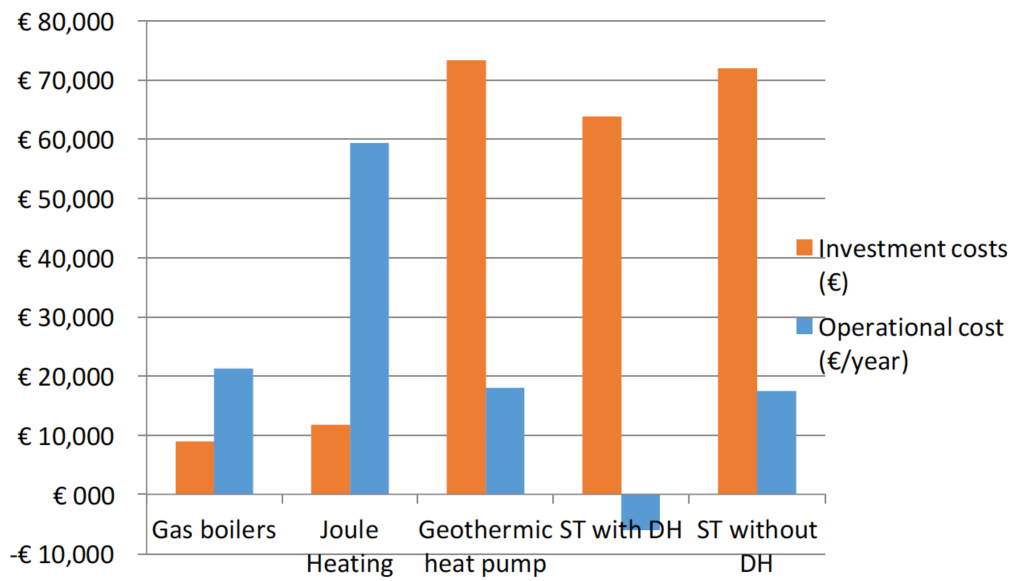

FIG. 7 Initial investment and operational costs for each technology

The case of the ST system coupled with DH has negative operational costs. For the calculation of such operational costs, it has been considered that all of the heat demand from the building is obtained from the DH supply line and the heat produced by the ST is, in its entirely, sold to DH. In this way, general data used for these calculations is recorded in Table 4.

Heat load (SH+DHW) (kWh/year)	424040
Solar production (kWh/year)	138196
Income from ST 70% (€/year)	9466
Income from ST 100% (€/year)	6626

TABLE 4 Operational cost overview

It is clearly seen that both ST systems, with and without the DH network, require a larger initial investment than typical natural gas boilers or electrical heaters. If a DH network is available, the possibility to deliver excess heat to the DH offsets the cost of heat purchased in winter periods. This results in negative operational costs. The income from heat sold to DH is higher than the cost of heat purchases from the DH network.

The evolution of the cumulative cost of each of the technologies is shown in Fig. 8. Natural gas boilers have been taken as a reference, thus, the accumulated differential cost against this technology is provided. The case of Joule heating has been removed due to its clearly anti-economic performance and in order to see the cost comparison in more detail. For the purposes of calculation in Fig. 8, the interest rate has not been considered.

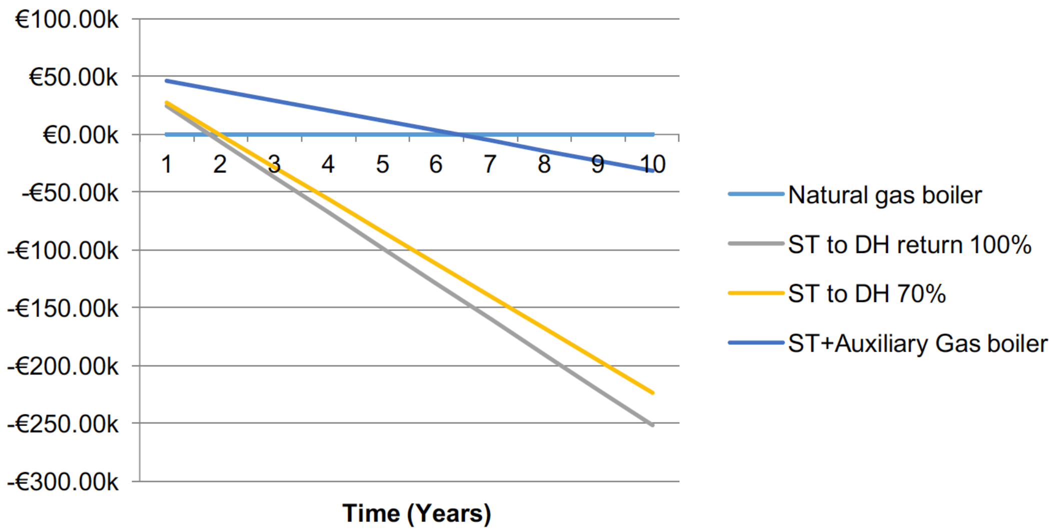

FIG. 8 Cost evolution for different technologies, with Gas boiler as reference

From Fig. 8, it is resolved that ST connected to DH return line shows better economic performance than conventional gas boilers when the second year has passed.

Table 5 presents the return of investment (ROI) for DH-connected ST façades for various interest rates. Interest rates of 5% and 10% are considered.

	ST to DH return 100%	ST to DH 70%
ROI (i = 5%)	5.554	6.858
ROI (i = 10%)	5.097	5.853

TABLE 5 Return of Investment for cases where DH is installed (years)

5 DISCUSSION

In this work the possibility to incorporate unglazed solar thermal collectors in the context of DH is studied.

The economic metrics of the presented case study show good feasibility, with ROIs in the range of 5-6 years. In this context, it is crucial to understand that heat purchase agreements need to be defined at a DH scale. These agreements substantially affect the economic metrics. In the presented study, the payback period is reduced by 1-2 years when heat purchase price is reduced to 70%.

Considering the data presented in Fig. 8, the connection to DH substantially improves the economic metrics of the ST systems, with payback periods reduced from 6-7 years to ~2 years.

Although the ST collector field incorporates relevant capital costs for the installation of the ST system, the connection to the DH avoids the need for large heat production systems to be installed for back-up, through reducing investments in auxiliaries, and reducing operational costs.

The main problem that may be faced by these installations is the capacity of the DH return line to absorb heat from ST when there are lots of distributed systems connected to them. Although, in actuality, this problem does not exist due to the development situation, in the future it will need to be taken into account to avoid the collapse of the DH network.

6 CONCLUSION & FURTHER WORK

This paper has studied the technical and economic feasibility for the integration of unglazed ST collectors in buildings, and its connection to DH infrastructure.

The presented solution relies on the DH in order to balance excess heat production and to supply energy in periods without local production. Overall, DH-connected ST seems to be a promising solution, as it pays back in the most favourable case within ~2 years when compared to traditional heating solutions.

With proven performance levels at collector level, and several standalone installations, the adaptation of ST into DH applications needs to be undertaken.

This activity will be carried out within the EU h2020 project RELaTED (2017). Within this project, among other activities, an unglazed ST system will be adapted for DH operation, and tested under a controlled test environment in the north of Spain. This same system will be integrated in up to 4 DH networks across Europe.

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