Modular and Prefabricated System for Waterproofing and Insulation of Flat Roofs

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Abstract: Recently, there has been an attempt to implement increasingly significant prefabrication in building construction, since this method is considered to represent an opportunity to reduce impacts in the construction sector. For pitched roofs, there have been relevant developments, such as sandwich panels, asphalt shingles, lightweight roof panels, among others. However, in relation to flat roofs, the advances have been of little relevance and are mainly limited to the improvement of technical characteristics and prefabrication of the construction materials used. The main goal of this article is to demonstrate the possibility of developing new solutions for more sustainable flat roofs in the carbon footprint, and for this purpose a system was developed called ADAPTIVE—Advanced Production System for Sustainable and Productive Roofing Retrofit, which consists of developing a composite solution for the rehabilitation of flat roofs, completely prefabricated and with zero waste, with the aim of increasing energy behaviour, collecting and storing rainwater, and using the roof as a garden leisure space. To obtain the validation results, computerised theoretical modelling was conducted with theoretical assessment of the components and the set of components developed, which allowed us to conclude that the system meets the high hygrothermal, acoustic, and structural requirements.

Keywords: prefabrication; off-site construction; sustainable development; building industry; retrofit

1. Introduction

The energy expenditure of buildings during their useful life represents a significant portion of the world’s energy consumption. According to the European Parliament and Council of the European Union [1], about 40% of the final energy consumed in Europe is for air conditioning purposes of the built environment, representing 36% of all emissions in the European Union. European Directives such as 2018/844/EU [1], which amends 2010/31/EU and 2012/27/EU, demonstrate the growing concern to make the built environment more sustainable. They refer to the importance of studying the technical, environmental, and economic feasibility of alternative high-efficiency systems in the design phase so that all new buildings have almost zero energy needs. Buildings with near-zero energy needs (NZEB) can be understood as those with very high energy performance, with much of the necessary energy covered by renewable sources and produced on site or nearby [2].

The analysis of the construction industry’s evolution shows the need to increase the productivity and sustainability of the sector, and it is essential to make changes in the production, concession, and execution processes. Only in this way will it be possible to respond to increased demand, reduce environmental impact, and increase the comfort and efficiency of buildings. Improving the productivity and sustainability of the construction industry and reducing economic, environmental, and social impacts will be feasible as construction moves towards building systems based on prefabrication and resource optimisation [3].
The impacts of the solutions advocated for the various construction systems therefore need to be increasingly reassessed in a circular economy perspective in order to ensure a reduction in material consumption, waste generation, and higher rates of reuse and recycling [2].

Currently, knowing that cities are home to a large part of the population, and that they are responsible for over 65% of global energy consumption and the emission of over 70% of greenhouse gases (GHG), waterproof areas also have a relevant impact on the quality and quantity of water and air [4,5]. By 2050, nearly 70% of the global population is expected to live in urban areas [6].

As evidence of the accelerated worsening of climate change, in which greater variations in the conditions that have occurred so far are expected, the surroundings of buildings, and specifically roofs, being one of the elements most exposed to weather conditions, should be subject to analysis and in-depth assessment for future context.

Knowing that there are relevant developments in the prefabrication of pitched roofs, [7–9] regarding systems for flat roofs, the advances verified cover mainly the technical improvement and prefabrication of the building materials considered for this purpose.

In this context, a partnership arose involving a consortium between companies and the university (academic community) with the aim of developing a research project to create a completely prefabricated and modular system capable of carrying out the layers of waterproofing, insulation, and cladding on flat roofs.

The basis of this project was a number of pivotal premises, such as the following: to allow for the integration of construction elements normally existing in roofs, namely chimneys, staircases, and elevator shafts; to ensure the possibility of applying the system in buildings in use, enabling its use in rehabilitation works through simple compatibility with existing elements; the components must use recycled and/or recyclable materials and raw materials in their constitution and ensure, whenever possible, the incorporation of carbon, so that the production and installation cycle presents a carbon footprint close to zero; all components of the system must be lightweight and with dimensions that allow for the use of lightweight lifting means, be easy to assemble, and capable of autonomous and serial manufacture.

The relevance of the ADAPTIVE research project stems from the analysis of the construction industry panorama, identifying the main impacts arising from the solutions/systems currently used for the realisation of waterproofing, thermal insulation, and cladding systems in new works or rehabilitation of flat roofs of buildings.

Background

The roof plays a major role in building performance as it is an important interface of heat exchanges with the outside, protecting against the weather and ensuring a comfortable and long-lasting interior environment. Historically, the roof appeared with the purpose of protecting humans in their habitat from aggressors, with natural materials being used in its construction [10]. Over time, concrete and steel revolutionised the development of new solutions, although the performance of a roof depends not only on the characteristics of the materials used, but also on how it will be designed and executed [11,12].

Indeed, roofs are the most critical and exposed constructive element of a building. During its life cycle, specifically, its cladding system is subject to severe environmental conditions, such as the direct incidence of solar radiation, variations in temperatures and humidity, the effects of wind and rain and, in some situations, snow, and the action of biological and chemical agents [13]. The selection of materials from the layers and their connections therefore has a causal relationship with their performance.

Essentially, there are two types of roofs: pitched and flat, where the main differentiation occurs in terms of the slope, materials, and layers—thermal insulation, waterproofing, and protection/cladding. Therefore, flat roofs have been increasingly used in buildings, to the detriment of traditional pitched roofs [14,15].
Recent literature shows several studies designed to establish a parallel between pitched and flat roofs, as well as comparative studies on these two systems and their applications, as is also the most recent case, of green roofs [4,8,15–17].

For pitched roofs with ceramic tile (most common cladding), it has been demonstrated that design and execution errors and the absence of reliable parameters on the durability of cladding materials are the main factors that reduce the performance of their service life, associated with the simultaneous interaction of different degradation mechanisms. Therefore, a different degradation pattern must be established according to the characteristics of the claddings in order to decrease the probability of occurrence of anomalies. It should also be noted that, for this type of roof, it is considered that a degree of degradation of 20% represents the end of its useful life, therefore, its ability to meet the performance requirements needs to be assessed [7,18].

Several studies on the useful life of the roofs have been carried out over the years; the European project INVESTIMMO estimated a useful life for the cladding of roofs between 32 and 54 years using a probabilistic base model. The Dutch Building Research Institute (1998) proposes different service lives for flat roofs, ranging from 40 years for green roofs to 75 years for metal roofs made of zinc sheets. The Royal Institution of Chartered Surveyors (RICS) [19] has defined an estimated useful life of 64 years, while the National Roofing Contractors Association (NRCA) [20] and the National Association of Home Builders assigned it an estimated lifespan of 50 years. These variations in the estimated service life for roofs demonstrate that their performance is considerably influenced by the quality of the materials, their geometry, the conditions of performance, and their maintenance.

Consequently, the result of the lack of adequate maintenance strategies and policies leading to a huge problem in their economic, cultural, and environmental impact should also be considered.

Regarding flat roofs, in the context of traditional construction, their application and development of solutions has been growing sharply, as the study aimed at ensuring their watertightness, insulation, and waterproofing has significantly improved with the emergence of various types of materials for insulation and membranes resistant to external factors [21].

Today, with flat roofs widely considered in the vast majority of building construction solutions in the context of prefabrication and modular construction, there is still extensive research work to be developed, since it is largely dependent on quantities of traditional labour and materials, lacking a global optimisation of resources and sustainable implementation solutions throughout the useful life [22].

More recently, the development of other solutions considered more sustainable was encouraged with the aim of improving resource optimisation. Rapid economic growth and urban development leads to a natural increase in the degradation of the surrounding landscape and a substantial reduction in permeable areas, with adverse effects on the environment [23,24]. As such, green roofs, which are basically roofs planted with different types of vegetation/plants on top of the substrate, appear, but still need other lower layers for waterproofing and insulation [25,26].

This modern concept began in the 1960s in Germany, when crises began to emerge in the energy sector, with the aim of seeking to reduce energy consumption; however, it was fundamentally from the 1980s that its application as a constructive solution in the roof of buildings began to have the greatest repercussions. Currently, there are several countries that promote and guarantee benefits in its application, such as the USA, Canada, Singapore, Australia, Canada, China, Hong Kong, Republic of Korea, and Japan; in the latter, for example, new building constructions must use green roofs, and in the case of public buildings larger than 250 m² and private buildings larger than 1000 m², they must have at least 20% green roof, or pay compensation if they do not comply [27].

There are several advantages presented for this type of solution, considered by several authors as a potential alternative for greater control and regulation of rainwater, reduction in energy consumption and noise pollution, contribution to the improvement of air quality,
and greater concentration of green areas in urban areas, as well as the reduction in global warming [26,28].

However, they also still present some limitations in their implementation as their initial cost is high, and the lack of knowledge about their construction mechanics (for example, the selection of the type of vegetation depending on the region, and its proper execution in order to avoid water leaks and structural failures) [29] with future consequences on their weight and storage capacity, in addition to the associated maintenance costs [25,30].

As mentioned, there are several studies on the characteristics and particularities of the types of roofs, and the search for the development of new solutions, that allow for the guarantee of increasingly more improvements in the performance, durability, and effectiveness of roofing solutions throughout the useful life. However, the research work presented identified that in relation to flat roofs, in the context of prefabrication, there are still gaps in their development and implementation of solutions in the market. That is why the ADAPTIVE project that is presented in this article came to be.

2. Materials and Methods

2.1. Goal and Scope

In response to the research gaps identified in the previous section, the ADAPTIVE project arose with the aim of identifying the main impacts stemming from the solutions currently used in waterproofing, thermal insulation, and cladding systems in new works or rehabilitation of flat roofs of buildings, as well as the clear understanding of the need to increase the productivity and sustainability of the construction sector, with changes to the production, concession, and execution processes being fundamental for this purpose, as only in this way will it be possible to respond to the increase in demand, reduce the environmental impact, and increase the comfort and efficiency of buildings.

As such, it is understood that for the creation of a more productive and sustainable sector, in the current context, the increase in prefabrication levels must be considered as this evolution’s main catalyst, and the construction must distance itself from artisanal production systems (among other factors, due to the high dependence on on-site production, and the lack of specialised labour).

The existing construction systems for flat roofs are also presented as a combination of independent subsystems, which, when combined, form different construction solutions, usually distributed over several layers, such as the resistant structure, subbase, thermal insulation, waterproofing membrane, and external protection. It is in the connection and articulation between these layers that their adequate level of performance exists.

This project proposes the creation of a prefabricated and modular system capable of carrying out the layers of waterproofing, insulation, and cladding on flat roofs with the following characteristics:

- Enable the integration of construction elements normally existing in roofs, namely chimneys, staircases, and elevator shafts;
- Ensure the possibility of applying the system in buildings in use, enabling its use in rehabilitation works through simple compatibility with existing elements;
- Ensure that the system components are lightweight and with dimensions that allow for the use of lightweight lifting means and easy assembly;
- Ensure that all components can be manufactured autonomously and in series;
- Allow for the components to be of recycled and/or recyclable materials and raw materials, and ensure, whenever possible, the incorporation of carbon so that the production and installation cycle has a near zero carbon footprint;
- Ensure that the components of the system are modular and integrative with each other, enhancing manufacturing in an industrial and autonomous manner;
- Development of an integrated support system in the components that allow for the installation of modular support structures for inclusion of the finishing layers. The support/installation system must necessarily allow for the simple application and
removal of the overlying components, thereby ensuring the ease of carrying out maintenance actions and functional adaptability;

- In environmental terms, the production of the components of the system should include choices, development, and research of materials and raw materials that aim for the lowest possible carbon footprint, while ensuring extended life cycles, especially in the components with the most volume, in addition to the possibility of incorporating—simply—equipment for energy production and water heating, as well as allowing for the filtration of solids, ensuring the possibility of storing the collected rainwater.

2.2. Development of Geometry

The development process was iterative, having been validated through 3D virtual assembly in typical roof environments; errors in connections and alignments were identified, as well as unwanted characteristics that required several changes in the components throughout the process.

The geometric development of the system was based on the development of well-defined groups of components:

- Water abstraction system composed of modular “basins”;
- Roof flashing system for connection and waterproofing between “basin” components;
- Modular perimeter roof flashing system to allow for the connection to platbands in existing buildings;
- Cladding support system;
- Final green-roof-type cladding system;
- Final deck-type cladding system;
- Drainage system.

The development of the prefabricated and modular roofing system began with modular “basins”, initially 475 mm high and with a false bottom with 175 mm free, and at the end of the investigation process with 70 (+52 mm) mm high and a false bottom of 78 mm, with a total height of 200 mm (Figure 1). This was the component that underwent the most significant changes throughout the process.

![Figure 1. Comparative schematisation between versions 5 and 6 (final).](image)

2.2.1. Rainwater Harvesting System

Five versions were developed for the rainwater harvesting system before the final solution could be defined.

The dimensions of the modular basin and a false bottom for filling with thermal insulation were initially defined, and the secondary drainage system was also designed (Figure 2) and would be through a watertight connection between the basins at a level higher than the main drainage channel, as well as the system for fastening flashings; small grooves were created for this purpose on the upper edges of the basins where elements (metallic or plastic) would be clipped on.
However, the initial idea of the component acting as a container for thermal insulation was excluded, among other hypotheses, as the basin supporting its entire bottom and exterior walls in a second level of ribbed thermal insulation, but this alternative made it difficult to match the alignments of the ribbed thermal insulation without resorting to a large number of different components when introducing basins of different dimensions, potentiating assembly errors.

After the various tests were carried out, it was concluded that it would be preferable to be able to simplify future manufacturing processes as much as possible and reduce their costs, which could be achieved by eliminating single components and adapting the geometry of components in order to simplify production processes. As such, it became obvious that there would have to be a reformulation of the system for fastening the flashings. For this purpose, the development team created a new fastening system incorporated into the geometry of the basin by introducing grooves in the internal walls that would allow for fastening with a fixing clip, thereby eliminating the clips solution (Figure 3). The remaining principles and characteristics of the component were maintained, namely the total height and drainage systems.

Based on the experimental results of this version, the decision was made to assess the possibility of reducing the useful height of the catchment area and to assess the positive and negative impacts of this evolution.

This change had positive impacts on the definition of the solution, since a decrease was identified in overloads in case of clogging or accumulation of snow, a reduction in the
use of raw materials in manufacturing and consequent reduction in costs, and an increase in the field of application of the system. Consequently, these changes made it possible to use a pressure drainage system that promotes the self-cleaning of the drainage ducts, with the purpose, on the one hand, of making it impossible to create vortices during the drainage, as they can introduce air into the system during the drainage and compromise its correct functioning, and on the other hand, of creating conditions to remove larger debris from the drainage path, reducing the probability of clogging and increasing the periods of the maintenance cycles.

2.2.2. Flashing System for the Connection between Components

In the initial phase of the project, it was defined that the flashing installation system would be proposed to be with a fixing clip in order to ensure ease of assembly, lack of fragile points in the waterproofing system, and the exemption of application of sealants and glues, both in the assembly phase and during the use phase.

In the first phase, the central flashing had as its main characteristics the possibility of being installed into the system using a fixing clip, the existence of top flaps that allow for the installation also with a fixing clip, the central caps, and the existence of support channels for installation. The cladding support system would be implemented through a set of crossbeams called corbel table, which would allow for the support of the cladding layers (green roof modules and deck modules).

However, some limitations were found, since the support system, in order to guarantee a sufficient rigidity for the correct support of the modular cladding elements, would have to be of a significant height, which could significantly reduce the system’s field of application, requiring the existence of large platbands. Nor did it guarantee the possibility of human movement on the roof for carrying out maintenance actions, making these tasks highly difficult and risky.

In this phase, having verified these difficulties in the flashing system, it was necessary to rethink the support system, which had implications for the geometry of the basins and the flashing.

Several prototypes were produced for this purpose using fiberglass laminates (Figure 4), which allowed for the assessment production processes, physically assess the geometry of the parts, and assess in the assembly phase the simplicity of assembly, alignments, and stability of the set.

![Figure 4. Prototype. Interim version.](image)

2.2.3. Central Caps Flashing System

The central cap, in addition to ensuring the tightness of the system, must allow for the ventilation of the spaces between the bottom of the basins and the thermal insulation layer,
reducing the probability of internal condensation under the waterproofing layer and the crossing of pipes.

Other important characteristics defined from an early stage of the development of this component were that its installation system must be carried out with a fixing clip. As a consequence of the use of this type of installation, the component material should be highly flexible in order to allow for the simple assembly and disassembly of the parts. For this purpose, two materials and two distinct production processes were analysed: Production using 3D printing on flexible plastic and production using flexible rubber injection.

2.2.4. System of Perimeter Flashing Connecting the Basins

These components have similar dimensions and characteristics to the flashing junction between basins. Its fastening is achieved with a fixing clip inside the basin. On the outer face, the junction is carried out through the installation using a simple flap.

The aim was that the conjugations of the anchorages in the walls produce a spring-like effect, which keeps the component firmly fixed.

The topology is also similar to the central flashing. They have flaps that allow for the installation with a fixing clip the closing caps, ensuring the tightness of the junctions.

2.2.5. Enclosure Cap System of Perimeter Flashing

To ensure greater stability of the junction (theoretically necessary because there are not enough degrees of freedom to allow for movements stemming from thermal variations, especially in corners and wedges), the decision was taken to make the junction using a fixing clip and installation. The operation of a fixing clip junction is the same as those existing in the junction to the central flashing.

With regard to the production process and constituent material, although it is permitted, more research will still be necessary, and it is believed that, due to the geometric complexity of the components, they can only be equated as hypotheses: production by injection in mould, the constituent material can be a flexible plastic or a rubber; production using 3D printing, in this case the constituent material is a flexible plastic.

2.2.6. Component System for a Fixing Clip for Traditional Flashing onto Existing Elements

This component is to create conditions for the simple fastening of traditional flashing in the compatibility of platbands or other emerging bodies existing on flat roofs. The component presents a simple geometry, fulfilling its objective including the creation of a “tooth” that allows for the fastening with a fixing clip for traditional flashing.

Regarding the production processes for the manufacture of these components, taking into account that they are intended to be highly rigid and consequently stable, it is understood that their production will be appropriate with stainless metal alloys (through bending and welding), or with fibre-reinforced polymers (through pultrusion).

2.2.7. Cladding Support System

The first support system developed was geometrically characterised by the crossing of 80 m high lightened beams, which formed a grid-like platform with large openings ranging between 500 × 500 mm and 300 × 300 mm.

However, a number of potential problems were identified with the geometry and operation of this support system, related to the high height of the beams in conjunction with their support location, which significantly reduced the scope of the system, making it difficult to be compatible with platbands. Further, this solution does not allow, without the development and use of new components, for the creation of a flat work surface, without openings, to allow for safe movement of people in maintenance actions.

Regarding the physical and chemical characteristics of the material to be used, there are no definitive conclusions yet. A set of properties is being assessed and studied with potential partners regarding the possibility of reconciling in order to ensure a sufficient elasticity to allow for an easy assembly and absorption of impacts, a sufficient rigidity to
minimise displacement, and a high resistance to degradation due to atmospheric elements, especially UV rays.

Regarding the height of the grid, it was understood that it would be related to the structural stability of the element and also to the type of material used in its production. As a result of the assessment of potential production processes, it was concluded that the height required to guarantee structural stability for each type of grid would be different, as larger spans would require the guarantee of greater heights (Figure 5).

![Figure 5. Studies of the cladding support system. Interim version.](image)

However, the decision to use the highest height required in all grids was taken, thereby simplifying the entire process.

The height defined for all components was 38 mm and the grid dimension was 38 × 38 mm.

2.2.8. Final Green-Roof-Type Cladding System

During the project, it was defined that the dimension of the green roof type cladding modules would be 500 × 500 mm with heights between 100 and 200 mm. These limitations were imposed due to two essential assumptions, such as the intention to combine the dimension of the components with the dominant dimensional modules in the system—that is, 500 × 500 mm—and also to limit the weight of the components and allow for their simple movement in the use phase, which is one of the main goals to be achieved in the cladding subsystem.

However, extensive research on modular green roofs has proved difficult to reconcile the following aspects:

- **Geometry:** width × length of 500 × 500 mm;
- **Robustness of the base parts that allow for the movement of the components in use.** Several existing solutions on the market are characterised by containers produced in thin plastic, and its goal is only to promote an easy and fast installation, with no preoccupations about future movements. These types of containers, which are very fragile, would not be considered suitable for the intended use in the system under development;
- **Possibility of incorporating a watering system with modular characteristics.**

Consequently, Wallbarn’s modular M-Tray system, produced in the United Kingdom, was selected after extensive research, since this system was already properly tested and has dimensions compatible with the ADAPTIVE project. The quadrangular modules of this modular system are 500 × 500 × 100 mm; they are made of recycled polypropylene and attachable, allowing for the geometric “rigidity” of the system to be maintained in a simple way. The connection between modules is carried out only with two connection points on two of its edges, allowing for an easy coupling of the basins and tight unions, with only
4 mm, in order to facilitate the uniformity of the development of vegetation; the containers have four hand grips on the sides, thereby being easily managed.

2.2.9. Watering System

Although the company that supplies the green modules has its own system, it is similar to current products on the market (drip irrigation systems with micro-sprinklers). Therefore, the decision to carry out research was taken to define the irrigation system with the use of products with the possibility of purchase in Portugal.

This system’s main network will consist of AZUD’s 16 mm drip irrigation pipe with an anti-suction mechanism that prevents substances from entering the interior and also with high resistance to clogging. The pipe wall has a thickness of 1.1 mm. This can also be self-compensating to allow for a uniform distribution of the water flow in the area to be watered. Accessories (such as elbows and Ts) will be required to ensure changes in direction and shunts.

For the assembly of this pipe, it is important to mark in advance the location of the sprinklers, ensuring that they are not more than 2 m away from each other and allowing the entire green area to receive water. The irrigation pipe is placed parallel to the assembly of the trays, ensuring that the piping is in the space between the modules. It will also be necessary to use some accessories such as coupling/screw thread or coupling/coupling adapters and diffusers.

2.2.10. Final Deck-Type Cladding System

The deck-type cladding will be similar to those applied in modular systems already on the market. However, the compatibility between the system’s dimensional modules and the other cladding components is dependent on the fulfilment of certain requirements (same dimension as the green roof components). In order to account for its use with the green roof modules, there must be two types: one with $500 \times 500$ mm and another with $1000 \times 1000$ mm.

However, for this specific type of final cladding, some limitations were found:

- Compatibility with all existing measures in the basins, particularly with the one with an edge size of 1250 mm;
- The enclosures in perimeter areas, where due to the existing elements for the fastening of traditional flashings and also due to the flashing itself, there is a reduction in the free dimensions for the application of cladding.

In order to solve the difficulties observed, two hypotheses were studied: one would be to develop enclosure components for perimeter zone with only one width, and develop a series of components to be used in a central current zone that would allow to carry out the enclosures with multiples of 250 mm, and the second would be not to develop enclosure components for the central current zone, limiting the use to components with $500 \times 500$ and $1000 \times 1000$ mm, and thus carrying out all the necessary enclosures in the perimeter zone.

Therefore, it was concluded that the development of the cladding components followed the second hypothesis (enclosures in perimeter zones), which despite presenting a greater number of components is not restrictive, allowing for the free design of the central area of the roofs.

2.2.11. Drainage System

One of the main concerns in the development of the system was to ensure that, in case of clogging, the system had the ability to function without causing leaks and infiltrations in the union of the parts.

As such, it was necessary to ensure that all pipes and connections used should not have any type of leakage in case of clogging, as they are designed to operate under load in watering systems. Additionally, there was a secondary drainage system (commonly overflow drains) that connects all basins to a higher elevation and that allows for the
passage of water between them in case of clogging, even if it was possible to reconcile the traces of the main and secondary drainage systems in order to create redundancy. The main drainage system was designed to create independent channels crossed by each “line” of components of the waterproofing system “basins”. This allows adjacent basins never to drain into the same channel and that in the event of a clogging of a basin or even a complete main channel, through the secondary drainage system, drainage using specific channels is guaranteed, thereby creating redundancy in the system. A component was developed that could be easily applied to the basin drains and that promoted the operation of the drainage system with the principle of the “Pythagorean cup”, a classical demonstration of fluid dynamics based on the siphon principle. The tests carried out were a success and allowed to prove that it is possible, in a very simple and cost-effective way, to provide the drainage system with characteristics that promote self-cleaning and that also (although indirectly) decrease the probability of occurrence of issues due to leaks in the system, since after each discharge cycle, it is completely empty (Figure 6).

![Figure 6. Assembly layout—Final Geometry—Application of the drainage system.](image)

2.2.12. Selection of Energy Production System

After assessing the different technologies on the market for energy production, the decision was made to select a photovoltaic panel solution, since it allows for greater dimensional freedom and is, as a rule, a more economical, compact, and simpler urban framework solution in urban and suburban environments when compared to other systems, such as wind turbines.

The size of the panels was defined, on the one hand, according to the need to make the components compatible with the metric modularity of the system, more specifically, with the measurements of the basin modules (mostly multiple of 1000 mm), and, on the other hand, to maximise the use of the useful roof surface allowing for the placement of juxtaposed panels, and also to enable the attachment of the panels to the support structure through singular supports.

2.2.13. Selection of Green Roof Species

In the selection of species for green roofs, it was understood that it would be advantageous to predict the existence of two distinct types: one, composed only of species that allowed for foot traffic, and another that did not allow for circulation. The advantage of having different types is related to the following:

- The maintenance of walk-on roofs is more demanding and expensive than ones that are not walk-on;
- Allow for the use of both walk on and non-walk-on components, with very distinct aesthetic characteristics, thereby allowing even more flexibility in the design of the “cladding” of the roofs.
Therefore, the choice of the type of species to be used can be divided into the following:

- Walk-on: Tall fescue grass;
- Non-walk-on type 1: Several species of *Sedum*;
- Non-walk-on type 2: Various species of wildflowers.

Regarding the selection of the type of turf to be used, it should be characterised by high strength and flexibility. Therefore, the tall fescue species meets the requirements, as it is robust, very dense, and high resistance to drought, and has great persistence, withstands large thermal amplitudes.

Regarding vegetation, there are several species of *Sedums* and wild flowers have excellent characteristics for their application in green roofs such as the one developed for the ADAPTIVE system. They are a highly resistant species that require very little maintenance.

3. Result and Discussion

The main results are presented in this section: achievement of goals and analysis of compliance, theoretical validation, and limitations.

3.1. Achievement of Goals and Analysis of Their Performance

3.1.1. Definition of Geometries and Volumes Adapted to Industrial Production, Enhancing Autonomous, Repetitive Production, Reducing Waste and Production Costs, and Increasing Productivity

In the research phase, all the components developed (with the exception of the perimeter flashing of the connection to basins) are likely to be produced in autonomous industrial production lines, reducing waste, reducing production costs, and increasing productivity.

The analysis of industrial and serial production processes applicable to the production of perimeter basin connection flashing remains under analysis, and these components may still undergo slight changes in the future. However, even if it is concluded that the referred to component requires a more “traditional” and less efficient production method, it is considered that the goal was achieved because all other components of the system are capable of being produced in series in autonomous industrial lines. As a result of the various studies carried out, one of the relevant changes to meet this goal was also the realisation of adaptations to the basin in order to maximise the volume in storage and transport phase. At this time, the basins are stackable, and their successive installation allows for a 75% reduction in volume. Openings were also introduced to facilitate transport and assembly on site.

3.1.2. Ensure through the Volumes, Geometries, and Constituent Materials That the Theoretical Weights of the Components Will Be Equal to or Less than the Intended Ones (in the Components of Intensive Use, Unit Weights Not Exceeding 10 kg and the Bulkiest/Heaviest, of Less Intensive Use, Limited to 50 kg)

In theory, the components have lower weights than the goals. The most intensive components (basins, flashing, supports, and grids) have weights of less than 10 kg, as intended.

The cladding components will be the heaviest, but still with values lower than the 50 kg, which was stipulated as a goal. The green roof component will have a maximum weight (when wet) of approximately 45 kg; the heaviest deck-type component will have an approximate weight of 36 kg.

3.1.3. Ensure That the Entire System Relies on Simple-Fit Mechanical Connections, Ensuring Ease of Assembly, Disassembly, Self-Construction, and Elimination of Glues and Sealants of Any Type

At this stage, the system presents only connections by installation, a fixing clip, and screw thread. It is believed that the assembly and disassembly processes are simple and boost self-construction. No type of glue or sealant is used throughout the system.
3.1.4. Assess and Choose Drainage System (Drains) Existing in the Market, Which Allow for the Execution of Drainage of Rainwater with Horizontal Piping, Such as the Geberit Pluvia; Assess and Ensure the Geometric Needs, Fastening, and Creation of Accessory Components for Correct Integration

By combining materials existing on the market, which are usually not used for the purpose now devised, it was possible to create a new modular drainage system which is believed to work under load and with horizontal pipes.

The system consists of low-profile drains, screw joints, and modular pipe sections (the latter used in irrigation systems, that is, intended to operate under load without any type of leakage), with the aim of promoting drainage under pressures and ensuring that after the drainage cycles, the drainage ducts become dry, which in addition to enhancing the self-cleaning of the drainage ducts, reduces the potential for leakage during the life cycle.

3.1.5. Definition of a Protocol with the Suppliers of the Selected Equipment, Aimed at Making Them Available by Loan or Long-Term

The systems are pre-selected. Its integrations into the system are still in the development phase, as it is essential to first carry out a geometric and functional validation of the system in order to study and specifically develop the conditions of assistance and support of the components, and also the definition of proper spaces for the inclusion of networks.

3.1.6. Creation of a Product Sheet

A product sheet (Figure 7) was created for each component containing the following: Reference; Name; Subsystem; Family; Direct relationship with other components; Schematic diagram; Technical information: Weight, Raw materials; Frequency of maintenance actions; Maintenance actions, and Expected service life.

Figure 7. Example of Product Sheet.
3.1.7. Assess and Experimentally Validate the Geometry of the Parts, the Various Installations, and Fastening Systems

Due to the tests carried out so far, there was no need to make significant adaptations to the geometry of the components. In the case of the connecting flashing between basins, it was necessary to review the geometry of the top flaps by creating a component, which, on the one hand, allows for the use of the flaps in the connecting flashing to be dispensed with, and, on the other hand, ensures a better positioning of the basins in the assembly phase of the system (Figure 8).

![Figure 8. Schematic diagram of the application of the central lower flashing and drainage.](image)

The new component was developed in order to eliminate the need for the flaps in the connecting flashing; it was the so-called “lower enclosure flashing”. This component, in addition to allowing for the support and drainage of rainwater from the connecting flashing, also has the advantage of facilitating the positioning and alignment of the “basin” components in the assembly phase.

3.1.8. Assess and Experimentally Validate the Ease of Assembly of the System

During the tests, the system proved to be easy to assemble and execute, and all connections were quite simple to perform. It is understood, however, that it will be necessary, in some components, to review the dimensional tolerances in order to facilitate the system’s assembly, which will be reflected in a millimetre increment of some components.

3.2. Theoretical Validation
3.2.1. Hygrothermal Assessment of Roof Solutions

For joint analysis of the temperature and humidity phenomena of the proposed system, the WUFI 2D 4.3, DELPHIN 6.1, and GLASTA 5.1 software were selected for acquisition, as they are identified as the most used in the analysis of the hygrothermal properties of the materials. For later definition of the theoretical models of performance assessment and identification of the input data, it was necessary to carry out the survey and analysis of the different software.

To verify compliance with the regulatory requirements, the thermal transmittance coefficient (U) was calculated.

The hygrothermal behaviour simulation was carried out for solutions A1, A2, and B, using the GLASTA and WUFI programs, and the application of the DELPHIN program with and without a steam barrier was under development, in which there was a need to install a vapour barrier to reduce the occurrence of condensation. In order to comply with the regulatory requirements (zones I1 and I2), thermal insulation in thistle composite and a 20 cm thick PU was required.

A hygrothermal simulation was also performed (GLASTA- SOLUTION A1, A2, and B|1st Phase: A2) (Figure 9).
In agreement with the results resulting from the theoretical validation, it was concluded that the roof solution has some weaknesses regarding the possibility of internal condensations and presents a value of thermal transmittance coefficient very close to the minimum requirements currently in force.

Regarding the verification of the minimum requirements and considering the introduction of the proposed material for thermal insulation (thistle + PU), this is only guaranteed if the material is 20 cm thick (I1 and I2).

The proposed thermal insulation material does not have thermal characteristics that allow it to be applied in replacement of the insulating material currently used (ref: XPS-Solution B).

Solution B meets the minimum regulatory requirements for all climate zones.

For similar values of thermal transmittance coefficient, the proposed composite material must have more than twice the thickness compared to the current thermal insulation.

Solution A1, corresponding to the basin with deck cladding application, is more disadvantageous than the green roof installation (A2) considering the use of the proposed composite material.

It is necessary to proceed with the simulations after providing the hygrothermal properties of the composite material under study and assess the performance of the solution for different cycles.

The simulation is under development with the DELPHIN program, whose results will later be compared with those obtained in the other simulation programs.

3.2.2. Experimental Theoretical Validation

With the preliminary definition of the system’s geometry, the carrying out of development tests was considered essential. Several prototypes of the system were produced and tested for this purpose, namely the following:

- Basins;
- Waterproofing flashings between basins;
- Central enclosure flashing;
- Grids;
- Final deck-type cladding.

The following components and subcomponents of the system were also purchased:

- Main drainage: piping, drains, and connectors;
- Secondary drainage: piping, washers, and threaded perforated caps;
- Components for green roofs.

3.3. Limitations

The development of this project suffered some limitations, especially regarding delays in the acquisition of simulation programs, and also difficulties for the university in hiring
human resources. It should also be noted that the lack of openness on the part of the vast majority of the companies contacted for the discussion and production of the prototypes caused delays in carrying out the tests. This obstacle was mainly due to the fact that it did not seem interesting for manufacturers to be producing specific parts in small quantities. The economic factor, the risk associated with uncertainty, and the short time for production were therefore a barrier.

Another difficulty worth noting was the geometric imperfections found in some parts, which forced, in some cases, the production of new elements, often with very long delivery times, and which, parallelly, made it difficult to assemble and interconnect different components.

4. Conclusions

The research work carried out under the ADAPTIVE project considered a prefabricated construction system for flat roofs that is completely new, integral, and enclosed. For the reasons already listed in the previous section, its development had some limitations, mostly as a result of the need to test and validate a series of components, dependent on each other, which necessarily corresponded to several changes and adjustments thereof. This made the iterative process much more complex and arduous than originally planned.

At this moment, and depending on the results obtained, in view of the previously defined goals and which were subject to validation, it can be concluded that the system meets the high hygrothermal, acoustic, and structural requirements.

In the case of the basins, in an early phase, the consortium members produced test moulds and a prototype “basin” in fiberglass. In addition to the obvious geometric validation at the production level, this test was for the understanding of the use of these raw materials and the benefits and limitations of the fiberglass lamination process.

With this test, the weaknesses in the level of tolerances that the process allows for and the type of cut-outs that make it impossible to demould and, consequently, the production process, was understood.

In a second phase, to carry out the experimental tests of the entire system, a company specialised in the production of fiberglass components for the manufacture of four prototypes of the element was used. The resulting components had some geometric imperfections. However, by carrying out small tests, it appears that the existing imperfections do not jeopardise the performance of the geometric and experimental validation tests. After meeting up and discussing the results with the component supplier, it was concluded that the production of the mould in this type of manufacturing is an iterative process, and the mould is corrected as soon as any irregularities or imperfections are detected. The production of the components is currently being assessed through the rotational moulding process using polyethylene and by injection of PUR—RIM. In view of the fiberglass manufacturing process, the aforementioned production processes have, as advantages, the possibility of greater geometric rigour and lower production costs.

In the case of waterproofing flashings between basins, a new component was developed in order to eliminate the need for flaps in the connecting flashings, which allows for the support and drainage of rainwater from the connecting flashings, and also facilitates the positioning and alignment of the “basin” components in the assembly phase. The connecting flashing between the basin is installed with a fixing clip. However, as with other components, the production of moulds showed very high production prices that were not compatible with the project’s investments. The same potential industrial partners referred to other solutions for production at this stage of testing that—although they use materials other than those chosen—allow for the desired geometric and experimental validations to be carried out, mainly due to the high non-resistance to degradation from UV rays.

In the case of the central enclosure flashing, it is proposed that this component be produced in rubber, with high resistance and an acceptable level of flexibility. However, the issue of the production cost of the moulds made it impossible to produce the component as idealized. Therefore, the component was produced using 3D printing, ensuring the
execution of geometric and experimental validation tests, not compromising in any way the assessment of results and goals.

The grids were produced in accordance with the studies carried out, using polymers reinforced with moulded fibres, as well as deck-like cladding, that were produced in panels of $1.0 \times 1.0$ m of traditional deck.

Experimental tests were also carried out successfully. The ease of assembly and positioning of the basins, flashings, grids, and cladding was verified. However, the following should be noted:

- The geometric imperfections in the basins resulted in some difficulty in the installation of the perimeter flashing and, consequently, in the central flashing;
- When coupling the waterproofing flashing between basins, the top flaps of some elements broke and/or came off;
- In the flashing made in more rigid PVC, the installation was extremely difficult due to the lack of flexibility of the material;
- During the assembly and consequent movement and shocks, the finishing gel of the basins began to detach.

The approach adopted at the time was to reduce the stiffness of the top flaps in order to give the component greater flexibility and therefore reduce the effort on the material during the assembly and disassembly process. At the same time, and as previously mentioned, new production processes for the basins are currently being assessed, namely manufacturing by roto moulding or PUR—RIM.

The system’s drainage tests were carried out after the assembly tests. The main goals were to simulate and assess the behaviour of the system based on a portion of it (drainage with two basins connected in series at full scale), determine the self-cleaning flow rate of the system, and verify which assembly procedures are most appropriate for the correct connection of all elements. Initially, it was the team’s opinion that the introduction of a siphon downstream of the basins would allow the drainage of the full section and, therefore, obtain the desired self-cleaning flow rate for the system. In addition to the difficulties experienced in creating a drainage system, the tests also made it possible to verify the need for some care in the process of assembling the drainage network. It was concluded that, in a more complex roofing system, the assembly must be “upstream to downstream” and that the first step would always be to connect the basin drain to the main tube and only then move to the next one. After checking the geometry of the parts, the watertightness of the system was assessed.

With the prototypes of the elements, a roof measuring $4 \text{ m}^2$ was simulated and then a large amount of water was poured onto it. During and after the end of the test, no leakage loss of the assembly was verified, including in the drainage system, and the water also drained satisfactorily.

Finally, it is believed that this system will have a very significant impact on the construction market, as it is the first prefabricated and modular system capable of being applied on flat roofs, combined with the fact that it allows for the modular incorporation of cladding, giving the system a unique ability to suit any market request.

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