

Article

New Use of BIM-Origami-Based Techniques for Energy Optimisation of Buildings

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Abstract: Outstanding properties and advanced functionalities of thermal–regulatory by origami-based architecture materials have been shown at various scales. However, in order to model and manage its programmable mechanical properties by Building Information Modelling (BIM) for use in a covering structure is not a simple task. The aim of this study was to model an element that forms a dynamic shell that prevents or allows the perpendicular incidence of the sun into the infrastructure. Parametric modelling of such complex structures was performed by Grasshopper and Rhinoceros 3D and were rendered by using the V-ray’s plugin. The elements followed the principles of origami to readjust its geometry considering the sun position, changing the shadow in real time depending on the momentary interest. The results of the project show that quadrangular was the most suitable Origami shape for façade elements. In addition, a BIM-based automated system capable of modifying façade elements considering the sun position was performed. The significance of this research relies on the first implementation and design of an Origami constructive element using BIM methodology, showing its viability and opening outstanding future research lines in terms of sustainability and energy efficiency.

Keywords: energy efficiency; BIM; origami-based technologies



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1. Introduction

Origami is the ancient art of paper folding and comes from Japanese cultural background: from *ori* meaning folding and *kami* meaning paper. It is a metamorphic art in which a piece of paper is transformed without the need to add or remove material. The geometries and volumes are obtained by means of folds and creases. Various practical applications in construction have taken place in the last few years despite the rich aesthetic history of this art [1,2]. Recent developments in computer science, number theory, and computational geometry [3,4] have led the way for powerful new techniques of analysis and design which nowadays extend beyond art. Space reduction in the folded versus unfolded position was found as an initial benefit [5]. However, when the effects of climate change were highlighted at the Paris Climate Conference in December 2015 [6,7] (melting poles, extreme weather events and rising sea levels), new challenges appeared. Moreover, an important increase of the greenhouse gas emissions was detected. This pointed out to an improvement of the global warming tendency.

The main aim of this study was to combine origami-based roofing elements with BIM methodology in order to allow considering the environmental conditions, such as sun radiation, throughout the infrastructure life span. The main research structure was focused on the origami-BIM design, analysing its modelling and programming viability.

This paper establishes future research lines that could be oriented to energy simulation or economic estimations.

For the viability component design analysis, the research hosts the whole process of element creation, dealing with all possible design barriers such as interoperability, programming, or visualization. Initially, elements based on origami principles were modelled for use in a roof structure. This was a simulation of both the roof and the movable cladding used in the infrastructure. Various software from major developers were considered to create the BIM model, i.e., Revit or Dynamo from Autodesk, OpenBuildings Designer or MicroStation from Bentley, and Grasshopper from Rhino for the animation of the elements have been considered. Other applications that were considered for additional functions were Synchro, Civil 3D, and Rhinoceros 3D. All of them require exhaustive research into the functions provided by each software in order to make best use of them. The simulation of the movement of the elements were carried out according to the project location and the season of the year, i.e., to favour the light passage in order to reduce heating and artificial lighting in its folded position or to reduce air-conditioning consumptions on its unfolded position. Therefore, careful consideration has been given to the selected origami technique and its integration into the environment for the studied application.

As a final result, the project sought to reach the main objectives:

- A complete process of BIM-based Origami implementation. Considering Software and Origami possibilities or data interoperability with Origami techniques
- A BIM-based automated system capable of modifying the geometry of façade elements based on the external sun trajectory

For this purpose, real applications of Origami techniques in the Architecture, Engineering, and Construction (AEC) sector, particularly on roofs and external façades, are shown in the first section of the paper, including a review of the published literature that has shown the advantages of BIM for energy management. Thereupon, a new BIM-based design method for external building elements is proposed given that multiple profits have been directly attributed to the use of BIM. Improvements of energy analysis or time reduction for the design of alternatives are examples of some possible benefits shown in previous published research. The Results section shows the BIM-based automated system with Origami techniques. This automates system was performed in this study on a generic building in order to implement the methodology. The conclusions show the outstanding possibilities and synergies of the use of these techniques simultaneously for future designers.

2. Overview

2.1. Origami on AEC Sector

The Architecture, Engineering, and Construction (AEC) sector must adapt to meet this challenge. In order to do so, new opportunities are opening through innovation, such as the use of Building Information Modelling (BIM) together with digitalisation and Internet of Things (IoT) [8–10], the use of metamaterials [11,12], and the use of programmable origami-based properties that allow mechanical unfolding. In this regard, the use of these singular elements is no longer only applied to achieve an impressive geometry in roof elements, mobility and automatization for energetic and functional purposes are also considered [13]. Therefore, the new design concepts tend to focus on adapting to the environmental climatic conditions and their changes, obtaining more competitive advantages. Energy efficiency becomes a key factor at the design phase. Wind and solar radiation are some examples of meteorological conditions that may rethink the projects to be designed and built in the following years. On the one hand, there are the high winds that carry sand from the desert. This causes a number of catastrophes in Arab countries, such as the covering of railway tracks, roads, or impact against building fronts. On the other hand, solar radiation can cause temperatures in buildings to rise up to alarming and sometimes unfeasible levels, e.g., curtain walls can reach temperatures of up to 80 °C, forcing the use of indoor air cooling [14].

Therefore, this possibility represents a great opportunity to reduce CO₂ emissions into the atmosphere. The use of façade elements that fold or unfold depending on the project location and the season of the year can reduce energy consumption as has been shown in previous published research [1–3]. Considering a folded position, an improvement of natural light usage instead of artificial lighting is possible. Moreover, half-folded or totally unfolded important heat transfer is reached allowing to decrease the use of air conditioning. There are examples of buildings with adaptable building façades in the world [15], or Origami implementations for shape optimization considering structural performance [16]. Figure 1 shows some of the most prominent applications in this field [17].



Figure 1. Origami applications on the AEC sector.

These projects were characterised by a dynamic adaptation of façade elements to external conditions. An example is the Kiefer technic Showroom built in 2007, with a fully automated façade control system. Each user has control over the façade element which affects only to the internal user space. Syddansk Universitet in Denmark holds a system that regulates the interior temperature according to the external climatic conditions. The One Ocean in South Korea uses natural materials that are susceptible to deformation depending on external conditions. Lastly, the Al Bahr Tower was built between 2009 and 2012 in Abu Dhabi, reaching 147 metres high. This building, due to its height and the important sun radiation along the day, was designed with intelligent façade based on origami techniques. This concept allows to each façade element to modify its geometry according to the sun position, reducing carbon dioxide emissions in the order of 1750 tonnes per year [18].

However, obtaining all information regarding temperature, humidity, ventilation, lighting, or even occupant behaviour is not so simple. There are discrepancies between simulation predictions and real energy use [19]. Designing efficient energy buildings with good indoor environment involves elements of expertise derived from multiple disciplines such as architects, civil, mechanical, and electrical engineers. Consequently, BIM is being increasingly used to design buildings. The integration of design and management in a single tool allows a faster and more flexible design process, enabling and easing the production of multiple alternatives that also consider the conservation and operation of

the building, in both construction aspects and energy savings [20,21]. All the shapes and volumetric possibilities of the design are assessed to optimise energy efficiency. In addition, it is possible to link the as-built model to other types of activities, such as the facility management once the project has been completed. Consequently, the costs derived from these activities can also be optimised.

2.2. BIM and Energy Management

Energy cost or infrastructure energy consumption simulation are concepts being increasingly important currently. Sustainability has become a key factor in construction projects and it is widespread in AEC tools. The same occurs with BIM. BIM profits in already existing buildings are well-known. As-built management documentation [22], maintenance [23–25], quality control [26,27], parameter monitoring [22–24,28], emergency management [19], or space management [28,29] are examples of it. In addition to all the referred profits, energy management has also shown to be an attractive alternative. Commonly named as Building Energy Modelling (BEM), BIM-based management techniques have been applied to control, analyse, and manage energy [22,30–33].

Published research has shown the outstanding possibilities of BEM for the energetic simulation of infrastructure [34,35]. Those BEM techniques permit connecting BIM models with external databases which collect the main material properties, allowing a detailed energetic analysis [34]. Another main advantage attributed to BEM is data visualization. Through use of the BIM model, data visualization environment is provided in a user friendly graphical way. This allows an ease understanding data and information [36,37]. In this way, Jen and Vernatha [37] performed a complete energy simulator based on BEM, providing real time data through the infrastructure BIM model.

Heritage management, as one of the most important BIM research lines for the built environment [22], has also been extrapolated to energy management field. Technical data, consumption projections, historical consumptions or location information are essentials for infrastructure management. Alahmad et al. [38] proposed a combination of sensors and elements of the BIM model for the electrical system of the infrastructure. Other researchers such as Woo et al. [39] associated energy consumption with parameters such as temperature, humidity or occupation. Another field related with BEM is the one referred to data interoperability. There are multiple information databases hosting various material properties and its synchronization with each element of the BIM model is not a challenge and even more if the great variety software is considered.

As has been reviewed, a large number of published research applied BEM for infrastructure energy management. However, concepts as BIM and Origami applied in a single way for energy management purposes would be considered a novel topic for future research lines due to the lack of research in this regard.

3. Methodology

Although there are published research and applications either in the application of origami techniques in building or in the use of BIM, it is not common to find applications of the two concepts together. On the one hand, origami techniques allow the geometry of building elements to be modified. In this way, the behaviour of these elements will change according to external parameters such as humidity, temperature or wind, making it possible to reduce their impact on the infrastructure. On the other hand, the application of origami techniques in construction elements implies an important challenge in all project phases, such as design, construction or operation and maintenance. It is precisely this factor that justifies the use of BIM for the development and implementation of origami techniques in construction and building fields.

The basic information associated with the AEC sector must be known before modelling the element in BIM, according to the origami technique. First, a multi-criteria analysis of all the properties of the various alternatives must be carried out. In addition, their application to an adaptive building element of the infrastructure must be considered in

order to determine which technique is most suitable for the project. Aspects such as the fit between geometric figures, construction requirements, slimness, wear of parts or behaviour of the cast shadow were considered. The element was then defined for modelling in BIM after selecting the origami technique to be implemented. This selection uses a multi-criteria analysis considering parameters such as geometry of the element, dimension, or material.

Subsequently, an adaptative element was added to the three-dimensional model of a generic building in order to simulate solar radiation by using specific software. As the project considers adapting the infrastructure model to the Origami element rather than the other way around, the modelling process began with the Origami constructive element. It started decomposing the element into simple geometric shapes. Then, the dimensions of the element were parameterised to affect its geometry considering the solar path phases. The element was then copied along to two of the four façades considered, obtaining 64 pieces. Finally, the solar trajectory was parameterised, affecting the opening and closing of the different adaptive construction components depending on the location of the building, its orientation and the relative position of the earth respect to the sun in each season of the year.

Figure 2 shows the methodology followed which main objective was the design and development of an adaptive construction element using origami techniques. This was placed on the outer surface of the building and can reply automatically according to the sun trajectory.

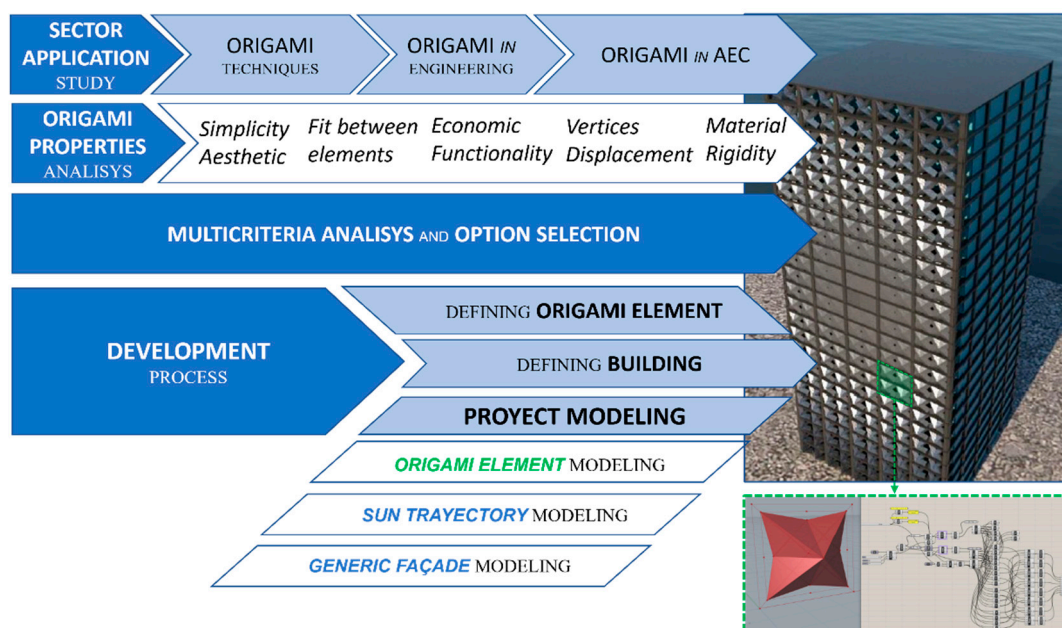


Figure 2. Graphical methodology outline.

4. Development

4.1. Origami Properties and Multicriteria Analysis

There are many applications of origami techniques in the AEC sector as well as a variety of ways of implementation. For this reason, research of the different possible geometries to be applied had to be carried out, in order to select the most adequate for the main target. A multi-criteria analysis of the different options was created, according to the following properties: simplicity, aesthetics, rigidity, fit between elements, economics, functionality, minimum displacement, and material savings. The shapes considered were: pai-pai, umbrella, quadrangular dome, triangular, pentagonal, wheel, and cordillera. Once all of them had been defined, they were confronted in a matrix ready to be valued. Based on the literature and the team criteria, each property of each origami shape was valued from 0 to 1. Results are argued and reevaluated during several evaluation rounds. The results

are shown in Figure 3. The multi-criteria analysis shows quadrangular as the most viable geometric shape, obtaining a total score of 0.84 out of 1. However, the shapes triangle and mountain were only one hundredth of a point behind, with a score of 0.83 out of 1. Further behind were the geometric shapes pai pai and pentagon. Lastly, and with the lowest score, was Umbrella.



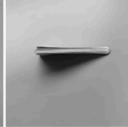
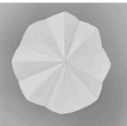

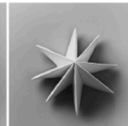


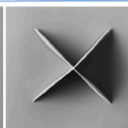





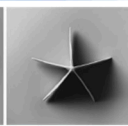
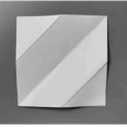

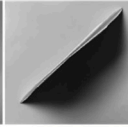
	UNFOLDED	HALF FOLDED	FOLDED	SIMPLICITY	AESTHETIC	RIGIDITY	FIT	ECONOMIC	FUNCTIONALITY	ALIGNMENT	DISPLACEMENT	MATERIAL	TOTAL
PAI PAI				0.6	0.7	0.9	0.4	0.6	0.5	X	0.1	0.5	0.54
UMBRELLA				0.4	0.6	0.3	0.2	0.6	0.3	X	0.3	0.5	0.40
QUADRANGULAR				0.8	1.0	0.8	0.9	0.8	0.8	0.9	0.8	0.8	0.84
TRIANGLE				0.9	0.9	0.8	0.9	0.8	0.8	0.7	0.9	0.8	0.83
PENTAGON				0.6	0.6	0.7	0.8	0.7	0.6	0.5	0.6	0.6	0.63
MOUNTAIN				0.9	0.8	0.7	0.9	0.9	0.8	0.9	0.7	0.9	0.83

Figure 3. Comparison of origami shapes.

Therefore, the quadrangular shape was considered the most suitable for the project. It has high qualifications in all properties, especially aesthetics and the so-called FIT, which refers to the fit with respect to other shapes. In addition, it had already been used in the Al Bahr Towers project, given its alignment aspect, which refers to the alignment between its vertices.

4.2. Solution

Once the most viable geometric shape for implementation in this project was selected, the final solution was developed. Three key aspects needed to be detailed:

- The definition of the construction element based on the selected shape.
- The definition of the generic building.
- The modelling of both the element and the building by using BIM.

4.2.1. Definition of the Origami Element

The properties of the selected geometrical option had to be defined for its implementation in BIM. In addition, constructive aspects such as the uprights and rails, needed to make the element fold according to origami principles, had to be considered.

One of the main concepts to be detailed was the geometry of the folded and unfolded position. As shown in Figure 4, the geometric shape bears resemblance of an x in the folded position, while the unfolded shape also resembles a + symbol. The central point of both was the vertex with the maximum height, so fewer lanes are required due to this feature.

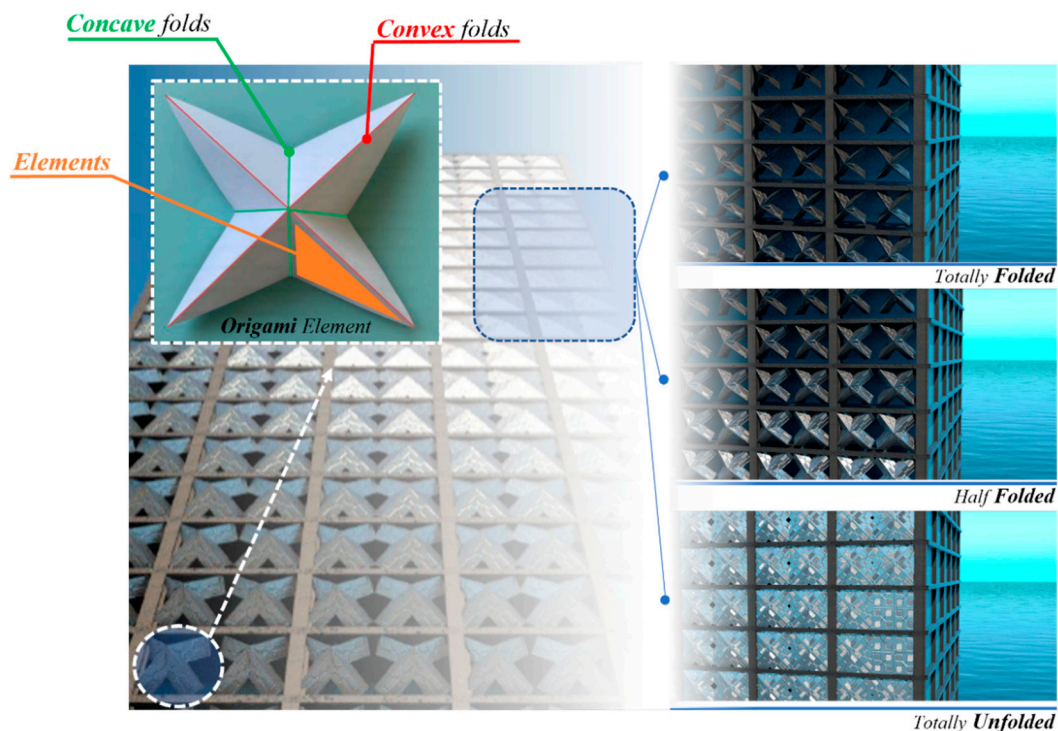


Figure 4. Geometric properties dynamic element.

Thus, the movement of the element will behave according to origami principles, allowing the creation of concave (+) and convex (x) folds as can be seen in Figure 4. These dynamic elements must be anchored to the structure, thus the distance between floors was considered as the main lateral dimension. Hence, each figure will have an affected area of about nine square metres in its unfolded state and the elements can be easily anchored. In addition, each horizontal row of the elements will cover one building floor. Like geometry, the material plays a fundamental role in the behaviour of the element. A lightweight material has been applied, which does not add too much overload to the building. This material is also resistant to adverse weather conditions, flame retardant and is not opaque when fully unfolded, i.e., it allows a minimum of natural light. There are two materials that meet these requirements: Teflon with fibreglass or silver carbon fibre [40]. Both materials can be suitable for covering the surface between the steel frames that form each triangular element, as shown in orange in Figure 4.

4.2.2. Definition of the Building

The objective was to model a generic building that can contain a façade based on the origami elements described above. To do so, a simple building design was sought, focusing on only two aspects: dimensions and orientation.

According to studies of actual applications of this type of façade, they tend to be more common in skyscrapers. Therefore, a building with an octahedral shape of 21 m on each side of the base and 48 m in height was proposed. This is equivalent to 16 floors in height with a distance between floors of three metres. It is important to note that the structure supporting the origami element must be three metres away from the internal face of the building. This is done to ease the circulation of air currents and to avoid heat accumulation, as well as to improve maintenance tasks.

One of the final objectives of the project was the development of an automated system that acts according to the solar path, whereby orientation is a key factor. This orientation varies according to the project location. As indicated above, the building had four façades, two of which will be shielded and two of which will be unshielded. If the building was located in the northern hemisphere of the earth, the best position of the edge between the two shielded façades was facing to the south. If the building was in the southern hemisphere, the edge should face to the north.

At the same time, the season of the year must be considered. As can be seen in Figure 5, in the summer, the sun rises over the horizon between east-northeast (ENE) and northeast (NE) and sets between west-northwest (WNW) and northwest (NW), which varies depending on the summer day. In spring and autumn, it rises between the near east-northeast (ENE) and east-southeast (ESE) directions and sets between west-northwest (WNW) and west-southwest (SW). Finally, the sun in winter rises between east-southeast (ESE) and southeast (SE) and sets between west-southwest (SW) and southwest (SW). It should be noted that the sun only rises in the east (E) and sets in the west (W) twice a year, called the vernal and autumnal equinoxes. The day of the year when the sun rises and sets closest to the north is called the summer solstice. The winter solstice occurs on the day of the year when the sun rises and sets closest to the south.

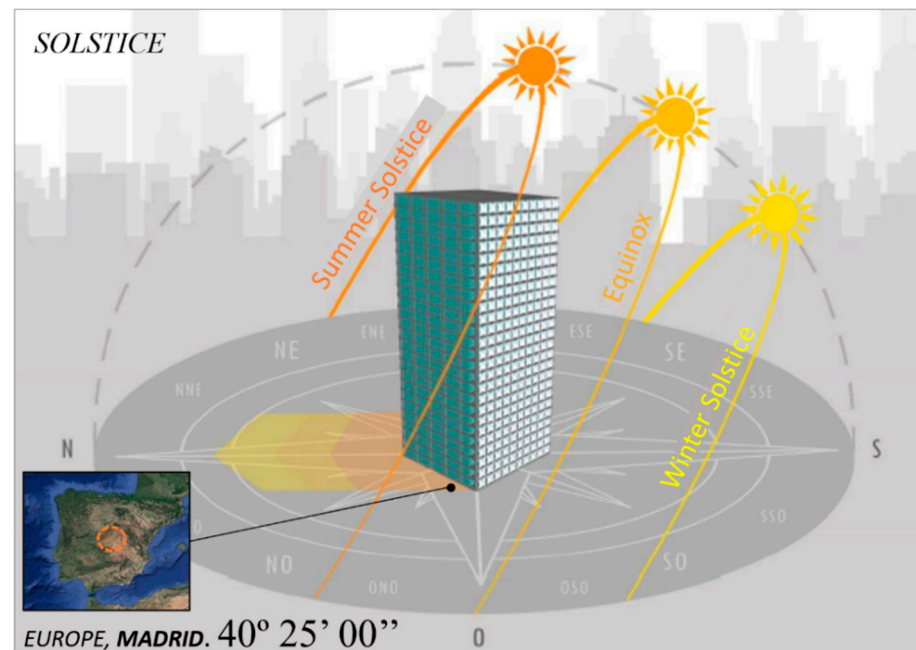


Figure 5. Solar path by season.

In this context, it was decided to place the building in the city of Madrid. Madrid is in the northern hemisphere with coordinates of $40^{\circ}25'00''$. By means of the logic previously described, it is established that the edge between the two shielded façades must be oriented to the South. Therefore, these two façades will face Southwest and Southeast.

4.2.3. BIM

Once both the infrastructure and the dynamic construction element had been defined, the next step was to apply BIM to carry out the simulation of the project. For this reason, a study of the various available software alternatives on the market (Autodesk, Bentley and Rhinoceros 3D) was previously analysed. The 3D geometries to be modelled were complex and had to be animated in order to represent the transition from folded to unfolded position. Another basic requirement was that any desired aspect could be easily modified once the model was finished. Among all the possible options, the software chosen was Rhinoceros

3D, with Grasshopper for the parametric modelling of both the origami element and the building, and V-ray for the project image rendering.

- Origami element modelling

The aim was to parameterise the geometry. For this purpose, the software Grasshopper was used. Figure 6 shows the process followed. The BIM element to be modelled is considered as “IfcShadingDevice”, according to IFC Standards. The complete inheritance of it is “ifcRoot” > “IfcObjectDefinition” > “IfcProduct” > “IfcElement” > “IfcBuildingElement” and “IfcShadingDevice”.

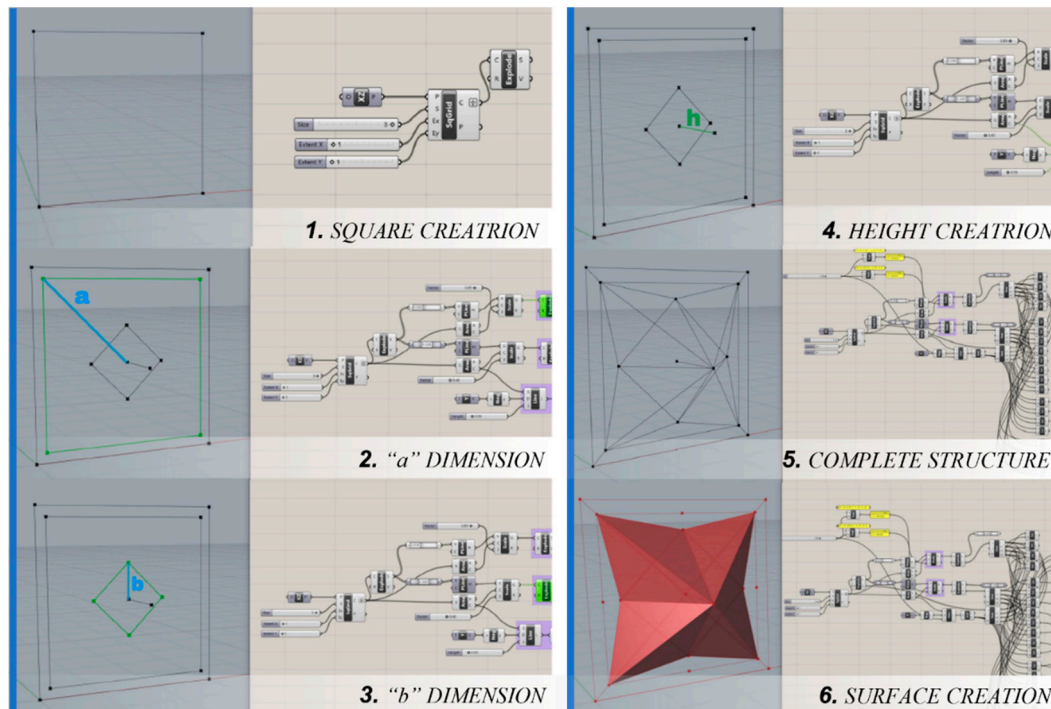


Figure 6. BIM origami element modelling.

The first step was to draw the plane that contained the base of the piece, which is the initial square. A base of three metres by three metres was made, as detailed in the definition of the origami element. In addition, a repetition function was prepared in both the X and Y axis (both coinciding with the plane of the façade), so that when the whole piece was modelled, it was possible to repeat it.

Subsequently, three dynamic parameters were added. They were associated with an outer square (like the initial one) and an inner square rotated 90° with respect to the previous one, which can be identified as the “inner square”. The outer square is shown in green at point 2 in Figure 6, while the rhombus is shown in green at point 3 in Figure 6. Dimension a was the distance from the centre of the squares to the vertex of the outer square. The distance “ b ” is the one between the centre of all squares and the vertices of the inner square. The distance between the XY plane and the furthest point of the XY plane is set as h . Once the three dynamic distances have been identified, the complete structure was created. To do this, the different points of the initial square, the outer square, the inner square and the height were joined together, as detailed in point 5 of Figure 6. Once all the points had been joined together, the surface is created that gives rise to the final origami figure. An example of how the parameterisation of this geometry works is shown in Figure 7, where the entire arrangement of points is modified according to a single value, the height h .

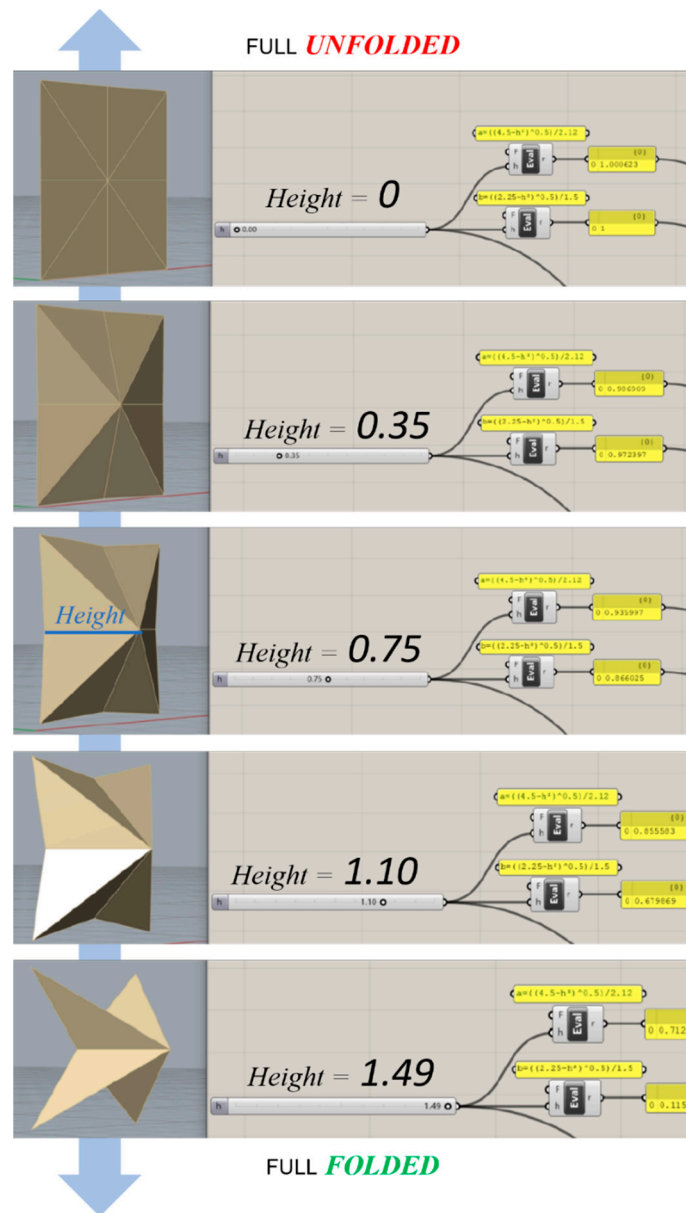


Figure 7. Parameterization of origami figure by height.

This fully parameterised origami element was replicated along the two fictitious façades. The origami elements were cloned along the X and Y axes. The elements of each façade created a panel in the XY plane. From this panel, a point of X and Y coordinates was created, which simulated the position of the sun. Depending on this point, the heights of the origami elements (4th point of Figure 6) vary between 0 and 1. In this way, the elements had different degrees of openness depending on this point, as it is detailed in Figure 7. The location of all the elements on the façade and the different degree of openness depending on the sun can be seen in Figure 8.

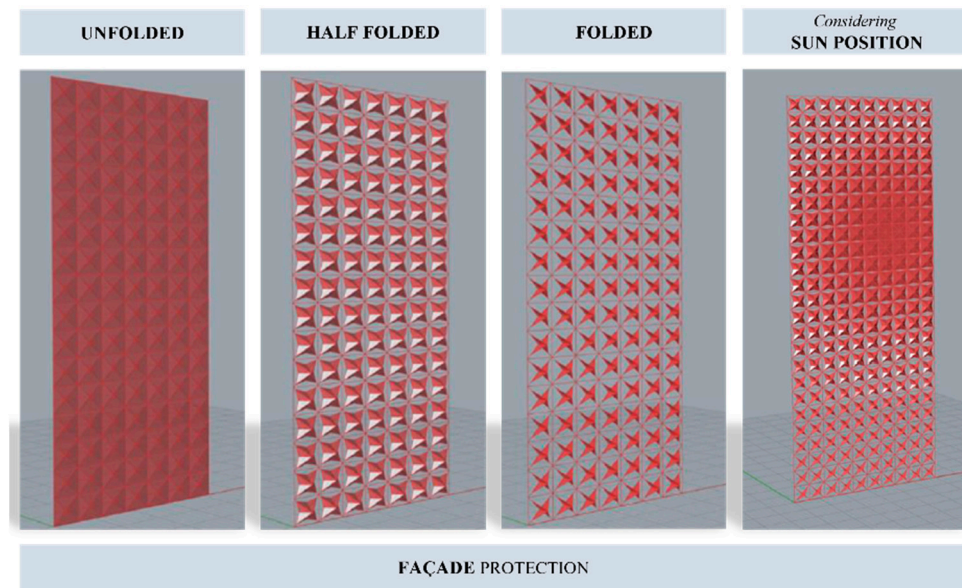


Figure 8. Protected Facade creation.

- **Generic building modelling**

As indicated above, an octahedral geometry with only three parametric distances was chosen: the diagonal of the base square and the sides of the square. This enabled modifying the façade areas quickly and easily. A common distance between floors of three metres and a distance between columns of six metres were considered. The modelling was done with the same tool used for the origami element modelling, the Grasshopper software.

Finally, the rendering of the infrastructure was performed. For this step, interoperability between tools plays as critical factor. For this reason, the render was performed by using the V-ray plug-in developed by Rhinoceros. Renderings were made in different time periods, showing the real behaviour of the façade's protective elements depending on the solar path.

5. Results

Considering the initial objectives, the research project achieved the results of the initial planning. The main objective was based on the successful application of BIM together with origami techniques. For this purpose, a study of the different possible techniques to be implemented and the real applications in the AEC sector were carried out. Subsequently, different geometries were studied to obtain the most suitable one according to a multi-criteria analysis. That showed the quadrangular as the most suitable origami shape.

A parameterisation of the origami façade element by means of BIM was performed. The use of Grasshopper software was chosen for the application of this methodology. A generic building with an octahedral shape was modelled. The base of the infrastructure was a square that could be parameterised in all its dimensions. The location of the infrastructure was assumed to be in Madrid in order to consider the solar path. Two of the four façades were designed to be covered, with the south-facing edge being the one chosen between the shielded façades. This origami element was dynamic and protected these facades by varying its geometry according to the theoretical position of the sun. The modification of its geometry was based on the application of origami techniques and its parameterisation by using BIM.

A BIM-based automated system capable of modifying the geometry of Origami façade elements based on the sun trajectory is the main result showed in Figure 9. Nevertheless, the process of Origami-BIM element can be considered as a significant result. The methodology followed in the project can be of interest and a useful tool for designers in order to consider the possibilities or Origami shapes and the use of software.

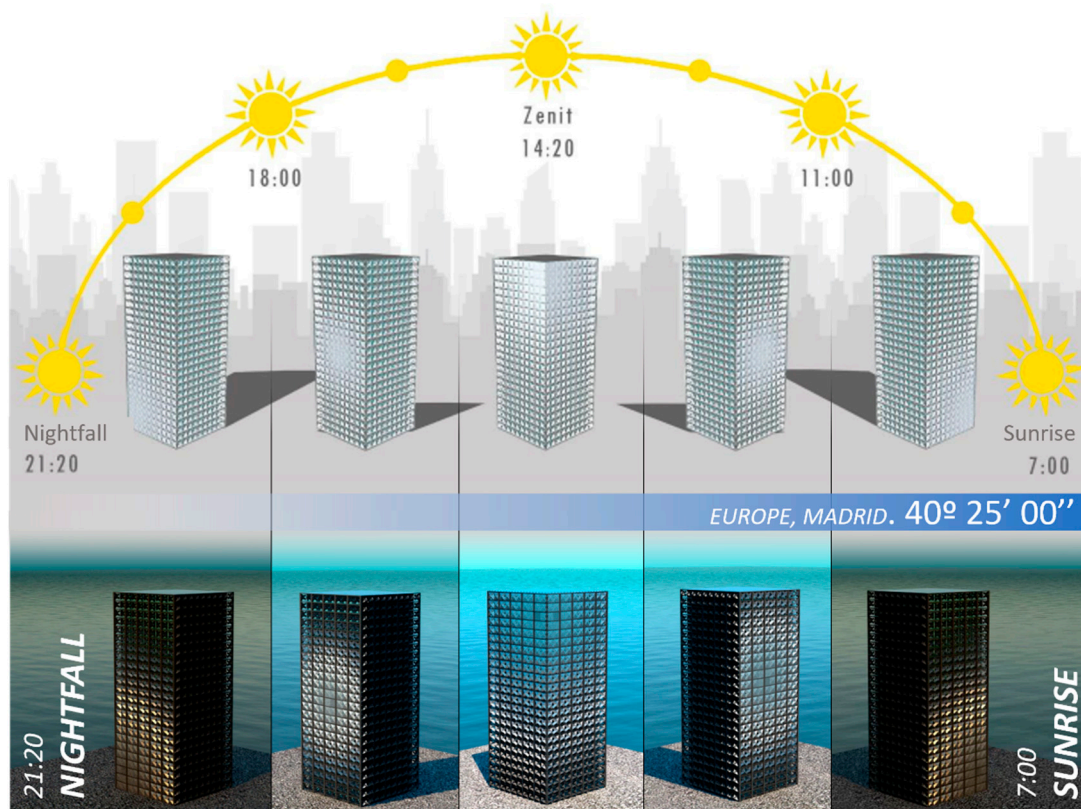


Figure 9. Façade behaviour according to solar path.

The scope of this study provides a great basis for the development of future studies, with sustainability and energy efficiency being their major objectives. The synthesis of BIM and origami techniques represents a breakthrough in the development of the sector, the technical feasibility of which was demonstrated by the project outcomes.

6. Conclusions

This study proposed a methodology for the design and management of the operation of a modular and adaptive façade for highly glassed buildings. The proposed modules were deployable and were inspired by the origami technique. This methodology combined BIM with the generation of the mobility of the modules based on the environmental conditions of lighting and temperature. These conditions were set in real time by the location and the season of the year under evaluation.

Façades are the first line of defence against environmental conditions. This study uses a dynamic envelope that prevents or allows the sun to shine into the building. Their use would provide significant savings in energy consumption and reductions in carbon emissions, as well as increases interior visual comfort (i.e., interior lighting levels). Therefore, the initial investment in the installation of adaptive façades would be balanced by these energy savings. In addition, it is very important that such elements follow the origami philosophy in order to change its properties in real time. This means adjusting their position and size according to the momentary interest, allowing or blocking the light flow.

Applying BIM to the design of the origami elements with conventional software had several drawbacks. When an element was modelled, its dimensions, position, or shape are usually static and invariable. However, a parametric design was needed to modify its parameters integrally. For this purpose, commercial parametric design software such as Grasshopper was used. This is an add-on to the Rhinoceros 3D CAD program that allowed the development of complex parametric designs from generator components. In addition, it also included the V-ray tool for obtaining high quality renderings. Therefore,

BIM may be incorporated into projects that follow the principles of origami, improving their sustainability and habitability.

In conclusion, the novelty of this project resides on the combination of BIM and Origami techniques in a single way. The origami technique most suitable geometry selection is reported as well as origami implementation, parametrization of origami element, BIM sun trajectory implementation, or Origami BIM element variation according to the sun trajectory. With these results, future investigation lines were opened, i.e., detailed mechanism for folding or unfolding origami elements, construction details of each origami element, or BIM-based operating system for manual operation of BIM elements.

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