A Matching Kit interface for building refurbishment processes with modules

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Abstract

There is a need for faster installation of prefabricated modules in the refurbishment market. Current solutions for installing and fitting prefabricated modules on existing buildings are indeed time-consuming. The objective of this research is to reduce the time currently required for the installation of timber-based 2D modules using innovative technologies while gaining placement accuracy. Consequently, a new solution was proposed based on a digitally-produced matching kit interface that corrects existing building deviations. This solution has been tested, validated and compared in several manufacturing contexts. The tests recorded measurable variables such as manufacturing time and the geometric tolerances of the modules. The results show a considerable decrease in installation time. Owing to the satisfactory results thus obtained, the testing of the proposed solution in a more relevant environment may be undertaken in future research.

Keywords: automated, customization, installation, refurbishing, prefabrication.

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1 Introduction

Realizing a zero-energy consumer building stock is a goal of various stakeholders that participate in building maintenance and renovation [1]. In order to achieve this goal, existing buildings must be adequately insulated. Traditionally, for manual on-site solutions such as the installation of a rain screen (or ventilated façades) [2], this procedure is time-consuming. According to several databases [2], it takes approximately 1.30–1.63 h/m^2, depending on the case, without considering the period needed for installing construction devices such as cranes or auxiliary platforms. Moreover, it involves working intensively during long periods at dangerous heights, implying high risks [3]. Several research projects [4] have aimed at improving the traditional methods of building renovation, such as the timber-based element system (TES) [5], Annex 50 [6], and großelement-dämmtechnik (GEDT) [7], which have focused on different solutions. In the aforementioned studies, various methods involving the use of prefabricated 2D modules to cover the building envelope have been presented (with 2D module, it is meant a timber-based prefabricated wall as seen in Figure 1). However, the techniques that these methods use in the manufacturing and installation processes do not differ significantly from the methods currently used in the construction industry. Therefore, those procedures are not automated and time reduction was not achieved.

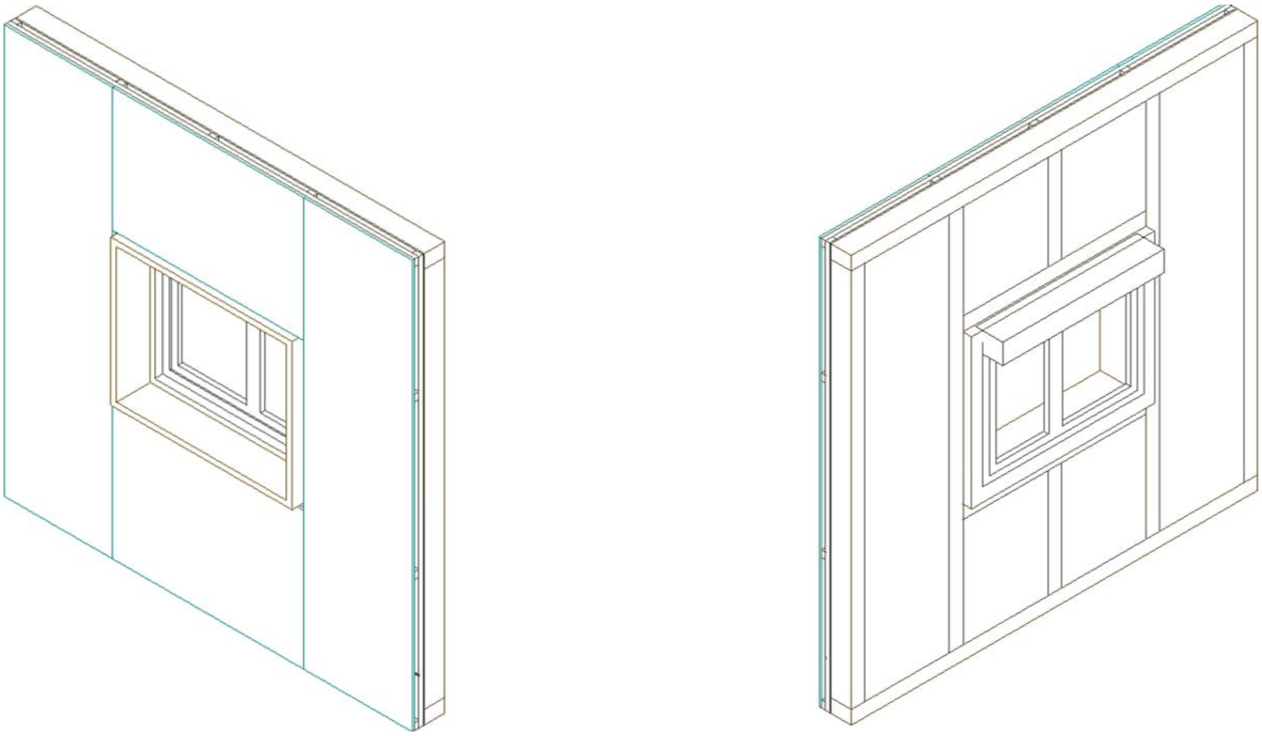

Figure 1. Front and rear views of a fully prefabricated 2D module.

Building renovation always requires custom-made solutions. It is therefore necessary to conceive a highly customizable 2D module, adaptable to the majority of the targeted building typologies. Moreover, the off-site manufacturing and on-site installation processes require to be (re)adapted to the existing circumstances.

Explain briefly the method for the research explained in this paper.

1.1 Analysis of current techniques

As a further development of the aforementioned projects [4], the BERTIM project [8],[9] is focused on improving the manufacturing and installation processes of prefabricated 2D modules with integrated renewable energy sources (RES). The objective of this project is to shift from individual manufacturing to mass-customization [10]. These aims are achievable using advanced tools (such as digital production and robotics) for integrating the value chain over the life cycle of the project. Within the context of this research project, an in-depth analysis of the current timber-based 2D-module manufacturing and installing system was performed [11]. In order to localize the main challenges and research gaps, an elaborate demonstration was performed [12]. This demonstration consisted of the installation of three 2D modules on an existing test building named “Kubik”. Techniques from previous experiences of building renovation with prefabricated modules were used. All the steps that comprised the demonstration were monitored, as explained in the next points (see also Table 1):

- The layout planning or re-engineering (sub-system 1) process comprised on-site data acquisition and module adaptation using non-parametric software for a total of 0.43 h/m². However, in BERTIM, a dedicated work package was used to develop a software that could facilitate the re-design process. Therefore, it was envisaged that this re-engineering time might be minimized within this research project by applying such a software.

- The manufacturing process (sub-system 2) required 0.87 h/m². It involved stud cutting, timber framing, insulation placement, and waterproof membrane fixing. In a parallel study, the manufacturing process will be improved.
- The data obtained from the demonstration show that it is necessary to improve the installation process (sub-system 3) explicitly to reduce the overall working hours. The on-site installation process, which is the most problematic phase, still requires up to 56 % of the time spent for the entire process, i.e., 1.73 h/m². Moreover, the primary time-consuming task of the installation process was the final rework (0.91 h/m²), which was performed after the fixing of the main body of the 2D modules (see **Error! Reference source not found.**).
- The accuracy of the final placement of the 2D module differs from that which was planned. This incurs in the need of further re-work, after the placement of the 2D modules onto the wall.

Figure 2. Installation of panels using current techniques. The prefabricated module was not completed and it required to be reworked.

The conclusion of this first demonstration was that the installation process was critical for reducing the overall renovation time. The prefabrication degree of the module was approximately 50%, thus requiring that the rest of the work be finished on-site. In this case, membrane overlapping and external finishing material fixing required 0.91 h/m². It was concluded that a higher degree of prefabrication could prevent the occurrence of this problem. Consequently, a higher degree of prefabrication for enabling fast fitting requires very accurate manufacturing of the 2D module and high precision in the positioning of the connectors onto the existing façade.

Table 1. Manufacturing and installation time required for the 2D modules at the Kubik bulding.

Task	h	workers	units(m^2)	h/m^2
MODULE ADAPTATION 0,43				
Data acquisiton	2,00	1,00	23,34	0,09
Re-design	8,00	1,00	23,34	0,34
MANUFACTURING PROCESS 0,87				
Battens cutting	2,00	1,00	23,34	0,09
2DM	6,60	2,00	23,34	0,57
Finishing	2,00	2,00	23,34	0,17
Transport l.	0,50	2,00	23,34	0,04
INSTALLATION PROCESS 1,73				
Transport u.	0,30	2,00	23,34	0,03
Connector	0,30	2,00	23,34	0,03
Insulation	1,50	1,00	23,34	0,06
Place and fix modules	5,50	3,00	23,34	0,71
Finishing	1,70	3,00	23,34	0,22
Perimeter finishing	8,00	2,00	23,34	0,69
TOTAL h/m^2	**3,02**			

For the accurate installation of fully prefabricated elements on existing buildings, acquisition of geometry data using 3D laser scanning, photogrammetry, or/and theodolites is necessary. According to Ishida [13], this data acquisition can typically be considered sufficient for manufacturing the prefabricated modules. The accurate adaptation of a construction module to the measurements of an existing building has been previously proposed and tested [13]. In this case, the allocation of the connector was not specified, and it involved generic data acquisition for an overall adaptation of the prefabricated modules. This situation might result in errors or inaccuracies because the location of the fix point of the module has not been determined. In this study, additional strategies for determining the exact location of the connector were considered. The accuracy of the joint system is primordial during the installation of any prefabricated element [11]. As there is a requirement for reducing the final re-work during the installation process while ensuring high accuracy and the usage of fully prefabricated 2D modules, the connector must be accurately fixed in the correct position or the location of the connector should at least be known.

One of the reasons for such time consumption is due to existing buildings' geometry; building façades do not fulfil planar geometric requirements that are needed for placing accurately prefabricated 2D modules. In a previous phase of this research, several façades were measured using

3D laser scanning tools. The obtained point cloud described that, even in an area of approximately 2000mm x 2500mm there are areas that deviate more than 20 mm. Thanks to the Recap™ software, in Figure 3, the points that are within a range of plane depth of 20 mm are in purple, while the points out of that plane depth are in green. This issue complicates the levelling and the correct positioning of the 2D module onto the existing wall.

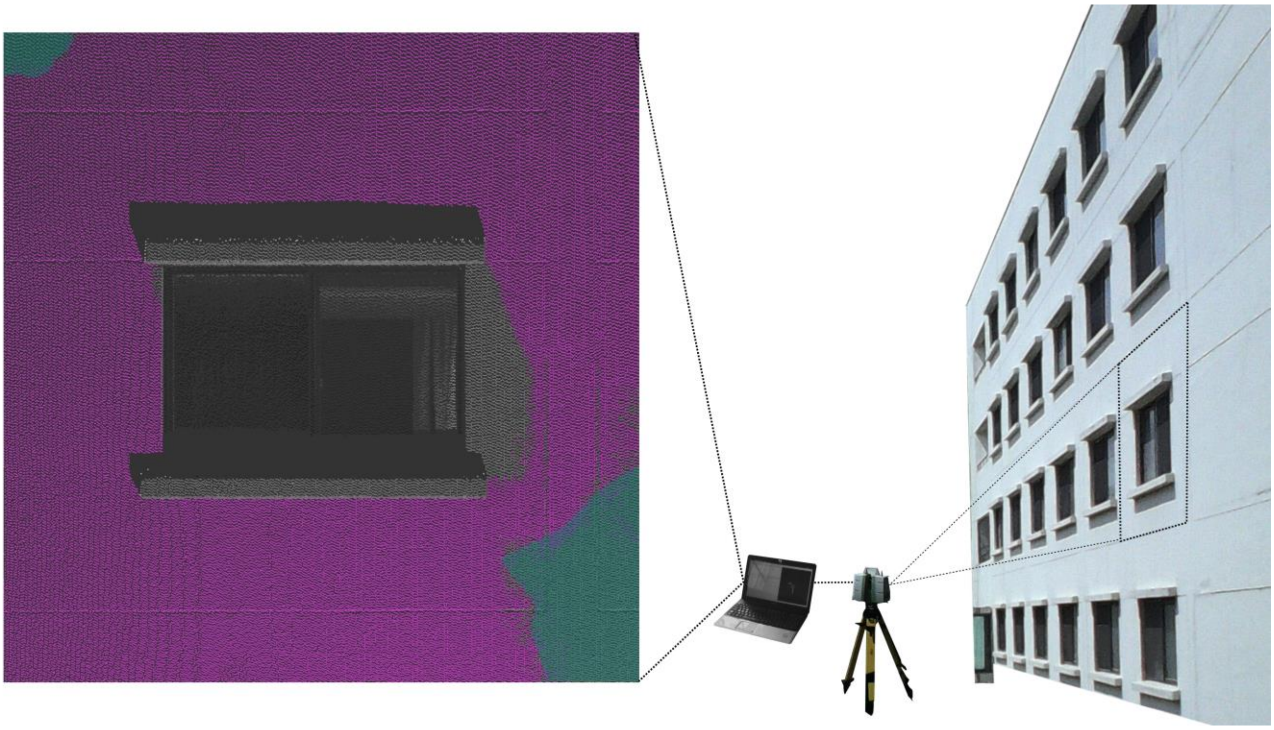

Figure 3. Data from a 3D laser scanner defines in purple points within a range of plane depth of 20 mm. Courtesy of SKKU.

1.2 Research question and method

The following are the central questions of this research project: how can the time used in the installation process be reduced by at least 30% as compared to a typical or traditional renovation? How can such goal be gathered while prevailing an accurate placement of the 2D modules? In order to achieve this objective, there is a necessity for an overall perspective that considers multiple aspects. Furthermore, the solution must be general and sufficiently flexible for implementation in various situations [14]. In order to shift to completely customized production [15], a set of solutions that consider the line balancing of the entire process [16] must be derived. If only the improvement of single tasks is addressed, the entire process workload might not be properly distributed, and contradictions might appear. Thus, for a better analysis of the process, three main sub-systems have been defined:

- The 2D module configuration that consists of the prefabricated 2D module and its layout. It has been considered that the data acquisition must be accurate and the definition of the layout must be automated.

- The manufacturing process of the 2D module off-site in the factory. An accurate manufacturing of fully prefabricated 2D modules is necessary.
- The installation process of the 2D module on-site. Similar to the previous point, an accurate location of connectors onto the existing buildings must be achieved.

The research and development described in this paper followed a matrix-based methodology called axiomatic design [17]. Moreover, in this research, the inventiveness for facing each decomposed problem was guided by specific methods that facilitated the problem solving during the design and development phases, such as TRIZ [18]. This technique has already been used in previous and parallel research phases [19]. The reminder of this paper explains and documents the development and validation of a procedure based on a digitally produced interface matching kit (MK) that enables a reduction of the time required for the installation process of the 2D modules

2 Development and validation of a novel installation concept

In previous instances [11], while trying to realize this objective, the connector was composed of at least two elements: Part 1, which is installed on the existing building, and Part 2, which is the portion that is installed in the 2D module (see Figure 4). The position of Part 2 in the module is dictated by the position of Part 1 on the wall and vice versa. Therefore, their coordinates should be synchronized. In the case of irregularities in a wall—for instance, an irregularity of 20 mm—the joint system must absorb these defects in order to obtain a planar envelope. Another issue is that, normally, the Part 1 is place onto the structural slabs' edge. On the edges of concrete slabs there is commonly a big concentration of steel bars, and this might impede the process for making holes in the planned location (see Figure 4). Traditional [2] and current [4] techniques for installation of semi and fully prefabricated element modules involves the installation of Part 1 of the connector with a low tolerance, i.e., obtaining on-site accuracy by installing Part 1 of the connector at its exact position, based on the location of the connector indicated by the designer or layout definer. The solutions in Strategy 1 are similar to the traditional methods. These solutions have been tested to some extent without optimal results [7], and they are time-consuming procedures.

But the novel installation process developed in this research involves installing Part 1 of the connector with a high tolerance, of up to 50 mm, and correcting the deviation with a matching kit (MK) interface. With this approach, it is possible to install the connectors using a traditional laser alignment system as the entire set of connectors might not be in the same plane, i.e., parallel to and equidistant from the existing wall. Therefore, after fixing, the accurate location of Part 1 should be measured using a digital measurement device. To facilitate the measurement by a digital theodolite for instance, target reflectors could be embedded into the connector. Once the exact position of Part 1 is known, some parts of the 2D module can be corrected (or modified). Similar techniques can be found in medical implant procedures [20] and aircraft repairing processes [21]. The objective of this novel concept based on a MK interface is to minimize the on-site installation time of the modules, and to especially reduce the time spent setting up the connectors. Besides, it is also an objective to minimize the rework after the placement of modules, by means of using fully prefabricated and accurate modules.

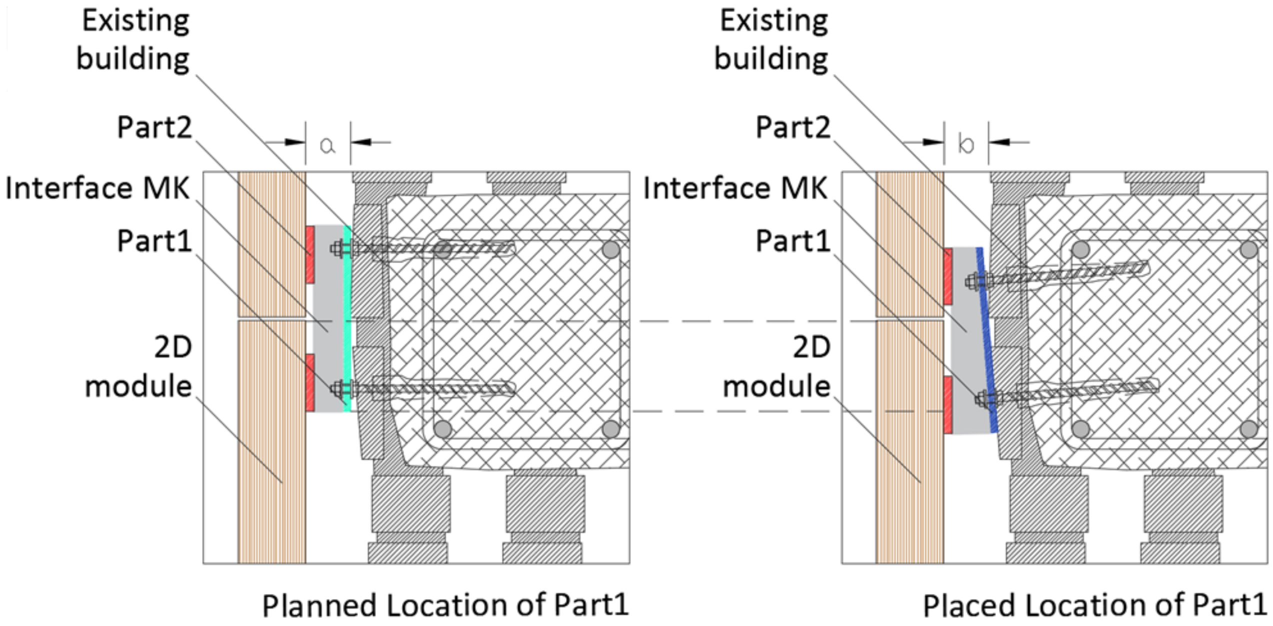

Figure 4. Cross-section of a wall with an incorporated 2D module. During installation, the planned location of Part 1 may differ between the planned layout and the placed implementation. An interface matching kit can correct this deviation.

For applying this novel concept and determining the shape of the interfacing matching kit, the location of Part 1 has primary importance. Therefore, it is necessary to measure the coordinates in Part 1 $(x_n, y_{n,} z_n)$. There are two equations, the line's equation (Ln, Equation 1) and the distance (Dn, Equation 2), that relate Part 1 and Part 2 (Figure 5). By solving these two equations, the perimeter lines FR1, FR2, FR3, and FR4 can be obtained. At this point, there is enough information for defining the geometry of the matching kit.

Equation 1

$$L_n = \frac{(x - K_a)}{(x_n - x_a)} = \frac{(y - y_a)}{(y_n - y_a)} = \frac{(z - z_a)}{(z_n - z_a)}$$

Equation 2

$$D_n = \sqrt{(x_n - K_a)^2 + (y_n - y_a)^2 + (z_n - z_a)^2}$$

In the scheme in Figure 5, the physical connection was not defined; however, it shows the first approximation of how this physical connection could be used to solve the repositioning of the connector part that is installed on the building. Moreover, the concept was conceived as a sequence;

therefore, it did not rely on any material or element. These equations can be inserted in current CAD and computational design software (such as Dynamo © [22]), and the shape of the matching kit is obtained in a rather automated procedure.

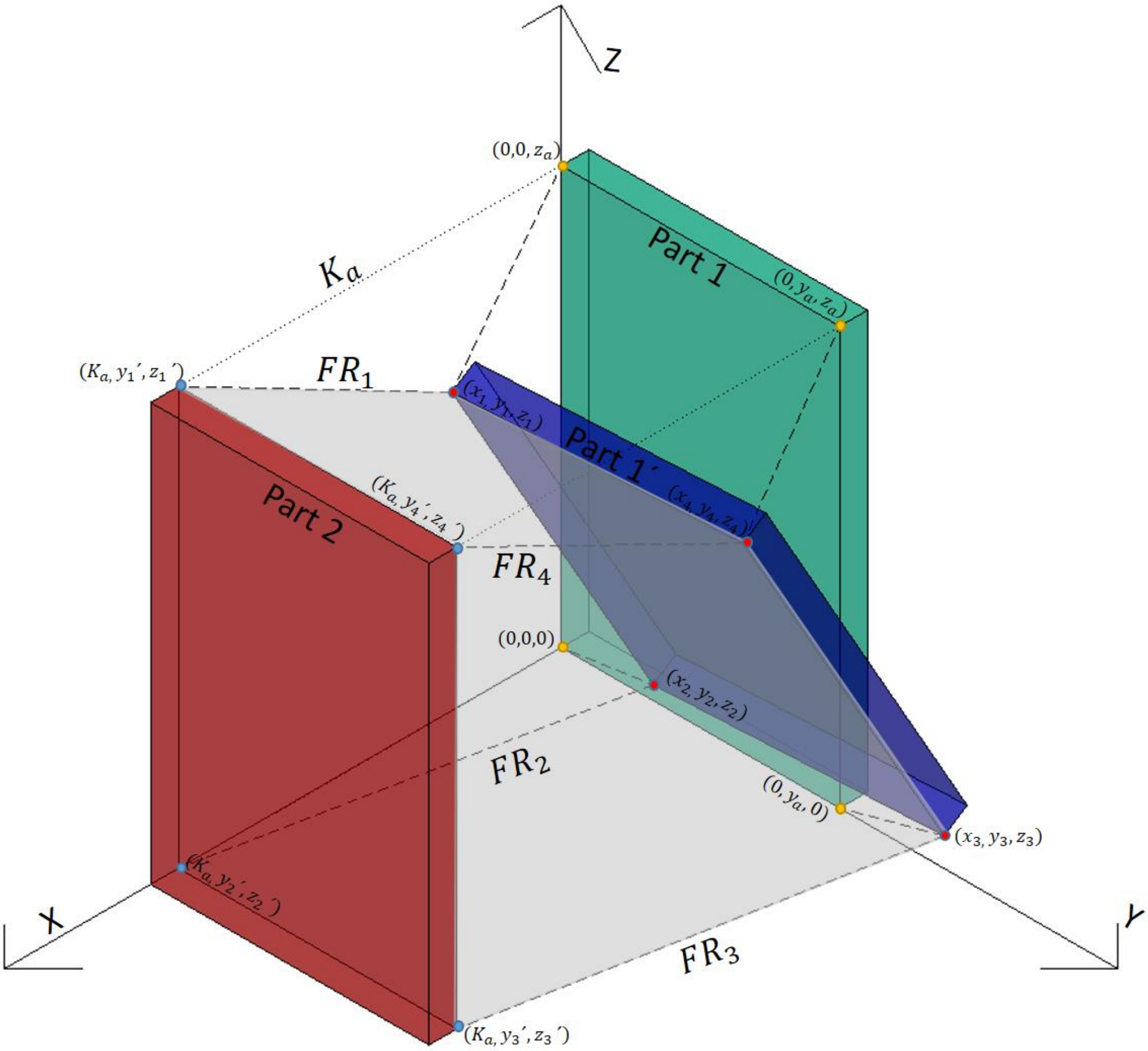

Figure 5. Geometrical definition the matching kit. The planned location of Part 1 is in green, the placed location of Part 1 is in blue, Part 2 is in red, and the interface matching kit is in grey.

In order to implement this abstract conception of the novel installation process, it was proposed that it should be performed in phases (Figure 6). According to the virtual sequence, first, Part 1s were placed on the building and then their locations were accurately measured. It was assumed that the irregularities in the existing building cause the actual position of the connector to differ from the one that was predicted in the design. Second, an interface MK was manufactured and installed on Part 1. Depending on the lack of verticality of the existing wall, the thickness and geometry of the interface MK varied. The interface MK was adapted using accurate measurement systems, the automated adaptation tools of the CAD software, and accurate digital manufacturing techniques. Once the MK was accurately manufactured and installed in its designated location, a planar situation was achieved.

Finally, the 2D module was installed on the connectors. Essentially, the proposed design relied on the correction of the deviation using an interface MK and the accurate manufacturing of all the parts of the 2D module.

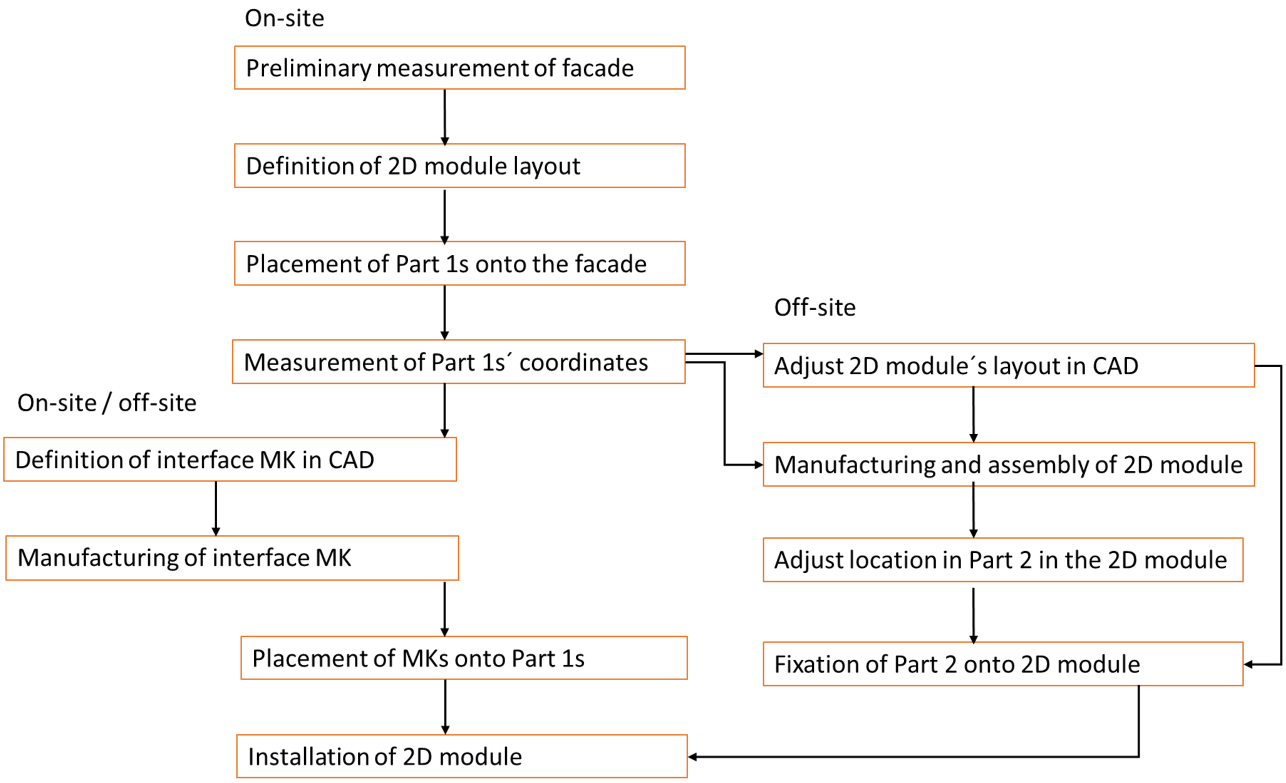

Figure 6. Scheme of the installation process or sequence.

In order to validate the aforementioned novel process, three tests have been carried out. The objective of these tests was to demonstrate the novel installation process in different manufacturing contexts and environments. The novel installation process does not rely on a particular material or specific type of connector, but instead on a step-by-step workflow or sequence. The parameters or measurable variables for validating the procedure are as follows:

- **Installation Time** of the 2D modules. If the tests are successful, there should be a reduction in installation time compared to that required for the current processes, which is 1.30–1.63 h/m² [2].
- **Accuracy**. The connector and the 2D module should be fixed with a maximum tolerance of ±1 mm. In other words, the maximum tolerance between the connector parts on the wall and the parts on the 2D module should be less than 1 mm. This tolerance is defined as the allowable variation. Working with wholly prefabricated 2D modules involves achieving airtightness between the unions of the modules and enabling RES service clipping. Therefore, high precision is indeed required.

In this validation, the solution consisted of installing the connectors on the existing wall with high tolerance and specifically using an interface MK to absorb the variation owing to possible irregularities. In order to verify the operability of the concept, three tests were performed in a laboratory environment. The tests were not used on a real outdoor façade or wall. In Test 1 and Test 2, an indoor aluminum frame was used for installing the connectors and 2D modules. This aluminum frame was characterized by regularity with respect to geometry and rigidity. Therefore, for simulating a building structure as closely as possible, it was necessary to create an irregularity in order to obtain a non-planar situation similar to that existing in the walls of a real building. In Test 3, a façade made out of OSB (Oriented Strand Board) was placed onto an indoor wall in a factory. The OSB façade was not planar and it contained non-aligned windows. The first test used extracting techniques for manufacturing the interface MK, while the second was based on additive procedures, as will be described in the following sections. Furthermore, in Test 1, the 2D module mockup was based on (or resembled) a cross-laminated timber (CLT) wall, while in Test 2, the mockup concept was similar to a timber frame. Finally, three sizes of 2D modules were tested: in Test 1, one single, large 2D module was used while, in Test 2, two smaller ones were employed. Additionally, in Test 3, commercialized timber-frame walls were used, with heights and widths that were close to two meters. In Test 3, the MK was produced using manual cutting and sanding tools.

2.1 Test 1

The materials, devices, tools, software, and main elements used for Test 1 are specified in Table 2. The main feature of Test 1 is the manufacturing of the interface MK using laser-cut elements. The same Part 1, Part 2, and connecting system were used for every case considered. It means that their geometries were defined in advance, and therefore, known. The Part 1 pieces comprised three reflectors on the corner to facilitate the measurement of the coordinate points. As a mechanical connection in Test 1, the Unicon-Basecon® system was used. This connector type required high installation accuracy owing to its geometry. The 2D module was approximately 2200 mm long and 1500 mm high and was made out of medium-density fiberboards (MDF) 20 mm in width.

Table 2. Devices and materials used in Test 1.

Software	
Design of the module	AutoCAD®
Digital fabrication of the module and the interface MK	Adobe Illustrator©
Manufacturing and measuring tools	
Interface MK cutting	Beam laser cutter, Universal Laser PLS6.75®
Module element cutting	Vertical saw, Festool TS 75 EBQ ©
Module element routing	CNC router, Zünd G3 ©
Point acquisition	Leica, MS-60©
Materials and elements	
Modules	MDF board, 20 mm
Interface MK	Gray cardboard 0.9 mm Cardboard 1.5 mm UHU extra tropffrei glue®
Reflector	Rothbucher Systeme©
Mechanical connection	Unicon-Basecon ®
Screwing system	Maytec®

Size of modules	
Module height	1500 mm
Module length	2200 mm

The following description illustrates the step-by-step correlation undertaken in Test 1 (see Figure 7). First, the aluminum frame was manually measured using traditional rulers. This aluminum frame was molded with grooves for a fast fixing of elements. Once the frame was measured, the 2D module and the connecting system were then defined using CAD.

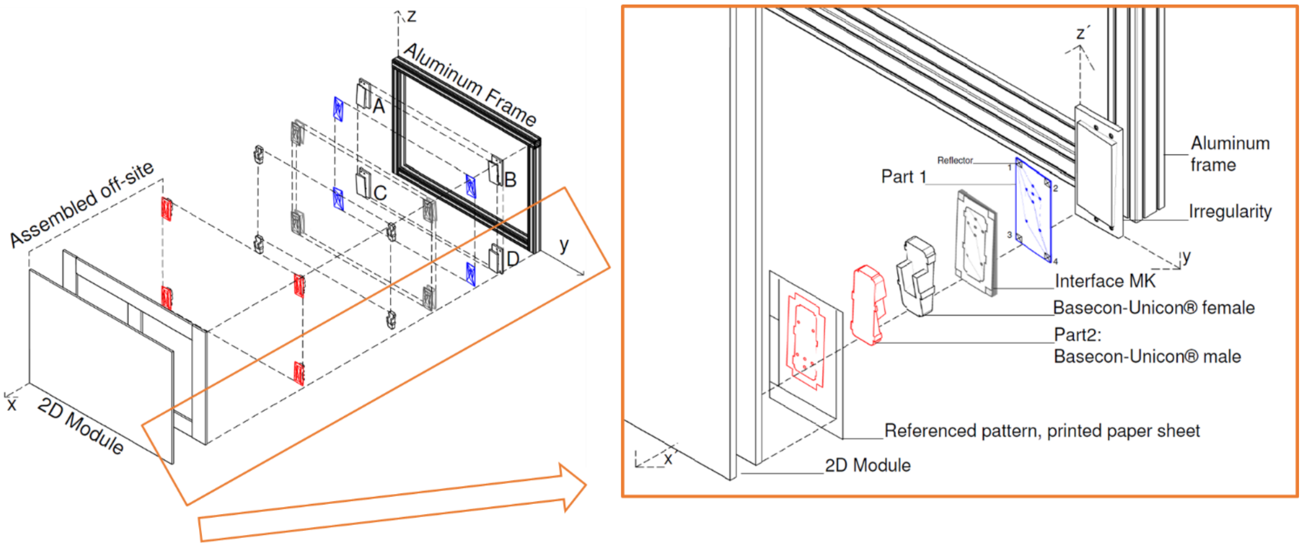

Figure 7. Exploded view of the module showing the order of installation of all the elements of Test 1. Part 1 in blue, the MK is shown in grey, and Part 2 are in red.

Next, the irregularity (the element used to create a “real” wall condition), prepared from a multi-layered and laser-cut MDF and cardboard, was fixed on the aluminum frame. At this point, the situation thus obtained was considered similar to an ordinary façade, i.e., it was geometrically irregular. Next, Part 1 pieces were installed on the irregularity. The Part 1 pieces had three reflector tapes that facilitated measurement with the total station or digital theodolite. Four Part 1 pieces were used: A, B, C, and D. Eight additional reflectors were included to measure the geometry of the aluminum frame in order to ensure the geometry of the perimeter of the aluminum profiles. In the next step, the coordinates of Part 1 pieces and the eight reflectors placed on the aluminum frame were measured. This was accomplished using a digital total station. Point C5 was considered to be the reference point (1000,1000,1000) (see Table 3).

Table 3. Test 1: coordinates of Part 1s and aluminum frame in mm.

Points	x	y	z
A1	980.6	811.3	2372.2
A2	975.7	915.7	2370.0
A3	967.0	909.9	2135.3
A4	1000.7	793.8	2085.2
A5	1000.3	1089.8	2403.3
B1	998.9	2790.1	2404.0
B2	966.0	2860.8	2366.0
B3	968.9	2965.3	2369.4
B4	974.9	2868.2	2131. 4
B5	999.2	2977.8	2083.4
C1	1000.4	792.9	1227.0

C2	965.0	804.1	1171.2
C3	970.7	908.4	1174.9
C4	974.0	812.1	936.9
C5	1000.0	1000.0	1000.0
D1	1000.2	2978.9	1237.2
D2	971.3	2866.5	1186.0
D3	966.6	2970.9	1181.9
D4	980.3	2858.3	951.3
D5	1000.0	2739.0	996.4

Once the exact locations of Part 1s were measured, the coordinates of the points were inserted into the CAD files to modify the shape of the interface MK. More specifically, the shapes of the interface MKs were calculated. The output obtained comprised objects with no parallel faces. This MK object’s description was used to generate the necessary information for multi-layering the object and laser-cutting the cardboard. Moreover, the deviations of the 2D module were adjusted according to the variations of the connectors. All elements of the 2D module were then accurately defined and contoured using a CNC machine, according to the descriptions of the CAD file. The CAD file was partially converted into an Adobe Illustrator© file to generate the CAM file. This CAM file was used by the laser cutter to manufacture the adjusted interface MK. Once the interface MKs were manufactured, they were placed on Part 1. At this point, a planar situation was generated. The female part of the Unicon-Basecon® was then placed on the interface.

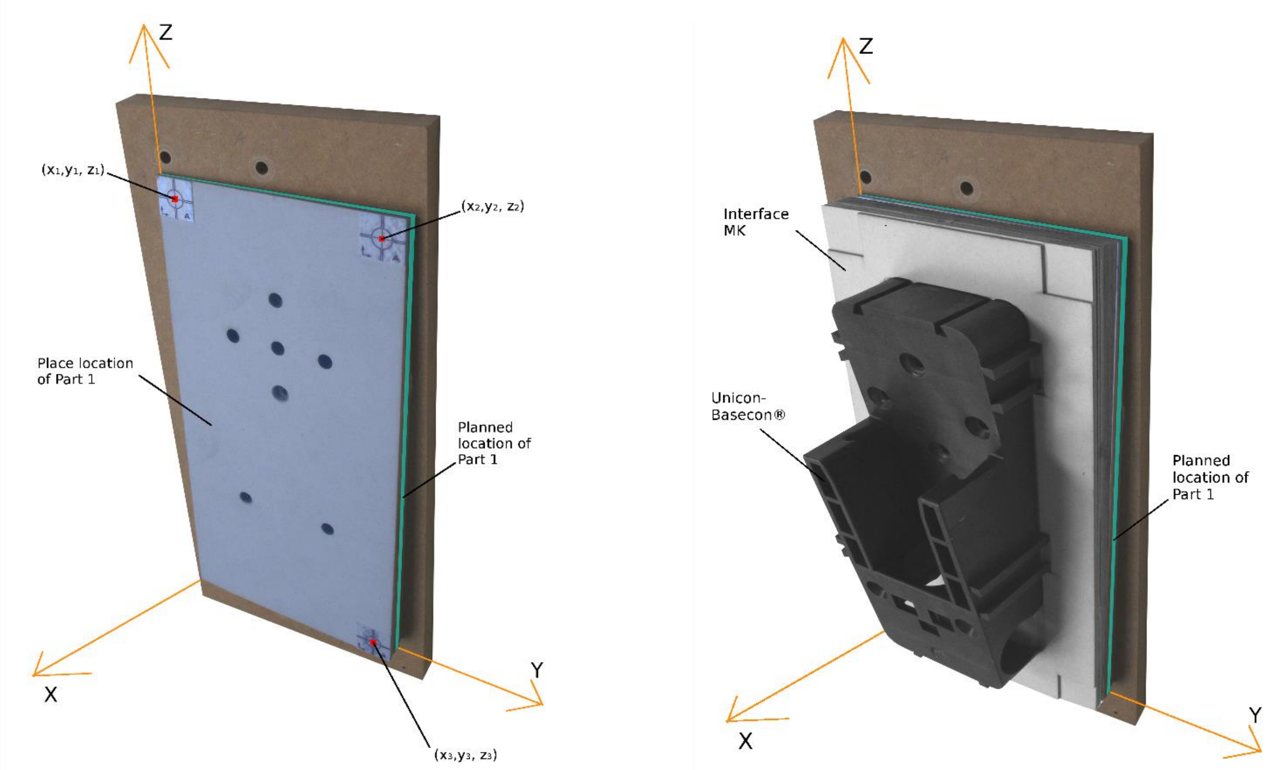

Figure 8. On the left, it is shown the planned location of Part 1 in green and the placed location of Part in blue 1. On the right, the interface MKs and the Unicon-Basecon® are fixed onto the placed Part 1.

Part 2 pieces were then fixed on the 2D module. In Test 1, Part 2 was the male part of the pair. As mentioned earlier, Part 2s could be moved parallel to the wall in order to compensate for the deviations in the y- and z-axes. Part 2s were required to be precisely located on the 2D module. For this purpose, as a reference pattern, a printed paper sheet containing the drawing of the modified location of the connector as well as the perimeter of the 2D module was placed on the 2D module. This model facilitated an accurate positioning of Part 2s. Thereupon, the module was ready to be installed. Finally, the 2D module was installed using a bridge crane. For this purpose, cinches were placed to hold the 2D module such that it could be lifted to the required position (Figure 9). The fixing of the module with the Unicon-Basecon® required vertical and horizontal movements. The accuracy of the connectors placed both on the wall and on the 2D module permitted a swift execution of this operation.

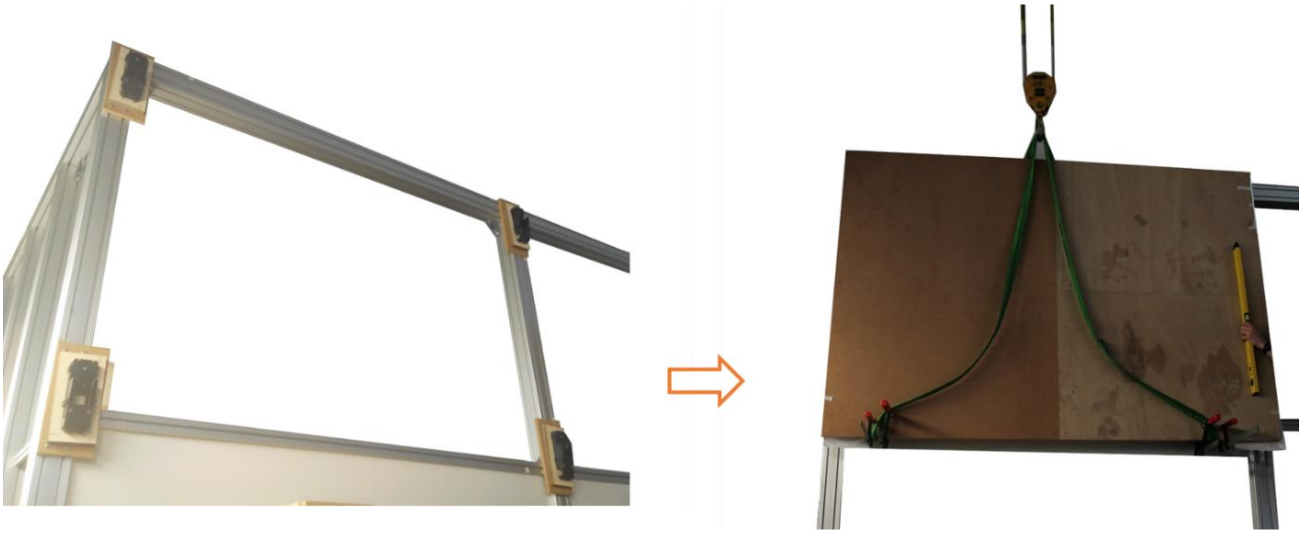

Figure 9. First, the four Part 1s with the MKs and the Unicon-Basecon® female elements were fixed. Then, the 2D Module was placed.

2.2 Test 2

For Test 2, the same aluminum frame as that used in Test 1 was utilized as a mockup of a real façade. However, it had several differences in comparison to Test 1. In Test 2 (see Table 4), there were two 2D modules that overlapped horizontally. This was made to validate the accuracy of the position of the two modules depending on an absolute position or coordinates. In other words, one module was placed on top of the other to confirm that they perfectly matched. During the design process, a gap of 1 mm was left at the overlapping section in such a way that the precision could be measured.

The 2D modules were approximately 1150 mm high and 1300 mm long and were prepared from MDF boards with a width of 16 mm. Each of the modules comprised eight MDF elements. Furthermore, in Test 2, Part 1s were already 3D printed along with the irregularities in a unique piece. Six different Part 1s were prepared in order to achieve significantly irregular geometries.

Table 4. Devices and materials used in Test 2.

Software	
Design of the module	AutoCAD®
Digital fabrication of the 2D module	Adobe Illustrator®
Digital fabrication of the interface MK	STL files
Manufacturing and measuring tools	
Interface MK manufacturing	3D printer: German RepRap X400©
Module element routing	CNC router, Zünd G3 ©
Point acquisition	Leica, MS-60©
Materials and elements	
Modules	MDF board, 20 mm
Interface MK	PLA German RepRap ©
Reflector	Rothbucher Systeme©
Mechanical connection	Sherpa_XS5 ®
Screwing system	Maytec®
Size of modules	
Module height	1500 mm
Module length	1000 mm

Part 1s were fixed to the aluminum frame manually, with no digital support. In one case, Part 1 had to be moved by a significant amount (approximately 44 mm) owing to a structural issue that was not considered in the first layout of the 2D modules. In Test 2, the Sherpa XS5® connector system was used. This connector type also requires high accuracy. As in Test 1, Part 1 had a mortise for placing three reflectors. Part 1s were manually set up using Maytec screws and measured using a digital theodolite. The sequence was started with data acquisition. The coordinates of Part 1s (listed in Table 5) were measured with the same digital theodolite as in Test 1.

Table 5. Test 2: coordinates of Part 1s in mm.

Point	x	y	z
A1	-3.8	-38.4	2550.0
A2	-2.1	35.9	2554.5
A3	-1.9	40.7	2479.8
B1	0.0	999.5	2555.1
B2	0.3	1073.3	2551.1
B3	-0.5	1069.0	2476.6
C1	-5.1	-37.4	1227.3
C2	-8.5	36.7	1226.4
C3	-6.2	36.2	1151.6
D1	-4.5	992.0	1224.7
D2	-0.1	1067.1	1225.3
D3	-6.1	1068.4	1150.4
E1	0.0	0.0	0.0
E2	-4.7	73.6	-0.8
E3	-11.9	73.2	-75.5
F1	-2.9	920.9	0.8
F2	2.3	994.6	0.7
F3	-4.9	994.6	-74.3

The coordinates obtained with the digital theodolite were inserted in the AutoCAD file, and the shape of the interface MK was manually generated. This shape was then exported to an STL file and 3D printed using the machine. Subsequently, each of the interface MKs were placed on the required Part 1s. At this point, a regular planar situation was realized.

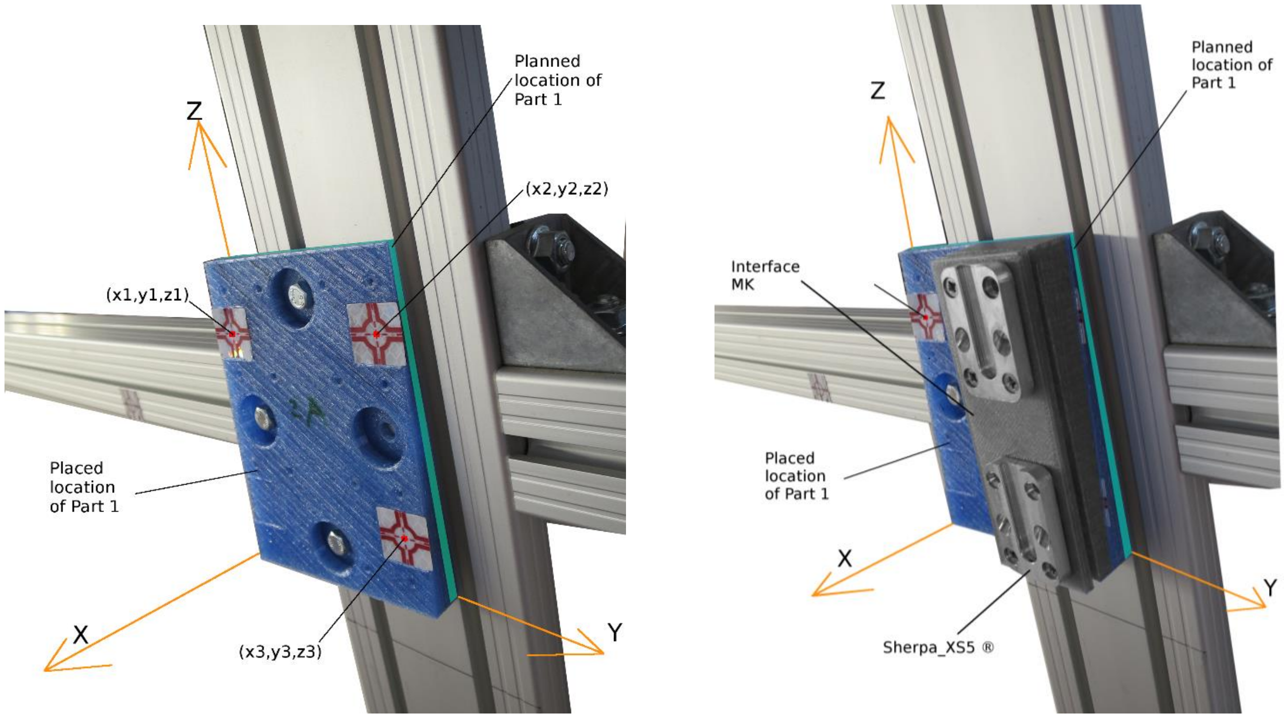

Figure 10. On the left, it is shown the planned location of Part 1 in green and the placed location of Part in blue 1. On the right, the interface MKs and the Sherpa_XS5 ® are fixed onto the placed Part 1.

However, the location of Part 1s along the x- and y-axes differed from that in the preliminary CAD file. Therefore, the location of Part 2s in the 2D module had to be adjusted. For that purpose, a mortise was designed for placing the connector. During the routing process of the elements that comprised the 2D module, the mortises were digitally milled using a CNC machine. Other contours, such as holes, were also drilled using the CNC machine.

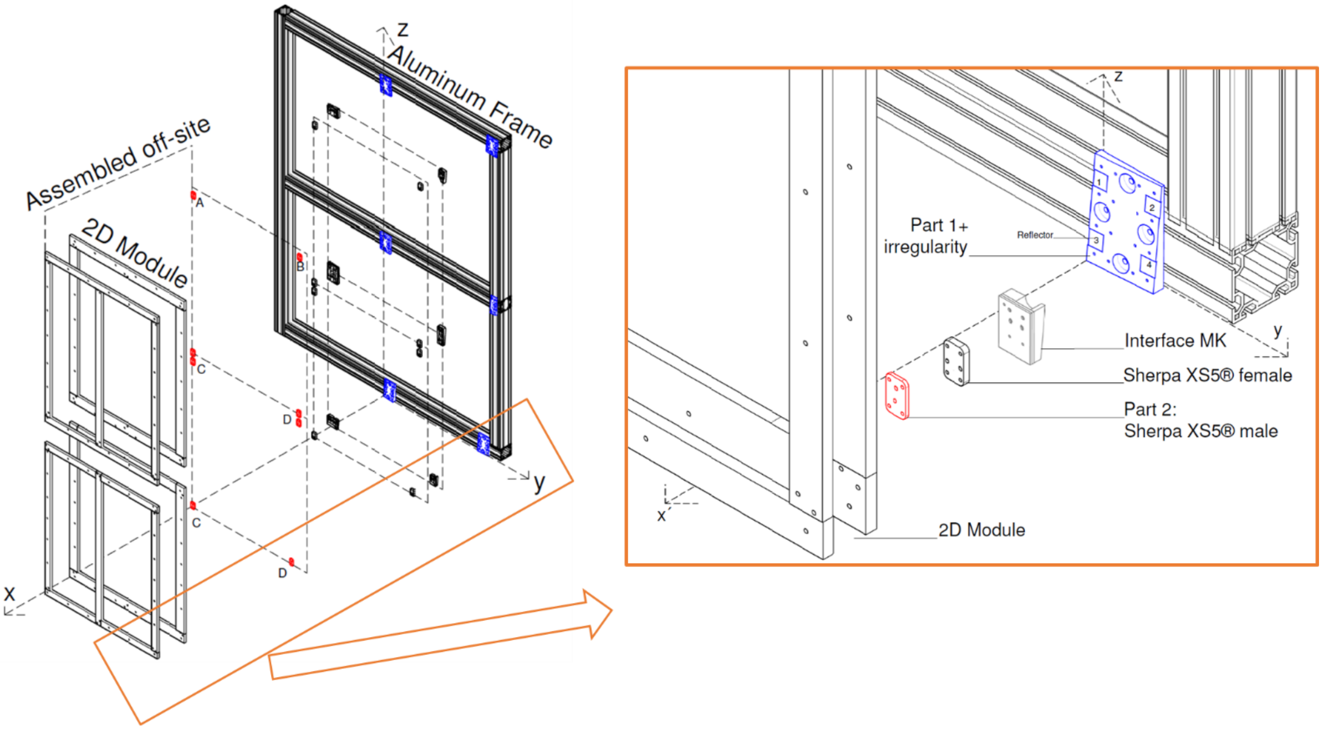

Figure 11. Exploded view of the 2D module showing the installation order of all the elements of Test 2. Part 1 in blue, the MK is shown in grey, and Part 2 are in red.

At this point, the 2D modules were assembled manually using a screwdriver. As mentioned before, the holes were already made, and these holes guided the positioning of each of the eight elements that comprised the 2D module as well as Part 2s. Once the 2D modules were assembled, they were manually installed and fixed at their required position on the wall (see Figure 11 and Figure 12).

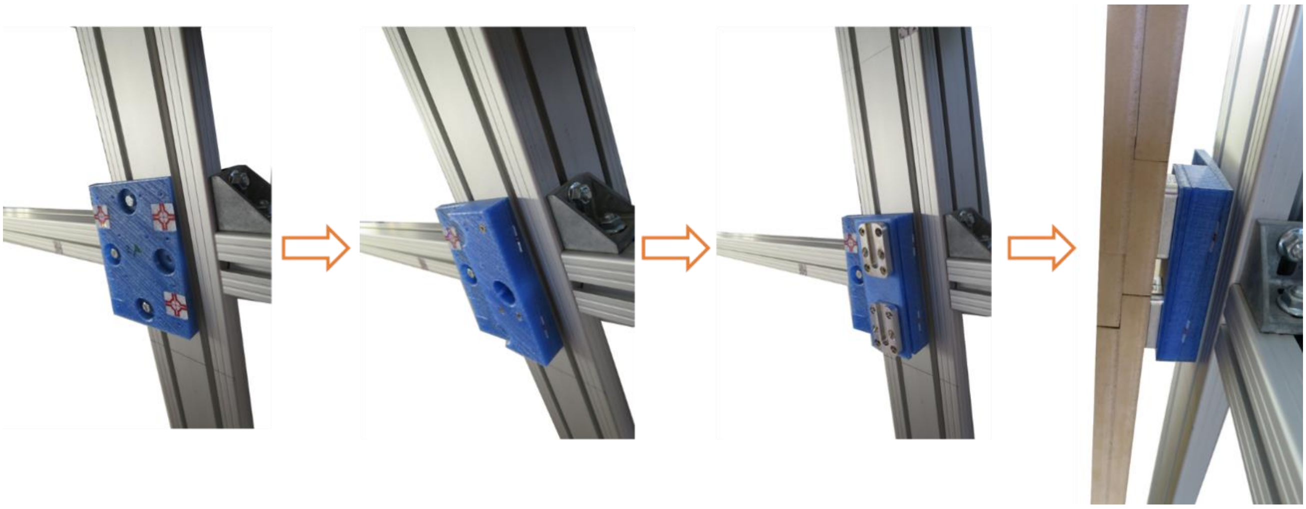

Figure 12. Step by step sequence of Test 2.

2.3 *Test 3*

Among all tests, Test 3 was the one closest to the real environment. This test was performed in a factory, with materials and elements that are part of the standard 2D module of the POBI company [23] (see Table 7). For instance, for configuring the 2D module, 16 mm width OSB boards and 120*80 mm pine-wood timber profiles were used. The whole manufacturing process was held using the current resources of the aforementioned industrial company. In this test, two modules were manufactured and installed. For the layout design, in this Test 3, the CAD software used was Dietrich´s © [24].

Table 6. Devices and materials used in Test 3.

Software	
Design of the module	Dietrich´s ©.
Digital fabrication of the 2D module	Dietrich´s ©.
Digital fabrication of the interface MK	STL files
Manufacturing and measuring tools	
Interface MK cutting	Makita ©
Module element routing	Hunddegger K2 and Weinmann ©
Point acquisition	Leica, Disto©
Materials and elements	
Modules	120*80 mm pine-wood +OSB 12 mm
Interface MK	120*80 mm pine-wood
Reflector	No reflector

Mechanical connection	Unicon-Basecon ®
Screwing system	-
Size of modules	
Module height	2145 mm
Module length	2500 mm

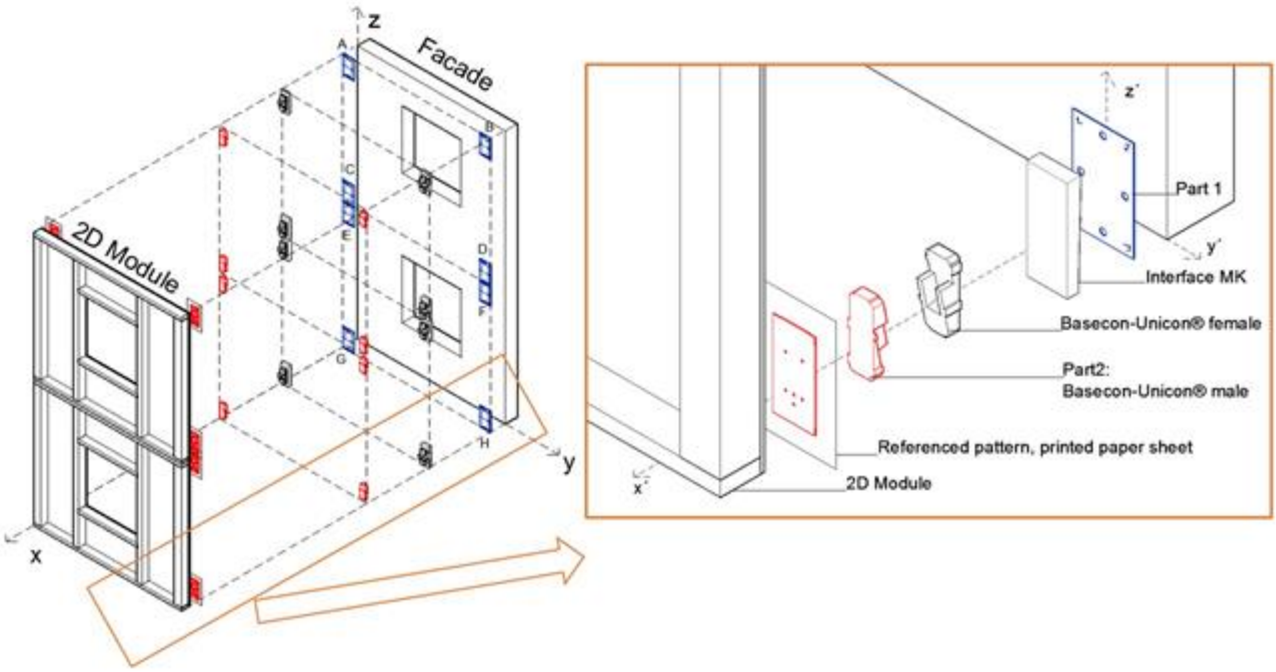

Figure 13. Exploded view of the module showing the order of installation of all the elements of Test 3. Part 1 in blue, the MK is shown in grey, and Part 2 are in red.

Regarding the connecting system, the techniques used were similar to the Test 1. Part 1s were the same as in Test 1, thus also made out of cardboard. These Part 1s were placed manually, with the help of a laser marking system. The operator in charge used a mobile crane for placing Part 1s onto the “existing wall”. Similar to Test 1, the UNICON Basecon® was also used as a mechanical connector. However, the MK in Test 3 was made out of 120*80 mm pine-wood profiles. The initial plan for manufacturing the MK was to use a CNC machine from Hundegger K2, but the results were not satisfactory due to the small size of the required element. Therefore, the Matching Kit was cut by a hand saw and shaped manually using a sanding machine from Makita©. This led to a satisfactory and fast solution as it can be seen in Figure 14.

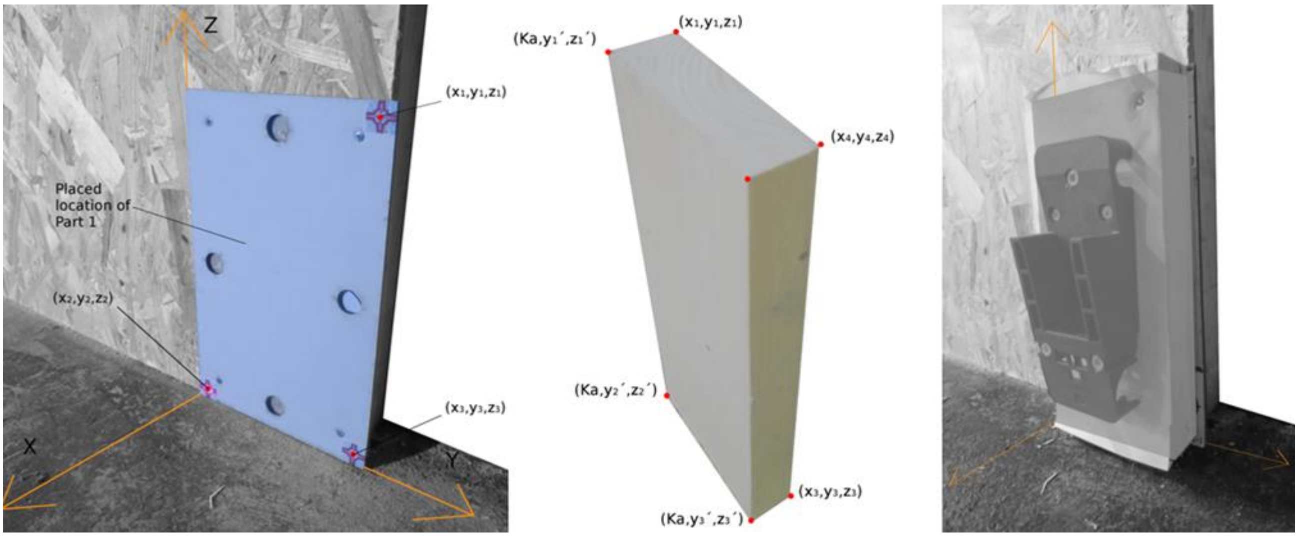

Figure 14. On the left, it is shown the placed location of Part in blue 1. On the middle, manufacturing of the MK concept by manual means. On the right, the interface MKs and the Unicon-Basecon® are fixed onto the placed Part 1.

The measurement of Part 1s was carried out using a Leica-Disto© device (see Table 7). The acquired points were automatically synchronized with Dietrich´s©; the software arranged automatically the layout of the studs with the modules as well as the shape of the MK. Once the layout was defined, the manufacturing process started following the current manufacturing process of the company. Similar to Test 1, Part 2s were placed with the help of a reference pattern, a printed paper sheet containing the drawing of the modified location of the connector as well as the perimeter of the 2D module was placed on the 2D module.

Table 7. Test 3: coordinates of Part 1s in mm.

	x	**y**	**z**
A1	14.47	-4.05	4,027.00
A2	14.93	127.66	4,028.00
A3	15.74	125.58	4,254.00
B1	8.52	2,327.63	4,012.00
B2	9.87	2,457.17	4.241.00
B3	10.13	2,459.39	4,014.00
C1	-1.78	9.29	2,155.00
C2	0.45	7.28	2,382.00
C3	0.91	138.99	2,384.00
D1	2.17	2,323.43	2,155.00
D2	3.23	2,454.35	2,156.00
D3	4.07	2,453.80	2,383.00
E1	-4.46	6.32	1,855.00
E2	-4.46	6.32	2,082.00
E3	-2.59	138.11	1,855.00
F1	-4.21	2,322.83	2,083.00
F2	-3.95	2,325.05	1,854.00
F3	-3.72	2,456.52	1,855.00
G1	-2.25	3.87	228.00
G2	0.00	0,00	0.00
G3	1.04	134.53	-2.00
H1	2.14	2,327.03	231.00
H2	4.31	2,459.63	232.00
H3	8.23	2,329.02	4.00

Once the 2D modules were produced, these were carried to the location and installed on the wall by a forklift. In total 3 operators were necessary for the fixing process of the 2D modules.

3 Results and discussion

The primary variables measured and monitored in Tests 1, 2, and 3 were the installation time and placement accuracy. Regarding installation time, after monitoring the processes in all tests, it was found that the installation time had been significantly reduced (see Table 8). The measured time is defined as the time from the initial placement of Part 1s onto the "existing wall" until the installation of the 2D module. The time marked on Table 8 is an average among all the similar steps taken within the process. The shape calculation and manufacturing process of the interface MK was time-consuming in Test 1 and Test 2. In Test 3, an existing parametric design software permitted the automated generation of the shape of the interface MK and the adjusted contour of the 2D modules. In order to improve the manufacturing process of the MK, the authors have considered using a five-axe CNC for production. For further development of the concept, there are some other points to be considered. The results show that the size of the module is relevant. According to the recorded data in Test 2, the handling of the 2D module required less effort and time owing to its smaller size. This should be taken into consideration for future robotic manufacturing and installation processes [25],[25][27],[28].

Table 8. Installation time recorded from Test 1, Test 2, and Test 3 and from various façade building renovation installation systems [2] **Error! Reference source not found.**.

	TOTAL h/m² for installation	2D module number	Connectors per module	m² per module	Placement of each Part1 in hours	Measuring each Part1 in hours	MK shape calculation in hours	MK manufacturing in hours	MK placement in hours	Part 2 fixation onto 2D module in hours	2D Module installation in hours	Operators during 2D module installation
Test 1	**1.29**	1.00	4.00	3.30	0.10	0.16	0.25	0.15	0.08	0.08	0.48	2.00
Test 2	**1.13**	2.00	3.00	1.50	0.10	0.16	0.16	0.10	0.01	0.01	0.07	1.00
Test 3	**0.45**	1.00	4.00	5.30	0.08	0.10	0.02	0.16	0.08	0.08	0.10	3.00
Rain screen	**1.63**											
Demo Kubik	**1.73**											

Regarding accuracy, the placement of the modules was realized with tolerances lower than 1 mm. In Test 1 and 2, the placement accuracy of the 2D modules was achieved with manual measuring levels and meters. In Test 1, the female and male parts of the Unicon-Basecon® fit each other properly during the test. Therefore, it was validated that the required accuracy level was achieved. In Test 2, the connector fixing was also accurate. Moreover, the two modules matched correctly as it can be seen in Figure 12. In this case, owing to the size and weight of the modules, they were manually mounted, and no cinching was necessary. In Test 3, the perimeter points of the 2D modules were measured using the Leica, Disto© device. The results, described in Table 9 and Figure 15, show that there is a deviation between the planned points and the

Table 9. Deviation of the modules in Test 3.

Planned Points	x_n	y_n	z_n	Placed Points	x_n'	y_n'	z_n'
1	0,00	0,00	4.195,00	1´	0,55	-0,29	4.194,72
2	2.455,00	0,00	4.195,00	2´	2.455,65	0,79	4.195,64
3	0,00	0,00	2.110,00	3´	0,59	0,24	2.110,19
4	2.455,00	0,00	2.110,00	4´	2.454,52	0,75	2.109,76
5	0,00	0,00	2.040,00	5´	0,47	0,56	2.039,58
6	2.455,00	0,00	2.040,00	6´	2.455,67	0,15	2.039,60
7	0,00	0,00	0,00	7´	0,00	0,00	0.0000

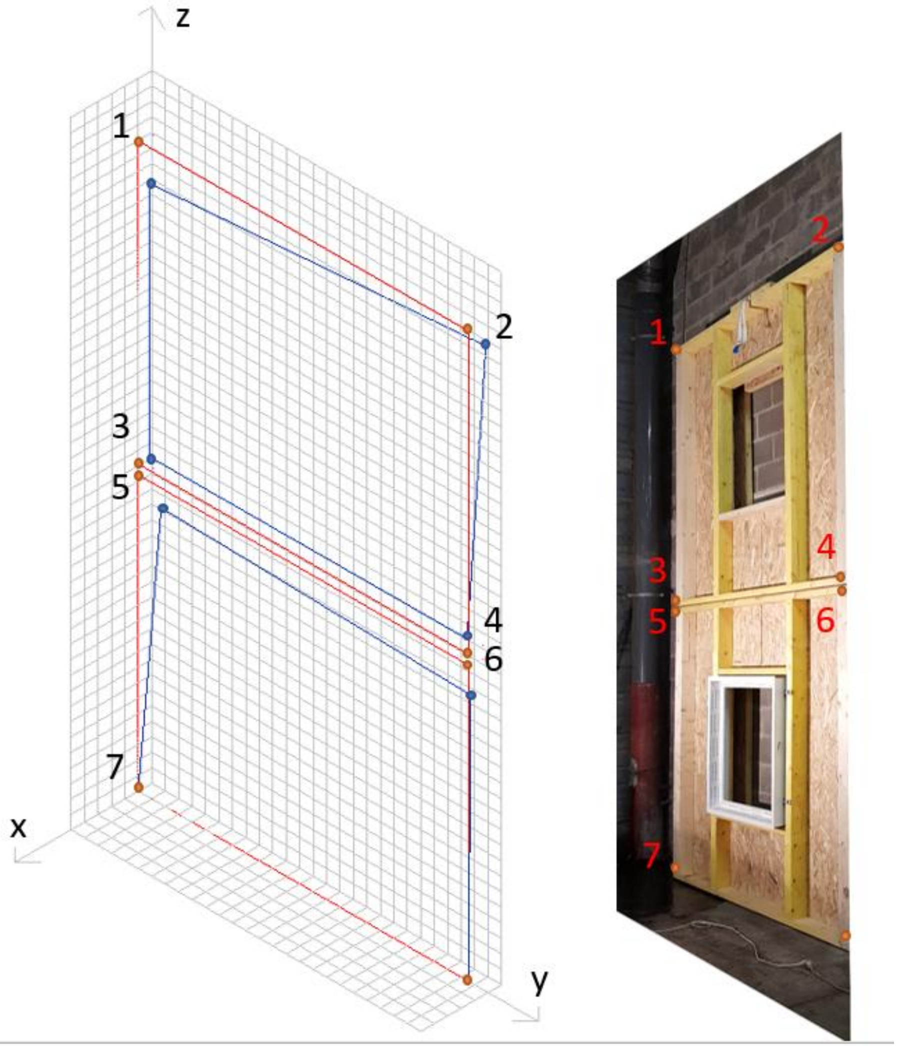

Figure 15. On the right, graphical representation of the planned and placed deviation graph magnified by a factor of 20x.

In the tests explained in this paper, the 2D modules did not have any services (pipes and ducts) to be fitted as was required in BERTIM and other projects [29]. It is expected that the connecting system will enable the necessary overlapping distance for service fitting. The connector system used in Test 2 was too small to facilitate this overlap.

With respect to the synchronization with the manufacturing process, usually, the manufacturing of the modules and the installation process are performed in parallel or subsequently. Therefore, the proposed concept needs to be adapted to the given situation. This means that while fixing Part 1s on the wall of the existing building, the location coordinates must be sent immediately for generating the MKs to ensure the proper location of Part 2s in the 2D modules.

Finally, there are some disadvantages inherent to the 2D module material, which is timber. Some foreseeable risks include the timber’s unstable physical properties under various humidity and temperature conditions, and thus, the alteration of the 2D modules’ geometrical properties to such an extent that the location of Part 2 might change, jeopardizing the installation process, i.e., Part 1 and Part 2 might not fit.

4 Conclusion

In the field of building renovation using prefabricated modules, the most significant technology gap with respect to automation is in the installation process. Therefore, significant time reduction may be achieved in this phase. According to the analyses described here, it is necessary to improve this phase in order to develop a more automated installation process of prefabricated 2D modules for building refurbishment. In this paper, the development of a novel concept for the installation process was explained. Furthermore, Tests 1, 2, and 3 proved that the on-site installation time could be minimized using fully prefabricated 2D modules and implementing the interface MK.

Developing a solution for an integrated product-manufacturing and installation system is a complicated process that needs to be decomposed into manageable and multiple sub-systems. In this research, supported by novel concepts in the building renovation process, the axiomatic design method was applied and the complexity of the overall process was successfully handled. The new concepts, based on the interface MK and accurately produced 2D modules, were successfully validated through three tests.

However, future tests should be performed in more relevant environments (such as “real” refurbishment projects, not in controlled environments) in order to improve the design of the connectors, protocols, and step-by-step processes proposed in this study. Following the novel concept development, additional connector solutions are currently under testing. In the upcoming trials and studies, the interconnection of several modules will be considered as well as the fast fitting of water and ventilation services. Finally, it should be noted that the approximate solution of this study is valid for a robotic installation system of modules on existing buildings.

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