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# Deviation-Correcting Interface for Building-Envelope Renovation

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**Abstract:** In order to reach a Zero-Energy-consuming building stock, it is necessary to insulate and add renewable energy sources on top of existing building envelopes. Off-site prefabricated modules have been used for covering building facades, but manual on-site installation procedures are still more competitive than prefabricated ones. Renovation with prefabricated modules requires high precision in order to obtain airtight and waterproof conditions. For that, an accurate installation of the anchors on top of the facade is crucial. With current techniques, this is a time-consuming operation. One of the attempts to solve the above-mentioned issue was to place the part of the anchor on top of a building facade with high tolerances and to use an interface to correct the deviations. In previous research, this concept, named Matching Kit, was validated, but improvements needed to be made to make it more competitive. In this paper, thanks to novel algorithms and the use of Point Clouds, an improved version is presented. The results show a reduction in working time and an increase in precision. With this research, the interface is closer to being used in the construction industry.

**Keywords:** automation in construction; robot-oriented design; building renovation; computational design

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## 1. Introduction

Building-facade renovation that includes extra insulation is becoming a topic for energy savings all over the world [1,2]. However, reducing the time and costs of facade renovation is needed in order to increase the economic feasibility of projects [3].

Conventional methods for insulating existing building facades are the so-called External Thermal Insulation Composite System (ETICS) [4] and the rain-screen or ventilated facade [5]. Installing these new envelopes is worker–time consuming. According to statistics, both for the ETICS and rain-screen methods, about 3 working hours per square meter are necessary in building renovation [6]. As a consequence, it is not always feasible to achieve a renovation project of a facade due to excessive time consumption. Moreover, the building facade needs to be covered by a scaffolding or platform, which is a risky task [7] and generates disturbances to the occupants of the building.

To avoid the inconveniences generated by the on-site manual procedures with the ETICS and rain-screen methods, prefabricated solutions have been developed for existing buildings' envelopes [8,9]. These prefabricated solutions are based on facade modules that are manufactured off-site and contain several elements, as shown in Figure 1. However, different stakeholders that participate in building-envelope renovation agree that facade upgrading with prefabricated modules also needs to be more efficient [2,10–14]. There is a general need for a more automated process to achieve a safer and more effective process [15–17]. The renovation of building envelopes using modules has not taken off, as expected, despite the effort put forth in the research programs [18]. The European Commission's latest call for research project proposals asked proposals to, among other things:

1. 'Demonstrate retrofitting plug-and-build solutions and tools reaching NZEB (Nearly Zero-Energy Building) standards suitable for mass production by the industry for buildings under deep renovation'.
2. 'Decrease of retrofitting time and costs by at least 50% compared to the current renovation process for the same type of building'.

These issues highlight the fact that there are still problems in the area of prefabricated module-based building refurbishment [19]. The requirement for mass customization is still present, as seen in point (1). On the contrary, point (2) reveals that the "current renovation process" or, in other words, the manual process, is more practical, affordable and effective than the approaches that use prefabricated modules [20]. Therefore, there is a real need to improve the renovation of the facade procedures with prefabricated modules [21]. In Figure 1, all the stages are explained. It must be remembered that the prefabricated modules are supported by connectors.

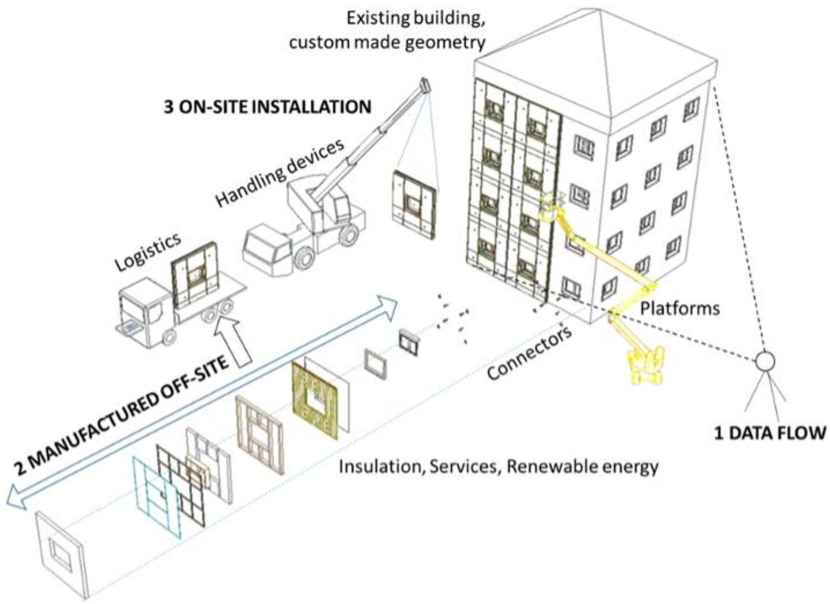


**Figure 1.** Building renovation process with prefabricated panels for the envelope.

The module can be accurately prefabricated according to a layout by using the correct manufacturing and assembly tools off-site. But on-site, how does one place a module with the required high accuracy on the existing wall? Currently, modules are installed on existing walls through two-piece connectors that are fixed partly on the module and partly on the existing facade (Figure 2). To avoid unmatched connecting and placements and ensure proper fitting, these connectors must be accurately fixed both on the wall and in the module. This topic is even more relevant when modules are highly prefabricated and need to be installed on the facade with high accuracy; otherwise, the airtight and waterproof properties would be diminished.

Another reason to ensure accuracy is that the prefabricated modules can be integrated with RES (Renewable Energy Source) technologies, such as PV cells or solar collectors; if the modules have embedded services and there are placement deviations, the pipes and cables will not fit, which will lead to unconnected services. Several reasons impede the correct fixation of the connectors on the existing facade. As can be seen in Figure 2, there is a high risk that the connectors cannot be fixed on the wall, as they could miss the planned location. These deviations that jeopardize the placement of the module in an existing building occur because of:

- A lack of awareness of the facade's wall geometry in terms of the placed wall's geometry, which is not planar, or at least has deviations of up to 100 mm; walls and floors do not fulfill the planar geometric requirements that are necessary for placing accurately prefabricated 2D modules. In a previous phase of this research [11], several facades were measured using 3D laser scanning tools (Figure 3).

- Errors during the transfer of data from the wall to the design and vice versa. A facade and a wall are not regular and known geometries. Surfaces have complex and unperceived geometries. Transferring information from and to that uncertain geometry tends to generate errors. At this point, there are two types of errors that might happen:
  - Errors due to a lack of marking during the measurement of the facade or wall. If the measurement of the existing building is carried out using a digital Total Station, all points need to be referenced. This might lead to errors or, better said, mistakes in referencing the points and their coordinates.
  - Once the layout is defined, errors during translating the coordinates to the real building might occur.
- Unexpected deviations while fixing the connector to the wall. The problem is also that when screwing and fixing the connectors to the existing wall, there are also deviations. The operator (or robots, see Figure 4 right) working with a drill bit at heights and with high wind is likely to perform the task with an error. Furthermore, there may be obstacles, such as steel bars in the concrete slab and the roughness of the mortar, that impede the location of the connector in its accurate location. This topic was also an issue while placing the anchors with robotic tools (see Figure 4).

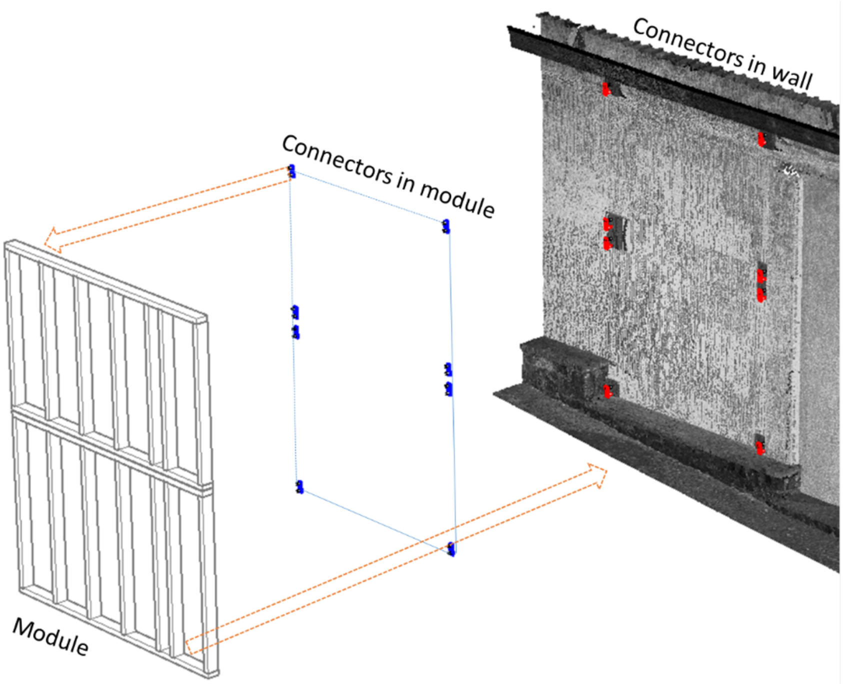


**Figure 2.** Exploded view of a module being placed in a wall with connectors. Point Cloud made in BERTIM project [22].

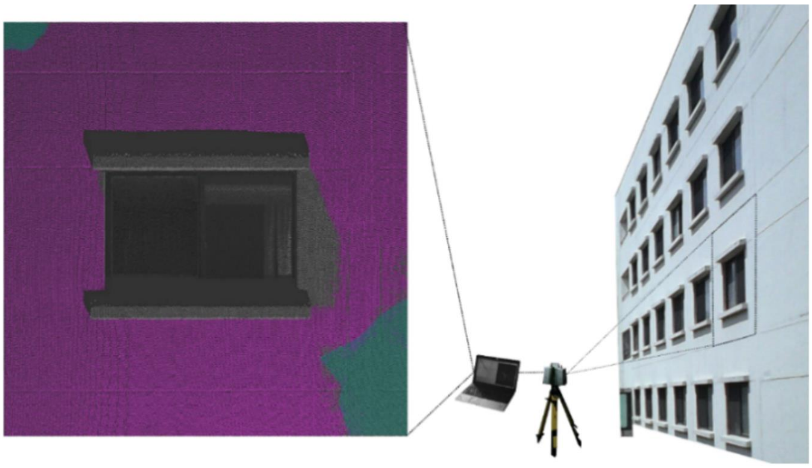

**Figure 3.** Data from a 3D laser scanner shoeing non-planar situation of a segment of a wall, with the help of Prof. Kwon at SKKU.

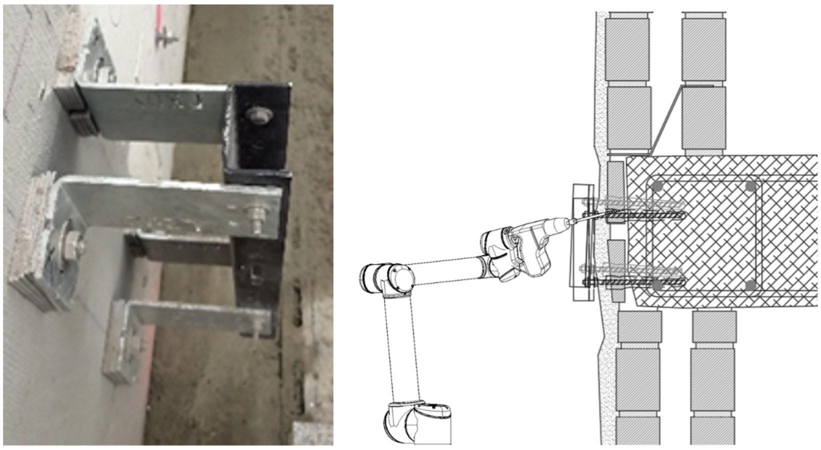

**Figure 4. Left**: accurately placed connector for rain-screen by using several wedges. **Right**: deviations occur while drilling and placing, manually or with robots.

All the points explained before refer to an information workflow. How does one transfer the data from the layout to the existing wall while placing the connector? And in the case of deviations while placing the connector, how does one transfer the data from the connector on the wall to the module? If this information workflow is missed or not considered, the connector in the module will not match the connector on the wall, and the installation process will fail. Previous studies have developed concepts to solve this situation with partially prefabricated elements adjusted to the required geometry [23] and prefabricated modules [24,25] and interfaces [26], but it is only focused on a proposal for using a cost-effective laser scanner [27]. Unfortunately, these developments did not further explore the question of fully prefabricated walls. Two strategies can be adopted for placing the connector on the wall:

- Strategy 1: Place the connector very accurately on the wall. It is necessary to reference the building and some points of the building. For this case, a Total Station is required twice on the site: once to measure the building and a second time to place the connector in its location. Additionally, this method does not consider possible deviations when the connector is being fixed.
- Strategy 2: Place the connector on the wall with some tolerances, measure the location and make adjustments to achieve the desired location. In the tests explained in [28,29], it was observed that the installation of rigid robotic supports and cranes to place connectors very accurately on buildings is still time consuming. A solution for this

issue might be to reduce the required accuracy of the robot (or manual operator's capabilities) and to create strategies for adjusting the tolerances.

Strategy 1 is used the most by current techniques, and it is an operation that could be improved, but, in the research explained in this chapter, Strategy 1 is not considered. Several examples show this strategy, such as marking the foundation with patterns to accurately fix the connectors in a Japanese construction or the rain-screen installation process (Figure 4 left).

On the other hand, Strategy 2 is often used in medical implant technology, where the deviations of the placed implants are adjusted and corrected [30–32]. Another field where upgrading is based on adjustments is aircraft repair processes, where automated machines, by using reverse engineering, create bespoke parts for replacing a damaged part [33].

Based on Strategy 2, a solution was developed based on a custom-made interface that corrects the deviations that were already validated in previous instances [11]. In the next section, this solution, named Matching Kit, is explained in more detail. This MK interface is only a geometrical concept and, in principle, it could be used in any kind of facade that can support prefabricated modules. Typologies such as facades with masonry bearing walls and facades on buildings with concrete and steel structures are the targeted ones. The prefabricated modules are lifted so far with mobile cranes in building renovation. Therefore, the height of buildings is limited to the reachable ones using these devices.

The main purpose of this paper is to show the development and the approval of Strategy 2 in the building renovation sector. In this article, four tests are explained. The first three tests are from a previous research project and are accounted as a benchmark. The main research development presented in this paper is shown in Test 4.

## 2. The Concept of Matching Kit (MK)

Matching Kit (MK) is a set of components that includes a bespoke interface to correct the deviations that occurred during the placement of the connectors on the wall. This MK is not based on a certain connector type, but on a concept that defines the interface between the facade and the wall. In previous phases of the research, the MK and its main components were defined. Several tests were carried out and accuracy and time saving were gained. The MK consists of three main parts (Figure 5 right):

1. Part 1, which is installed on the existing building;
2. Part 2, which is the element fixed in the 2D module;
3. A custom-made interface between Part 1 and Part 2.

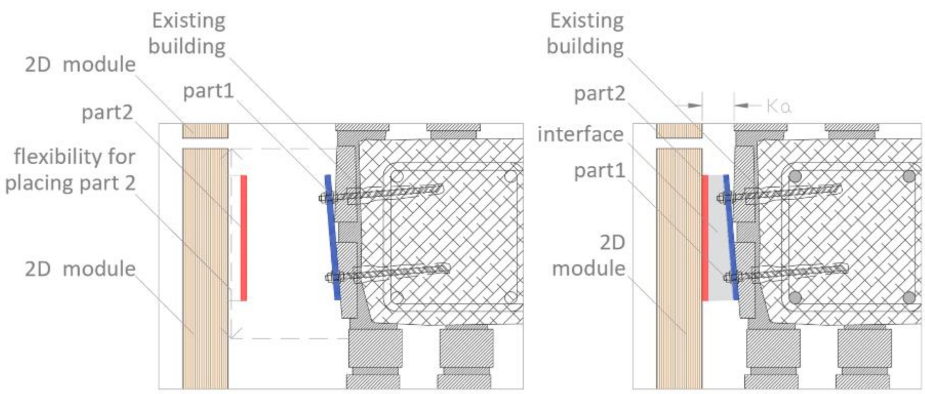


**Figure 5. Left**: Flexibility for placing Part 2. **Right**: The shape of the interfaces.

The position of Part 2 in the module and the shape of the interface are dictated by the position of Part 1 on the wall. It is, therefore, necessary to measure the position or location of Part 1 and, for that purpose, a digital measurement device is necessary.

The maximum tolerance for placing Part 1 on the wall depends on the flexibility of the prefabricated module for fixing Part 2. A big fixation area for Part 2 onto the module would offer a high tolerance for Part 1 (Figure 5 left).

The position of Part 1 can be determined using at least three coordinates ($x_n$,$y_n$,$z_n$) concerning a given origin point (0,0,0) of the facade. Additionally, there are two equations, namely the line equation ($L_n$, Equation (1)) and the distance equation ($D_n$, Equation (2)), linking Part 1 and Part 2 (Figure 6). In Equations (1) and (2), $K_a$ is the constant distance between the outer surface of the existing wall and the inner surface of the 2D module (Figures 5 and 6). This constant distance is defined by the designer of the refurbishment process. With these, sufficient information is available for defining the MK geometry. In Figures 5 and 6, 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 MK is in gray.

$$L_n = \frac{(x - k_a)}{(x_n - x_a)} = \frac{(y - y_a)}{(y_n - y_a)} = \frac{(z - z_a)}{(z_n - z_a)} \tag{1}$$

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

These equations can be inserted and combined into current computational design software, and the MK interface's shape is obtained automatically.

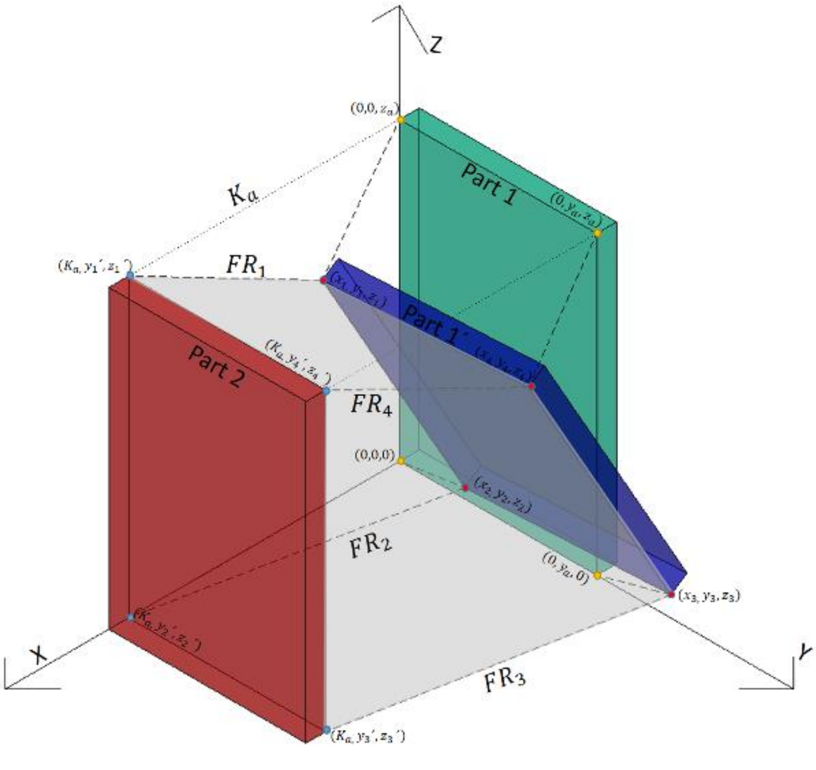


**Figure 6.** Geometric definition of the MK.

But the MK is not only a set of components, it is also a process. The Matching Kit concept was conceived based on its procedure and information workflow. The steps of the procedure are integrated within the rest of the subcategories, like data acquisition of the building and manufacturing of the prefabricated module. In summary, these are the points of the process:

1. Fixation of Part 1s on the building facade according to the preliminary definition of the layout of the building, the modules and the set of components of the MK. For this purpose, laser measurers and rulers are sufficient for the marking process. Deviations

are assumed to occur, as well as that the actual Part 1s' position differs from that predicted in the design.
2. Accurate measurement of the location of Part 1s.
3. Definition of the interface of the MK. The thickness and geometry of the interface MK varies depending on the lack of verticality of the existing wall.
4. Manufacturing of the interface MK by using digital techniques (CNC cut or additive).
5. Installation of the interface on top of Part 1s. Once the MK is accurately manufactured and installed in its designated location, a planar situation is achieved.
6. Place Part 2 onto the module depending on the location of Part 1s.
7. Installation of the 2D modules onto the MK set of components and their attached mechanical devices.

Although mechanical devices are not described in these steps, they are attached to elements of the MK, as will be explained in the next sections. This scheme was used for the previous tests explained in the next section.

The method to demonstrate this concept was based on two iterative rounds. On the first round, three tests were carried out in laboratory and controlled environments. These three tests were carried out in the initial stages of the research. The objective of these tests was to demonstrate the MK concept and its process in different manufacturing contexts. Different techniques and procedures were used for data acquisition, manufacturing and installation to obtain results in different scenarios. But more importantly, these initial tests were monitored: the parameters or measurable variables for validating the procedure include the installation time and placement accuracy of the 2D modules.

On the second iterative round, an analysis of these three tests was undertaken and Research Gaps were determined. This analysis led the way for an improved version of the MK. This improved version was proofed in Test 4.

During the first iterative round, the questions before proofing such concept were:

- Would a customized interface improve the installation process without affecting the rest of the steps?
- Would accuracy be gained by doing so?
- Is the Matching Kit a better solution than Strategy 1 presented in Section 1?

As stated above, these three tests were performed in a laboratory environment to verify the operability of the concept in various manufacturing contexts. The materials, measuring devices, digital manufacturing tools, software, and main elements used in Test 1 are specified in Table 1.

**Table 1.** Devices and materials used in Test 1, Test 2, and Test 3.

| | **Test 1** | **Test 2** | **Test 3** |
|---|---|---|---|
| SOFTWARE | | | |
| Design of module | AutoCAD® | AutoCAD® | Dietrich's® |
| Digital fabrication | Adobe Illustrator® | Adobe Illustrator® | Dietrich's® |
| MANUFACTURING AND MEASURING TOOLS | | | |
| Interface MK | Universal Laser PLS6.75® | 3D printer: German RepRap© | Makita© |
| Module element cutting | Vertical saw, Festool TS 75 EBQ© | ---- | Weinnmann© |
| Module element routing | CNC router, Zünd G3© | CNC router, Zünd G3© | MHundegger K2© and Weinnmann© |
| Point acquisition | Leica, MS-60© | Leica, MS-60© | MLeica, Disto© |

**Table 1.** *Cont.*

| | Test 1 | Test 2 | Test 3 |
|---|---|---|---|
| MATERIALS AND ELEMENTS | | | |
| Modules | MDF board, 20 mm | MDF board, 20 mm | 120 × 80 mm pine-wood + OSB 12 mm |
| Interface MK | Gray cardboard 0.9 mm Cardboard 1.5 mm UHU extra tropffrei glue® | PLA German RepRap© | M120 × 80 mm pine-wood Marker stickers from Dietrich's©. |
| Reflector | Rothbucher Systeme© | Rothbucher Systeme© | ---- |
| Mechanical connection | Unicon-Basecon® | Sherpa_XS5® | Unicon-Basecon® |
| Screwing system | Maytec® | Maytec® | Unicon-Basecon® |
| Manufacturing accuracy | 0.5 mm | 0.5 mm | 3–8 mm |
| MODULE SIZE | | | |
| Module height | 1500 mm | 1500 mm | 2145 mm |
| Module height | 2200 mm | 1000 mm | 2500 mm |

It is important to outline that the three tests were different:

- Test 1: All the elements of the modules were fully routed in a CNC and a solid wall was created. The accuracy of the module was high (0.5 mm). For the MK manufacturing, laser-cut MDF boards were used.
- Test 2: All the elements of the modules were also fully routed on a CNC, but in this case, the walls were not solid and resembled a curtain wall. Low tolerances (0.5 mm) were achieved in the manufacturing process. For the MK, a 3D printer was used.
- Test 3: Standard-produced timber framed modules were used. Due to module manufacturing tolerances, the contour of the 2D modules was manually rectified after the manufacturing process was finished (modules were manually routed to gain an accuracy of around 2 mm). The MKs were produced manually with a hand sander.

Figures 7 and 8 illustrate the concept used in Test 3. Two modules were installed onto an existing building mockup.

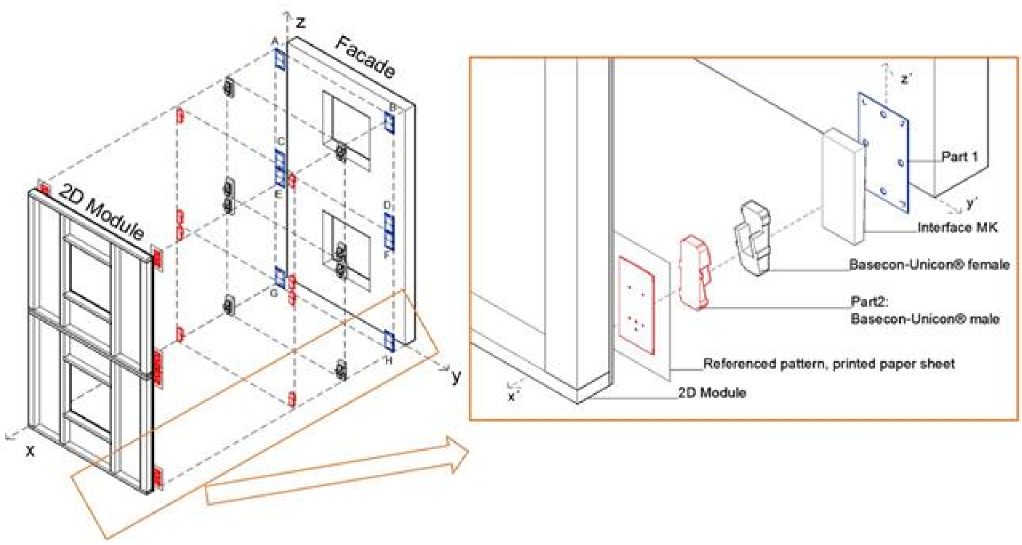


**Figure 7.** Exploded view of the 2D module in Test 3.

Figure 8 shows the exploded view of the real components of Test 3. Part 2s were placed thanks to a printed pattern.

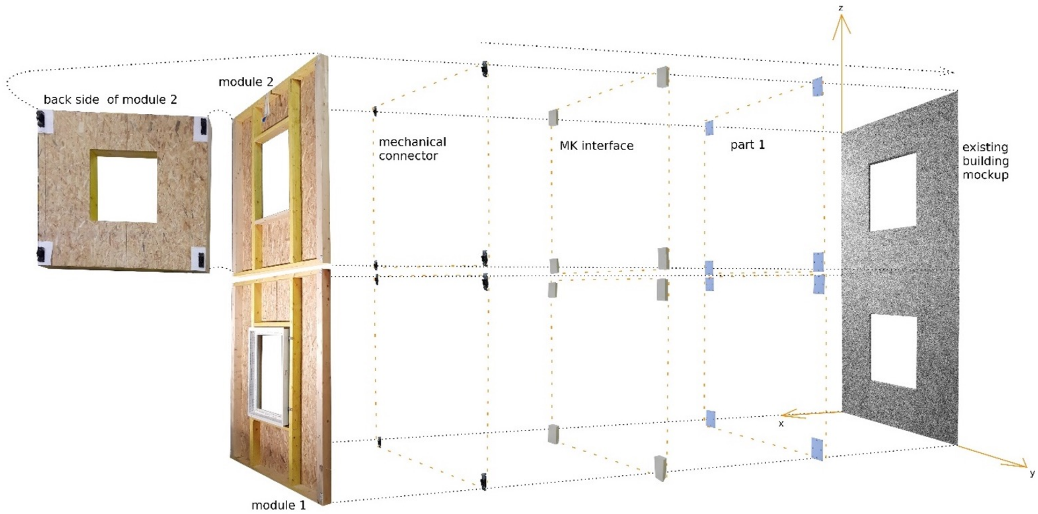


**Figure 8.** Exploded view of the 2D module in Test 3.

The installation sequence of Part 1 and the MK interface in Test 1 are shown in Figure 9. The MK interface in Test 1 had laser-cut bed (Figure 9).

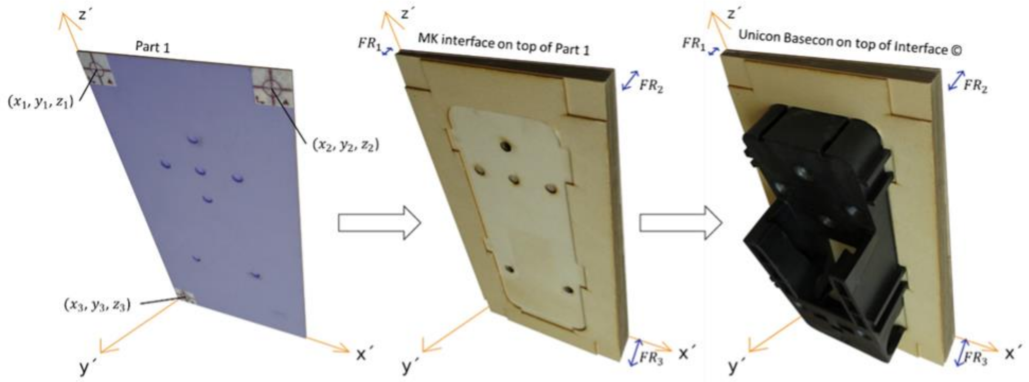


**Figure 9.** Three phases for installing the MK on top of the building facade.

The holes (Figure 9) are for fixing the mechanical connector to the wall. These holes vary depending on the inclination of plan and the location of Part 1 in regard to the 0,0,0 (shown in Figures 7 and 8) point of the existing building.

### 2.1. Installation Time

The measured time was from the initial placement of Part 1s onto the 'existing wall' until the installation of the 2D module. The time marked in Table 2 is an average among all the similar tasks within the process. For this result analysis, the time is defined as the necessary period for the operator to achieve a task. In tasks a, b, c, d, e and f, a single operator was required (Table 2). In task g, the necessary operators varied depending on the 2D module size. The entire process consisted of the following tasks.

**Table 2.** Installation time recorded from Tests 1, 2 and 3. a: Placement of Part 1; b: measuring of Part 1; c: MK shape calculation; d: MK manufacturing; e: MK placement onto Part 1; f: Part 2 fixing onto 2D module; g: 2D module installation; h: operators for 2D module installation; i: 2D module number; j: MKs per module; k: m² per 2D module.

| | | **On-Site** | **On-Site** | **On-Site** | **Off-Site** | **On-Site** | **Off-Site** | **On-Site** | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | TOTAL | a | b | c | d | e | f | g | h | i | j | k |
| Test 1 | 1.29 h/m² | 0.10 h | 0.16 h | 0.25 h | 0.15 h | 0.08 h | 0.08 h | 0.48 h | 2.0 | 1.0 | 4.0 | 3.30 m² |
| Test 1 | 1.32 h/m² | 0.10 h | 0.16 h | 0.16 h | 0.10 h | 0.01 h | 0.08 h | 0.07 h | 1.0 | 2.0 | 3.0 | 1.50 m² |
| Test 1 | 0.45 h/m² | 0.08 h | 0.10 h | 0.02 h | 0.16 h | 0.08 h | 0.08 h | 0.10 h | 3.0 | 1.0 | 4.0 | 5.30 m² |

The total time for installation per square meter (T) was calculated using Equation (3). For Test 1, T was 1.29 h/m², for Test 2 it was 1.32 h/m² and for Test 3 it was 0.45 h/m².

$$T_n = \frac{(a+b+c+d+e)\cdot j + f \cdot 4 + g \cdot h \cdot i}{k} \quad (3)$$

In the BERTIM project [22], two buildings' facades were fully renovated and monitored: the Kubik building nearby Bilbao and an apartment building in La Charité sur Loire. Compared with the information workflow monitored in these two renovation processes, it can be stated that the installation time in these three tests was reduced considerably. More precisely, in the "Kubik" building 1.72 h/m² were necessary, and that in La Charité sur Loire was 0.5 h/m², of which 0.15 was for data acquisition and 0.35 was for installation (without considering finishings) [34]. The reasons for a bigger consumption in Tests 1 and 2 might be that the modules in all tests were smaller, which induced a higher time per square meter. Additionally, as it is explained in the next section, the accuracy achieved in the tests was higher, which means that full prefabrication could be guaranteed.

### 2.2. Placement Accuracy of 2D Modules

Two parameters must be validated regarding the accuracy of the MK system. Firstly, the mechanical connectors in Parts 1 and 2 must fit. It was confirmed that the required accuracy level provided by the MK was achieved in all tests. Second, the final position of the 2D modules had to be accurately measured to verify their location once installed and fixed. The tests were carried out in a controlled environment where the digital theodolites did not exceed the measurement range. In Test 1, the deviations from planned to placed coordinates ranged between 1.3 mm and 0.3 mm. In Test 2, the deviations from planned to placed coordinates ranged between 11.0 mm and 3.4 mm. In Test 3, the deviations from planned to placed coordinates ranged between 5.6 mm and 2.6 mm (Figure 10).

In conclusion, it can be stated that the 2D modules that were routed in a CNC in Tests 1 and 2 reached a higher accuracy. In Test 2, there was no board enclosing the 2D module; therefore, the perimeter was not as rigid as in Test 1. The absolute position differed considerably (It should be remarked that the measuring devices (Leica, MS-60© and Leica, Disto©), as well as the operator, are prone to errors. Consequently, target points facilitate the measurement of coordinates). As stated above, these three tests were used as a benchmark for the improved version explained in the next section.

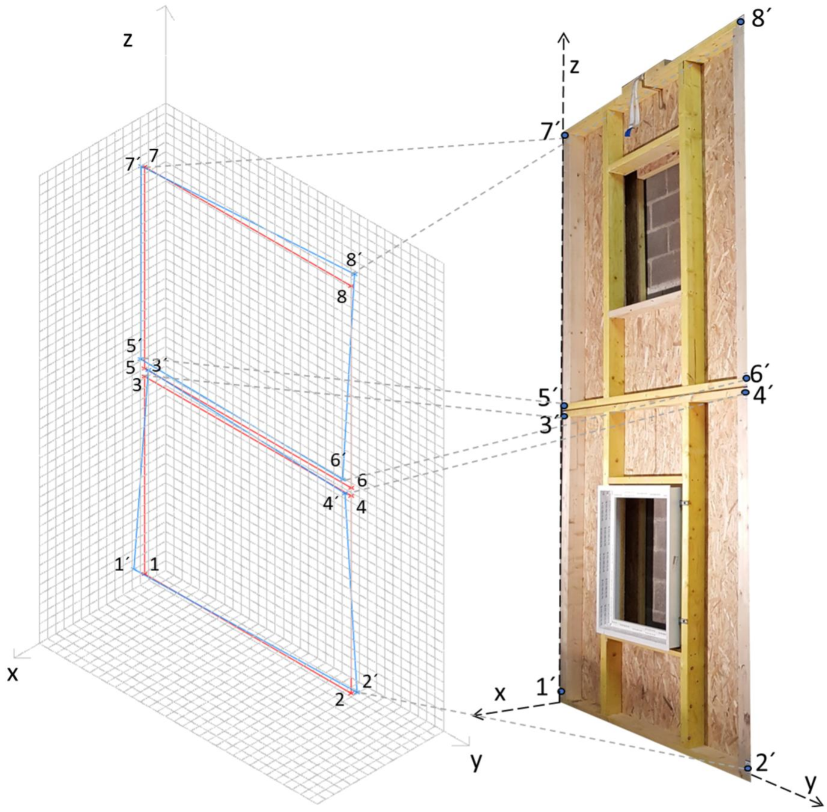


**Figure 10.** Results of Test 3.

## 3. Research Gaps Found in Tests 1, 2 and 3 and Improved Concept and Proofing in Test 4

In this section, the second iterative round is explained, where the improved version was gathered and tested. The three previous tests were carried out in a laboratory environment. When working with real buildings, the information and material workflow and the necessary logistics grow in complexity and, therefore, the solutions need to be optimized. To do so, the following Research Gaps were identified in previous phases:

- Reduce time spent on-site. Prefabricated companies work not only at a regional level, but internationally as well. It is important to minimize the time spent on-site, which is a relevant reason for overrun costs in the renovation process.
- Reduce redundant measurement. If the scheme for obtaining an automated layout using a Point Cloud and the process for the MK concept are combined, contradictions and redundancy of measurements appear. It is necessary to define the layout of the modules at a low level of detail by using online data like cadaster or even any other image-based street-view program that would provide the information for this phase before the first on-site worksite visit. In other words, the arrangement of Part 1s' layout needs to be processed before reaching the site and starting the accurate measuring process.
- Recognition and readjustment of Part 1 only with the coordinates' measured point. One of the most time-consuming points was the recognition of Part 1 with the measured coordinates. In the previous test, the measured coordinates did not fit the known geometry of Part 1, as there were measuring deviations of around 2 mm. There might be several reasons for this, such as the calibration of the Total Station or the wrong placement of targets in Part 1. It was necessary to adjust these measurements to the known geometry of Part 1, and this was achieved manually. An algorithm must recognize the points and readjust them according to the known geometry of Part 1.

- Create an automated layout with the information of Part 1s as an alternative to the automated layout created with the input of the Point Cloud. It is necessary to compare both approaches.
- Integrate Point Cloud in the MK and layout definition. The MK concept could be synchronized with the Point Cloud information. It is necessary to determine if, by integrating the Point Cloud in the sequence of the MK concept, the measuring time of the position of Part 1s would be reduced.
- Create a new sequence considering the aforementioned points.

To reduce the steps in the sequence with the MK, it was necessary to divide the procedure into five main phases, as explained in Figure 11.

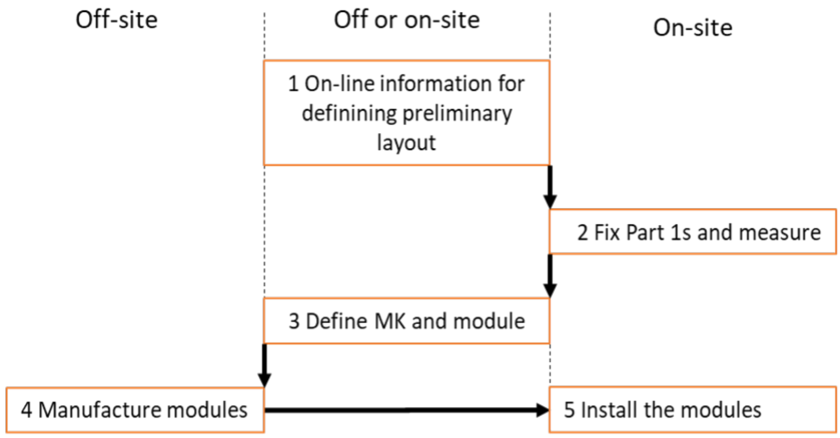


**Figure 11.** Process scheme.

The phases are organized not so much considering possible distribution of tasks among different stakeholders, but to reduce the on-site working time. Organizing this in such a way would imply a better collaboration between stakeholders or multidisciplinary companies that combine different competences. Companies currently partner with engineers and topographers who can provide these services. As a strategy for adding a module onto these facades, Part 1s are also placed in each corner of the window as a reference target and not necessarily as a spot for a mechanical connector (Figure 12).

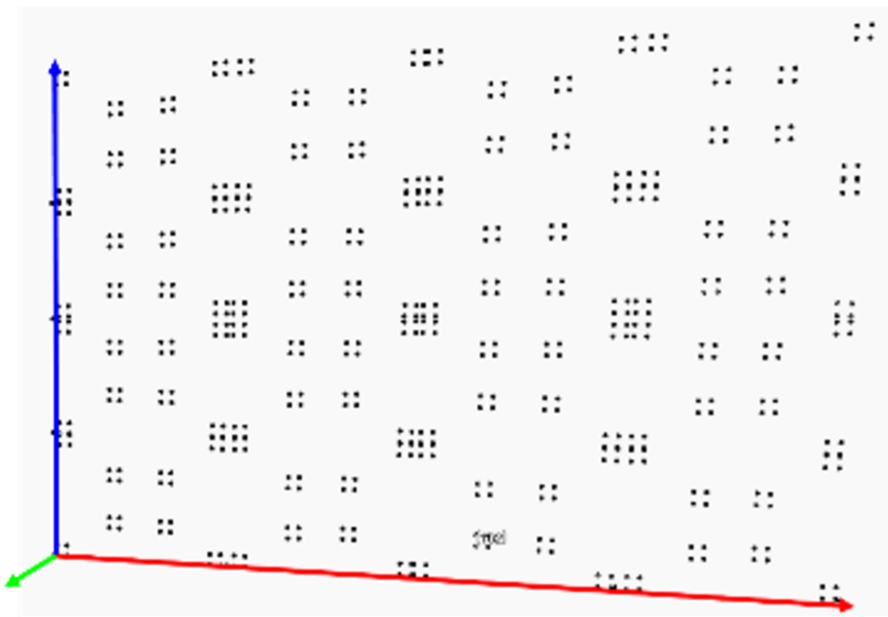

**Figure 12.** Location of Part 1 coordinates.

It is important to focus on one of the steps in Phase 3, which is a data processing and automated layout and MK interface definition. These data need to be processed to automatically create the layout of the modules. A new flowchart was created which includes the data from the Point Cloud (Figure 13) and creates the shape of the interfaces with developed Python™ nodes within Dynamo™.

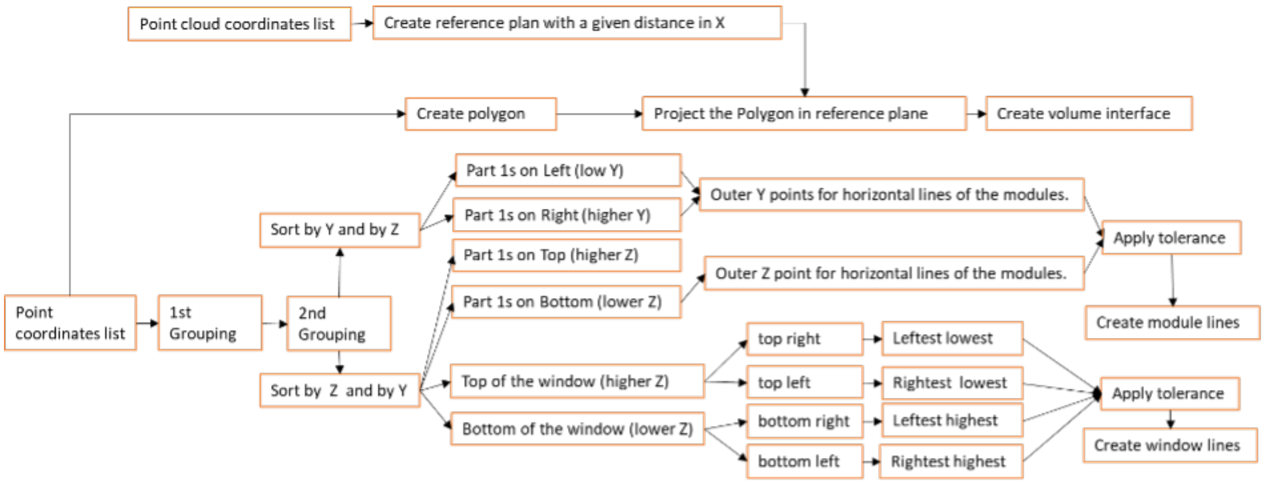


**Figure 13.** Process flowchart.

The procedure defined by the flowchart in Figure 13 allows one to use either the Point Cloud or Part 1 coordinates to define a reference plan. Since the coordinates of Part 1s are not in the same plan and do have inclinations, a reference or an average plan is necessary. In parallel, Part 1s, as a known geometry, need to be recognized. To achieve this, each of the points in every Part 1 must be clustered. To do so, two groupings must be formed. The first grouping consists of the points that are in the range of 100 and 170 mm.

The second grouping consists of separating Part 1s in the same cluster of four. The first and second groupings already consider that the measurement of the points in Part 1s with a Total Station might have tolerances up to 3 mm. After the recognition of each of the Part 1s, the layout of the modules, including the window opening, needs to be determined. For that purpose, the midpoint and maximum and minimum sizes of the modules were considered.

It is necessary to locate the line to avoid overlapping and to cover the borders of the facade correctly. Part 1s of the Matching Kit are put with high tolerances and, therefore, there might be overlapping points. As can be seen in Figure 14, the whole process explained in previous chapters is reduced to a few algorithms and scripts in Dynamo™ (that include Python™ codes).

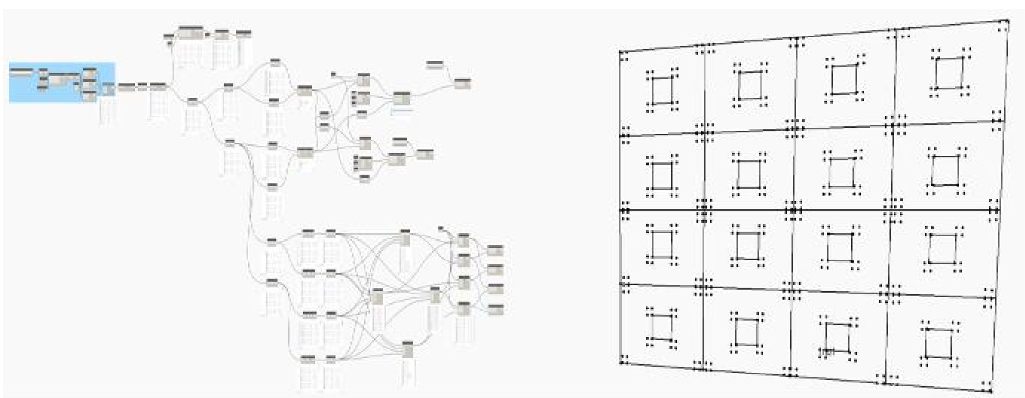

**Figure 14.** Definition of the layout using Matching Kit.

## 4. Results

To validate concepts, Test 4 was performed outdoors, in the BERTIM project, on a wall in the Egoin factory [35] with materials and elements that are part of the standard 2D module of the company (Table 3). To configure the 2D module, 12 mm width OSB boards and 62 × 140 mm pinewood timber profiles were used. The whole manufacturing process was carried out using the current resources of the aforementioned industrial company, which, in this case, was based on a Weinnmann manufacturing line (HOMAG©). Two modules were manufactured and installed in this test. The CAD software used for the layout design was CADWorks©. Insulation, a waterproofing membrane and timber cladding were not installed in the modules, since the objective of the test was to test the MK. In this test, unfortunately, there were no windows, nor slabs. But, the wall had a protrusion and collisions needed to be avoided. The Point Cloud was used for determining the planar situations and avoid collisions.

**Table 3.** Devices and materials used in Test 4.

| | |
|---|---|
| **SOFTWARE** | |
| Design of module | Recap™, Dynamo™ |
| Digital fabrication | CADWorks™ for transforming the data from Dynamo™ |
| Interface MK | Biesse© CAM for transforming the data from Dynamo™ |
| **MANUFACTURING** | |
| Module element cutting | Weinnmann© |
| Module element routing | Weinnmann© |
| Interface MK | Biesse Rover© CNC |
| **MEASURING TOOLS** | |
| Point acquisition | Leica©, MS-60©., provided by Infolur |
| Laser scanner | Leica© |
| **MATERIALS AND ELEMENTS** | |
| Modules | |
| Frame | 62 × 140 mm |
| Board | 12 mm OSB |
| Interface MK | Oak solid wood |
| Reflector mark | Rothbucher Systeme© |
| Mechanical connection of the MK | Knapp Walco®40 |
| Anchor | 1Mechanical Anchor with a plastic cap |
| **MODULE SIZE** | |
| Module height | 1998 and 2219 mm |
| Module length | 3342 mm |

As in medical reports and papers, this article gathers the outcome of an experiment or test. The test was carried out as an experiment in progress or as a proof-of-concept of the scheme (Figure 13). For this reason, while implementing this scheme in the test, unforeseen issues and weaknesses or study limitations appeared, and it is important to highlight them. These problems are explained to guarantee repeatability of the methods and results and further improve the MK concept.

**Phase 1: Using geographic information systems in the preliminary design phases**

To reduce the time spent on-site, it was necessary to determine the layout of the modules with an accuracy of 10 cm before traveling to the site. This phase consisted of preliminary data definition of the layout with online services. Today, there is no 3D cadaster available [36], although this is a topic that needs to be discussed further. Preliminary information of the existing building facade was gathered by using GIS and online data. For this test, Google Street Maps™ Invalid source specified. and GeoEuskadi (Basque GIS portal) were used to decide the location of the modules. After that, the approximate layout of the modules was decided. References, such as the semi column and the basements, facilitated the distribution of the modules (Figure 15).

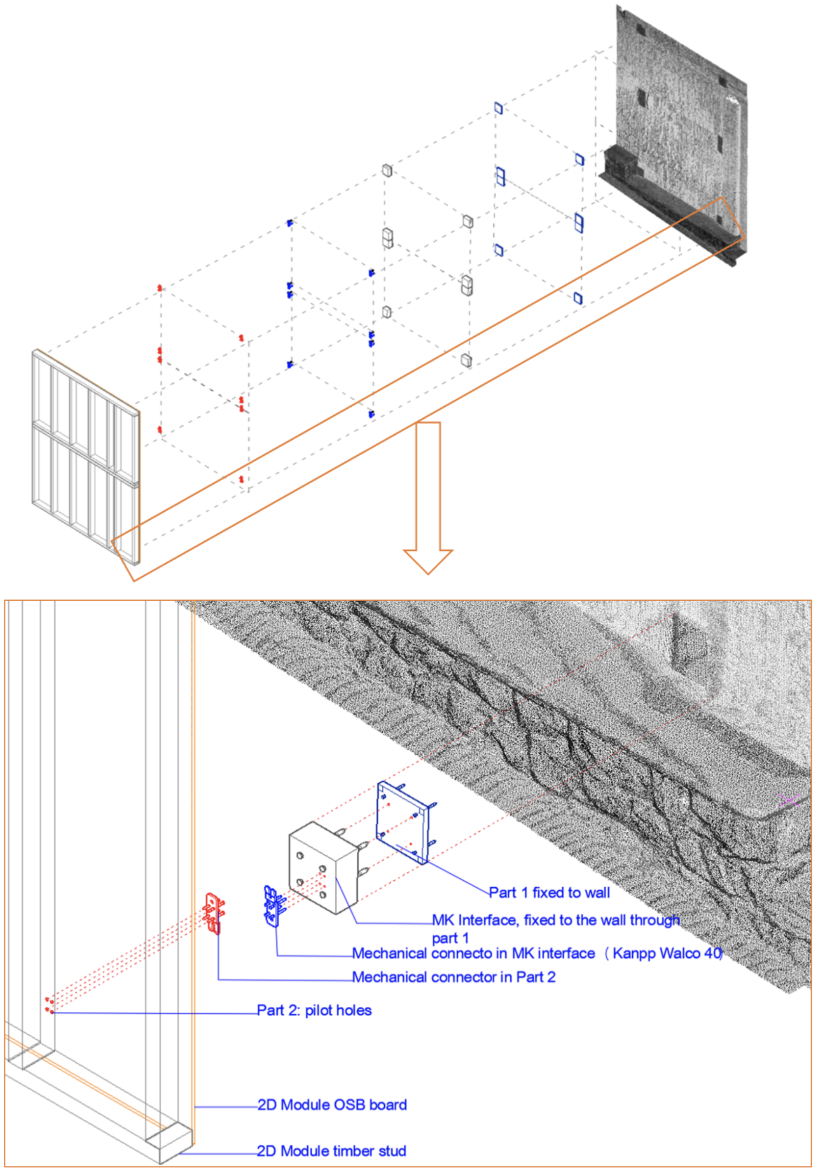


**Figure 15.** Installation process of the Matching Kit at Test 4.

**Phases 2 and 3: Part 1 placement, data acquisition, data processing, layout and MK definition**

Following the scheme in Figure 13, the first on-site task fulfilled several steps. Part 1s were previously prepared and cut into squares of 200 mm by 200 mm and markers were placed on them (Figure 16). At this point, the facultative engineers could also prescribe any type of solution that the facade renovation required:

- Phase 2.1: Part 1 placement and fixation. With the information gathered in the previous phase and with the help of physical references on the wall, it was possible to place each Part 1 within about 0.09 h. As can be seen in Figure 16, no marking device was used, only simple tape measures.
- Phase 2.2: Data acquisition. After placing Part 1, it was possible to start with the data acquisition. For the test, the acquisition of data from the existing building consisted of two means. The first technique used was a digital theodolite or Total Station. The second technique was a Laser Scanner. For both processes, the same coordinate

reference was set up. The Total Station was used to measure the location of Part 1s of the Matching Kit. The position of the marker in the corners of Part 1 and the position of these were measured. An error of almost 2 mm was detected on the measurement, but these were minimized by using the closest point algorithm (Table 4). In addition, the Point Cloud was surveyed with a 3D Leica laser scanner. The 3D density of the Point Cloud grid was 5 mm.

- Phase 3.1: Data processing. After data acquisition, it was necessary to reduce the density of the Point Cloud™ to around 8000 points, instead of the millions of points harvested using the 3D Laser scanner. Furthermore, irregular corners, such as the column and the basement, were reduced to avoid interferences. After that, it was possible to generate an Excel file with the reduced Point Cloud in Recap™. In parallel, directly from the Leica system, an Excel file of the point coordinates of Part 1a of the MK was generated.
- Phase 3.2. After the minor processing of the Point Cloud, the point coordinates taken with the Total Station and the Point Cloud were inserted in Dynamo™. The georeferenced Point Cloud and the coordination of Part 1s were set up in the same Dynamo™ algorithm.
- Phase 3.3. This output was inserted in AutoCad© and compared with the manual process. There were only minor deviations compared with the manual process. The information of the layout was completed in time for the manufacturing process. The location of the Knapp Walco 40© mechanical connectors was achieved manually and it matched the vertical stud in the module (Figure 15).

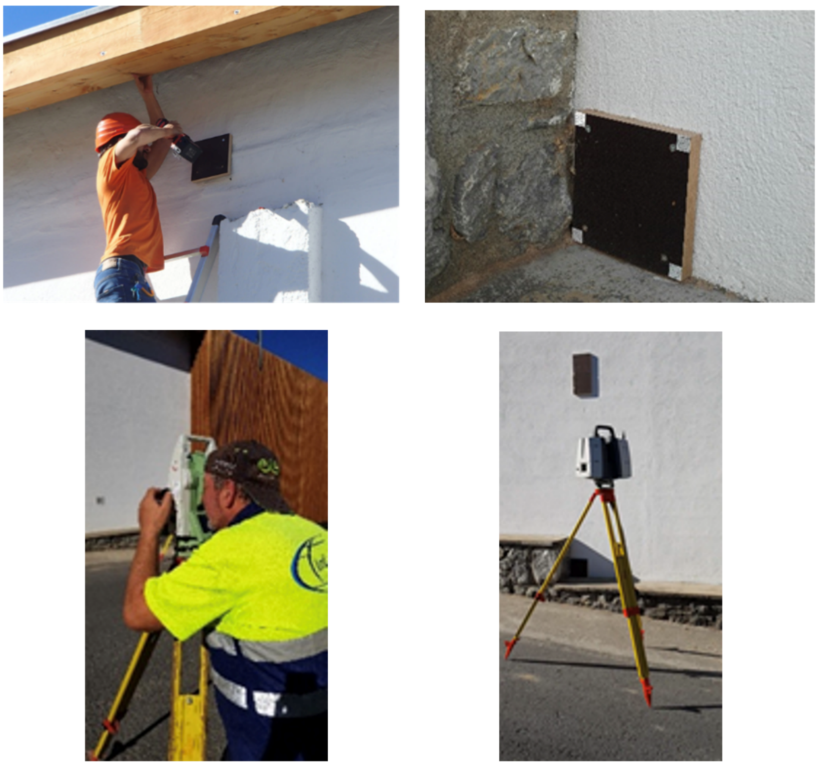

**Figure 16. Top left and right**: fixation of Part 1. **Bottom left**: point survey using Total Station. **Bottom right**: laser scanner at work.

**Table 4.** Part 1 targets' coordinates in mm (georeferenced).

| Position X | Position Y | Position Z |
|---|---|---|
| 993,899 | 4,997,544 | 102,807 |
| 993,900 | 4,997,545 | 102,600 |
| 993,901 | 4,997,540 | 102,986 |
| 993,901 | 4,997,542 | 102,779 |
| 993,904 | 4,997,493 | 100,796 |
| 993,905 | 4,997,725 | 102,604 |
| 993,905 | 4,997,723 | 102,812 |
| 993,905 | 4,997,719 | 102,992 |
| 993,906 | 4,997,721 | 102,783 |
| 993,911 | 4,997,673 | 100,795 |
| 993,911 | 4,997,522 | 104,604 |
| 993,911 | 4,997,492 | 100,616 |
| 993,914 | 4,997,527 | 104,782 |
| 993,915 | 4,997,702 | 104,598 |
| 993,915 | 4,997,672 | 100,616 |
| 993,918 | 4,997,707 | 104,778 |
| 993,975 | 5,000,200 | 103,019 |
| 993,975 | 5,000,197 | 102,839 |
| 993,976 | 5,000,197 | 102,811 |
| 993,976 | 5,000,192 | 102,633 |
| 993,982 | 5,000,375 | 102,836 |
| 993,982 | 5,000,371 | 102,627 |
| 993,983 | 5,000,379 | 103,016 |
| 993,983 | 5,000,376 | 102,807 |
| 993,984 | 5,000,178 | 100,803 |
| 993,991 | 5,000,358 | 100,804 |
| 993,991 | 5,000,178 | 100,624 |
| 993,996 | 5,000,237 | 104,555 |
| 993,998 | 5,000,358 | 100,624 |
| 993,999 | 5,000,417 | 104,555 |
| 993,999 | 5,000,237 | 104,735 |
| 994,005 | 5,000,417 | 104,733 |

If the time for developing the algorithm is not considered, the process from step 3.1 to step 3.3 was reduced to few minutes. Figure 17 shows the information generated from the Excel © file to Dynamo™ and then exported to AutoCAD™ for minor adjustments. With that information, it was possible to generate the information for the manufacturing and installing processes (Figure 15).

**Phase 4: Manufacturing**

With the information provided in the previous phase, the CAM was created. Module manufacturing was not monitored. The module manufacturing error was measured with a linear tape. The profile frame presented differences of 3 mm and the boards presented those of about 6 mm. This inaccuracy was assumed to be acceptable.

The MK interface shape was drafted in the Biesse CAM software and produced at the Biesse CNC (Figure 18).

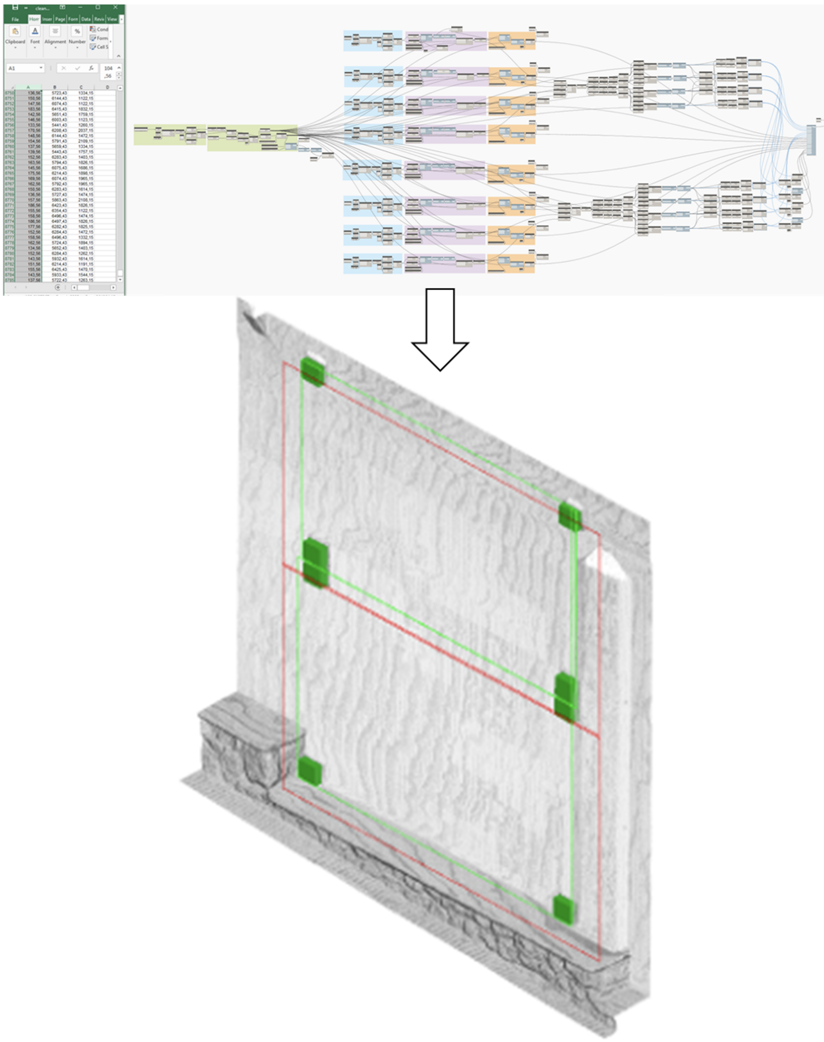

**Figure 17.** The figure shows the output of the automated process of layout generation, from the Excel file to the layout and MK definition. In red: the perimeter of the prefabricated modules. In green: the MK interfaces and accessory lines.

**Figure 18.** MK manufacturing process.

**Phase 5: On-site Installation**

Two means of handling the modules were used: a forklift and a crane. Both presented similar installation times. In both cases, three operators were needed: one for the crane and two for the modules. Regarding the allocation of the MK interfaces on the modules, the location of these connectors was manual, without using the capabilities to make holes accurately with a CNC. The tolerance of the Knapp Wilco®40 connector defined the tolerance for the installation process in this case. After that, the MK interface was installed onto Part 1s and the modules could be installed (Figures 19 and 20).

**Figure 19.** Installation sequence of the modules. The module below installed with a crane.

**Figure 20.** Installation sequence of the modules.

**Necessary working time**

Table 5 shows the time spent on each step. Compared with previous tests explained in Section 3, the time consumed in Phase 1 was not considered because it is an extra step that previous tests did not include.

**Table 5.** Installation time recorded from Test 4. a: Placement of Part 1; b: measuring of Part 1; c: MK shape calculation; d: MK manufacturing; e: MK placement onto Part 1; f: Part 2 fixing onto 2D module; g: 2D module installation; h: operators for 2D module installation; i: 2D module number; j: MKs per module; k: m² per 2D module.

| | | On-Site | On-Site | On-Site | Off-Site | On-Site | Off-Site | On-Site | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | TOTAL | a | b | c | d | e | f | g | h | i | j | k |
| Test 4 | 0.45 h/m² | 0.09 h | 0.09 h | 0.05 h | 0.19 h | 0.15 h | 0.08 h | 0.10 h | 3.0 | 2.0 | 4.0 | 7.15 m² |

The total installation time per square meter (T) was calculated using Equation (3). For Test 4, T was 0.45 h/m².

The existence of four connectors for each module is an issue that must be reduced. Furthermore, the machining of the interfaces in an industrial CNC was time-consuming when compared with the 0.10 in Test 2.

**Accuracy of the final position**

In Test 4, the maximum deviation between the planned and placed coordinates was registered at point 8 (7.2 mm), while the lowest deviation was at point 1 (2.9 mm) (Table 6). In Figure 21, the deviation is magnified by a factor of 20.

**Table 6.** Deviation of the modules in Test 4 (measuring deviation might be around 3 mm).

| Planned Points | Xn (mm) | Yn (mm) | Zn (mm) | Placed Points | xn′ (mm) | yn′ (mm) | zn′ (mm) | Deviation in mm |
|---|---|---|---|---|---|---|---|---|
| Point 1 | 0.00 | 0.00 | 0.00 | Point 1′ | 2.23 | 0.90 | 1.50 | 2.90 |
| Point 2 | 3342.00 | 0.00 | 0.00 | Point 2′ | 3337.20 | −2.20 | 1.50 | 5.40 |
| Point 3 | 0.00 | 0.00 | 2219.00 | Point 3′ | 2.72 | −1.50 | 2216.50 | 4.00 |
| Point 4 | 3342.00 | 0.00 | 2219.00 | Point 4′ | 3338.20 | −2.20 | 2215.50 | 5.50 |
| Point 5 | 0.00 | 0.00 | 2239.00 | Point 5′ | 4.59 | 2.40 | 2242.50 | 6.30 |
| Point 6 | 3342.00 | 0.00 | 2239.00 | Point 6′ | 3337.20 | −0.05 | 2241.50 | 5.40 |
| Point 7 | 0.00 | 0.00 | 4237.00 | Point 7′ | −0.30 | 0.30 | 4230.50 | 6.40 |
| Point 8 | 3342.00 | 0.00 | 4237.00 | Point 8′ | 3335.30 | −1.20 | 4234.50 | 7.20 |

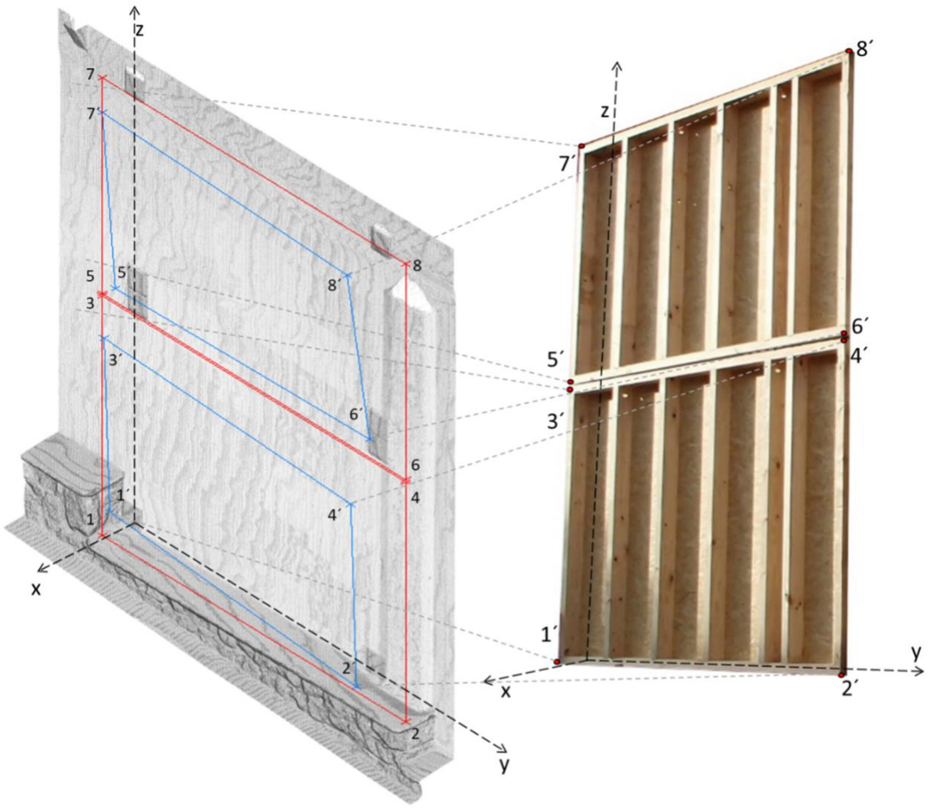


**Figure 21.** On the left: graph of the planned layout in red and placed deviation in blue magnified by a factor of 20 in Test 4. On the right: picture of the installed prefabricated modules with the corresponding points.

## 5. Conclusions and Current Work

The technological developments shown in Test 4 have improved the time performance of the previous three tests. In Test 4, the improved version of the MK was tested with successful results. Compared with Tests 1, 2 and 3, Test 4 gradually gained complexity and got closer to real cases.

Regarding the potential marketability of the technology, it is important to remark that the results show that regulation such as DIN 18202 [37] was fulfilled. Moreover, the MK concept, its set of components and its process were implemented in a real building refurbishment (Figure 22). This was the first real case using MK without the assistance of the authors during the manufacturing and installation of the BERTIM project [22]. According to the data given by the company that manufactured and installed the prefabricated module with the MK, the cost of this process was about EUR 200 per square meter. The cost of conventional methods such as ETICS and rain-screen is less, around EUR 90 to 150 per square meter [6], depeding on the country. The cost of the improved version of the MK could be reduced by improving some points:

- Potentialities of 3D cadaster should be explored to maximize online data acquisition. In the future, potential clients could complete the data and use photogrammetry to measure the facade.
- The use of a Total Station is tedious; therefore, using devices for the recognition of Part 1 automatically could be enhanced by the use of the recognition of AprilTags.
- A leaner production of the MK interface is necessary.

All three points are being achieved at the ENSNARE project [38]. For instance, in this project, an online building model is being developed and an UAV for placing targets is being tested.

**Figure 22.** First achievements with photogrammetry and a module installed with an MK concept in a real project. Bottom picture by Mr Hervé Coperet (POBI Industrie).

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## Abbreviations

The following abbreviations are used in this manuscript:

| | |
|---|---|
| ETICS | External Thermal Insulation Composite System; |
| NZEB | Nearly Zero-Energy Building; |
| MK | Machining Kit; |
| RES | Renewable Energy Source; |
| CNC | Computer Numerical Control; |
| OSB | Oriented Strand Board; |
| CAD | Computer-Aided Design; |
| GIS | Geographical Information System; |
| CAM | Computer-Aided Manufacturing |

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