Compilation and Assessment of Automated Façade Renovation

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Abstract –

Broad research concepts are usually developed in different phases where advances are carried out separately. That is the case of the automated and robotic façade renovation with modules. In this case, solutions were developed independently in the context of two research projects. In order to offer a holistic vision, analyze the current state, and solve gaps, a conceptual framework was defined. This conceptual framework contained three main subcategories: a) Information Flow, b) Off-site Manufacturing, and c) On-site Installation. Within this conceptual framework, four Novel Solutions were achieved: 1) Semi-automated Primary Module Layout Definition, 2) Partial routing and novel assembly sequence, 3) Robotic Installation of Modules, and 4) the Matching Kit Concept. These Novel Solutions were assessed depending on the working time per square meter and the accuracy of the attached façade modules. In order to have a general overview of the results, these were compiled and evaluated, which offered a perspective for future challenges.

Keywords –

renovation; evaluation; time; accuracy

1 Introduction

This paper is a part of a broader research named “Study on Automated and Robotic Renovation of Building Façades with Prefabricated Modules” [1]. The paper consist on an assessment of diverse technologies that are part of broader research projects.

Automation and robotics may be able to help with productivity issues. When it comes to marketing robotics for construction, productivity is a major concern. During the asset price bubble in the 1980s, the field of robotics in construction was achieved, primarily in Japan. [2]. Some robotic systems have remained in use since then, primarily in the prefabricated industry and less in the on-site construction. [3]. When developing robotics for construction, there are significant financial implications. Skibniewski [4] and Balaguer [5] already made approaches for quantifying that. The key, according to Warzawski [6], relies on the adoption of robotics and automation in the lifespan of the building, and on the economic viability of the established techniques. This requires a greater level of productivity when using robotics. To develop technology in such complex contexts, matrix-based decision-making methods were defined [7–9]. Besides, more specifically on the field of robotics, several criteria were specified to develop robots in construction [10–12]. Finally, specific problem-solving methods are common in engineering development [13–17].

“Façade renovation with prefabricated modules and its automated and robotics solutions” is a complex and multidisciplinary task that needs to consider multiple aspects [18–20]. For this reason, a conceptual framework was created to organize different issues. The reminder of this paper is to explain how this conceptual framework was used during the analysis, development and assessment of different solutions. Moreover, the conceptual framework was used as a basis for the compilation of the results.

2 Conceptual framework

Following the structure of previous research [21], the subcategories of the conceptual framework were defined as in the next points:

- SC1Information or Data Flow:
  - SC1.1: Measuring the geometry and acquiring the state of the building façade.
  - SC1.2: Processing the acquired data.
  - SC1.3: Defining the layout of the modules.
  - SC1.4: Create the necessary data for the manufacturing process.
  - SC1.5: Mark the necessary data for the installation of the modules on-site.
- SC2: Off-site Manufacturing of the modules:

  - SC2.1: Prepare (Cut/machine) the elements.
  - SC2.2: Assembly elements.
- SC3: On-site Installation of the modules:
  - SC3.1: Setting up the robotic device.
  - SC3.2: Fixing connectors.
  - SC3.3: Placing the module.

2.1 Current procedures with modules

Based on the aforementioned list, an analysis was carried out regarding the time spent during each of the subcategories and the accuracy of the installed modules [1]. In Table 1**,** the operator working time per square meter of the lowest and highest records of several cases is shown.

Table 1 Lowest and highest records

	Working time h/m²	
	Lowest	Highest
Data flow (SC1)		
Data acquisition	0,09	0,15
Defining the layout	0,17	0,34
Data marking	0,04	0,13
Manufacturing total time (SC2)		
Cutting and routing	0,21	0,45
Assembly	0,40	1,74
Installation (SC3)		
Connector fixation	0,03	0,08
Installation of modules	0,34	0,71
TOTAL	1,28	3,60

Regarding the accuracy, standards such as the DIN 18202 [22] specify the accuracy requirements of external walls depending of the segment size, which, in normal conditions is up to 25mm (see Table 2).

Table 2 Tolerances in external walls according to DIN 18202

	Wall segment size				
	0,1 m	**1 m**	**4 m**	**10 m**	**15 m**
Normal condition	3	5	10	20	25
Restricted conditions	2	3	8	15	20

The DIN 18203-3 specifies the maximal deviation at 5 mm for timber walls, in any case. However, these data needs to be updated or checked in real projects. For instance, a demonstration was carried out during the early stages of the BERTIM research project [23], which consisted of the installation of three 2D modules onto an existing test building. In this case manufacturing and installation processes caused visible accuracy issues. On one hand, the modules were not manufactured to the specified level of precision (+/- 1 mm). Stud‘s location reached tolerances of up to 8 mm once the process was completed (see Figure 1 top). In the other hand, the final coordinates of the 2D module placement deviated by more than 20 mm from what was planned. This necessitated additional rework once the 2D modules were installed on the wall by overlapping the waterproof layers. For this reason, the DIN 18203-3 was not fulfilled (see Figure 1 bottom).

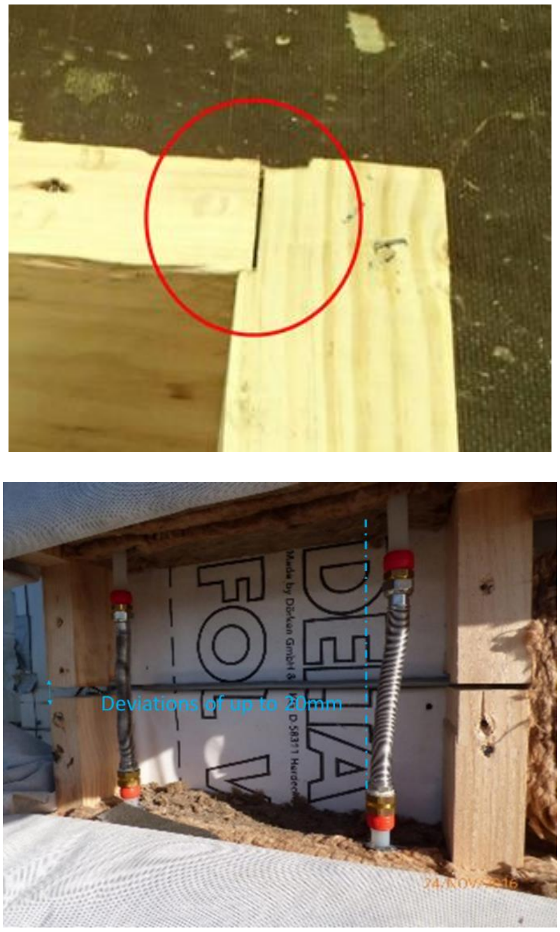

Figure 1: Top: deviations due to assembly inaccuracies. Bottom: deviations during installation.

2.2 Research Gaps

Following the quantitative analysis on previous section, the next research gaps of the manual methods were defined:

- **RG1:** Lack of automated data flow. Automation is required for the data workflow. It is necessary to save time and eliminate redundant measuring and marking. The data and information must flow easily from the existing building's data acquisition to the installation of the façade modules. Two points

should be addressed:
  - RG1.1. The need for an automated module layout definition.
  - RG1.2. Facilitate the connector fixation of the modules by transferring data to the existing facade.
- **RG2**: Lack of Automated Manufacturing modules. It is vital to save working time while improving accuracy and the proper placement of module pieces. The more routed the pieces are, the more precise the modules are, but manufacturing time increases. A balance between precision and production consumption is required. Two points are outlined:
  - RG2.1. Reduce routing and manufacturing time.
  - RG2.2. Lack of fully automated assembly.
- **RG3**: Lack of automation in the installation of façade modules. To reduce installation time, a precise and automated robotic technique for the installation of façades is necessary. A focus on the following two subtopics is necessary:
  - RG3.1: Lack of automation installation of the connector.
  - RG3.2: Lack of automation installation of the Module onto the connectors.

On the next section, the solutions to these research gaps are explained.

3 Developed Novel Solutions

The experiments presented are diverse and focus on different issues. Moreover, the solutions solve different research gaps. The four different Novel Solutions are presented on the next points:

- **Solution 1:** Semi-automated Primary Layout Definition with a "Point Cloud". One of the most significant impediments to commercialize the usage of prefabricated modules for façade rehabilitation is the lengthy time required for data processing and module design. This solution provides, with the only input of the current building facades' Point Cloud, a novel method that enables a semi-automated definition of the module layout. [1]. The solution developed here facilitates a semi-automated generation of the shape of the modules that will be installed on top of the existing building (see Figure 2). Because of this solution, time was saved.
- **Solution 2**: Partial routing and novel assembly sequence. Currently, the precision routing, machining and calibration of the pieces that are part of the module determine the accuracy of robotic assembly. The approach given in this solution is based on a minor increase in the machining of the current timber frame module's pieces by using dovetailed unions, as well as a design that makes robotic assembly unidirectional [1]. Thanks to this solution, the working time was reduced while the accuracy was gained (see scheme in Figure 3).

Figure 2. Generation of the module-layout from the Point Cloud coordinates.

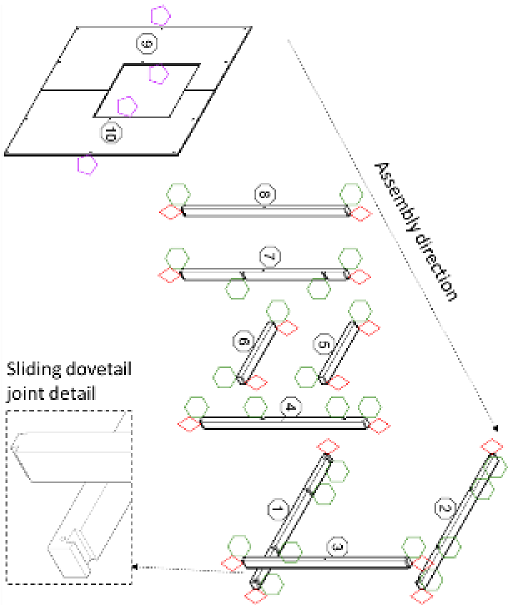

Figure 3: Unidirectional assembly of timber frame by dovetail joints thanks to a partial routing.

- **Solution 3:** Robotic Installation of Modules with a cable-driven parallel robot (CDPR). The solution is based on the on a CDPR that hosts a solution of tools on its platform named Modular End Effector (MEE). The MEE is based on a robotic arm with different changeable end-effectors, a Stabilizer, and a Vacuum

Lifting System. [24].This solution provided an automated fixation of connectors on top of the building slab as well as the installation of CWM. Even though this solution was initially foreseen for building renovation, the tests were carried out in new building construction sites (see Figure 4).

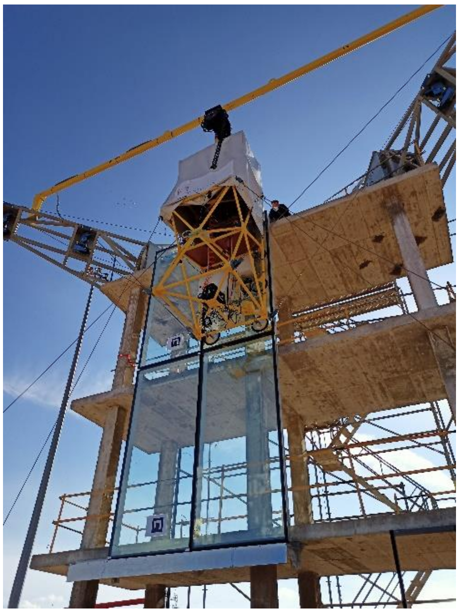

Figure 4: Robotic Installation of Modules with a CDPR.

- **Solution 4:** Matching Kit Concept. The Matching Kit (MK) is a set of components that includes a bespoke interface to correct the deviations occurred during the placement of the connectors in the wall [25]. The initial test carried out with the Matching Kit reveal a reduction of time compared to current strategies based on an initial accurate localization of connectors in the existing buildings (see Figure 5).

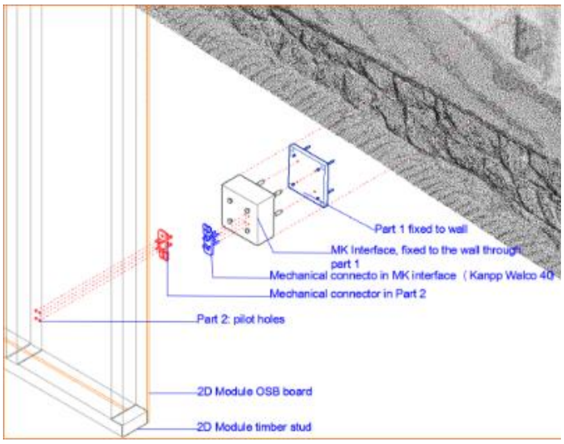

Figure 5: Installation process of the Matching Kit.

4 Compilation and evaluation

The aforementioned Novel Solutions focused on the working time and the accuracy for achieving a task. However, in terms of how the Novel Solutions should be evaluated with a holistic perspective of the renovation process, that is, the aforementioned conceptual framework. For this reason, the solutions developed in the previous chapters need to be compiled and combined to set up a comparable result. A compilation of results regarding working-time per square meter (h/m²) of all the solutions defined was considered first (see Table 3)

Table 3: Time spent in the selected Novel Solutions.

	Solutions			
	1	**2**	**3**	**4**
SC1:Data flow				
SC1.1: Data acqusition	0,012			0,05
SC1.2: Data Processing	0,002			
SC1.3: Layout definition	0,002			0,05
SC1.5: Transfer On-site data			0,02	0,18
SC2:Manufacturing		0,18		
SC2.1: route elements				
SC2.2: assembly				
SC3:Installation				
SC3.1: Setting up device			0,3	
SC3.2: brackets fixation			0,05	0,18
SC3.3:module installation			0,06	0,084

Some notes on the data in *Table 3* include the fact that the SC1.4 is not considered since the creation of the CAM is a task that is already solved almost automatically with current software [26]. Besides, the data need to be considered in different contexts.

- **Solution 1**. This solution is fast at defining the layout of the module but it requires a considerable effort around acquisition to generate reliable and accurate data.
- **Solution 2**. The data gathered in solution 2 shows a significant reduction in working time. It needs to be pointed out that the time for assembling the timber frame is only around 20% of the whole module manufacturing process. However, it shows a strategy, albeit further CNC machining of elements that might be a solution to some issues in the future.
- **Solution 3**. Regarding the installation robot presented, the biggest handicap is the set-up of the robotic system (173 hours that for an optimal workspace,

0,36 hours per square meter in the analyzed case). The rest of the operations are work-time efficient and accurate enough according to the first tests. For the calculation of solution 3, the following remarks were considered:

  - The data transfer to the CDPR and the MEE of the robot takes 0,05 hours for each bracket. Considering that two brackets are necessary for at least one curtain wall of 4,8m², then 0,0208 hours are necessary per square meter.
  - The bracket installation takes 0,13 hours, excluding the aforementioned data transfer. Similarly, considering that two brackets are necessary for at least one curtain wall of 4,8m², then 0,0542 hours are necessary per square meter.
  - The CWM installation takes 0,33 hours, therefore, 0,06875 h/m² are necessary.

- **Solution 4** requires higher consumption time in the initial phases but it provides a smooth connector fixation and module installation because there is no need of adjustment.

The solutions explained before do not offer a complete façade renovations process, which is why they should be combined. Three combinations were drafted with the data of each of the sets:

- **Combination 1**: It combines the Solution 1 (Semi-automated Primary Layout Definition with a Point Cloud), 2 (Partial Routing and Novel Assembly Sequence) and 3 (Robotic installation of modules with a CDPR).
- **Combination 2**: It combines Solution 2 (Partial Routing and Novel Assembly Sequence) and 4 (Matching Kit concept).
- **Combination 3**: It combines Solution 1, 3 and 4. In this case, the Matching Kit concept is combined with the robotic installation of the modules. Combination 3 overlaps different solutions since the robotic installation with the MK was not approached.

In all combinations, for the manufacturing subcategory (SC2), the data achieved in solution 2 is multiplied by 5 (as the data gathered is only 20% of the module manufacturing process) to represent the manufacturer of the whole prefabricated module. This is only an estimation.

Data shows that combinations 1 and 2 have a very similar performing result (1,05 h/m² for Combination 1, and 1,08 h/m² for Combination 2), as shown in Table 4. In both cases, less time is necessary than the combination of the lowest records in the analysis in Table 1 , which is 1,28 h/m², specifically 18% and 19% less time, respectively. The sum in Combination 3 is slightly higher than the lowest records but considerably lower than the combination of the highest records. These results show a significant reduction of working time in regards to the manual processes specified in Table 1(3,60 h/m²).

Table 4: Time of the combinations

	Combination 1	**Combination 2**	**Combination 3**
SC1:Data flow			
SC1.1: Data acqusition	0,0127	0,05	0,05
SC1.2: Data Processing	0,0021		
SC1.3: Layout definition	0,0021	0,05	0,05
SC1.5: Transfer On-site data	0,0208	0,18	0,18
SC2:Manufacturing			
SC2.1: route elements	0,108*5	0,108*5	0,108*5
SC2.2: assembly			
SC3:Installation			
SC3.1: Setting up device	173h=0,36		173h=0,36
SC3.2: brackets fixation	0,054	0,18	0,054
SC3.3:module installation	0,068	0,084	0,068
TOTAL	**1,06 h/m²**	**1,08 h/m²**	**1,30 h/m²**

But are the results in Table 3enough for assessing if a combination of the set of solutions is an optimal choice or whether further development is even worth it? Accuracy needs to be part of the evaluation as well. In the case of selecting the best solution, how to decide which of the combinations has further development and success possibilities? A Multi-Criteria Decision Making [18,27] that includes the accuracy parameter is necessary. In other words, accuracy needs to be evaluated within a weighting equation that includes the working time.

In the next paragraphs, an evaluation of the Combinations 1 to 3 is explained. The evaluation range is measured on a 0-100 scale, where 0 is the worst case and 100 is the best case. The highest record stands for 0 and the lowest record stands for 100 on that scale. The indicators are explained as follows:

- Indicator A: Working time of the combination (A in Table 5) which is based on the lowest and highest records and the combinations from Table 1. The benchmarked lowest record is 1,28 h/m² and the highest record is 3,60 h/m². The weight (W) of this indicator is considered as 50% (or half, 1/2).

- Indicator B: Manufacturing accuracy (B in Table 5). As mentioned in section 2.1, the initial objective was that fabrication tolerances must be lower than 1 mm, and that is considered as the lowest record. For the highest record, section 2.1 shows a maximum deviation of 8 mm, which has been considered as highest record. For all Combinations 1 to 3, the experiments in solution 2 showed a maximal deviation of 1,5 mm. The W weight for this indicator is considered as 25% (or a quarter,1/4).
- Indicator C: Installation accuracy (C in Table 5). The initial objective of this research was that installation tolerances must be lower than 5 mm, as the DIN 18203-3 specifies. This value will, therefore, be taken as the lowest record. On the other hand, in the analyzed cases in BERTIM, deviations were bigger than 20 mm (see section 2.1), and this value is taken as the highest record. For solution 3 and, therefore, Combination 1, the installation accuracy showed an absolute deviation of up to 11,66 mm in regards to the planned position. For solution 4 and, therefore, Combinations 2 and 3, the installation showed absolute inaccuracies of up to 7,2 mm. The W weight for this indicator was considered as 25% (1/4).

  In Table 5, all the indicators of the Lowest (L) and the Highest (H) records and the three combinations (C1, C2, and C3) are shown. To normalize the value of the indicators, Equation 1 is used and applied for getting Normalized Indices ($\bar{I}_{ij}$).

$$\bar{I}_j = \frac{I_j}{\left(\sum^j I_j\right)} * W \qquad (1)$$

By applying Equation 2, the Normalized Indices' $\overline{I\iota j}$ values are summed and the Combination‘s significance Rj is achieved (see R in Table 5)

$$\bar{I}_{ij} = \frac{I_j}{\left(\sum^j I_j\right)} * W \qquad (2)$$

By applying the Normalized Indices' $\bar{I}$ values are summed and the Combination‘s significance Rj is achieved by Equation 3 (see R in *Table 6*). Finally, the Combination´s degree of efficiency in 0-100 scale is achieved by applying Equation 4 (see N in *Table 6*).

$$R_j = \sum^j \left(\bar{I}_j\right) \qquad (3)$$

$$N_j = \frac{R_j - R_{min}}{R_{max} - R_{min}} * 100 \qquad (4)$$

Table 5: Indicators.

	W	**L**	**$\bar{I}_L$**	**H**	**$\bar{I}_H$**	**C1**	**$\bar{I}_{C1}$**	**C2**	**$\bar{I}_{C2}$**	**C3**	**$\overline{IC}_3$**
A	1/2	1,28	0.08	3,60	0.22	1.06	0,063	1.08	0,065	1.3	0,076
B	1/4	1	0.02	7	0.14	1.5	0,030	1.5	0,030	1.5	0,029
C	1/4	5	0.02	20	0.10	11.66	0,057	7.2	0,035	7.2	0,035

Table 6: Final assessment.

	Lowest	**Highest**	**C1**	**C 2**	**C3**
Sum of normalized indices (R_j)	0,12	0,45	0.15	0.13	0.14
Degree of efficiency (N_j)	**100**	**0**	**90.57**	**96.73**	**93.49**

The results show that the objectives have not been reached 100%. Future research should solve the remaining issues. The future needs (FN) are compiled and their numbering re-adjusted as in the next points:

- FN1.1.1: Accuracy of the measuring device. One of the issues in solution 1 was the inaccuracy of the Point Cloud itself.
- FN1.1.2: Potentialities of online data for the initial measurements of the building should be explored, in order to avoid excessive visits to the existing building.
- FN1.1.3: Recognition of the Matching Kit automatically. One of the issues regarding the Matching Kit concept was that the connectors placed on the wall had to be measured manually. Photogrammetry can be useful for these cases.
- FN1.3.1: Accuracy of the selected segments of the

Point Cloud. The solution 1 relies still in designers' criteria that might tend to errors.

- FN1.3.2: Recognition of slab. The solution 1 is based on the localization of the slab of the building. If the building doesn't show the slab, the solution 1 is useless.
- FN2.1.1: Adjustment in design to facilitate assembly process. The design needs to facilitate a robot based assembly.
- FN2.1.2: Design should consider rigidizing during the assembly. During experiments it was noticed that a key point that facilitates the assembly is a rigidizing union between elements. This future need might be in contradiction with the FN 2.1.1.
- FN2.1.4: Adjusted Robot Oriented Design [28] depending on Assembling Tolerances. Depending on the robotic accuracy, the assembled module's tolerances should be adjusted accordingly.
- FN2.2.1: Adjust the manufacturing line, depending on the most suitable configuration.
- FN2.2.2: Agile robot path adjustment depending on CAD of the modules. It is of a vital importance to generate a parametric adjustment of the robot path depending on the CAD file of the module.
- FN3.1.1: Faster set up of the robotic device is necessary. In Solution 3, the main burden for a rapid installation is the need for a fast set up of the robotic device.
- FN3.2.1: A leaner production of the Matching Kit interface is necessary. In Solution 4, the manufacturing time of the interface was time consuming.
- FN3.2.2: Consider uneven surfaces. The robotic device in solution 3 did not consider the unevenness of the façade of the existing building.
- FN3.3.3: Accurate Recognition of the modules. The robotic device in solution 3 will be more accurate if the device would recognize the modules from its picking rack.
- FN3.3.4: Recognition of the connector. As in the previous point, the robotic device in solution 3 will be more accurate if it recognized the connectors on the slab while installing the modules.

5 Conclusion

The results show that the different combinations of options might depend on the automation level and different strategies for reaching high accuracy. On the one hand, automation in all subcategories is still needed. On the other hand, learnings from the experimentation show that reaching absolute accuracy in a façade workspace leads to time-consuming setting up of the robotic device.

The data gathered in this research can be used as a basis for future business plans. However, the Technology Readiness Level (TRL) of the Novel Solutions is still around 5 or 6, which means that there might not be sufficient data for accurately calculating the cost of the automated and robotic solutions presented in this paper. However, some approaches have already been made [29]. The question of how to manage technology and make it ready for the market must also be addressed. This topic has been approached in two different research projects, namely BERTIM and HEPHAESTUS [30], where this research has been contextualized and several deliverables have been reported. Once the latest points highlighted in this chapter are properly improved, a potential reduction in time with necessary accuracy can be achieved by applying automation and robotics in the field of Automated and Robotic Renovation of Building Façades with Prefabricated Modules. Projects like ENSNARE [31] will address some of the aforementioned needs.

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