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Study on Automated and Robotic Renovation of Building Façades with Prefabricated Modules

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Dr. Maider Uriarte-Idiazabal (5th of January 1981; † 22nd of August 2016).

Tesi hau zure omenez idatzi dut.

Zusammenfassung

(**Hintergrund**) Um den Energieverbrauch zu reduzieren, ist es notwendig, die Wärmedämmfähigkeit bestehender Gebäudefassaden zu verbessern. Zu diesem Zweck werden Schichten, die Isolierung, wasserdichte Verkleidung und sogar erneuerbare Energiequellen umfassen, an bestehenden Gebäudefassaden angebracht. Die manuelle Durchführung dieser Aufgaben an Gebäudefassaden ist oft eine mühsame, gefährliche und ineffiziente Tätigkeit. Um die manuellen Tätigkeiten vor Ort zu minimieren, werden extern vorgefertigte Module oder Wände auf die bestehenden Gebäudefassaden montiert. Um die Luft- und Wasserdichtheit der Module zu sicherzustellen, sind strenge Maßtoleranzvorgaben über den gesamten Prozess hinweg notwendig. Darüberhinaus muss die Sicherheit während aller Arbeitsschritte erhöht werden. (**Ziel und Hypothese**) Um das oben genannte Thema weiter zu untersuchen, ist es der Gegenstand dieser Dissertation, die Arbeitszeit zu reduzieren und gleichzeitig eine ausreichende Genauigkeit zu erzielen, indem neuartige automatisierte und robotische Lösungen in verschiedenen Phasen der Fassaden-Gebäudesanierung mit Modulen angewendet werden. (**Methode)** Die Komplexität und der Umfang des Themas erfordern eine Einteilung in mehrere Unterkategorien, basierend auf den verschiedenen Phasen des Gebäudesanierungsprozesses: 1) Erfassung der Maße der bestehenden Fassade; 2) genaue Fertigung der vorgefertigten Module oder Wände außerhalb der Baustelle; und 3) präzise Installation der Module. Um die Forschung zu strukturieren wurde ein konzeptioneller Rahmen festgelegt. Dieser konzeptionelle Rahmen, oder auch Arbeitsmethodik, wurde zu Grunde gelegt um jede der Unterkategorien zu organisieren, zu strukturieren und miteinander in Beziehung zu setzen. Auf diese Weise wurden die einzelnen Probleme und Lösungen in den Kontext des übergeordneten Themas eingebettet. Diese Arbeitsmethodik lieferte das Konzept für die Durchführung der Hauptforschungsphasen, die in dieser Dissertation vorgestellt werden, nämlich a) die Analyse und Definition von Forschungslücken (**RG)**, b) die Entwicklung neuartiger Lösungen (**DNS**) und c) die Bewertung des zukünftigen Bedarfs (**FN**). Zwei Hauptparameter, nämlich Genauigkeit und Arbeitszeit, wurden für die Bewertung der verschiedenen Unterkategorien während der Forschungsphasen herangezogen. (**Analyse**) In der bisherigen Literatur zur Fassadensanierung mit vorgefertigten Modulen fehlt der Blickwinkel auf Genauigkeit und Arbeitszeitleistung. Daher wurde eine Analyse durchgeführt um Maßstäbe zu definieren und die Forschungslücken in jeder der Unterkategorien zu identifizieren. Zu diesem Zweck wurden Fallstudien der Modulvorfertigung und -installation analysiert und fünf RG entdeckt. (**Entwicklungen**) Diese fünf RG wurden durch die jeweiligen DNS behandelt. Die erste DNS konzentrierte sich auf die Erstellung eines neuen automatisierten Prozesses zur Bestimmung des primären Layouts der Module unter ausschließlicher Verwendung einer Punktwolke aus einem 3D Scan der bestehenden Gebäudefassade. Die zweite DNS bietet einen verbesserten Ansatz für die externe Montage von vorgefertigten Modulen, indem sie den Bearbeitungsgrad einiger Elemente anpasst und gleichzeitig eine ausgewogene Fertigungslinie erreicht. Die dritte Lösung korrigiert Abweichungsprobleme bei robotergestützten Montageprozessen in externen Produktionsstätten mit kalibrierten und maschinell bearbeiteten Holzelementen. Die vierte DNS befasst sich mit der Vor-Ort-Montage von Modulen durch ein System, das auf einem seilgetriebenen Parallelroboter (CDPR) basiert und in einer Situation umgesetzt wurde, die realen Bauumgebungen mit realen Ergebnissen sehr nahe kam. Und die fünfte DNS befasst sich mit einer Schnittstelle, die Abweichungen während der Vor-Ort-Installation der

Module korrigiert. Die Ergebnisse zeigen vielversprechende Resultate. Für jede DNS wurde eine FN benannt. (**Schlussfolgerung**) Im Abschlusskapitel wurden die FN zusammengefasst und ein Überblick über den entwickelten konzeptionellen Rahmen und die potenzielle Forschungslinie erstellt.

Abstract

(**Background**) To reduce energy consumption, there is a need to improve the existing building façade thermal insulation capabilities. For such purpose, layers that include insulation, waterproof cladding and even renewable energy sources are fixed onto existing building façades. Achieving these tasks manually on building façades is often a tedious, dangerous, and inefficient activity. To minimize manual activities on-site, prefabricated modules or walls have been installed on top of the existing building façades. To fulfil airtightness and waterproof conditions of the modules, strict dimensional tolerance constraints in all phases is necessary. Moreover, safety must be increased in all phases. (**Objective and hypothesis**) To further investigate the aforementioned topic, the objective of this dissertation is to reduce the working time while achieving sufficient accuracy by applying novel automated and robotic solutions in different phases of the façade-building renovation with modules. (**Method**) The complexity and broadness of the topic require the determination of several subcategories based on different phases of the building renovation process, which are 1) data acquisition of the existing façade; 2) accurate off-site manufacturing of the prefabricated modules or walls; and 3) precise installation of the module. To structure the research, a conceptual framework was determined. This conceptual framework or working methodology was used as a tool for organizing, interrelating and decomposing each subcategory. With the conceptual framework, particular problems and solutions were encompassed within the perspective of the general topic. This working methodology provided the context for accomplishing the main research phases presented in this dissertation which were a) the analysis and definition of Research Gaps (**RG**), b) Development of Novel Solutions (**DNS**) and the c) assessment of Future Needs (**FN**). Two main parameters, namely accuracy and working time were used for assessing the different subcategories during the research phases. (**Analysis**) The previous literature on façade renovation with prefabricated modules lacked a focus on accuracy and working time output. Therefore, an analysis was carried out to define the benchmarks and to identify the research gaps in each of the subcategories. To achieve this, case studies of module prefabrication and installation were analyzed and five RGs were detected. (**Developments**) These five RGs were addressed by the respective DNSs. The first DNS was centered in creating a new automated process for determining the primary layout of the modules with the only input of 3D scanned Point Cloud of the existing building façade. The second DNS provides an improved approach for the off-site assembly of prefabricated modules by adjusting the machining level of some elements while reaching a balanced manufacturing line. The third solution corrects deviation issues with robotic assembly processes in off-site factories with calibrated and machined timber elements. The fourth DNS is about the on-site installation of modules by a system based on a cable-driven parallel robot (CDPR) which was achieved in a situation very close to real construction environments with real results. And the fifth DNS is centered in an interface that corrects deviations during the on-site installation of the modules. Results show promising achievements; however, FNs were appointed for each of the DNSs. (**Conclusions)** Finally, the conclusion chapter gathered the FNs and set up the overview of the evolved conceptual framework and the potential line of research.

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Acronyms and Glossary

Absolute and Relative Accuracy: Absolute Accuracy is the positioning accuracy of a module in regards with the origin (0,0,0) of a facade or a building, while relative can be the positioning accuracy in regards to an adjacent module or element.

Anchor: A system, normally a plate or angle that are used for supporting a rain screen and other prefabricated modules. Anchors are fastened by bolts.

Assembly: The process for putting together different elements and creating a prefabricated module.

Automation: Refers to the minimization of human manual work for achieving a task

Bracket: A CWM supporting plate that is fixed with bolts to a concrete slab.

BIM: Building Information Modelling. A software tool that includes physical and management information of the built environment.

Connector: Similar to an anchor, but it might include fluid or electricity transfer.

CLT: Counter Laminated Timber panels.

CNC: Computer Numerical Control machine. Accuracy is very good if the Cartesian is a stable system. Good for routing and manufacturing.

Current manual methods for facade renovation: Refers to the set of techniques where materials are cut manually on-site in order to arrange them onto the existing façade.

CWM: Curtain Wall Module, which is a type of prefabricated curtain wall.

Number of Degrees of Freedom: when referring to a robotic system, the Number Degrees of Freedom is the capability of moving the mechatronic tool in a three dimensional space. The Number of Degrees of Freedom varies depending on the capability to turn or move in three Cartesian axes.

Design: The arrangement of the materials and elements to conform to a prefabricated module.

ETICS: External Thermal Insulation Cladding System, that it is very used as a system for upgrading current buildings.

Industrial Robot: An automatically controlled, reprogrammable, multipurpose manipulator programmable in three or more axes, which can be either fixed in place or mobile for use in industrial automation applications. Industrial robots can be classified according to mechanical structure:

> Cartesian robot: robot whose arm has three prismatic joints and whose axes are correlated with a Cartesian coordinate system

SCARA robot: a robot, which has two parallel rotary joints to provide compliance in a plane

Articulated robot: a robot whose arm has at least three rotary joints

Parallel/Delta robot: a robot whose arms have concurrent prismatic or rotary joints

Cylindrical robot: a robot whose axes form a cylindrical coordinate system (taken from [1])

Installation: Refers to the placement and fixation of an element or module on the construction site.

Finishing: The way a task is finished in façade renovation, corners, materials etc. Finishing is necessary to gain waterproof and airtight condition.

Manufacturing: Refers to the production of elements, pieces that will be assembled in a module.

Machining: Shaping and drilling an element with a high precision router and driller, normally with a CNC.

Module: A façade module is a prefabricated wall. In the field of building refurbishment, the façade module is attached to an existing building, on top of the outer layer of the existing façade. It can contain **Renewable Energy Services.**

Laboratory or controlled environment: An environment for testing prototypes where there are no real hazards as in a real construction site.

Layout of the modules and Primary layout: The layout of the modules refers to the arrangement and design of the modules in existing buildings. Specifically, the primary layout is the separation line that the modules have between each other and other elements of the building.

Rain-screen: A type of cladding system that works as a first water stopper and sometimes contains waterproof insulation.

Real or close-to-real environment: An environment for testing prototypes where there are real hazards. In close to real environments, there the construction sites are specifically built for the tests.

Rework: Refers to the task that needs to be achieved to guarantee airtightness and waterproof conditions after a module is installed.

ROS: A package of different libraries for simulating and controlling several robot types.

Robot Calibration: is a task so robots work in known paths in regards to one or several Cartesian axes.

Routing: Shaping an element with a high-precision router, normally with a CNC.

On-site: Refers to the construction site, in this dissertation the existing building under renovation.

Off-site: Refers to the place where activities are carried out for assisting the on-site construction.

Point Cloud: It is a collection of points that represent a space. Normally, these are gathered by 3D Laser Scanners. Several thousands are necessary for representing the facades.

Service robots: The International Organization for Standardization defines a “service robot” as a robot “that performs useful tasks for humans or equipment excluding industrial automation applications”. (ISO 8373). According to ISO 8373 robots require “a degree of autonomy”, which is the “ability to perform intended tasks based on current state and sensing, without human intervention”. For service robots, this ranges from partial autonomy - including human-robot interaction - to full autonomy - without active human-robot intervention. The IFR statistics for service robots therefore include systems based on some degree of human-robot interaction or even full teleoperation as well as fully autonomous systems (taken from [2]).

Structured and unstructured environment in robotics and automation: A structured environment is when a robotic device and the elements that interact with are located in a known position while an unstructured environment is when the elements are not known and not located in a known position.

Tolerance: In this dissertation, it refers to the positioning deviations that an element or module has in regards to the planned position.

Total Station: It is an instrument that is used for surveying and acquiring point on the (built) environment.

Working time: In this dissertation, it refers to the necessary time that operators must spend to refurbish a façade. It spans form data acquisition to final finishings and it is measured in hours per square meter (h/m²).

1 INTRODUCTION

The remainder of the research presented in this dissertation focuses on developing automation and robotics in façade energy-renovation with prefabricated modules to improve efficiency and safety aspects. In this introduction chapter, two points are addressed: 1) overarching motivation; and 2) dissertation structure. At the end of the chapter, some notes explain the authorship of the research presented in this paper.

Overarching motivation

Organizations such as the European Commission are seeking [3] to minimize the building's energy consumption to and [4] to improve the socio-economic and environmental aspects of the building stock. Envelope upgrading is necessary for the achievement of the Nearly Zero Energy Building (NZEB) [5]. To achieve this goal, it is a usual practice that existing buildings are insulated from the outer layer. Disturbances and obtrusion to the inhabitants should be minimized during the façade renovation process [6] and for that reason, a common strategy is adding a new insulating layer without tearing down the existing building façade. Adding a new layer onto an existing façade for insulation purposes is a technique with a rich historical background [7]. Moreover, multiple services can be added to the building envelope [8]. Lately, multiple renewable energy services are being added to the envelope which increases the complexity of the system [9].

Besides, data show that the maintenance, renovation and upgrading of existing buildings are gaining a bigger proportion of the construction sector in developed countries due to population growth stagnation [10]. In this situation, socioeconomic studies show that the refurbishment of existing buildings enhances the local economy [11]. According to the BPIE organization, there will be around 38 billion m^2 useful floor area in 2050 [12]. With this data, it can be estimated that there are 25 billion square meters of façade that need to be upgraded (during the lifetime of the building) in Europe to fulfil with NEZB requirements [13]. Therefore, there is a real need for upgrading building envelopes. Within that socio-economical context, the scope of this research is to find automated and robotic solutions for the façade upgrading with prefabricated modules while keeping the existing wall.

With current marketed manual techniques, façade renovation needs to be accomplished mainly on-site. For this reason, upgrading a façade is a dangerous task, because it implies working at heights. According to a study by Haslam *et al.* [14], falls from heights account for up to 55% of all fatal accidents and 38% of major injuries in the construction industry, as explained in a study conducted in the United Kingdom. Besides, according to Eurostat data [15], in the year 2016, 716 fatal accidents and 371,732 non-fatal accidents occurred in the construction sector. On the other hand, construction is a sector where many tasks are performed outdoors and under significant physical effort, which increases fatigue, as Chang *et al.* argue [16], and subsequently increases the risk of accidents. Moreover, according to Fellini [17], construction is not an attractive sector where young people would like to work, thus the workforce is getting older across Europe [18]. The decrease of active population or labor force in proportion to the rest of inhabitants can cause serious problems in the construction sector, where local nationals avoid to work [19], [20]. According to Jebens *et al.* [21], the elderly workers in construction are “more exposed to overload when performing heavy manual work”. To overcome these shortages, Leichsenring [22] suggests that new “life-long learning” and “technological approaches” are needed to improve the issues in the construction sector. For all the aforementioned reasons, robotics and automation might be a solution to avoid dangerous activities for the envelope renovation of buildings as euRobotics association remarks [23].

Another key point nowadays is the low productivity per worker hour in construction. The productivity index in construction has had a very low development in comparison with other industries [24], [25]. Therefore, improvements in automation can find a niche in the market. Besides, there is growing complexity in the construction due to new requirements that buildings need to fulfil [26]. For achieving an optimal building performance according to the standards, the stakeholders and guilds that participate in construction, in general, and building renovation, in particular, have multiplied [27]. For this reason, improving the current productivity avoiding time-consuming steps is a goal to gain efficiency during any construction process in general and in the renovation process in particular.

Automation and robotics can offer a solution to the lack of productivity. Actually, productivity is a key issue when marketing robotics for construction. The field of robotics in the construction industry was developed in the 1980s, mainly in Japan, during the assets price bubble [28]. Since then, some of the robotic systems are still in use, mainly in the prefabricated industry, and not so much in on-site construction [29]. There is an important economic implication when developing robotics for construction and Skibniewski [30] and Balaguer [31] already made approaches for quantifying that. The key, according to Warzawski [32], for adopting robotics and automation in the façade lifecycle depends on the economic feasibility of the developed techniques and, for that purpose, construction productivity must be higher when using robotics. Warzawski defined an equation for calculating the economic feasibility of robotics in construction. In that research, only 4 types of robots were considered.

The general hypothesis of this dissertation is that automation and robotization of building façade renovation with prefabricated walls is a solution for improving productivity aspects, explained in the previous paragraphs, while enhancing sufficient quality. To evaluate such hypothesis, this study presents five experimental approaches explained in chapters 5 to 9, as remarked in the next section. The results of these experiments can be used as a basis or criteria for further development in the field.

Dissertation structure

Within the context explained in the previous section, it is necessary to structure the research process. The topic of this dissertation is “*automated and robotic façade renovation with prefabricated modules*”. The first part of the dissertation (chapters 1-4) explains the overarching literature review and the general objectives and the conceptual framework. In this part, there is also an analysis of current technologies for façade renovation that considers which are the technologies, phases and steps that need to be improved. And with that data, in the second part of the thesis, (chapters 5-9) the empirical and experimental part of the study is presented. This comprises developed new concepts, achieved tests and the comparison to the analyzed cases. Moreover, future needs are outlined. To address the aforementioned needs, the chapters are articulated as in the next points:

- **Chapter 2**. Overarching Literature review. This chapter is an overview that shows the current techniques of façade renovation and the research carried out in the field of façade renovation with prefabricated modules. Besides, it explains the latest advances in automation and robotics in façade renovation and construction. The literature review outlines the general lack of the research of building façade renovation with prefabricated modules and remarks the need to define a novel research context or area. The overarching Literature Review is completed by the more specific and topic-oriented State of the Art in Chapters 5 to 9, as it will be explained later.

- **Chapter 2**. Objectives and Conceptual Framework. The overarching objective of the research presented in this dissertation is to gain efficiency during the renovation process of façades with prefabricated modules by using automation and robotics while achieving sufficient accuracy. Which parameters do the new solutions need to be solved and evaluated? Two of the main parameters considered for the analysis are accuracy and necessary working time. The field of robotized and automated façade renovation of existing building façades with modules requires a specific context and, for this reason, a novel conceptual framework and method is defined. It was considered necessary to define a conceptual framework that permits the analysis of the current steps of the façade renovation process and facilitates the development of automated and robotic solutions with prefabricated modules. Within this Conceptual Framework, concrete experiments must be carried out to improve productivity and enhance safety. This Conceptual Framework reflects and includes several research phases: Current Subcategories of the Façade Renovation Process, Research Gaps of the subcategories, Developed Novel Solutions by using automation and robotics, and Future Needs.

- **Chapter 3**. Analysis of the current techniques and Research Gaps. To narrow down the objectives, it is necessary to analyze the current techniques and have a benchmark for assessing the automated and robotic solutions developed for this dissertation. Before defining novel concepts and solutions, comparable evidence is needed and, therefore, an analysis of different case studies are explained in this chapter. To narrow down the topic, two types of modules or walls are analyzed in this chapter: a) timber-based modules; and b) aluminum-based curtain wall modules. Some cases refer only to manufacturing, some to complete building renovation processes and in the case of aluminum modules, to new buildings. At the end of the chapter, the selected Research Gaps that are covered within this dissertation are summarized.

- **Chapters 5 to 9**. Development of Novel Solutions. The dissertation does not focus on developing only one solution within the renovation process with prefabricated modules, but rather developing several necessities that aroused at the analysis. Each of the chapters covers a topic within the conceptual framework. There are several concepts (or hypotheses) that have been tested. It is necessary to remark that not all developed solutions have the same readiness level. At the beginning of each chapter, there is a brief finer state of the art and analysis to put some concepts, solutions and tests into context. At the end of each chapter, the Future Needs of the specific DNS are defined. In brief, these are the DNSs in each chapter:

- **Chapter 5**. Semi-automated Primary Layout Definition with a “Point Cloud”. One of the main barriers for marketing the renovation of façades with prefabricated modules is the excessive time used for data processing and design of the modules. A novel concept is presented which achieves a semi-automated definition of the layout of the modules and its synchronization with the CAM with the only input of the existing building façades’ Point Cloud and the coordinates of its points.

- **Chapter 6**. Partial routing and novel assembly sequence. Currently, a robotic assembly accuracy is dependent on the precision-routing-machining and the calibration of the elements that comprise the module. The concept presented in this chapter provides a minor increase of the machining of the elements of the current timber frame module and a design that facilitates robotic assembly.

- **Chapter 7**. Deviations and Adjustments during Robotic Assembly. Another problem in robotic assembly processes in the prefabricated module industry consists of the inaccuracies associated with picking and placing of objects. In the novel concept developed in this chapter, the deviated grasped object’s location is measured and possible deviations detected. The location of the deviated object is then calculated and compared with the planned location so the robot could divert from its original path and adjusting the pose.

- **Chapter 8**. Robotic Installation of Modules with a CDPR. This chapter presents the first achievements of a system based on a cable-driven parallel robot (CDPR) that host a set of tools on its platform named Modular End Effector (MEE) that is based on a robotic arm with different changeable end-effectors, a Stabilizer and a Vacuum Lifting System. This system was developed for the installation of unitized curtain wall modules (CWM) in new buildings, the prototype was not focused on building renovation. However, the issues and solutions presented in this chapter can be considered also for building renovation. The data gathered during prototyping were extrapolated to a real case of a building to study and evaluate the feasibility of the proposed system compared to the current traditional manual methods.

- **Chapter 9**. 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. Several tests are explained with special focus on a novel step-by-step process.

- **Chapter 10**. Compilation and Conclusions. In this final chapter, a compilation of the Future Needs, an analysis of the results, and conclusions are presented.

In *Figure 1*, the aforementioned phases of the research and the synchronization with the chapters is visualized.

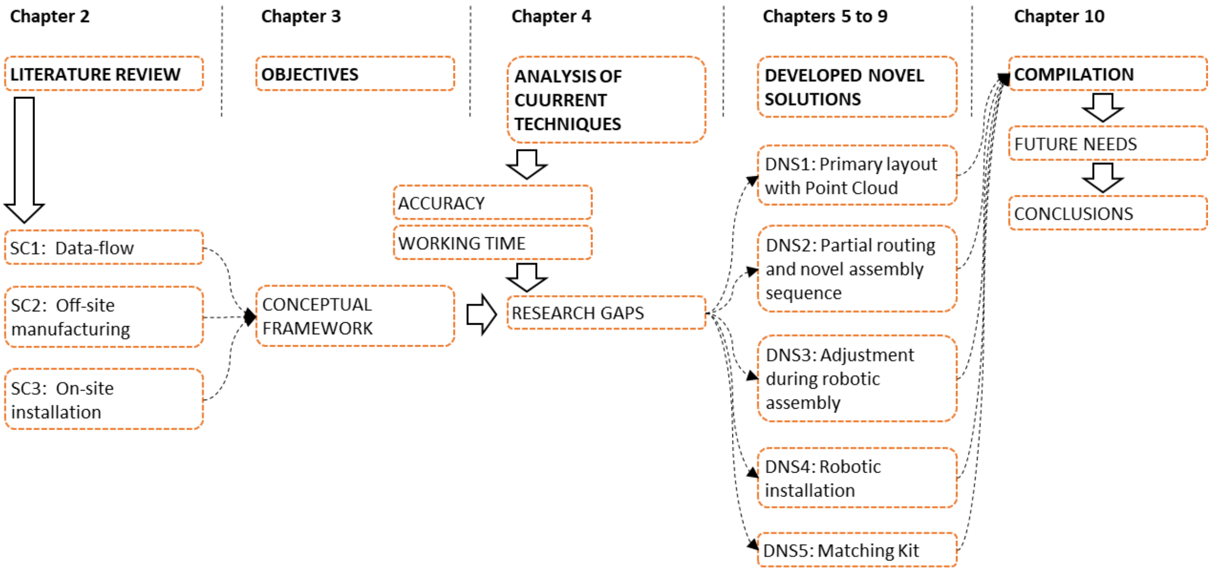

Figure 1: Research scheme.

Some notes need to be clarified. The dissertation is meant to be read in the linear sequence, as chapters are interrelated. However, chapters can be read independently, since the topics are linked but different.

Notes

The research explained in this dissertation, was fully developed and conducted by the author. However, this statement needs to be contextualized. The novel concepts and experimentation were carried out within the context of two European Horizon 2020 Research Projects: BERTIM (01.06.2015-30.05.2019) and HEPHAESTUS (01.01.2017-31.12.2020). On the other hand, the author of this dissertation has worked as a lecturing assistant since 15.10.2015 at TUM, Chair of Building Robotics and Realization. On his lectures, the topic of Automated and Robotic Renovation of Building Façades with Prefabricated Modules has been explained on the courses. The author of this dissertation has guided students on their coursework. Some definitions of authorships need to be highlighted:

- Chapter 2. The majority of the analysis was gathered during the projects. There is a table that includes images developed by students under the guidance of the author of this dissertation.

- Chapter 5 was developed aside the BERTIM project as work that was not foreseen in the Grant Agreement. Mr Taku Kinoshita assisted the author of this dissertation, especially with the coding in Python™.

- Chapter 6 was developed aside the BERTIM project as work that was not foreseen on the initial description of the project. The personnel, facility and material and resources of the POBI Industrie company [33] were used and the research was conceived and directed by the author of this dissertation.

- Chapter 7 was developed within the BERTIM project as work that was not foreseen on the initial description of the project. Mr Taku Kinoshita assisted the author of this dissertation especially with the coding in ROS.

- Chapter 8 was developed within the HEPHAESTUS project. The author of this thesis participated actively in the proposal of the HEPHAESTUS Project and in the first development phases. Later, the author of this dissertation developed the stabilizer, controlled manually the CDPR during the tests, and was in charge of the time assessment and accuracy of the CWM installation.

- Chapter 9 was developed within the BERTIM project as work that was not foreseen on the initial description of the project. For Test 4, the research was conceived and directed by the author of this dissertation and the personnel, facilities, material and resources of the EGOIN company [34] were used.

Further detailed notes are marked on chapters 5 to 9. Moreover, the majority of the figures are from the author of this dissertation. The use of external figures was minimized in order not to create any conflict regarding intellectual property. Every time a figure was created fully or partially by an external author, this is explicitly remarked in the figure caption or footnotes.

Apart from the Publication List provided, the research presented in this dissertation might be published as a Journal article before or after publishing this dissertation. Finally, it must be mentioned that the whole manuscript was language proofread by Oxbridge Editing. For the referencing, IEEE (version 2006[1]) style was used.

1 This version doesn't publish the DOI in the Reference list. Other Styles that included the DOI were considered, however these styles included the surnames and the year on the citation in the text, and in many cases led to confusion if the author had different citations from the same year. For this reason, IEEE (version 2006) was selected.

2 OVERARCHING LITERATURE REVIEW AND SUBCATEGORIES

The Overarching Literature Review, the content of which is partially explained in [35] together with the deliverables of the BERTIM project [36], encompasses three different topics. First, the current manual and mainstream façade renovation strategies and their deficiencies are remarked. Second, the most recent strategies to achieve façade renovation with prefabricated modules are explained. Third, the current research, the main subcategories for achieving an automated and robotic façade renovation process are explained and the main lacks are outlined.

2.1 Current manual methods for facade renovation

How façades are upgraded and insulated nowadays? Currently, there are two manual, on-site techniques, for adding a layer onto an existing building. The most common is the External Thermal Insulation Composite System [37] (see Figure 2). This technique requires cutting the insulation on the site, fixing the insulation with special nails to the existing wall and applying several layers of glue and mortar on top. Some pathologies related to hygrothermal behavior have been appointed [37], [38].

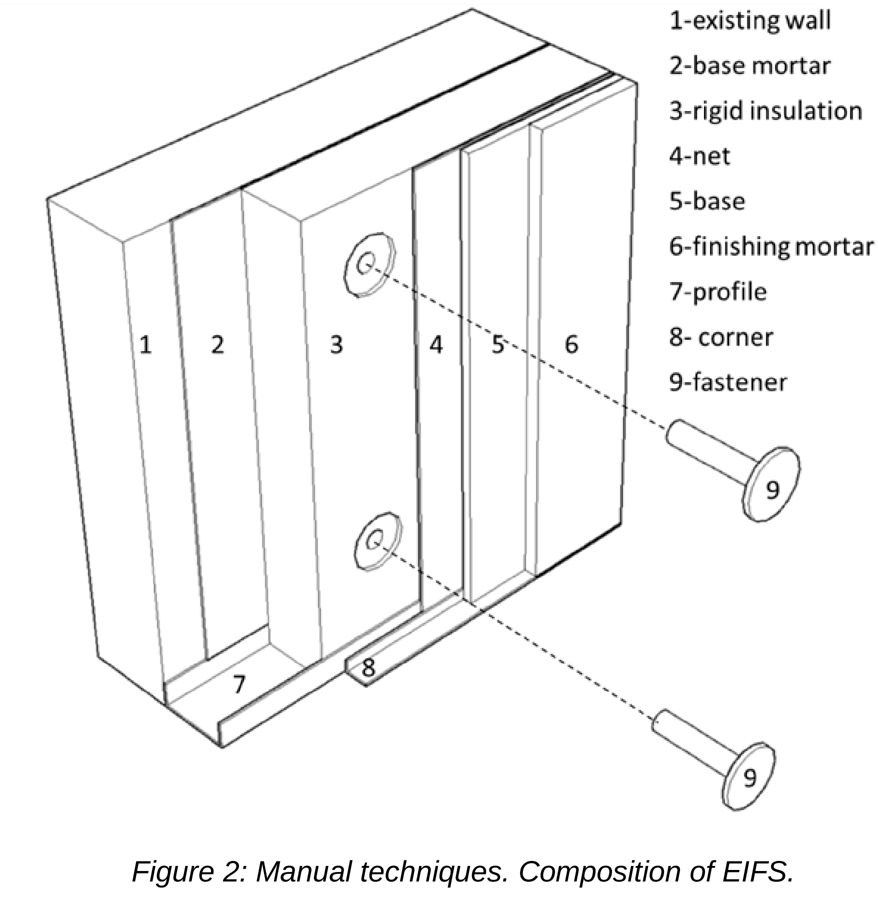

Figure 2: Manual techniques. Composition of EIFS.

Another common method is the rain-screen or ventilated façade [39], [40]. Connectors and rails are placed first and, in between, the insulation is fixed to the existing wall. To cover that, the outer layer is fixed to the rails. The outer layer normally requires precutting off-site (*Figure 3*).

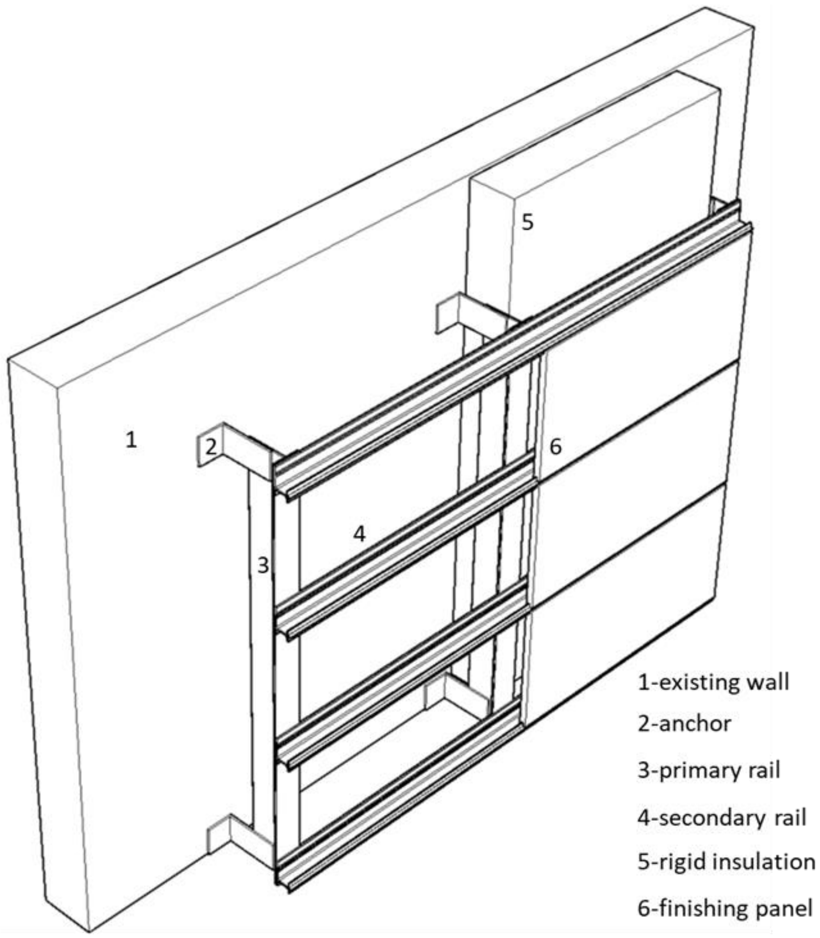

Figure 3: Manual techniques. Rain-screen.

The elements described in *Figure 2* and *Figure 3* have some requirements for being installed. Every construction site is different when working in building renovation, but in *Figure 4*, current generic installation needs, logistics and handling devices are shown. Most of the time, scaffolding and/or platform-cranes are necessary. Usually, the storage of material, such as mortar, boards and insulation occur in the adjacent areas of the building, obstructing the sidewalks and roads. Moreover, the building users suffer from darkness due to covering the windows, noise and dust during the works and lack of privacy, which can extend to weeks or months [41].

Figure 4: Manual techniques and logistics (Images courtesy of Artzamendi Eraikuntza S.L.).

Both ETICS and rain-screen techniques require intensive work on-site. The productivity of such techniques was evaluated in a previous analysis [42], [43], where the working hours per installed square meter were reconsidered. On the other hand, databases have collected the working time per square meter of the necessary tasks to be achieved [41], [44]. In any case, the installation of ETICS and rain-screen is in the region of 3 working hours per square meter, without considering the time needed for the scaffolding, which takes around 0,20 h/m², and reception and disposal of materials (see *Table 1*).

Table 1: Worker time required for ETICS [41], [44].

Task	h/m²
Profile bottom	0,01
Profile top	0,01
Profile vertical perimeter	0,06
Base mortar	0,65
Rigid insulation	1,00
Glassfyber net	0,12
Mortar finishing	1,00
Painting	0,30
TOTAL	3,36

To install ETICS and ventilated façades, there is a need for auxiliary devices which are also part of the final cost of the façade or envelope upgrading. Moreover, there are preliminary tasks that need to be achieved, such as the removal of old mortar and damaged windows (see *Table 2*) [45]. All these points have an impact on the efficiency of the façade upgrading process.

Table 2: Costs of different points during renovation processes [41], [44].

Support devices	Approx. cost	Unit
Self-standing scaffolding	6-8 euro	Façade square meter per four weeks
Tower crane	1200-2800 euro	One unit per month
Hoists	1592-3132 euro	One unit, per four weeks
Aerial work platform	50-210 euro	One unit per day
Removal costs	**Approx. cost**	**Unit**
Complete wall	34-360 euro	Wall square meter
Window removal	17-11 euro	Window square meter
Wall finishing removal	6,90-22 euro	Finishing square meter
Element costs	**Approx. cost**	**Unit**
EIFS, complete external system, no support	57-94 euro	Wall square meter
Ceramic rain-screen	112-157 euro	Wall square meter

To avoid the inconveniences created by the on-site manual procedures with ETICS and rain-screen, prefabricated solutions have been developed to install them onto existing buildings' envelopes [46], [47] as explained in the next sub-chapter.

2.2 Current façade renovation with prefabricated modules

The idea behind prefabrication is to avoid on-site tasks as in *Figure 4*. The prefabrication degree depends on how finished a module is. In other words, the higher the prefabrication degree, the less rework or extra work is necessary on-site. Ideally, a fully finished façade should not require any further work after the module is placed in its location. The benefits of prefabrication are widely explained by several authors [48], [49]. Studies were made to analyze the prefabricated timber manufacturing and installation processes and its management [50]. Unfortunately, fully prefabricated installation of modules is not a goal that has been achieved in renovation processes, as there is always a final task to finish after the modules are installed.

The prefabricated module, manufactured off-site, consists of several items and elements, such as a frame that rigidizes the module, insulating material, waterproof and humidity barriers, windows, and even services such as renewable energy sources (RES) [51] and mechanical active climate actuators [52]. For this reason, the prefabricated modules need to reach low geometrical tolerances to fit not only all the water and air barriers but also service and ducts together [53]. *Figure 5* and *Figure 6* show the module type that was used for the BERTIM project, based on a timber frame [42], [54] which is anchored to an existing wall by connectors.

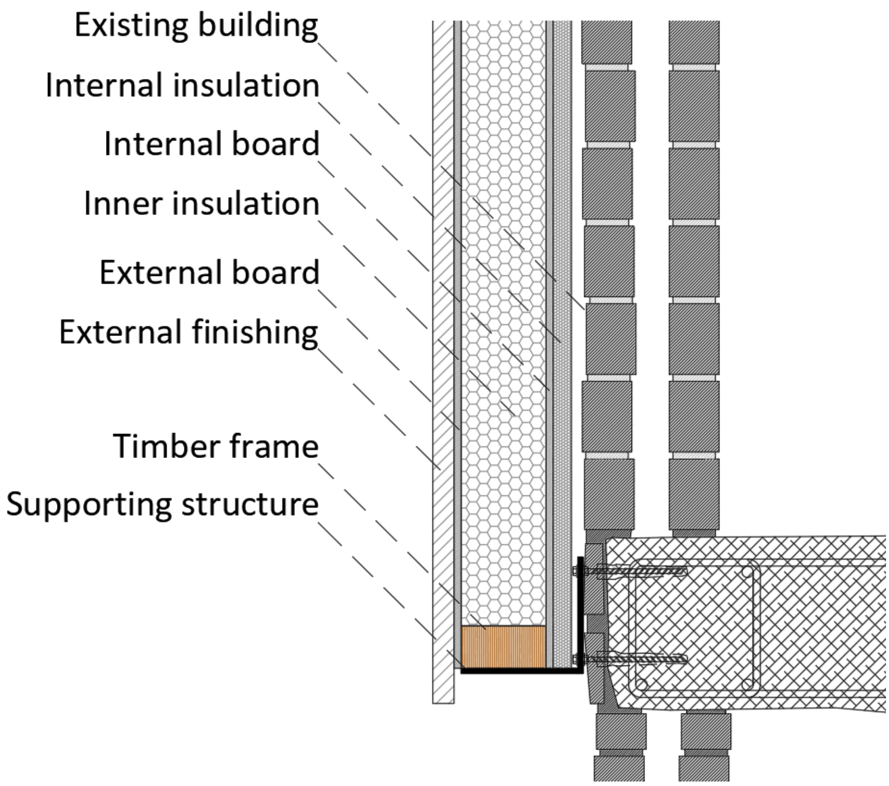

Figure 5: Cross-section of the prefabricated of modules as in the BERTIM project[2].

The renovation process with modules has probably focused on external vertical envelopes because it is the simplest element in the building, compared, for instance, with building roofs or interiors [55]. Simple façades can be considered as 2-dimensional geometries and that facilitates and simplifies data acquisition, the definition of the standard object, manufacturing and installation. Previous studies focused on the renovation of timber structure of old buildings [53] but during the decision-making process (see decision-making process in APPENDIX 5: Stability of the cable robot platform), it was concluded that this issue was too convoluted due

2 Window and roof details were not that developed.

to geometrical complexity. However, the installation of façade modules can also be more complicated due to obstacles such as trees, traffic signals and the variant floor types that impede a correct performance of the cranes and handling devices. Handling and logistics differ from manual procedures. Mobile cranes and storage spaces are necessary for short periods. Moreover, the off-site manufacturing and on-site installation processes require (re)adaptation to the existing building's circumstances.

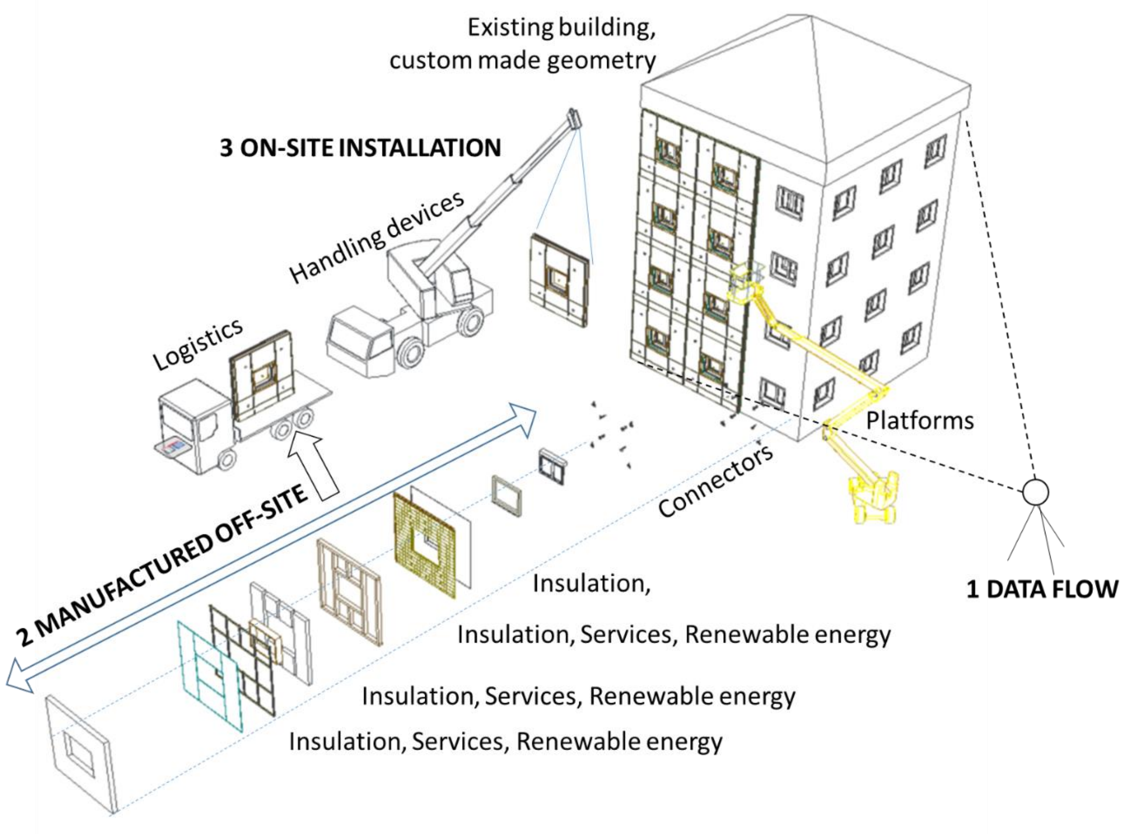

Figure 6: Scheme of the prefabricated installation of modules as in the BERTIM project [42].

In new building erection, Landin already warned that the more industrialized and prefabricated a building module is, the more serious the tolerances need to be minimized [56]. Façade installation, in general, requires accuracy if no rework is desired after installing the panels. Vastert analyzed several cases for concrete wall prefabrication [57] and concluded that the manufacturing tolerance is approximately a "few millimeters", whereas the installed position of the walls might differ by approximately 11,5 mm. The analyzed project did not install fully finished walls, and they needed rework. In another study about concrete panels erected in Eastern Europe, it was concluded that the façade walls were not cladded and reworked and, for this reason, the inaccuracy of the panels allowed the penetration of water into the building interior [58]. So, the stigma of the prefabrication is not around the disposition of materials (design), but around the accuracy of the different materials on the wall. These issues are solved in the standardized Japanese prefabrication industry by following a strict modularization and size standardization [59]. Finally, half of the defects in module prefabrication happens in off-site prefabrication [60], therefore, it is necessary to consider the prefabrication process as a source of possible errors.

Besides, cranes need to be balanced horizontally to operate and avoid overturning (see *Figure 7*). Moreover, the complex geometry of certain buildings is also inconvenient to adapt the modules to the existing geometry [36].

Figure 7: Issues while installing the modules in the BERTIM project [36].

Relevant façade upgrading projects

Building external wall renovation with prefabricated modules dates back to the 1980s in Japan [61]. During this period, the most relevant building renovation project was carried out at the Osaka Merchandise Mart (OMM) building during 1987 and 1989 [62]. In this project, a second skin was added to the existing building, separated from the initial one at about 700 mm, and creating a Double Skin Façade [63]. To achieve this, during the first phase, a connector was fastened to the structural slab which penetrated the precast concrete wall. These connectors were accurately placed by using a laser alignment system; a Total Station was used to place the connectors onto the existing building (see *Figure 8*). Thereafter, the intermediate or in-between secondary steel structure was placed. During the second phase, the unitized or prefabricated curtain wall modules were installed. According to data collected by the curtain wall company (YKK AP [64]), the daily installation rate per worker during the first phase was 3.2 m^2, and 2.6 m^2 during the second phase. If the working days consisted of 8 hours, 2,5 to 3,07 working hours were necessary for each square meter without considering the manufacturing process[3]. This project can be considered as a benchmark owing to the high prefabrication as well as the digital adjustment and placement of connectors onto the existing building.

3 Compared to European systems, the curtain wall needs to be supported in 4 points to provide more stability and prevent damages caused by earthquakes.

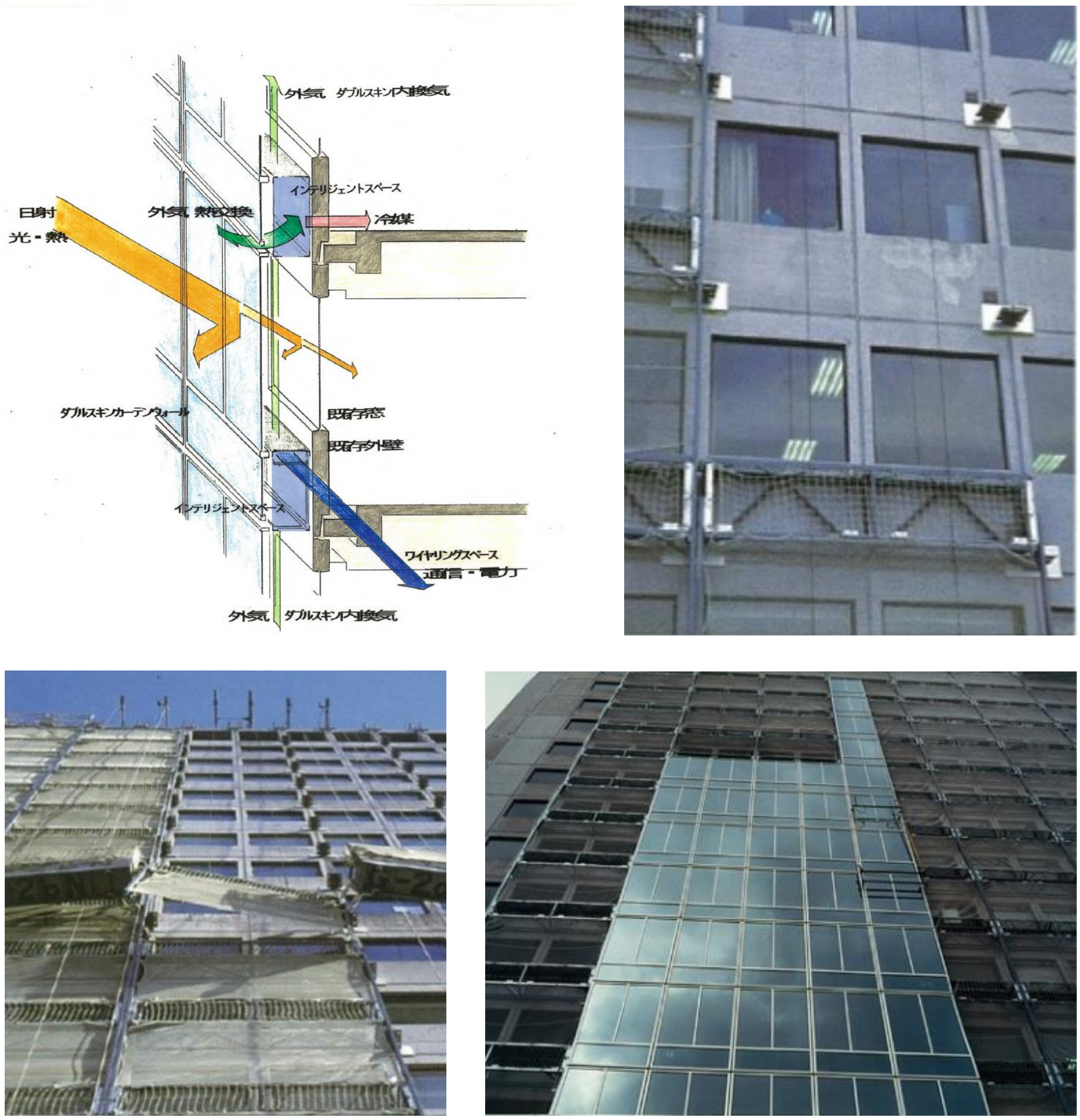

Figure 8: OMM building renovation. Top left: the concept of the attached new envelope. Top right and bottom left: installation of the sub-structure onto the existing building with anchored connectors. Bottom right: placement of CWM. Images courtesy of YKK AP.

Similar projects were carried out years later in Switzerland [65], the Netherlands in 2001 [66], Spain in 2005 [67] and France in 2011 [68]. The architects, Lacaton & Vasal, were awarded the Mies Van der Rohe prize in 2017 for a project in Bordeaux [69]. In this project, a complete new livable layer was added to an apartment block.

The aforementioned projects were achieved mainly by using aluminum curtain walling techniques. However, there are some examples of timber modules for façade renovation. One example of using a timber-based curtain wall system with highly routed and machined elements was the renovation of the Basque-Navarrese Chambers of Architects’ headquarters in Bilbao [70].

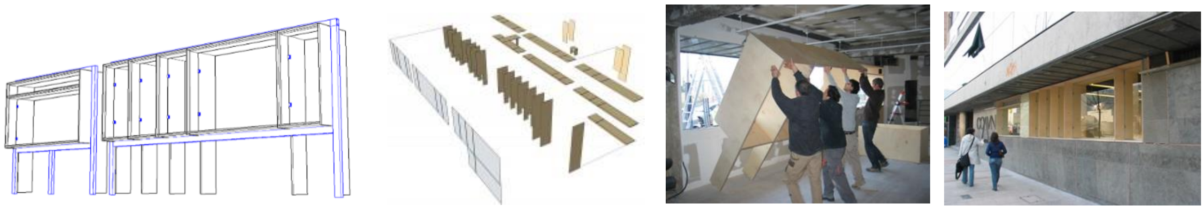

Figure 9: Fully routed elements for façade renovation in timber. Chambers of Architects in Bilbao. Metak Arkitektura, Facade designed by the author of this dissertation,2008.

However, an impediment in achieving such concepts is that the price of these façades, which can reach up to[4] 3000 €/m², are higher compared to a common façade renovation with ETICS and rain-screen (90-200 €/m² [41]). Additionally, these types of curtain walls have plenty of assembling peculiarities and expertise are required to assembly them; hence, it is difficult to automate the process.

European research projects for renovation of building stock

Apart from the relevant projects, in the European context, several publicly-funded projects were and are being carried out to retrofit the built environment and reduce energy consumption. There are two main types of projects. On one hand, projects that focus on data and managerial processes. In the field of management, the main goal is to reduce steps, simplify and improve cost, advice, and decision making (see APPENDIX 2: European Projects for Management). On the other hand, some projects deal with new technological devices that are added to the existing building (APPENDIX 3: European Projects). Sandberg et al. [71] gathered several research projects that aimed at improving the traditional building renovation methods.

One of the first research projects dealing with prefabricated modules were Annex 50 [72], GEDT (*Großelement-Dämmtechnik mit Vakuumdämmung*[5]*)* [46] and TES [47]. There is research in the extensive literature regarding these projects; remarkably, D'Oca *et al.* focus on the technical, financial, and social barriers but conclude that excessive investment costs are the essential problem [73]. They found that the main barriers of the projects were the process of getting a BIM model from the Point Cloud (information workflow); the speed of the mounting (i.e., installation process); sizing of the prefab elements (dimensioning of the layout); and gauging in practice (measuring). Recently, Du *et al.* listed developed projects with modular façades [74].

As an example of the objectives marked by the European Commission, the H2020 EE-01-2014 call named 'Manufacturing of prefabricated modules for (energy) renovation of buildings' [75] defined the next main requirements:

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4 Data taken from the project explained in [70] by the author of this dissertation.

5 In English "Large module insulation technology with vacuum insulation".

- Use prefabricated modules. It must be said that there is an underlying objective to integrate energy efficiency devices and renewable energy sources in the prefabricated multi-functional modules.

- Use advanced computer-based tools for integrating the value chain over the life cycle of the project.

- Move from individual manufacturing to mass production. A more accurate term would be mass-customization [76].

- Reduce the installation time by at least 30%, compared to a typical renovation process for the building type. This term must be defined more accurately. In this research, we compute or determine the total time of re-design, manufacturing and installation processes. And that time should be lower than the traditional methods.

- Reduce costs. This is related to the manufacturing and installation processes.

- Ensure quality.

- Facilitate dismantling and re-use.

- Improve on-site health and safety during manufacturing and installation.

In the aforementioned research projects, in general, lead time has not been measured thoroughly as a key point. For the research presented in this dissertation, a consultation was made with the responsible people for the projects. The objective was to get information about the productivity and especially the lead time of data acquisition, manufacturing and installation processes. The answers were very few[6] and productivity and time consumption were not addressed thoroughly. There are exceptions, though. In project named *GEDT,* a novel connecting system was developed [77], to place almost fully prefabricated modules. In this case, the accuracy was a must in order to create a vacuum and a tight enclosure. However, in the test conducted in 2007 [46], the connector system itself was too complicated and one hour was necessary to install one prefabricated wall[7]. Finally, in the project TES, it was already reported that "*Time and practicability factors are central to achieve economic advantages and positive social impact*" [78].

In conclusion, regarding time consumption, there is a lack of monitoring and analysis. Without this analysis, improvements cannot be appointed and, as a consequence, the solutions cannot be massively marketed as expected.

6 Only two project coordinators answered and the answers were very generic.

7 First, it was necessary to present the module to the connector placed in the wall and after that marking the holes in the module.

2.3 Subcategories of automated and robotic façade renovation with prefabricated modules

In previous research within the BERTIM project, there was a survey and consultation to prefabrication industry stakeholders [42] (See APPENDIX 4: Scheme of the Questionnaires). In brief, the survey explained the potential use of robotic and automated technologies for the manufacturing and installation processes. As a conclusion of the survey, the stakeholders considered valuable any novel solution, as long they improved productivity and efficiency. Moreover, the façade renovation was deemed more suitable for robots because the working environment is almost 2D. In this research, three main subcategories (SC) were considered for the automated and robotic building renovation with modules: i) data acquisition design, processing and information workflow; ii) off-site manufacturing; and iii) on-site installation [79]. These concepts are further explained in the next sub-chapters[8].

SC1: Data acquisition and processing, design, and data flow

Façade upgrading with prefabricated modules requires more effort and resources than manual procedures regarding data acquisition, design processes and data flow.

On-site manual procedures do not require previous accurate geometry data of the building since the material is cut on-site just after the operator measures the specific part to be covered. On the other hand, façade upgrading with prefabricated modules requires accurate measurement of the existing building to manufacture with low tolerances and fit the module exactly on its place. According to Volk *et al.*, data acquisition of the existing building is achieved by image-based (photogrammetry) range based (laser), or manually with tapes [80].

On the other hand, compared to manual on-site procedures, façade renovation with modules requires a detailed design. Moreover, building renovation requires custom-made solutions. It is, therefore, necessary to conceive a highly customizable 2D module that is adaptable to the majority of the targeted building typologies and their geometries (see *Figure 10*) [42], [53]. Kobler *et al*. [81] defined readymade designs or a library of solution. To reduce the load of design or adaptation work, the design process needs to be automated thanks to standard modules that need to be parametrically adaptable to given physical conditions of the building [79]. Several platforms facilitate this possibility through algorithmic modelling [82], [83]. Furthermore, when it comes to simple walls, such as the ones used in *Figure 6*, there are commercialized solutions for walls like Dietrich's© [84] solution.

8 Uninstallation and dismantling of the modules are not considered as a subsystem, though, it needs to be considered as an efficiency parameter of the rest of the categories.

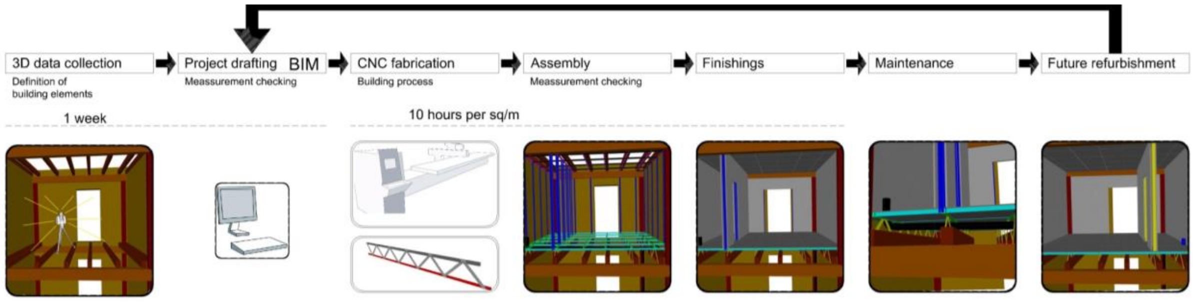


Figure 10: Preliminary schemes presented in ISARC 2012 [53].

Besides, there must be defined information or data flow between data acquisition and processing, design, manufacturing and installation processes. In 1988, Kodama [85] already reported issues and challenges regarding the link with the CAD/CAM information, in other words, the information workflow. This topic was appointed by several authors [46], [47], [86], [87]. However, the information workflow was mainly manual and data needed several transformations for being used in different software environments. As a further step, a fully automated information workflow named RenoBIM was conceptualized in the BERTIM project [88]. In that context, further studies were carried out [89] (see scheme in *Figure 11*) but the final output did not successfully achieve the necessary automated sequence.

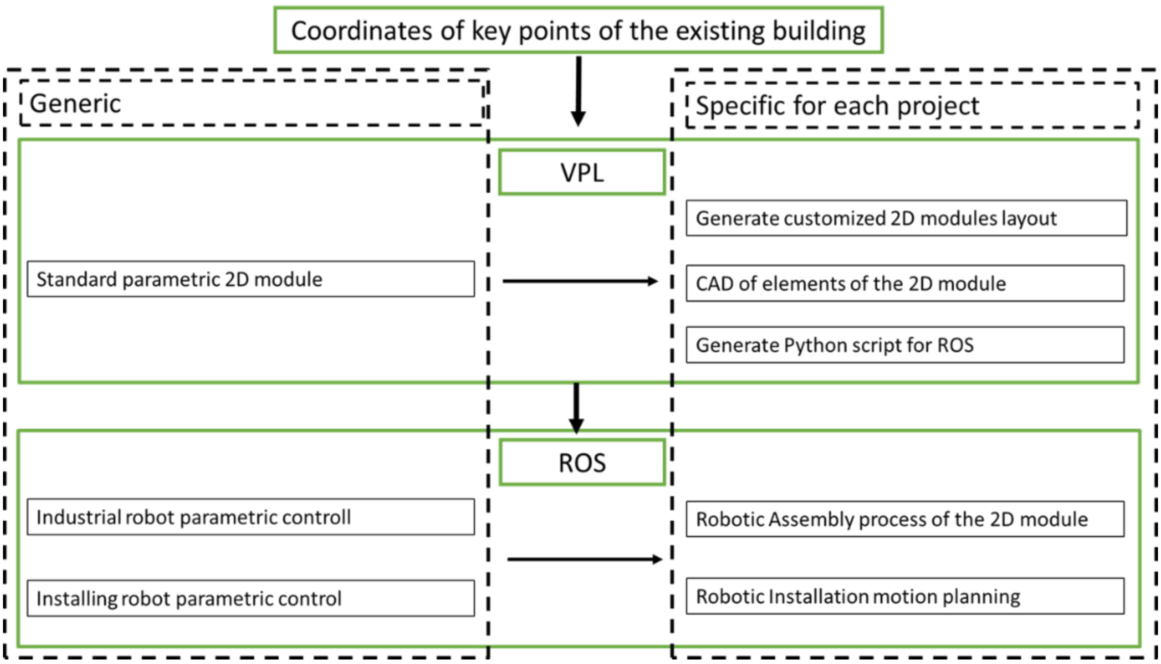


Figure 11: Scheme for an automated information workflow developed in previous research [89].

As a part of the data flow, it is important to remember that after the design, data needs to be implemented in the existing building envelope. Marking the key points on the existing building wall is necessary to check the correct position of the modules during the installation process [46], [47]. Difficulties to implement an accurate element on an existing building and the need to find a customized element were already reported in previous research [90], [55], [53]. If the information workflow is not achieved successfully, the modules are installed in a non-planned position.

Aldanondo developed a BIM-centered process from existing building description to final installation of the module [91]. In other previous research, the BIM was created from the data of Point Cloud [47] and, after that, the modules were designed on top of the BIM modules. However, effort reduction in acquisition, processing, recognizing and creating a BIM is necessary [80]. This is a time-consuming and manual process. Automation in data processing and design is necessary because in the future, more and more elements will need to be defined in the prefabricated modules. In that sense, the parametric and automated design are already services that marketed software already provide [92] and the proper use of this tools can prevent time-consuming activities while defining the modules.

Aforementioned topics reinforce the idea that it is necessary to improve the data acquisition and processing, design, and information workflow techniques.

SC2: Off-site manufacturing processes

Prefabricated module manufacturing is a topic that has been thoroughly explained in previous research [93]. Some of the techniques are implemented in the market and robots are used for the assembly, especially in the Japanese market and in companies like Sekisui Heim [59], [29]. Prefabrication fits with standardized dimensions like the tatami measurement system [94] but building renovation requires bespoke modules and this affects the manufacturing process. On the other side, robotic assembly normally requires structured environments and that might be complicated when manufacturing bespoke modules. In the European context, some companies have developed prefabricated lines in timber, aluminum, concrete, brick and steel [93].

On the other hand, non-standardized prefabrication has been developed for achieving complex building shapes by using parametrized design, CNC technology and robotics [95], [96], [97], [98], [99].

Within this context, some issues need to be addressed on the bespoke production and assembly of modules.

- Depending on the constructive system**,** tolerances bigger than 10 mm can be considered as production errors. Robotic assembly is not necessarily more accurate, and accuracy issues during assembly have been reported in the robotic assembly [100]. In 1988, Kodama [85] already reported issues and challenges that are still necessary to solve regarding accuracy. In current reports, it has been described that accuracies in timber-based prefabricated modules range from 5 mm [47] to 10 mm [43] for modules around 3 meters by 3 meters. As a solution to these inaccuracies, all the objects of the prefabricated modules, should be contoured in a CNC machine and then robotically assembled to create a façade module [90], [101], [35], as shown in *Figure 12* (Developed for BERTIM [36]).

- On the other hand, improving accuracy in manufacturing processes might be an issue if concepts such as mass customization [102] need to be implemented. Similar to the aforementioned manual processes, the question is if the effort to get a millimeter-accurate module would increase the whole manufacturing processing time and, therefore, harass the feasibility of the solution [43]. To prove the manufacturing layouts, software such as Process Analysis [103] offer easy to handle simulations**.** However, these studies require some input data such as the routing time of the timber studs and boards. Without this data, it is difficult to predict whether the machines were under-used or not and if the line would be balanced and optimized. Therefore, there was a need for defining a benchmark for each of the processes and it was necessary to monitor each of the activities for manufacturing the timber frame.

There are studies focused on how to optimize the precast concrete wall production [104] and productivity analysis of timber prefabrication companies [101] but there is lack of data on the accuracy of the output and time consumed during the manufacturing and assembly of prefabricated modules.

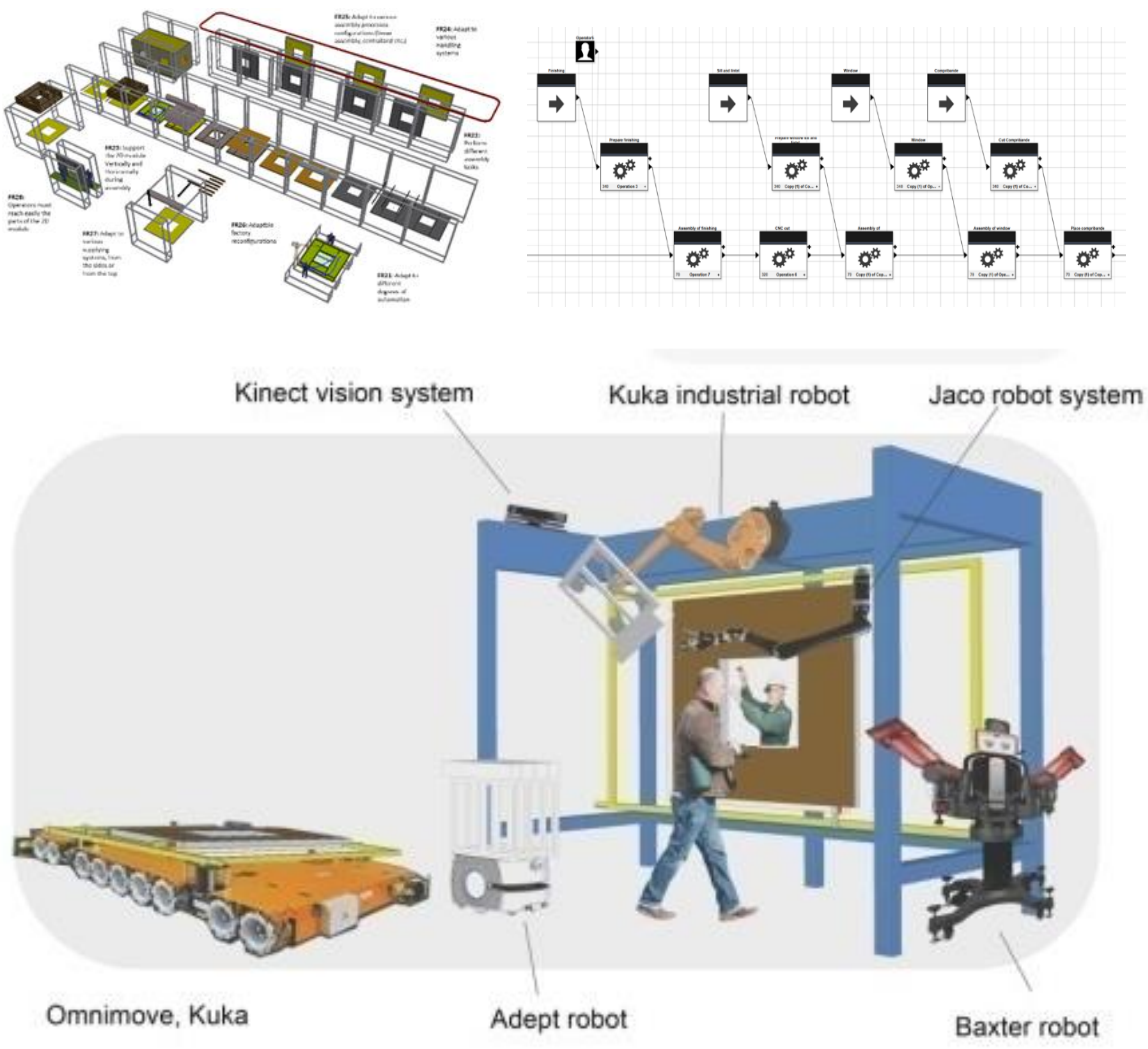


Figure 12: Schemes for fully automated production of timber-framed modules.

Therefore, a further study is necessary to check how to improve the current manufacturing processes. Based in previous research, there are two main issues that need to be addressed:

- To define where the limit of an optimal balance of routing in a CNC and assembly line is. and to check if CNC manufactured element assembly is more accurate
- To determine which are the impediments faced by the robotic assembly of customized modules.

For all the aforementioned issues, a further analysis and development is necessary.

SC3: On-site installation process

Different robots for installing, painting, cleaning, delaminating, maintaining and inspecting any kind of façade were developed in the past [105]. More specifically, several robotic devices have been classified for façade module installation [35]. Besides these single-task robots, on-site factories like ABCS [106], Fujita [107] and SMART [108, 109] developed techniques for installing fully prefabricated façade modules during the erection of new buildings.

Apart from façade modules, there were experiences in the on-site assembly of walls like in the Rocco project, in this case, for assembling building blocks [110], [111]. Lee *et al.* [112] developed a robot on top of a platform that helps the human operator handle a CWM. Removal of mortar and ETICS is also a task that has been approached [113]. Another instance of the installation of a façade module with a robot is a manually operated robotic crane [114]. Test results show that in the worst-case scenario the achieved repeatability of handler end-effector positioning is 7.0 mm. This result might not be sufficient for the installation of prefabricated modules.

It can be concluded that the support system is not accurate and stable enough to carry out the works with the required accuracy. It was detected that a multipurpose end effector is necessary to correct the deviations of the support system [115]. Therefore, it can be stated that there is a need for using two systems for achieving such tasks as previous research already detected [116]. It is necessary 1) a support system for rough positioning and 2) an attached fine positioner and task performer (see *Figure 13*).

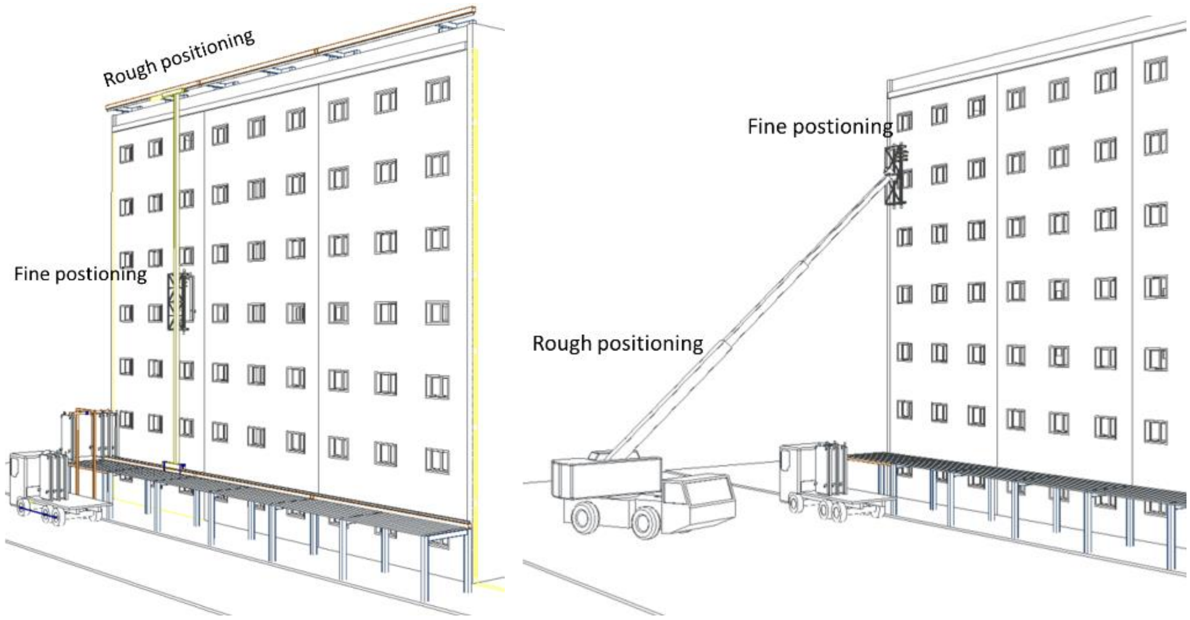


Figure 13: Rough positioning and fine positioning with different support systems.

Regarding the rough positioning and supporting system, previous research included an analysis of different devices that compared systems for installing façades automatically and different types of robot bodies were already envisioned [117], classified and evaluated [118]. In the latest research, the classification was further detailed as shown in *Table 3* and *Table 4* (see also [35]). However, these developments and evaluations were weak and the solutions were only based on simulation and, therefore, no real experience and no real results could be gathered (see *Figure 14*).

Table 3: Classification of supports and rough positioning in façade renovation [35]*: supported with cables.*

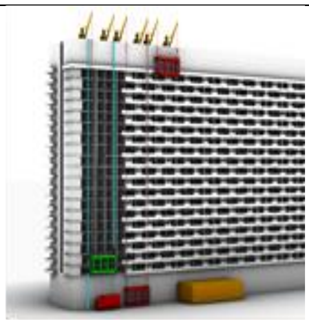
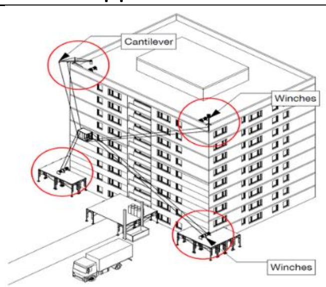
Support with cables		
		
Gondola type Image by Matteo Carotta under the guidance of the author of this dissertation.	Cable robot Image by Marcel Schlandt under the guidance of the author of this dissertation.	Hanging robot Image by David Habermann under the guidance of the author of this dissertation.

Table 4: Classification of supports and rough positioning in façade renovation [35]*: cranes and other types.*

<table>
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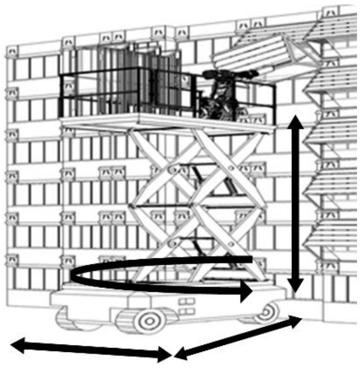
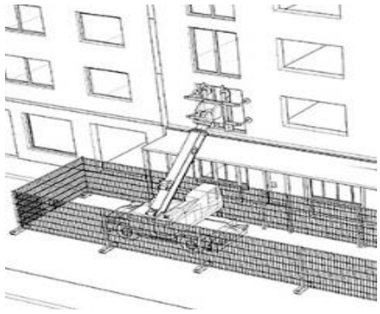
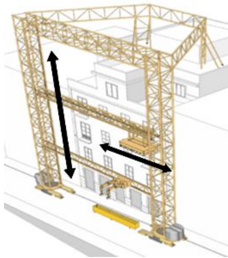
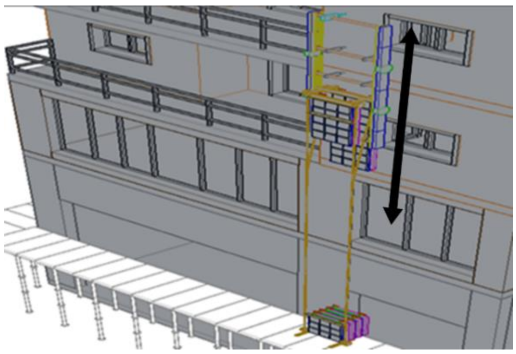
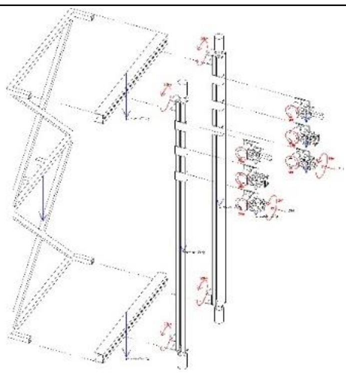
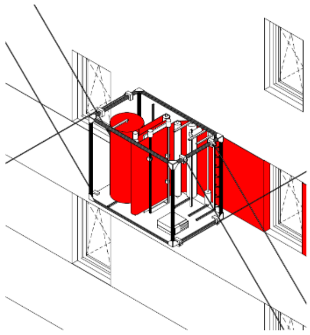
<tr><td colspan="2"></td><td colspan="2"></td><td colspan="2"></td></tr>
<tr><td colspan="2">Scissor platform. Image by Ziyu Liu under the guidance of the author of this dissertation.</td><td colspan="2">Container handler.</td><td colspan="2">Mobile crane. Image by Karl Greschner under the guidance of the author of this dissertation.</td></tr>
<tr><th colspan="6">Axial movement cranes</th></tr>
<tr><td colspan="3"></td><td colspan="3"></td></tr>
<tr><td colspan="3">Vertical bridge crane.</td><td colspan="3">Image by Diana Mejia, Thomas Haseneder, Yana Shcherbakova, Lars Hühnken, Annika Reiter, Troy Thompson and Daria Glebova under the guidance of the author of this dissertation.</td></tr>
<tr><th colspan="6">Other types</th></tr>
<tr><td colspan="3"></td><td colspan="3"></td></tr>
<tr><td colspan="3">UAV Image by Alice Cluzeau-Tomatis, Ilaria Giacomini, Florian Hirschel, Leyang Zhang under the guidance of the author of this dissertation.</td><td colspan="3">Climbing robot.</td></tr>
</table>

As a result of the analysis, it was concluded that a more solid background with real tests was necessary to evaluate the capabilities of robotic support systems. In that sense, the HEPHAESTUS project [119] determined some challenges for the installation of façade modules [120].

Regarding the tools for achieving these tasks, there have been several approaches in the construction sector. Three types can be highlighted: a) robotic arm [121], b) Cartesian system [115], and c) special systems [122] (see *Table 5*). In that sense, there are already robots that are used for painting or insulating in the market [123] and P2Endure [124].

Table 5: Classification of fine positioning and working tool.

		
Robotic arm. Image courtesy of nLink [121].	Cartesian system	Special systems. Image by Marcel Schlandt and the author [122].

Apart from the rough positioning and fine positioning systems, there are some other issues to consider regarding the robotic installation of modules:

- The controlling system has special importance. Previous research based on ROS [125] simulated the path control of some of the aforementioned devices (see *Figure 14*).
- It has to be noted that robotic installation requires specific conditions. The process explained in the GEDT project [126] would be quite difficult to be carried out by robotic systems, due to the complexity, especially of the connector. To get the required low tolerances and not to spend extra time, it is necessary to create a construction system that increases the accuracy of the placement, as well as facilitates the operations of the robot. Moreover, the accuracy of both systems might force the adjustment of the compliance design of the modules, that is the Robot Oriented Design (ROD) concept [127] might be necessary to be applied. According to ROD, a connector or anchor must be designed after analyzing the capabilities of the accuracy of a given robot.
- On-site, the relative accuracy between the fully prefabricated modules on the final on-site position has major importance. Construction is always an unstructured environment, where the elements are not placed in a known position by the robot. The object’s location changes while being handled by the robot and there might be errors while grasping by the end effector tool.

- Finally, logistics have been developed and marketed [128].

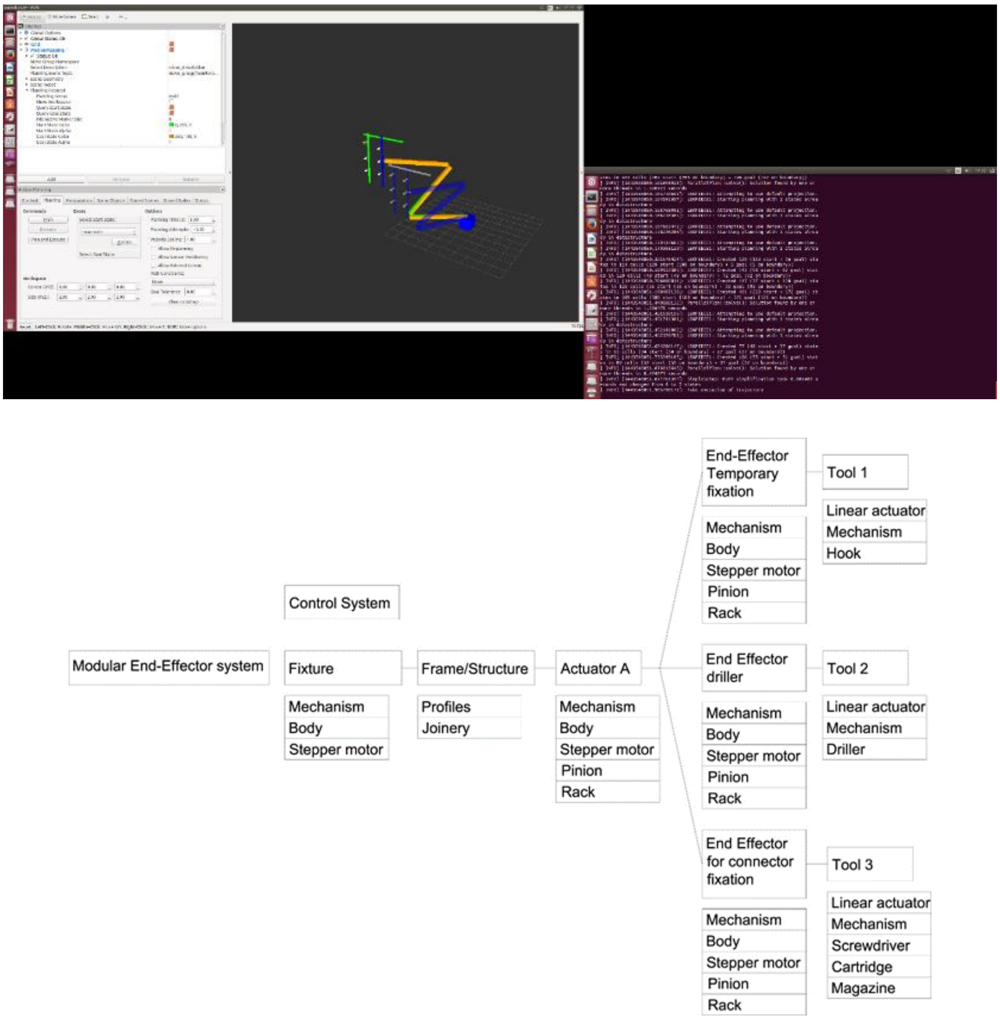


Figure 14: Simulation and Control in ROS [118].

In this subcategory of installation with robots, as in the previous subcategories in SC1 and SC2, there is a lack of data in regards to the accuracy and performance efficiency of the developed systems.

3 OBJECTIVES AND CONCEPTUAL FRAMEWORK

Different stakeholders that participate in building envelope renovation agree that façade upgrading with prefabricated modules needs to be more efficient [43]. There is a common background that is seeking for a more automated process to achieve a safer and more efficient process. However, it needs to be highlighted that regardless of the effort achieved in the aforementioned research projects (see APPENDIX 2: European Projects for Management and APPENDIX 3: European Projects), the renovation of building envelopes with modules has no taken off, as expected. As a significant fact that reflects the situation, the recent research project call of the European Commission [129] was asking to:

a) *"Demonstrate retrofitting plug & build solutions and tools reaching NZEB standards suitable for mass production by industry for buildings under deep renovation."*

b) *"Decrease of retrofitting time and costs by at least 50% compared to current renovation process for the same building type."*

These points bring to light that there are still gaps that need to be solved in the field of building renovation with modules. Point a) exposes that there is still the need for mass-customization [102]. Moreover, point a) also shows the need for accuracy, as plugging services require fitting the modules with lower tolerances to guarantee fluid transmission for services and airtightness and waterproof conditions [36]. On the other hand, point b) exposes that the "*current renovation process*"[9] is more feasible, competitive and efficient[10] than the methods using prefabricated modules.

3.1 Objectives

As explained in chapter 2, there have been advances with more or less successful try-outs to reduce the lead time by automating the process [74]. But the conclusions that can be outlined from the literature review in chapter 2 match with the facts that reflect the call of the European Commission [129]. Prefabrication, automation and robotics in the field of building renovation still need to solve issues to be feasible, efficient and, in the end, marketable.

The overarching objective of the research presented in this dissertation is the reduction of working hours to be more efficient than manual procedures and, therefore, reduce obtrusion during the renovation process of façades with prefabricated modules, by using automation and robotics while reducing risks of accidents. It is another explicit requirement of that objective that quality in terms of accuracy should be achieved.

9 It is supposed that the EC refers to ETICS and rain-screen.

10 Economically and socially.

As reflected in the literature review, there are few experiences in the topic and the author is aware that solving all the issues is not going to be completed by the research explained in this dissertation. But the aim is an approximation to a fully automated procedure in all three aforementioned subcategories**.**

The targeted building façade typology for being renovated presented in this dissertation is a very simple wall with interior windows with a healthy and rigid structure that can support the load of the modules, as shown in *Figure 15*. Moreover, the targeted façade should be free from obstacles such as trees or traffic signals. In this dissertation, there is a special focus on timber-based prefabricated modules. But there are also cases of aluminum-based curtain walls which are analyzed in this dissertation.

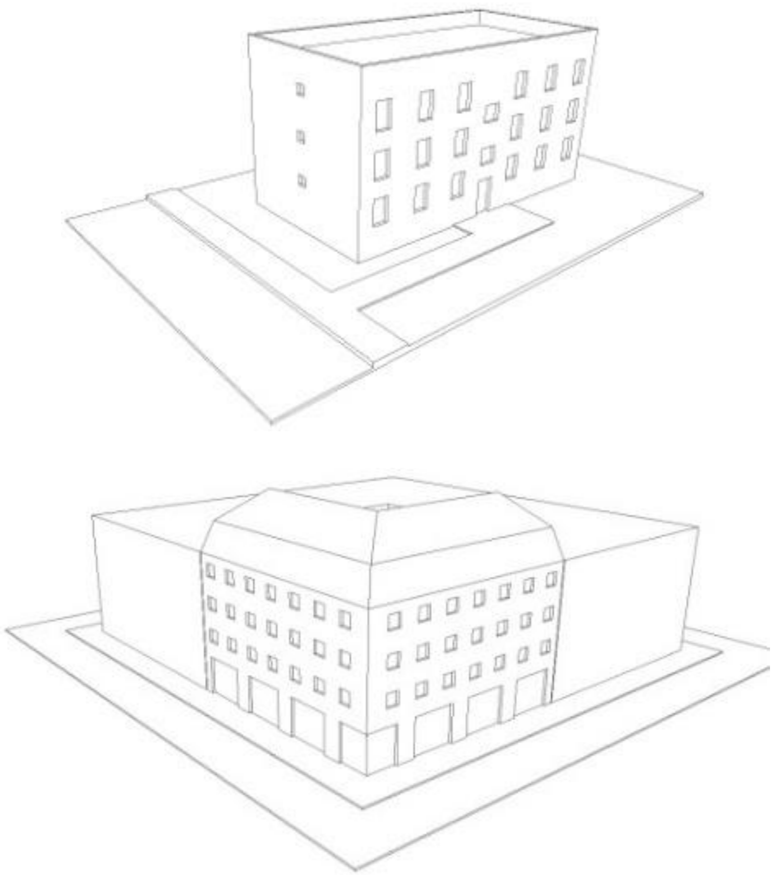


Figure 15: Scope of the building and façades types of this research.

Before developing solutions for automated and robotic building façade renovation with modules and improving the current state of the art, some issues should be highlighted. First, it is necessary to know which are the points that need to be improved in the field of building envelope renovation with prefabricated modules, especially regarding productivity and efficiency. As explained in the literature review, previous research did not thoroughly analyze this topic. For this reason, further analysis is necessary to determine the research gaps in current techniques.

Moreover, after determining the research gaps and defining the solutions, testing of solutions is needed in real environments and/or with real data. The simulations analyzed in chapter 2 slightly reflect the issues that occur in real conditions. Compared to other industries there is a lack of real testing and results in the field of robotics in construction [130] and for façade renovation with prefabricated façades, in particular. For this reason, tests and proof of concepts are necessary to create enough research output and gather a database with issues and problems.

In this dissertation, the key parameters are based on the performance of the solutions. Key parameters can present the first outlook about the performance of the initial development phases. It is an objective, therefore, to get the data of key parameters and use them to analyze the current techniques and to assess the automated and robotic solutions developed for this dissertation. In this research, two main parameters have been considered 1) accuracy of the data flow, manufacturing, and installation of the modules; and 2) necessary working time. These parameters are more detailed in the next points. Besides, and even though it is not measured in this dissertation, safety offered by robots must be taken into consideration as an improvement of working conditions that enhances the reduction of risks [131].

Accuracy as a quality parameter

It is necessary to comply with accuracy requirements of the final renovated façade because airtightness needs to be achieved and standards require it. In that sense, the applicable standard in Europe is the EN 13830 [132], which refers to curtain walling but also to rain-screen or lightweight façades. Therefore, this is the appropriate standard to be applied. It is true that in building façade renovation, the waterproof condition of the new layer might not be so important when keeping the existing wall.

However, regarding tolerances, the DIN 18202 [133] specifies the accuracy requirements of external walls. For the case analyzed in this dissertation, the restricted condition should be applied, see *Table 6*.

Table 6: Tolerances in mm for each wall segment 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 coditions	2	3	8	15	20

The DIN 18203-3 [134] specifies the maximal deviation at 5 mm for timber walls, in any case. Therefore, it is necessary to check the accuracy of the current building envelope renovation with prefabricated modules. In other words, case studies are necessary to measure the accuracy of current off-site manufacturing of the modules and the on-site installation of the modules. This is explained in the next chapter 3. The solutions presented in chapters 5 to 9 need to be compared to these analyzed cases. Moreover, the automated and robotic solutions presented in this dissertation need to be assessed according to the DIN 18203-3 as well. Two topics are normally considered: 1) absolute accuracy in regards to a coordinate system of the building; and 2) relative accuracy. The appropriateness of the arrangements of different elements within the module (design of the module) and the relation with the existing building (design of the new façade as a whole) are not parameters to be analyzed in this dissertation.

Working-time as a productivity parameter

Defining performing time as productivity parameter has several variants, such as machine time and lead time among others [135]. In this dissertation, the analysis of current building envelope renovation with prefabricated modules focuses on one parameter, namely the working time that the operator(s) need(s) for completing a task and, more precisely, the working hour per façade square meter (h/m^2) to achieve a task.

The benchmark to consider for a successful automated and robotic procedure is a manual procedure. Therefore, the manual renovation processes with prefabricated modules need to be analyzed thoroughly before considering the automated and robotic procedure. Therefore, case studies that monitor the working time are necessary to detect the weakest steps, or better said, the steps that require more time consumption.

Previous research objective in the field of using prefabrication was to reduce 30% working time with the current techniques such as in the H2020 EE-01-2014 call named 'Manufacturing of prefabricated modules for (energy) renovation of buildings [136]'. Therefore, it is necessary to maintain that objective compared to analyzed cases.

In fields where robotics is not yet mainstream or have a similar development level such as agriculture, detailed studies were carried out to analyze the feasibility of robotics [137], [138]. Parameters such as operational performance, investment for developing the robot and running costs (cost structure) are compared to the costs of conventional systems. In the construction field, a feasibility study for the robotic tile placement compares the cost per square meter as a benchmark [139]. Here, the operational time of the robot is considered and the hourly cost for an American operator is considered. The cost of a robot was estimated on some simulations [140], [141], [115] but that was only a mere approximation that needs more detailed input.

In the field of robotics for construction, similar parameters were used. Warszawski *et al* analyzed the economic feasibility for a robot working in the interior [142]. The analyzed robot is based on the performance min/m^2 and the subsequent productivity per year. Even though the task is mainly achieved by a robot, an operator was foreseen to assist the process. This study [142] argued that the fewer operations on-site, the better the robot operates. In conclusion, a higher degree of prefabricated modules is better for robotic installation.

3.2 Conceptual Framework

Robotic and automation in construction and, more specifically, in building renovation are topics that require contextualization before identifying specific solutions. As explained in chapter 2, "*Façade renovation with prefabricated modules and its automated and robotics solutions"* is a complex and multidisciplinary task that needs to consider multiple aspects. A research context is necessary to organize the different subcategories explained in chapter 2.

To develop such complex contexts, matrix-based decision-making methods were defined such as the Method for Checking the Consistency of Precedence Matrices [143], Design Structure System [144], and Axiomatic Design [145]. With these methods, it is possible to foresee or to avoid contradictions among the different requirements and solutions taken within the complex system. Specifically, to the field of construction, important research has been conducted in structuring the context for construction robot development [146], finding a framework of indicators for assessing construction automation and robotics in a sustainable context [147] and assessing the influencing factors of the future utilization of construction robots for buildings [148].

On the other hand, specific problem-solving methods such as TRIZ [149], V model [150], Agile model [151], Waterfall model [152] or Six Sigma [153] among others, have been used. In robotics for construction, a technology management system for the development of single-task construction robots was developed [154].

The field of robotized and automated façade renovation of existing building façades with modules requires a specific context and, for this reason, a new conceptual framework and method were defined. There were previous experiences with a combination of Axiomatic Design and TRIZ [43] but the research carried out in this dissertation requires a specific contextual framework. Therefore, a conceptual framework was defined with the following purposes:

- To analyze current techniques and cases based on the subcategories of the conceptual framework, and to detect the needs in different aspects.
- To determine the research gaps in each of the subcategories.
- To develop all three subcategories in a synchronized manner, avoiding solutions that disturb or contradict the rest of the subcategories.
- Every subcategory needs a different research approach. Some developments necessarily need to breakdown the subcategories to gather tangible solutions.
    - To assess the results globally and to pinpoint the main lacks for future activities and developments during intermediate or final phases of the research.
    - To evaluate the solutions in every subcategory depending on the nature of the developments, but also within the conceptual framework’s context.
    - The results should be evaluated also in a different range: not always accuracy and time can be considered at the same level. Moreover, some other parameters should be assessed if the solution’s context requires it.

A Conceptual Framework for an Automated and Robotic Building Façade Renovation with Prefabricated Modules adapted from the Axiomatic Design method [145] was conceived. The

Conceptual Framework utilized during the different research phases and the topics of each subcategory evolved to research gaps, solutions and future needs. The research scheme of this dissertation is explained in the next steps:

A. Define a broken-down list of Subcategories (SC) based on current façade renovation procedures. The basis for ameliorating the whole steps of the process was the current procedure.

B. Analysis of current procedures in all SCs. The previous chapter 2 pointed out the need to analyze the current technology, to find the research gaps and to develop and test novel concepts. Based on the analysis, this means pointing out Research Gaps (RG) in selected SCs. By analyzing current techniques, these objectives are transformed into more specific RG. The RG define specifically what the needs are. When necessary, each of the SCs will be subcategorized in more than RGs.

C. Development of Novel of Solutions (DNS). Once the RGs are defined, the DNSs are presented to solve the needs and accomplish the goals. The DNS can be considered as a set of solutions that fulfil the RGs. All the DNSs are decomposed and hierarchized in smaller solving units to make the problem-solving issue affordable and achievable until a final, concrete, and feasible solution is set up.

D. As a final approval of the developed solutions, it is necessary to assess the achievability and also to find future necessary work. Future Needs (FN) were defined and the results were analyzed by comparing them with current technologies.

A version of the sub-categories and the conceptual framework was already determined [79] and adjusted [43], [88] in a previous phase. Three main different subcategories on the automated and robotic renovation of façades were defined in chapter 2.3. The perspective of this dissertation evolved during the research process and the subcategories used for this dissertation are as follows:

- **SC1.1:** Measuring the geometry and acquiring the state of the building façade. Achieved on-site.

- **SC1.2:** Processing the acquired data. Achieved off or on-site.

- **SC1.3:** Defining the layout of the modules. Achieved off or on-site.

- **SC1.4:** Create the necessary data for the manufacturing process. Achieved off or on-site.

- **SC1.5:** Mark the necessary data for the installation of the modules on-site. Achieved on-site.

- **SC2.1:** Prepare (Cut/machine) the elements of the modules (off-site).

- **SC2.2:** Assembly elements and conform modules (off-site).

- **SC3.1**: Setting up the robotic device for installation (on-site). The device needs to be uninstalled after the works are finished.

- **SC3.2**: Fixing connectors on the required position (on-site).

- **SC3.3**: Placing the module in its location and fixing it onto the connector (on-site).

This definition of SCs doesn't mean that subcategories cannot be modified, adapted or added. Even more, the conceptual framework is dynamic during the research process and it was used as a development tool that organizes the different aspects of research. Some other conceptual frameworks could be possible, such as maintenance (SC4) and uninstallation of modules (SC5).

For this dissertation, the aforementioned subcategories are analyzed, five research gaps (RG) are determined and five development of a novel solution (DNS) are presented in chapter 4. These DNSs are developed and tested in chapters 5 to 9. Some of the solutions (DNSs) are interrelated and solve the issues of several RCs.

In chapter 10, a discussion is presented concerning the automation and robotics for the renovation of existing building façades and whether the DNSs presented are feasible solutions. The research approached in this dissertation could be used for further studies for business development in the aforementioned field.

4 ANALYSIS OF CURRENT TECHNIQUES AND RESEARCH GAPS

Prefabricated façade module manufacturing and installation are diverse regarding materials and techniques. To narrow down the topic, two types of modules are analyzed in this chapter: a) timber-based modules; and b) aluminum-based curtain wall modules. There was a limitation to analyze all the same SCs in several cases, as the analyzed cases did not follow the conceptual framework defined in chapter 10. For this reason, the analyzed cases cover the SCs differently [11]. There are several sub-chapters to analyze various aspects of the subcategories determined in the conceptual framework:

- In sub-chapter 4.1, the analysis is focused on the manufacturing accuracy (SC2) of timber-based frames[12]. Two types of timber frame are analyzed:
  - Non-calibrated and un-routed wooden timber frames.
  - Timber frames with calibrated and fully CNC routed elements.
- Sub-chapter 4.2 focuses on the working time for manufacturing (SC2) and installation (SC3) of aluminum for new buildings. Data workflow (SC1) is partially analyzed in this chapter because it refers to works executed during the erection of new buildings.
- In sub-chapter 4.3, the complete cycle of two building renovation cases with timber-framed modules are analyzed. In this case, data flow (SC1) is also analyzed.
- Finally, sub-chapter 4.4 presents a summary of the results, the research gaps (RG), and the developed novel solutions (DNS).

All the analysis presented in this chapter corresponds to a specific context and the results cannot be generalized. However, the analyses open a broader perspective regarding manufacturing and installation with prefabricated modules in refurbishment. For this reason, sub-chapter 4.4 summarizes the main research gaps.

11 This analysis is based on cases gathered in two projects: BERTIM and HEPHAESTUS. These projects differ substantially in the prefabricated module type. In BERTIM, the modules were based on timber frame, and the project was on the holistic energy building renovation. On the other side, the HEPHAESTUS project deals with the installation of curtain walls with a cable robot for new buildings. The aspects analyzed in each of the cases from these projects differ substantially.

12 Aluminum-based curtain wall manufacturing fulfils accuracy DIN 18202 due to its manufacturing process based on accurately CNC cut and machined profiles and cover. Therefore, it is not analyzed.

4.1 Analysis of manufacturing (SC2) timber-based façade frames

The question that must be answered is if the current timber-based module manufacturing fulfils the needs of the DIN 18203-3 for being used as a module onto the existing buildings.

There are different degrees of accuracy in timber manufacturing industries. For this analysis, two main methods for manufacturing timber-based modules have been analyzed in the next sub-chapters.

Non-calibrated and un-routed wooden façades based in timber frame

Studies were carried out that highlight that current timber frame off-site prefabrication requires improvement [155]. In timber frame-based wall prefabrication, the timber frame is often used as a guide. The rest of the added materials and elements are adjusted to the timber frame size and geometry [79]. It is the frame where the elements (insulation, vapor layers, service pipes, cladding, and windows) are put on. Therefore, if an accurately prefabricated module is the objective, the timber frame needs to be accurately manufactured.

The accuracy of timber frames has special relevance because the timber frame s used as a guidance, template or pattern for the assembly of the rest of the elements (such as insulation, mortar layers or cladding) (see *Figure 16*). In *Figure 16*, a very simple module is shown.

The procedure explained in this sub-chapter is the common way of manufacturing a timber-frame module [156]. Companies have developed almost fully automated manufacturing lines for timber-frame based modules [157], [158]. The machine manufacturers claim that timber framing in their machines can reach tolerances near 1-2 mm[13].

13 This data was provided by certain module manufacturing companies. The machine manufacturing companies withdrew the possibility to share any data with the author of this dissertation.

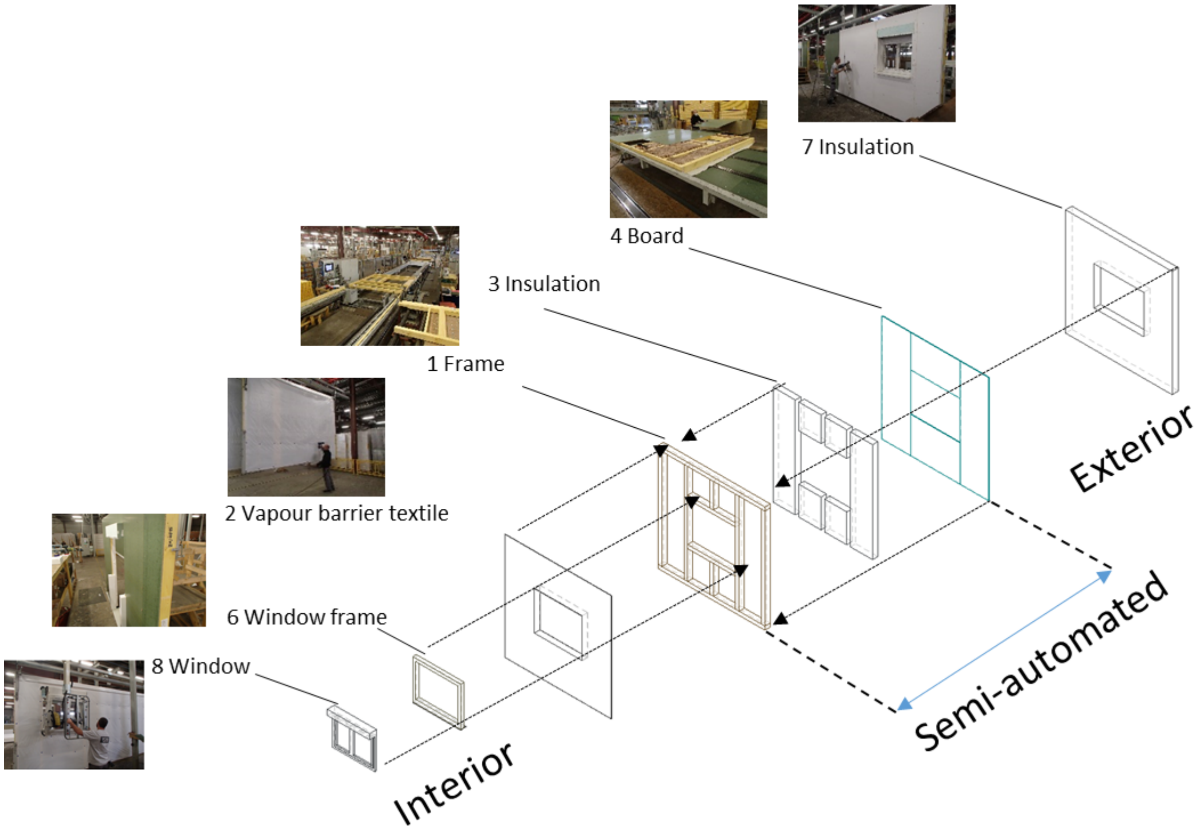


Figure 16: Prefabricated module with timber-based elements and the assembly of the rest of the elements.

However, questions arose in previous phases, during timber frame factory visits [36][14], as it was detected that the manufacturing of the modules could not achieve the desired level of accuracy (+/- 1 mm). Once the process was finished, the tolerances could reach up to 8 mm on only one side of the stud (see *Figure 17*).

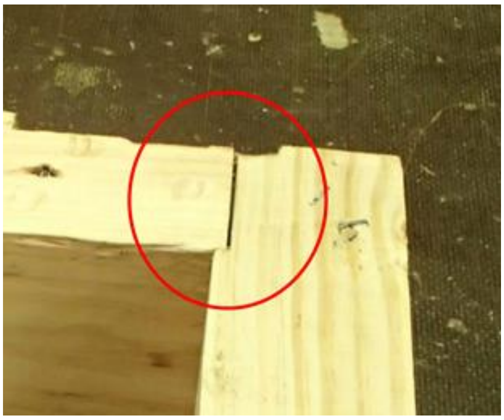


Figure 17: Deviations due to assembly inaccuracies.

14 In BERTIM project.

Briefly, the process for manufacturing timber frames follows the next steps. First, the studs are cut in a saw. The studs around the window are partially machined in a CNC. Once all studs are cut and machined, they are inserted in an assembly line. In the assembly line, first the studs are nailed together and then a board is placed on top. The in-built CNC machine on the assembly line nails the board to the frame and, after that, it cuts and routes the board to the required size. The rest of the elements, like insulation and windows, are fixed to these frames.

To analyze the accuracy of the timber-frame, eleven different walls (see one sample in *Figure 17*) were analyzed that were produced in a manufacturing line. The deviations were shown in *Table 7*. There are two results: measurement of the frame, and measurement of the board. The results in *Table 7* show that the tolerance in the frame can reach up to 7 mm and inaccuracies around the window frame are especially relevant. Besides, inaccuracies of up to 10 mm occurred in the boards. In previous phases of the research, companies took measures to solve the deviations and already give a tolerance of 10 mm for cutting the board.

Table 7: Accuracy of the measured timber-framed modules[15].

	Frame								**Board**							
	Perimeter				Window				Perimeter				Window			
Modules	Top	Low	Left	Right	Top	Low	Left	Right	Top	Low	Left	Right	Top	Low	Left	Right
Planned	4460	4460	2785	2785	3129	3129	2150	2150	4592	4592	2823	2823	3145	3145	2160	2160
Produced	4460	4460	2785	2786	3130	3130	2157	2157	4591	4591	2821	2821	3142	3141	2156	2157
Difference	0	0	0	1	1	1	**7**	**7**	-1	-1	-2	-2	-3	-4	-4	-3
Planned	4800	4800	2785	2785	1420	1420	1395	1395	4932	4932	2823	2823	1430	1430	1415	1415
Produced	4798	4798	2785	2786	1419	1421	1393	1392	4929	4929	2821	2817	1427	1426	1411	1411
Difference	-2	-2	0	1	-1	1	-2	**-3**	-3	-3	-2	-6	-3	-4	-4	-4
Planned	2864	2864	2785	2785	1020	1020	2285	2285	2995	2995	2823	2823	1040	1040	2305	2305
Produced	2864	2863	2786	2785	1017	1020	2285	2285	2993	2993	2822	2821	1036	1035	2300	2301
Difference	0	-1	1	0	-3	0	0	0	-2	-2	-1	-2	-4	-5	-5	-4
Planned	3000	3000	2785	2785	1020	1020	1395	1395	2997	2997	2823	2823	1030	1030	1415	1415
Produced	3004	3004	2785	2788	1019	1020	1391	1394	2994	2995	2821	2820	1026	1027	1410	1410
Difference	**4**	**4**	0	3	-1	0	-4	-1	-3	-2	-2	-3	-4	-3	-5	-5
Planned	4023	4023	2785	2785	1320	1320	1395	1395	4019	4019	2823	2823	1330	1330	1415	1415
Produced	4025	4025	2785	2785	1318	1320	1398	1398	4015	4015	2823	2821	1326	1325	1410	1410
Difference	2	2	0	0	-2	0	**3**	**3**	-4	-4	0	-2	-4	-5	-5	-5
Planned	5018	5018	2785	2785	1420	1420	886	886	5146	5146	2823	2823	1430	1430	906	906
Produced	5015	5015	2785	2785	1420	1419	884	884	5142	5144	2821	2822	1425	1426	900	900
Difference	**-3**	**-3**	0	0	0	-1	-2	-2	-4	-2	-2	-1	-5	-4	-6	-6
Planned	4588	4588	2785	2785	720	720	886	886	4720	4720	2823	2823	730	730	906	906
Produced	4586	4586	2785	2785	717	717	884	884	4715	4715	2822	2821	726	725	900	900
Difference	-2	-2	0	0	**-3**	**-3**	-2	-2	-5	-5	-1	-2	-4	-5	-6	-6
Planned	5238	5238	2785	2785	720	720	1095	1095	5238	5238	2823	2823	730	730	1115	1115
Produced	5235	5236	2785	2785	720	721	1095	1095	5234	5233	2821	2820	725	725	1110	1110
Difference	-3	-2	0	0	0	1	0	0	-4	-5	-2	-3	-5	-5	-5	-5
Planned	2968	2968	2785	2785	1920	1920	2495	2495	2968	2968	2823	2823	1940	1940	2500	2500
Produced	2967	2967	2785	2785	1920	1925	2496	2497	2964	2964	2821	2821	1935	1935	2510	2510
Difference	-1	-1	0	0	0	**5**	1	2	-4	-4	-2	-2	-5	-5	10	10
Planned	4200	4200	2785	2785	1920	1920	2495	2495	4332	4332	2823	2823	1940	1940	2515	2515
Produced	4200	4199	2785	2785	1917	1922	2495	2495	4330	4329	2821	2818	1936	1935	2510	2510
Difference	0	-1	0	0	**-3**	2	0	0	-2	-3	-2	-5	-4	-5	-5	-5
Planned	3279	3279	2785	2785	1020	1020	1395	1395	3407	3407	2823	2823	1030	1030	1415	1415
Produced	3280	3280	2787	2786	1020	1020	1393	1391	3404	3402	2820	2821	1025	1025	1410	1410
Difference	1	1	2	1	0	0	-2	**-4**	-3	**-5**	-3	-2	**-5**	**-5**	**-5**	**-5**

Regarding the reasons for such deviations, there are various aspects to be considered:

15 The data in the table was gathered jointly by Grégoire Castelleta from POBI Industrie and the author of this dissertation.

- One of the reasons that can be deduced is that timber profiles are not calibrated right before cutting and assembling but this is done before in a mill. For this reason, they suffer from geometrical changes during storage and transportation due to temperature and humidity (hygrothermal) variations.

- Calibration of the machine regarding the workshop floor. The board cutting CNC and its rails are supported directly onto the workshop floor, any differential settlement of the workshop floor.

- During the manufacturing process of the timber frame, these profiles are only cut to size with a (table) saw that holds the timber profile at one point, and due to this, the profile is not steady and the saw might push the profile while cutting and, therefore, deviations might occur.

These results show that, with current manufacturing timber-framed modules, it is unlikely to reach the tolerances determined by DIN 18203-3. Previous research projects that worked with timber frame modules [47], [36] did not consider this issue of inaccuracy. Therefore, there is a need for improving the manufacturing accuracy of these modules.

Regarding the time spent for the manufacturing of the analyzed modules, an average of 0,12 h/m² were necessary for manufacturing and assembling the frames.

Wooden façades with calibrated and fully CNC-routed and engineered timber elements

The lack of accuracy presented in the previous sub-chapter led to more accurate solutions and developed the so-called timber-based curtain wall as explained in sub-chapter 2.2. Resuming, three main concepts are applied for manufacturing timber modules accurately:

- To get accurate boards and profiles, these can be calibrated by sanding machines to get closer to the desired thickness. Windows, doors and timber furniture are normally accurately produced by using calibrated profiles and boards.

- Use of certain engineered timber materials, such as plywood or glulam, tends to change less in terms of their properties.

- The elements of curtain walls, windows and furniture are normally routed in CNC machines. All elements are fully routed and intensively machined in CNC machines.

There is a lack of information on the manufacturing performance and output of such type of modules. It is, therefore, necessary to analyze the manufacturing accuracy and working time of these types of modules. For that purpose, two experiments were conducted in a laboratory environment to verify accuracy and time consumption. These experiments were carried out to record evidence regarding the manufacturing accuracy and time. The experiments meant to resemble a timber frame module with fully-routed elements. In both cases, 12 mm thick MD (Medium Density) boards were used for manufacturing such mock-ups of the timber frame. A *Zünd G3 XL-1600©* [159] CNC machine was used for the carrying out the experiments. This

CNC is not a powerful tool for routing and cutting MD boards, it is rather used for other purposes. For these reasons, perimeters had to be routed in several depths until reaching 12 mm. The routing speed is a variable that needs to be considered. The routing speed of the *Zünd G3 XL-1600©* was around 1000 mm/min while in “professional” routing machines can be up to 5000 mm per minute. The two experiments differed in terms of the design (see *Figure 18*):

A. The first had an approximate size of 2,2 m wide by 1,5 m high which resulted in an area of 3,30 m². Two layers of boards where placed. In total 24,93 m were needed for the perimeter routing.

B. The second consisted of two modules. One module was 1,12 m wide and 1,42 m high and the other 1,12 m by 1,28 m high. Here, two layers where placed but there was not a whole board covering it. Both covered an area of around 3,03 m² and 46,89 m of the perimeter were routed.

Apart from routing, the elements were machined to assembly them with screws and steel connectors. The elements were assembled manually.

Figure 18: Assembly scheme and measures of the experiment. Left: Case A. Right: Case B.

For measuring the tape and the Leica, 3D Disto© was used for measuring purposes. With these tools, in the case of the experimentation A, the accuracy of the planned element was, as expected, very high. The dimensions varied less than a millimeter[16]. However, in the case of experiment B, the accuracy results were not as good as in case A**.** In the second test, there is no top board, which means that there is no guidance for the placement and no rigidizer; therefore, the location and placement were prone to movements.

However, the issue is the time consumed for the manufacturing process. Case A and B differ, mainly, due to the routing perimeter. In case A, the cutting and CNC machining was 0,27 h/m², while in case B, it was 0,45 h/m². This difference leads to a higher total time consumption in case B (0,97 h/m²) than in case A (0,67 h/m²). It is necessary to notice that these experiments show only frames that are not fully prefabricated.

16 Bigger deviations could not be detected with the used devices.

Table 8: Necessary time for the manual timber frame manufacturing.

MANUFACTURING AND ASSEMBLY	Case A	Case B
Cutting and CNC machining (SC2.2:)	0,27 h/m²	0,45 h/m²
Load CNC program	0,04 h/m²	0,04 h/m²
Prepare CNC workstation	0,05 h/m²	0,05 h/m²
Load boards	0,05 h/m²	0,05 h/m²
Machining of profiles	0,13 h/m²	0,26 h/m²
Unload boards	0,05 h/m²	0,05 h/m²
Assembly of profiles (SC2.3)	0,40 h/m²	0,52 h/m²
TOTAL	**0,67 h/m²**	**0,97 h/m²**

These experiments show the accuracy of these types of highly routed frames but, on the contrary, due to the high time consumption, the use of fully routed frames is questionable if we compare it to non-calibrated procedures explained in the previous sub-chapter (which was 0,12 h/m²).

4.2 Time analysis of Aluminum Curtain Wall Module (SC1, SC2 and SC3)

For this occasion, the analyzed cases are complete modules, meaning that not only the frames are considered but a module with almost 100% of prefabrication degree. The analysis was achieved in two phases[17].

First, the curtain wall module (CWM) manufacturing (SC2) was analyzed. For that purpose, 15 modules with a size of 3,4 m by 1,5 m were monitored during manufacturing and assembly in the factory. Several operators participated during the manufacturing process. As in the previous sub-chapter, measurement deviations are less than 1 mm. However, the time consumption for achieving a fully prefabricated module (not only the frame as in the previous sub-chapter) is relevant (see *Table 9*).

Figure 19: Installation of CWM. Images courtesy of Focchi SpA [160].

17 The data on this chapter was gathered by Mr. Alessandro Prascucci from Focchi SpA and re-ordered by the author of this dissertation.

Cutting and CNC machining took about 0,21 h/m², similar as in case A of the previous sub-chapter. The manual assembly of different elements (aluminum profiles, gaskets, glass, etc.) took 1,74 h/m². In total, 2,8 h/m² were needed to manufacture the complete modules (SC2) without considering the glass panel[18]. Moreover, each of the modules needs to be stored for three days to cure the structural silicone (the data is not considered in the table).

Table 9: Necessary time for the aluminum curtain wall manufacturing (SC2) procedures.

MANUFACTURING (SC2)	h/ module	h/m²
Cutting and CNC machining (**SC2.2**)	1,10	0,21 h/m²
Assembly of profiles and rest of elements (**SC2.3**)	8,85	1,74 h/m²
Quality inspection and finishing	0,89	0,17 h/m²
Logistic (**SC2.3**)	3,54	0,69 h/m²
TOTAL	14,38	**2,8 h/m²**

Second, the installation process (SC3) was analyzed. For this purpose, an installation project was taken as a case study. The installation of 80 curtain wall modules per floor (20 on each side of the building) was analyzed. The modules were 1,5 m by 3,2 m, therefore, covered a surface of 4,8 m² each, 384 m² in total. *Figure 20* shows the steps that are necessary for installing the CWM.

Figure 20: Installation of CWM Images courtesy of Focchi SpA.

There were two main SCs during installation time, namely the survey marking (SC1) and the curtain wall installation (SC3). The results in *Table 10*, show that 0,47 h/m² were necessary for installing each of the modules.

18 In the analyzed cases, the manufacturing of glass panels were sub-contracted.

Table 10: Necessary time for the manual curtain wall installation (FR3) procedures.

DATA FLOW (SC1)	hours	Op.	h/m²
Determine the cast in channel location during form working process (SC1.5)	8,00 h	1	0,02 h/m²
Survey for determining location of brackets-connector (SC1.5)	8,00 h	1	0,02 h/m²
ON-SITE INSTALLATION (SC3)			
Cast in channel fixation to the rebar during form working process (SC3.2)	8,00 h	1	0,02 h/m²
Brackets-connector installation and setting out (SC3.2)	6,40 h	2	0,03 h/m²
Panel Preparation (SC3.3)	6,67 h	2	0,03 h/m²
Panel Transportation to launching Bed position (SC3.3)	2,40 h	6	0,06 h/m²
Panel on Launching Bed and Lubrication (SC3.3)	6,67 h	6	0,10 h/m²
Panel Connected to Crane, Lifted and Rotated (SC3.3)	5,33 h	6	0,08 h/m²
Panel Alignment on side (mullions engagement) (SC1.5 and SC3.3)	2,67 h	6	0,04 h/m²
Panel Alignment to Brackets (SC1.5 and SC3.3)	1,33 h	6	0,02 h/m²
Panel Leveling (SC1.5 and SC3.3)	6,67 h	2	0,03 h/m²
Gasket Placement per 5 units	3,44 h	1	0,01 h/m²
Panel Protection Installation per 10 units	2,08 h	2	0,01 h/m²
		TOTAL	**0,47 h/m²**

For installing the brackets, a survey (which corresponds to SC1) is necessary for marking, with a Total Station, the exact location of the cast in channels in the formwork and brackets on the top of the concrete slabs according to the planned location (see *Figure 20*).

The rest of the process steps are part of the installation (SC3) but that includes a levelling of the CWM, which requires the data of the planned location. It is remarkable that the Survey, Panel Alignment on the side, Panel Alignment to Brackets, and Panel Leveling, all of which require data flow (SC1), take up to 0,13 h/m².

Comparing to the results of the OMM building [61] explained in chapter 2, installation time is less because the module can still swing while the operators hold it from the interior and steadiness of the CWM is not so necessary as in renovation processes.

In total, it would make 3,27 h/m² (sum of *Table 9* and *Table 10*), which makes it very similar to manual processes for a rain-screen (see chapter 2.1).

4.3 Analysis of façade renovation with prefabricated modules

In this chapter, two cases that show the whole renovation processes are analyzed. Timber-frame based non calibrated modules were used in these two case studies. These case studies are part of the BERTIM project [36] which focused on improving the manufacturing and installation processes of prefabricated 2D modules with integrated renewable energy sources (RES) [161]. The objective of this project was to shift from individual manufacturing to mass customization [76]. An in-depth analysis of the current timber-based 2D-module manufacturing and installation systems was conducted [79].

Case study 1: BERTIM demo Kubik Zamudio-Bilbao[19]

During the first phases of the BERTIM research project, a demonstration was performed, which consisted of the installation of three 2D modules onto an existing test building known as “Kubik” [162] (see *Figure 22*)[20].

Manual techniques from previous building renovation experiences with prefabricated modules were used for achieving the data acquisition (SC1), manufacturing (SC2) and installation process (SC3). The modules, as it is shown in *Figure 22* did not have a 100% degree of prefabrication. The inner layer of insulation was fixed before the installation of the modules. A base connecting profile supported modules 2, 3 and 4 (see *Figure 21* and *Figure 22*). Modules 2 and 3 included hot water pipes and ventilation ducts. For this reason, these modules were reinforced with CLT which was more time consuming than regular procedures. Moreover, the finishing external cladding grid was installed after the modules. Finally, to guarantee the water-proofing condition, a stainless-steel perimeter cover was adjusted on the borders.

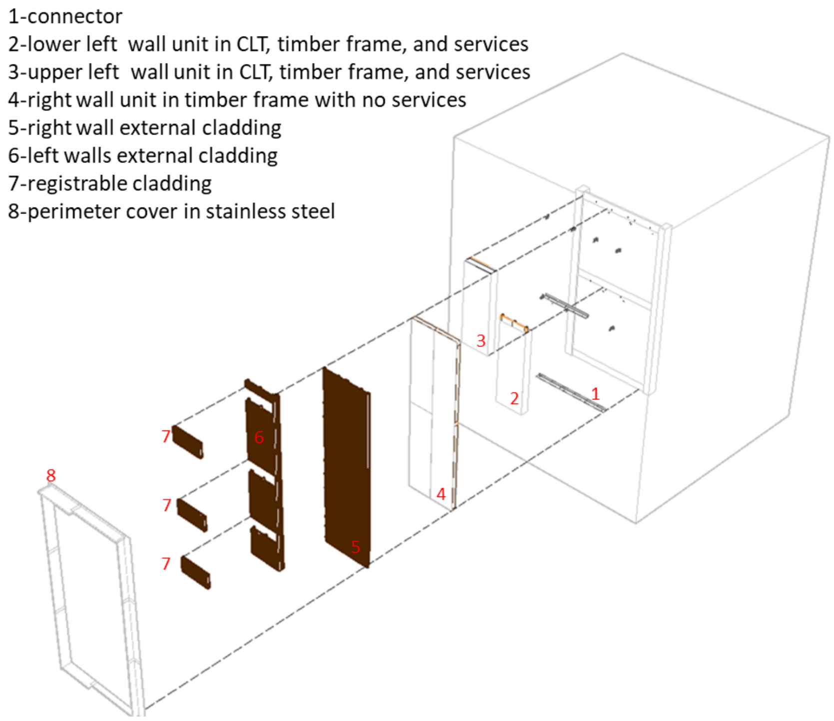


Figure 21: Exploded view.

19 The results are partially exposed in Automation in Construction paper [157].

20 The main participants of the Demonstration were Tecnalia, Egoin and TUM. The author of this dissertation, as a member of TUM, was responsible for gathering the data explained in this chapter.

Figure 22: Installation of 2D modules using current techniques.

Visible accuracy issues occurred due to manufacturing and installation processes. The coordinates of the final placement of the 2D module differed in more than 20 mm from that which was planned. This incurred the need for further rework following placement of the 2D modules onto the wall by overlapping the waterproof layers (see *Figure 23*). For this reason, the DIN 18203-3 was not fulfilled.

Figure 23: Deviations appeared during the installation of the modules.

In total, 23,34 m² were covered with the modules (see *Table 11*). Remarkably, Data Workflow (SC 1) took up to 0,43 h/m²; the main factor for such a time consumption was the manual design process, without using parametric features. The 2D module prefabrication took up to 1,18 h/m², and the modules prefabrication degree was approximately 50%, thereby requiring the rest of the work to be finished on-site. In this case, the membrane overlapping and external finishing material fixing required 0,91 h/m². Time for preparing transportation and arrival time were also monitored. In total, the analyzed case study took up to 3,33 h/m².

Time on-site with prefabricated modules would be almost halved, compared to the manual methods, but as a conclusion, it can be deduced that the overall time of the prefabricated solution should still be reduced. It was also concluded that a higher prefabrication degree could prevent this problem. Consequently, a higher prefabrication degree 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 11: Manufacturing and installation time required for 2D modules at the Kubik building.

BERTIM at Kubik	(h: hours; NoW: Number of Workers)				
	h	NoW	sum h	surface	h/m²
DATA FLOW (SC 1)					0.43
Data acquisition (SC1.1)	2.00	1.00	2.00	23.34	0.09
Layout definition (SC1.3)	8.00	1.00	8.00	23.34	0.34
MANUFACTURING PROCESS (SC 2)					1.18
Manufacturing (SC 2.2 and SC2.3)	2.00	2.00	4.00	23.34	1.14
Prepare for transportation (SC2.4)	0.50	2.00	1.00	23.34	0.04
INSTALLATION PROCESS (SC 3)					1.72
Reception (SC3.1)	0.30	2.00	0.60	23.34	0.03
Connector profile (SC3.3)	0.30	2.00	0.60	23.34	0.03
Place and fix modules (SC3.4)	5.50	3.00	16.50	23.34	0.71
Finishing and cladding (SC3.5)	8.00	2.00	16.00	23.34	0,97
		TOTAL h	77.70	TOTAL h/m²	3.33

The results of this project were compared to a renovation process based on manual on-site techniques such as ETICS, according to the data in *Table 1*. The total time consumption of the virtual simulation shows that the results would be similar to the renovation process with modules, that is 3,36 h/m².

Case study 2: BERTIM in La Charité sur Loire: all subcategories

During the final phases of the BERTIM project [36], another case study was conducted[21]. In this case, a real building renovation where the building dwellers remained living in their apartments was the object of the study. The apartment building was located in La Charité sur Loire in France and was designed by the architect H. Vauzelle (former disciple of Jean Prouvé [163]) and built in 1962. The supporting structure was concrete and the enclosure was made by brick cavity walls. There was a first attempt to use Point Cloud as data acquisition, but it

21 The main participants of the Demonstration were POBI, Dietrich's, FCBA and TUM. The author of this dissertation, as a member of TUM, was responsible for gathering the data explained in this chapter.

was withdrawn due to the complexity of processing data. The building was more complex than in the previous case as the covering area had windows and corners. This affected the data workflow process (SC1) and more points on the façade were necessary to be acquired with the Total Station which required more time, up to 0,15 h/m² (see *Figure 24* and *Table 12*). Moreover, a draft of the building was necessary for marking the points during the survey and a crane was necessary to reach the points [36].

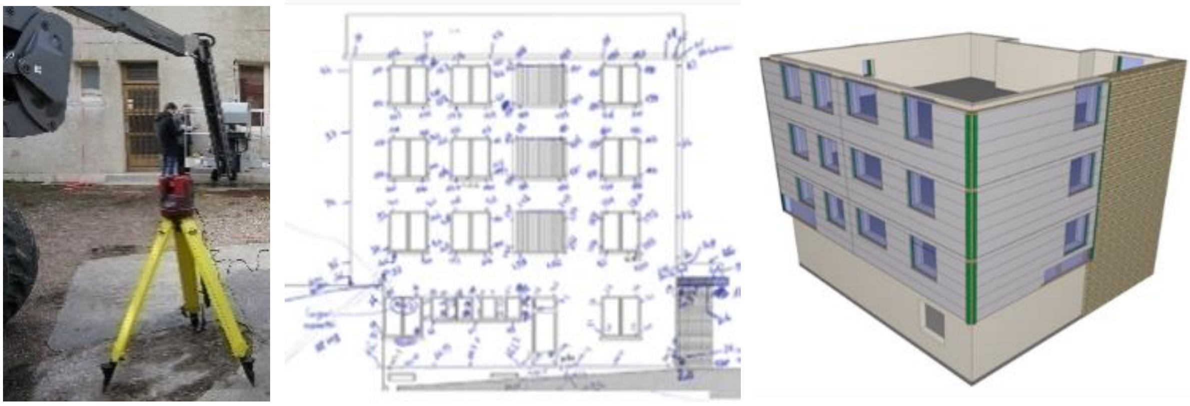


Figure 24: Data acquisition and CAD/CAM definition.

Each module covered one story and three stories were covered in total. Balconies or terraces were not covered, only façades with simple geometries. 520 points were measured with the Total Station.

Due to protocol changes within the process of the company, the design needed up to 0,17 h/m². Besides, the manufacturing time was longer than expected (1,30 h/m²). This time, it included windows. In normal circumstances, this would be between 0,62 and 1,53 h/m² (see deliverable 2.5 in BERTIM project [36]) depending on the complexity of the module.

Table 12: Manufacturing and installation time required for 2D modules at the Kubik building.

BERTIM La Charité sur Loire					
Task	h	NoW	sum h	surface	h/m²
Data acquisition (SC1.1)	7.00	5.00	35.00	234.85	0.15
Defining the layout of the modules (SC1.3)	40.00	1.00	40.00	234.85	0.17
Manufacturing of the modules (SC2)	306.00	1.00	306.00	234.85	1.30
Connector fixation (SC1.5 and SC3.2)	5.00	4.00	20.00	235.85	0.08
Installation of the modules (SC3.3)	20.00	4.00	80.00	234.85	0.34
Finishings					0,80
				TOTAL	2.85

On-site, first the location of the connectors was marked with a Total Station and, after that, the connectors where fixed only on the first floor. All the modules were supported on to these connectors. The fixation of connectors took up to 0,08 h/m². The installation of the modules finished in 0,34 h/m². There are several reasons for achieving such a low record. One is that the modules were wider than in previous cases, and reached up to 6 meters long. Each module was installed in about one hour, including the unloading of the modules from the truck. The other reason is that the cladding material was already integrated into the module. That led to a total of 2,05 h/m^2. However, the modules had a prefabrication degree of about 70% the perimeter and corner finishing were not monitored as part of the process but it was estimated in 0,80 h/m² (see *Figure 25*).

Figure 25: Top left and right: connector fixation.

Bottom left: Marking with a Total Station (SC3.2). Bottom right: Module installation (S3.3).

In this case, the accuracy of the finale placement was not measured. The company that implemented the renovation process (POBI Industrie) estimated that the price per square meter could be around 200 €/m².

As in the previous case, the results of this project were compared to a virtual renovation process based on manual on-site techniques such as ETICS (see *Table 1* in chapter 2). The total time consumption of the virtual simulation show that the results would be higher to the renovation process with modules, that is 3,27 h/m².

4.4 Summary of the analysis and definition of the Research Gaps

The analyzed cases show that, to be competitive, the subcategories still need to be improved. The analyzed cases are heterogeneous but these show a trend as it can be shown in *Table 13* where the lowest and highest records of the analyzed cases are compiled.

Table 13: Time spent in the selected SCs.

	Working time h/m²	
	Sum of Lowest records	Sum of Highest records
Data flow (SC1)		
Data acquisition (SC1.1)	0,09	0,15
Defining the layout of the modules (SC1.3)	0,17	0,34
Data marking on existing building (SC1.5)	0,04	0,13
Manufacturing total time (SC2)		
Cutting and routing (SC2.1)	0,21	0,45
Assembly (SC2.2)	0,40	1,74
Installation (SC3)		
Connector fixation (SC3.2)	0,03	0,08
Installation of the modules (SC3.3)	0,34	0,71
TOTAL	**1,28**	**3,60**

Considering that the compilation and sum of the lowest records is not an achieved solution, the objective of this research is to reach that benchmark. With the data shown in *Table 13* and based on the analysis of the SCs in previous subchapters, the Research Gaps (RG) found during the analysis phase are next:

- **RG1:** Lack of automated data flow. The data workflow requires automation. There is a need for diminishing the time consumption and avoid redundant measurement and marking. From data acquisition of the existing building to the installation of the façade modules, the data and information must flow smoothly. Two aspects should be covered:
    - **RG1.1.** The need for an automated module layout definition which links data processing and CAM obtention. It is necessary to reduce the time of design while linking it to BIM or any other software with CAD/CAM. One must also take into consideration the difficulties presented with the Point Cloud for the demonstration in La Charité sur Loire. A solution is appointed in chapter 0.
    - **RG1.2.** Facilitate the connector fixation of the modules by transferring data to the existing facade. Data workflow from data acquisition to the installation process should be improved. In chapter 1, the robotic fixation of connectors is achieved by calibrating the robot. In the other hand, in chapter 8, a novel solution is presented based on a Matching Kit interface.
- **RG2.** Lack of Automated Manufacturing of the modules. It is necessary to reduce working time but also to gain accuracy and the correct arrangements of elements of the module. The more routed the elements are, the more accurate the modules are, but also the more time it takes to manufacture. A balance is needed between accuracy and manufacturing consumption. Besides, there is a need for a fully automated process that considers the

changes in the size of the modules. But all that should consider time consumption. Two points are outlined:

- **RG2.1**. Reduce routing and manufacturing time. It is necessary to generate a more accurate module while reducing the operations of routing and the assembly sequence. A solution is presented in chapter 6 where partially routed studs are used for the assembly of timber frames.

- **RG2.2**. Lack of fully automated assembly of elements. In chapter 1, the main goal is to improve the robotic assembly of the timber-based prefabricated modules with calibrated and machined timber studs. A new joinery system that facilitates a robotic assembly is approached.

- **RG3:** Lack of automation in the installation of façade modules**.** Accurate and automated robotic system for the installation of façades to reduce the installation time. In chapter 7, a robotic system is explained that focuses on the next two subtopics:

  - **RG3.2**: Lack of automation installation of the connector. The connectors must be placed automatically and with sufficient accuracy.

  - **RG3.3**: Lack of automation installation of the Module onto the connectors. The current picking, handling, and placing of the modules or walls is still a manual process that requires manual operators working in dangerous situations.

As explained before, the Developed Novel Solutions (DNS) covered the Research Gaps (RG) not necessarily point by point but some of the DNSs address and solve different RGs (see *Figure 26*).

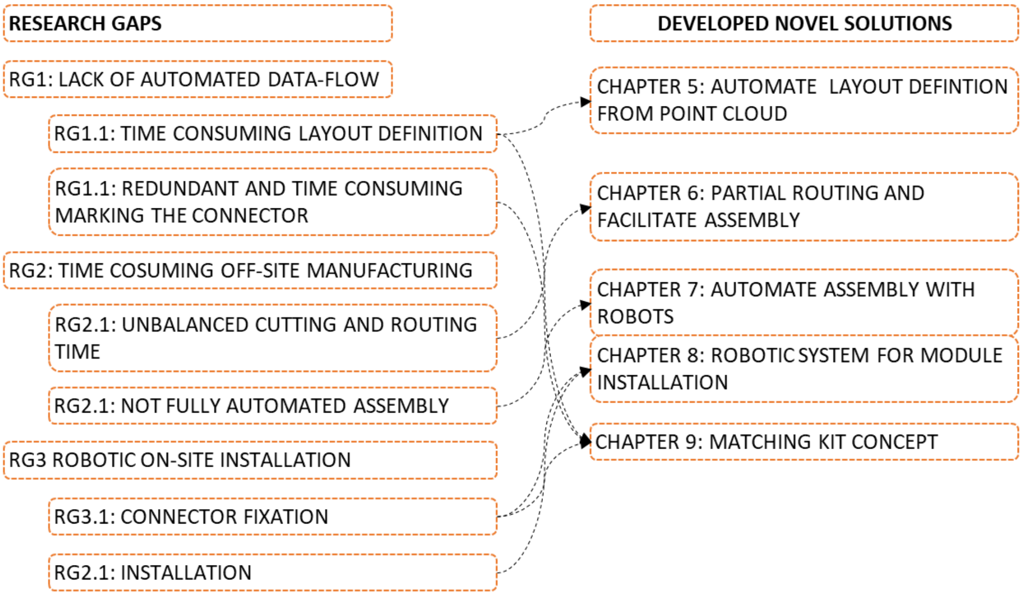


Figure 26: Scheme of the RDs and DNSs.

The experiments presented in the next five chapters are diverse and focus on different topics. In some cases, new assessing parameters and concepts need to be introduced. Moreover, each chapter offers a set of DNS that will be compiled and combined in the conclusion chapter (see chapter 10. To contextualize the topics, the next chapters briefly explain the state-of-the-art in each of the sub-categories and extra RGs were also appointed. Some of the DNSs explained in the next chapters were hierarchized and broken down. The results gathered during the tests of each of the DNS were contextualized and relativized.

5 SEMIAUTOMATED PRIMARY LAYOUT DEFINITION WITH A POINT CLOUD

In this chapter, the *data flow* scopes the process that starts with the data acquisition of the existing façade (SC1.1) and ends with the generation of the modules layout (SC1.3). The research presented in this chapter seeks for a semi-automated definition of the layout of the modules and its synchronization with the CAM (SC1.4) with the only input of the existing building façade Point Cloud and its point coordinates (see *Figure 27*). In the research made in this chapter, the data acquisition was made by 3D Laser scanners that generated Point Clouds.

One of the main barriers for marketing the renovation of façades with prefabricated modules is the excessive time used for data processing and design of the modules. Manual on-site procedures need fewer details and lower accuracy than prefabrication with modules. Façade upgrading by using prefabricated modules requires further detailing and accuracy on the design. As a consequence, building renovation with modules requires accurate information of the building because the modules need to fit in the existing building's geometry. For the energy calculation of a building, a very accurate model is no needed. It can have tolerances. But for the manufacturing of the modules, it is necessary to have an accurate measurement.

Figure 27: Generate the layout of the modules from the Point Cloud coordinates.

Besides, it is necessary to find a solution that avoids time-consuming and redundant measurement and data processing. The questions that need to be formulated are:

- Is accuracy guaranteed with an automated layout generation?
- Is the time spent in an accurate Point Cloud acquisition of the building and an automated layout generation faster and more accurate than a manual marking and data acquisition procedure and a manual design defined in chapter 4.3?. Moreover, a secondary objective is to define the characteristics of the Point Cloud in terms of point density and accuracy.
- Which are the key points in a Point Cloud to automatically generate the layout?

The targeted building facade type of this chapter is not damaged façades that present wall deviations of more than 100 mm but only façades that have a planar situation are addressed. Moreover, only façades with internal window sill and jambs (the so-called inner windows) are taken into consideration.

5.1 State of the art in data acquisition and processing

Preliminary approaches for data acquisition with 3D laser scanners were focused on matching geometries for as-built documentation. For these cases, there was graphic documentation to compare with, meaning the CAD file. One of the preliminary studies was developed by Bosché [164] and consisted of a two-phase construction steel profile recognition by matching to a previously drafted 3D CAD. It was not an automatic procedure though, mainly used for as-built documentation. Later, the automatic reconstruction of as-built building information models from laser-scanned Point Clouds were developed [165].

The maintenance of civil engineering works and assets is also a field that Point Cloud is relevant for the inspection mainly of structures. As a difference for as-built processes, on renovation processes, the existing building's geometry is in principle unknown. Several procedures were defined to transform the Point Cloud from a terrestrial laser scanner data in CAD or BIM [166], [167], [168]. There were approaches in the field of bridge-columns inspection, [169] and the recognition of edges of these columns [170] but the accuracy was about 1 to 10 cm.

To reduce the time spent on the Point Cloud processing of buildings, semi-automated methods were developed [171] in some cases by using segmentation [172]. In regards to accuracy, there are experiences that recognized the Point Cloud for building renovation purposes, but the error was still remarkable [173]. To increase the speed of the data acquisition, mobile mapping such as UAVs have been used for 3D scanning of façades [174], earthwork projects [175] and objects [176] where the accuracy depends on the range distance. Automated detection of building elements such as windows was approached [177] by using RANSAC [178] and from UAV scanner [179], but still with low accuracy for the purposes in this dissertation. However, advances are being made in the field of target-oriented scanning [180] and Automatic Space Analysis Using Laser Scanning and a 3D Grid [181].

PCL libraries have helped in the recognition and processing of Point Clouds [182], [183], [184] and the segmentation of objects [185] when there is no CAD or image of the object. On the contrary, Convolutional Neural Network for Real-Time Object Class Recognition is interesting for known objects and when the 3D CAD of the object is available [186]. Moreover, the combination of pictures and 3D laser scanner points makes possible to recognize the main features of an object, even façades [187] but extent image libraries are necessary, although accuracy is still an issue.

If automation in the layout definition is required, some geometry parameters and patterns must be defined. First approaches such as Shape Grammars [188] generated drawings automatically by applying certain rules and with only a few input rules. The current applications are generative and parametric design [189] are used for generating complex geometries depending on algorithms. In that sense, fields like urban design [190] have developed an automated layout definition depending on certain parameters. In the building renovation field, an automated primary module layout generator was already developed for existing façade geometries [191]. But this case required previous data acquisition and a CAD drawing of the existing building.

Photogrammetry is an option for measuring façades [192]. Leberl *et al*. presented several ways of automating the obtention of dimensional models of urban spaces [193]. There is also research about the detection of windows with images but they do not offer much accuracy [194]. Software such as Photomodeler™ [195] offers an interesting solution with photogrammetry. But it is necessary to use targets to localize the points. A combination or hybrid method by using 3D laser scanning and close-range photogrammetry for buildings documentation was used but accuracy reached 2,97 mm [196].

Currently, marketed software offers the possibility to define all the necessary parts of a prefabricated façade module with just the primary layout [84]. The secondary layout can then be automatically generated with software such as Dietrich's© [84] which automates the design of every single part of the wall once the primary layout is set up. The aforementioned software already generates the CAM for certain machines. It is not, therefore, the scope of this research to develop a complete wall design automatically.

Moreover, software such as Dynamo™ offers the possibility to integrate algorithms in Python™ to execute commands that can process Point Clouds [82].

The primary layout should be generated as in a Mass Customization [76] concepts as the development of mass manufacturing. For all these reasons, automatically obtaining the layout of the module with the only input of the gathered data should be part of the future of this workflow, as shown in *Figure 28*.

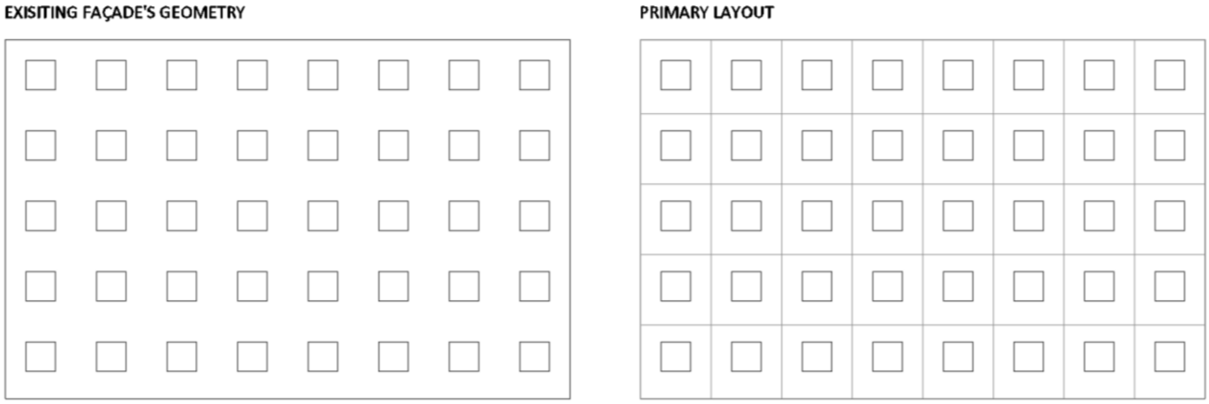


Figure 28: Automated primary layout generation of a very simple façade.

Within the BERTIM project, research was conducted to define the layout by using Point Clouds of existing buildings. In this project, the so-called RenoBIM software was developed (see scheme in *Figure 29*). The concept of RenoBIM required the Point Cloud as an initial input. This Point Cloud was used in a BIM to create the model of the existing building. This model was exported to a *.ifc* file, which was inserted in the RenoBIM software. In RenoBIM software was able to define the modules by using the size and the perimeter of each of the modules. From RenoBIM, the work was exported to a *.ifc* file, and from there to BIM or to a parametric software such as Dietrich's©, with which the CAM can be generated. This process was time-consuming and required effort. Moreover, drafting the BIM model from the Point Cloud required reducing the complexity of the building geometry. This caused losing the information of the building, such as the irregular surfaces that a wall might have.

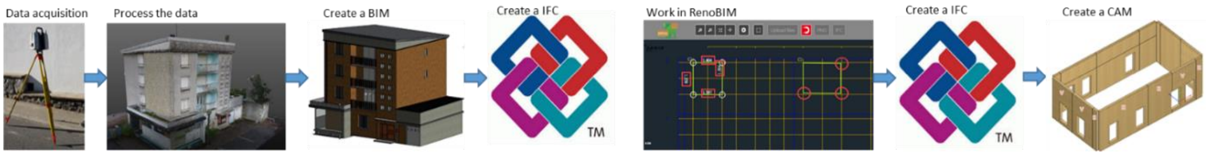


Figure 29: Process proposed for RenoBIM in BERTIM.

As a summary of the state of the art, the next points can be outlined:

- The automated data acquisition and recognition of construction objects is a topic that has been developed but it lacked the required accuracy.
- Recognition of known shapes is not applicable for acquiring and processing data with high accuracy.
- The automated design was based on previously drafted existing buildings.

For these reasons, it was necessary to create a semi-automated process that defines the geometry of the modules by using the Point Cloud of the existing building.

5.2 Development of Novel Solution

As said before, the objective of the research was to create a primary layout of the modules with the coordinates $(x_n, y_{n,} z_n)$ of the Point Cloud. Ideally, the data acquisition of the building should automatically generate the necessary information for manufacturing the modules. The research presented in this chapter gets as close to that goal as possible. Manually defining the primary layout accurately onto a Point Cloud is a decision-making process because the boundaries of the different construction elements are not defined by lines or surfaces and the cloud's appearance changes depending on the point of view. For these reasons, the process tends to be time-consuming and that leads to errors (see *Figure 30*) [22].

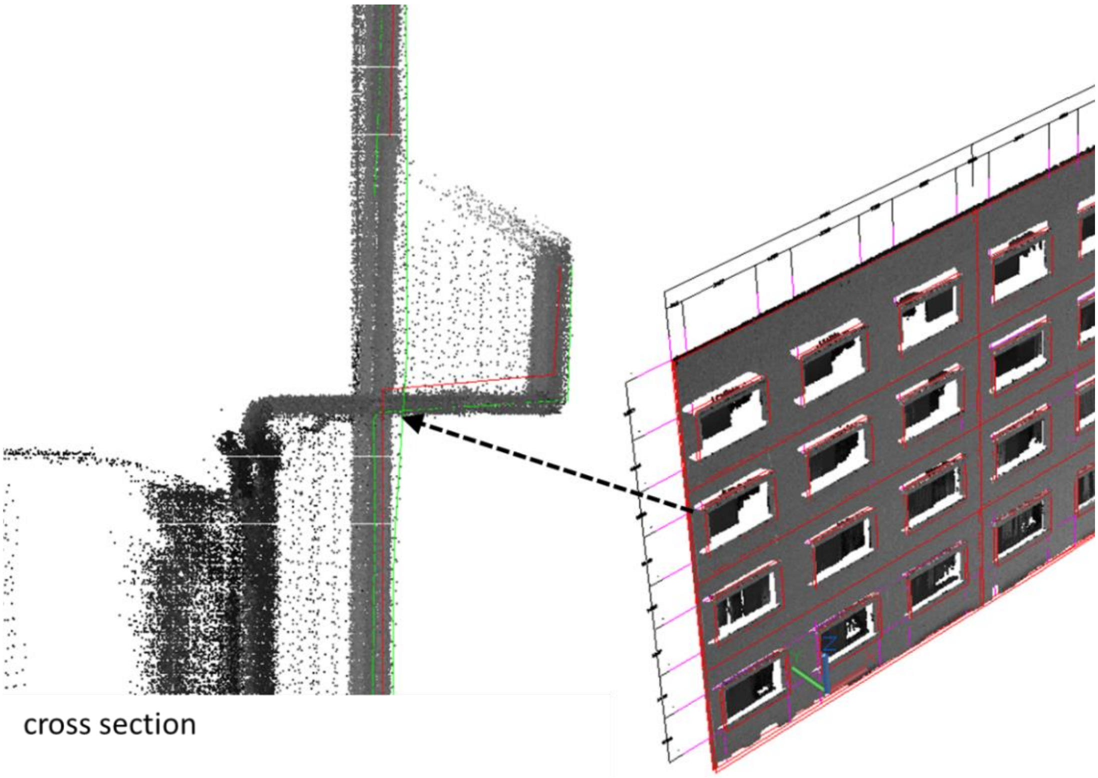


Figure 30: Manual primary layout generation of a very simple façade with Point Clouds.

Comparing to previous experiences, it was necessary to simplify the process. As it was observed in the BERTIM project [36], defining the layout of the prefabricated modules with this procedure was a time-consuming task.

For achieving such a layout semi-automatically, the acquired data needed to be processed adequately. This research is not solving the issues in data acquisition (SC1.1) and data processing (SC1.2) but only regarding layout definition (SC1.3). However, the SC1.1 and SC1.2 as well as the novel solutions (DNS 1.3) need to be part of a novel step-by-step

22 The Point Cloud acquired in this sub-chapter 5.2 was gathered during the stay of the author at SKKU at the chair of Prof. Kwon.

workflow defined in this research. The configuration of the steps is new, although the algorithms, the tools and techniques in SC1.1 and SC1.2 are currently used. The DNS1.3 is based on novel developments as explained in *Figure 31*:

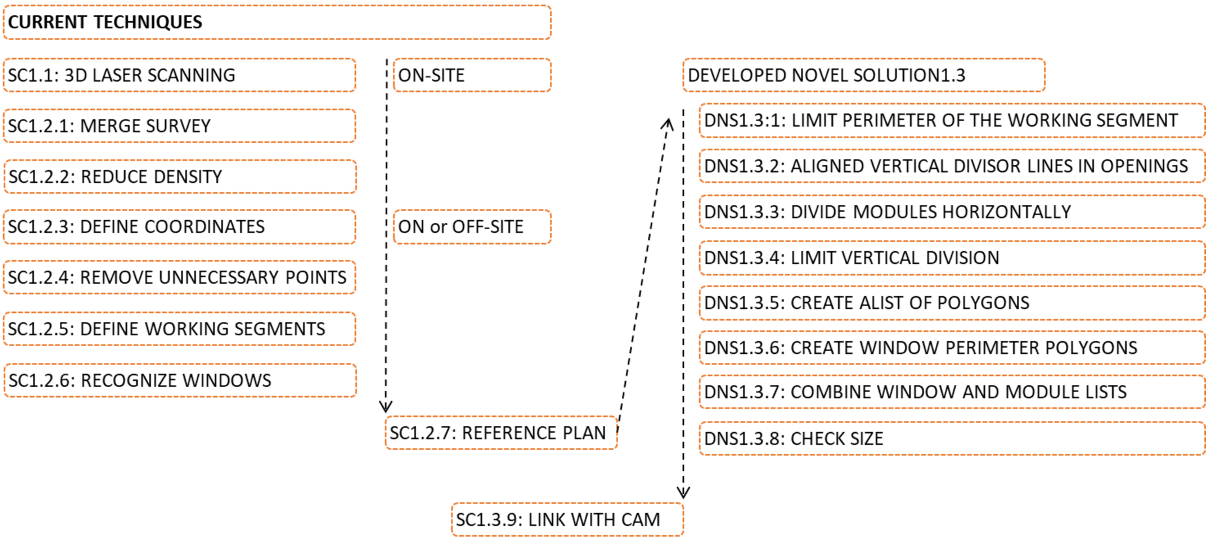


Figure 31: Scheme of the step-by-step process.

In the next points, the steps shown in *Figure 31* are explained:

- **SC1.1.** With current techniques, data acquisition is achieved with a 3D Laser Scanner as the one in *Figure 32*. Several scanning surveys might be necessary, depending on the size of the façade.

- **SC1.2.1.** After data acquisition, these surveys can be merged with current software [197].

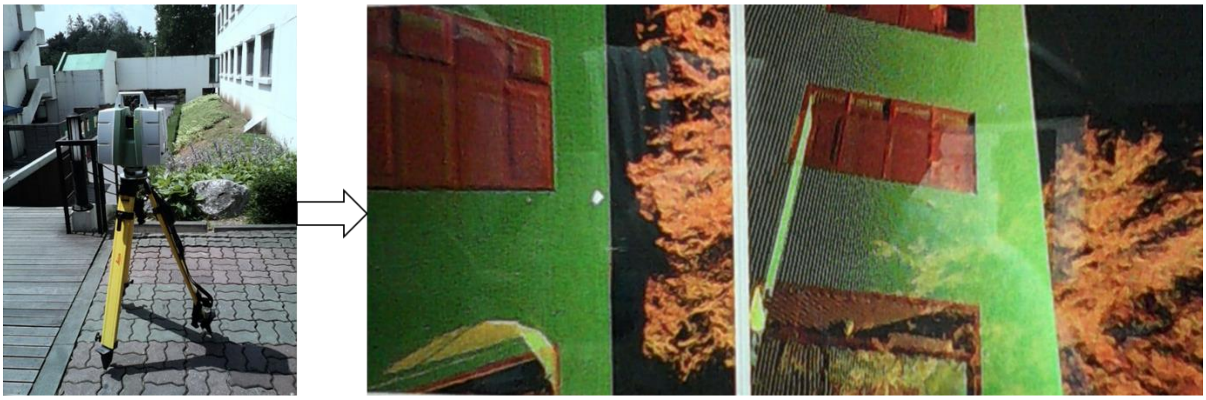


Figure 32: Data acquisition with 3D laser scanning and processing.

- **SC1.2.2.** For the application explained in this dissertation, it is recommended to reduce the point density of the Point Cloud to a grid that is manageable. In the case of 3D Point Clouds, the points to be processed could reach hundreds of millions. At this moment, it can be said that this is too big data processing [198] and, therefore, the density needs to be minimized. The density will depend on the processing capacity of the computer.

- **SC1.2.3.** After the density is reduced, the coordinates of the building origin must be defined to manage the Point Cloud more efficiently.

- **SC1.2.4.** The next step consists of removing the points that are not necessary, which means all the points that are out of range of the building façade.

- **SC1.2.5.** The next step consists of defining manageable working segments of the façades. Buildings normally have heterogeneous envelopes. Therefore, in this step, façade segments that comprehend that characteristics need to be isolated and defined as a manageable working segment. For that purpose, the points that include these segments should be selected.

- **SC1.2.6:** Recognize windows (wall openings). The building elements should be recognized for determining elements such as walls and windows in the façade. Point Cloud processing software permit, in a semi-automated way, to categorize points within a range of distance concerning a plan. The inner window has an outdoor sill and a jamb and can be classified separately from the façade plan. The window is placed in the interior in regards to the wall plan. The depth difference in the x axe facilitates the categorization of the window opening. Apart from that, the z coordinate of the slab is necessary for defining the horizontal module separator of the primary layout. The rest of the points would be part of the solid wall.

- **SC1.2.7**. Selecting the appropriate reference plan for each of the working segments. Walls and façades have irregularities and the Point Cloud collects these irregularities. The selection of an appropriate reference is necessary. If an inappropriate coordinate system and preference plan are selected, excessive separation and non-parallel location of the modules might occur (see where the dashed coordinate systems are exaggeratedly deviated to explain the importance of the topic). As a consequence, excessive insulation might be foreseen to cover the gap between the existing wall and the module. Due to this, the module's internal insulation might collide during insulation. Besides, the separation between the existing wall and the modules also needs to be considered, which normally depends on the insulation thickness that the modules have in the inner face. Therefore, there is a need for automatically defining the points of the cloud the coordinate system accurately. For this reason, an average plan needs to be determined for each manageable working segment. The Working Plan is where the primary layout is arranged. It needs to be parallel to the average façades plan which is determined by the Point Cloud of the façade. For defining such plan, a coordinate system must be determined.

Figure 33: Left: merged Point Cloud of a building and surrounding area.
Right: after processing.

With the processed Point Cloud shown in *Figure 33* (right), the objective of this chapter was to generate the primary layout. But to reach that goal, some research gaps needed to be solved. RG1.3 refers to the lack of automation layout of the modules. Once the data is processed and the building elements have been recognized, the primary layout should be generated automatically, depending on given parameters such as a minimum and a maximum length of the modules. Regarding the height, it must be noted that the modules, or better said, the connectors are normally fixed to structural floor slabs, and for this reason, the slabs normally mark the division of the modules. Therefore, the strategy is to define the polygons of the module out from the coordinates of the points by using PCL libraries [182], [184].The next sub-solutions (DNS) are necessary to gather the polygons of the modules:

Once the plan of a façade is categorized, the window is considered as the part of a Point Cloud that was inside or, better said, out of range of the plan. For that purpose, a Python™ script taken from the PLC libraries localize the points that are out of the range of the plan. The recognition of the construction elements such as windows, balconies and floors should permit the division of the layout of the modules. For now, simple construction elements such as windows are only recognized.

For that reason, the next sub-solutions (**DNS**) are necessary to gather the polygons of the modules:

- **DNS1.3.1**: Limit the perimeter of the working segment. Create the geometry of the wall by finding the outer points of the wall segment and complete the geometry of a façade if necessary. Check what happens in the corner when there is a blind spot. For that purpose, partial reconstruction is needed and suppose that the geometry follows a certain pattern.

- **DNS1.3.2**: Modules with aligned vertical divisor lines in openings. When upgrading a building façade, it is normally desirable to plumb the lines of the modules and the lines of the window openings, not only for aesthetic aspects but also to regularize the size of the windows and the production of the modules. Selecting correctly the axe of the window vertical limit is crucial. The strategy used in this research consisted on getting the outer points of the window hole.

- **DNS1.3.3**: Divide the modules horizontally according to the mid Z value of the floor slab, or in other words, obtain the medium Z value of the slab to divide the modules horizontally. Besides, it is a requirement that the horizontal modules division meets with the slab of the existing building. That way, the connector can be placed on structural support. The importance of the primary layout lies not only in the module's divisor and window openings but also implies the location of the connector in the corners of the modules (see blue squares in *Figure 34*).

- **DNS1.3.4**: Limit the vertical division of the modules according to a given width. Module size according to given parameters. When defining the module's layout, it is necessary to consider the maximum and minimum sizes of the manufacturers.

- **DNS1.3.5**. Create a list of polygons of modules.

- **DNS1.3.6**: Create the window perimeter geometry segment by joining the lines generated in DNS1.3.and create a list of polygons. The window lines should be aligned.

- **DNS1.3.7**: Combine the window list and module list.

- **DNS1.3.8**: Check the size is according to the parameters given (height and width).

The steps from DNS1.3.1 to DNS1.3.8 are reflected in *Figure 34*.

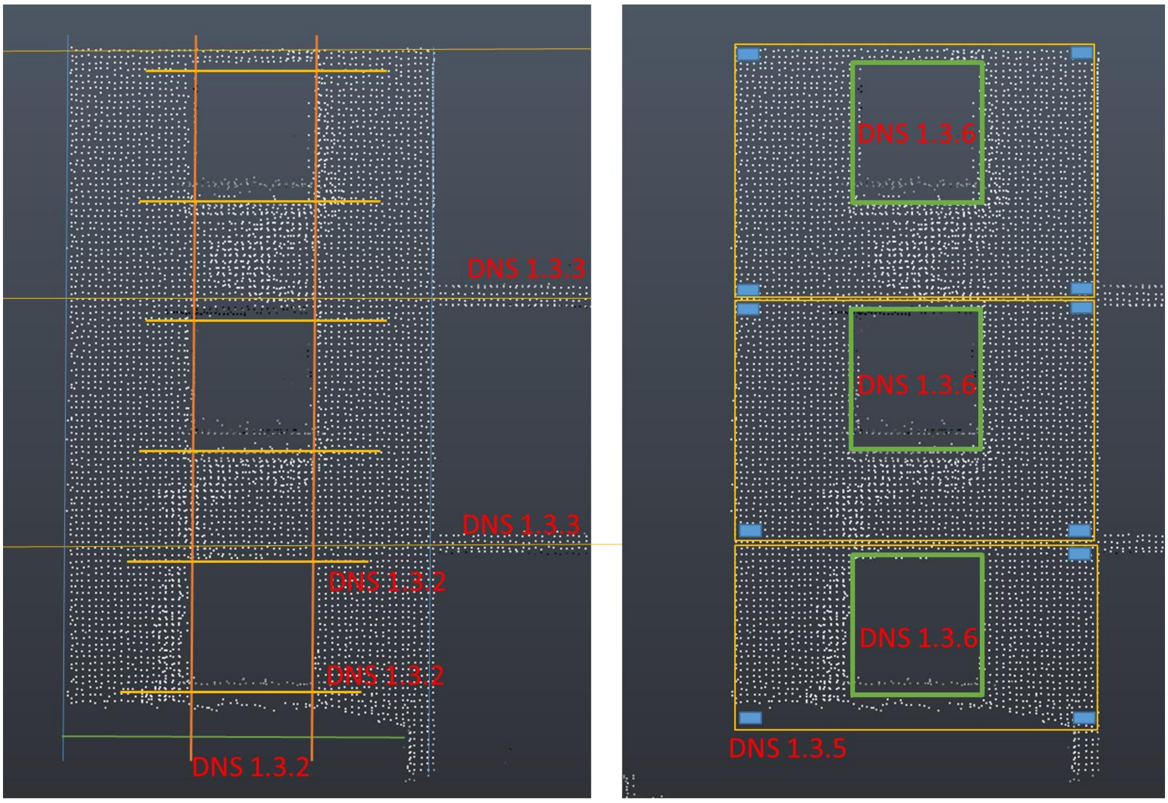


Figure 34: Definition of limits and polygons of working segments. Left: DSN1.3.2 and 1.3.3. Right: DNS1.3.5 and 1.3.6.

After the polygons are defined, these should be processed to any CAD or CAM:

- **SC1.3.9:** Link with BIM (and CAM). Once the layout is obtained, is it is necessary to remark that the output should be linked to the BIM file. Moreover, the primary layout should be connected and interrelated with all processes, especially with CAM for manufacturing. This primary layout should be the binding and link for the entire process, from data acquisition to robotic manufacturing and installation.

On the next chapter 5.3, the primary layout generated in the previous step was linked with the Revit, which is a BIM (see [82]) by using a simple built-in node of Dynamo™ or any other parametric design software tool.

5.3 Tests of the novel process

The concept was tested using real Point Cloud data. The software environment for processing the concepts was Recap™ and Dynamo™ [199].

Dynamo™ software was used, firstly because it allows Python™ scripts to be integrated into the visual computing and secondly because it is connected to Revit™ [199] (BIM) and can generate CAD output. Moreover, visual programming software such as Dynamo™ facilitates visualizing the code and its output during the development process. The Point Cloud used in this test is the same to the case building analyzed in chapter 4.3 (case study 2) [23]. The building envelope analyzed in chapter 4.3 (case study 2) is heterogeneous. Therefore, for the test, some façade parts needed to be selected which met the scope of this research, that is, a simple façade with window openings in a regular grid.

The Point Cloud presented some deviations compared to the survey achieved in the case studied in chapter 4.3 (case study 2). The data from the 3D Laser Scanner differed with the Total Station survey data especially on the upper floors, with deviations up to 20 cm in window corners. As can be seen in *Figure 35*, the lines in red refer to the window perimeter lines measured by the Total Station and the white dots refer to the Point Cloud. This is a fact that needs to be considered; the Point Cloud used was not as accurate as the points acquired within the Total Station. The “accuracy” of the output is, therefore, estimated to be low due to the tolerance of the Point Cloud.

23 The Point Cloud was subcontracted by POBI Industrie within the BERTIM project.

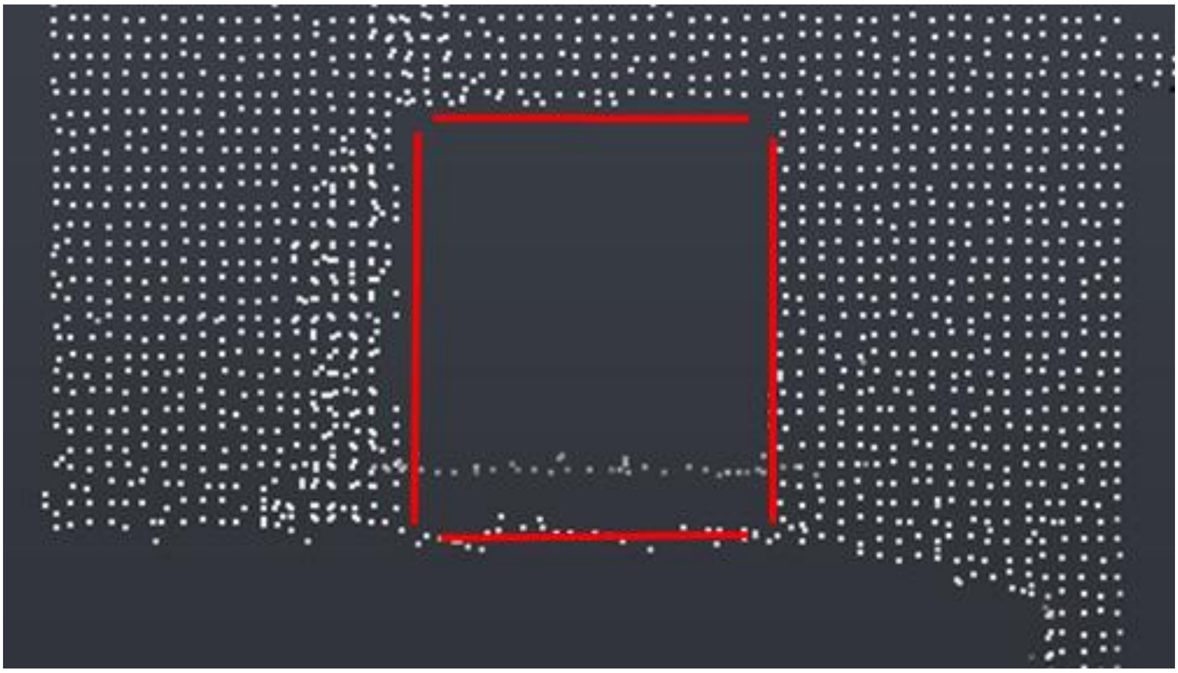


Figure 35: Point Cloud vs Total Station surveys.

To compare the layout generated manually, the areas to arrange the primary layout corresponded with the case analyzed in chapter 4.3 (case study 2) (see *Figure 36*).

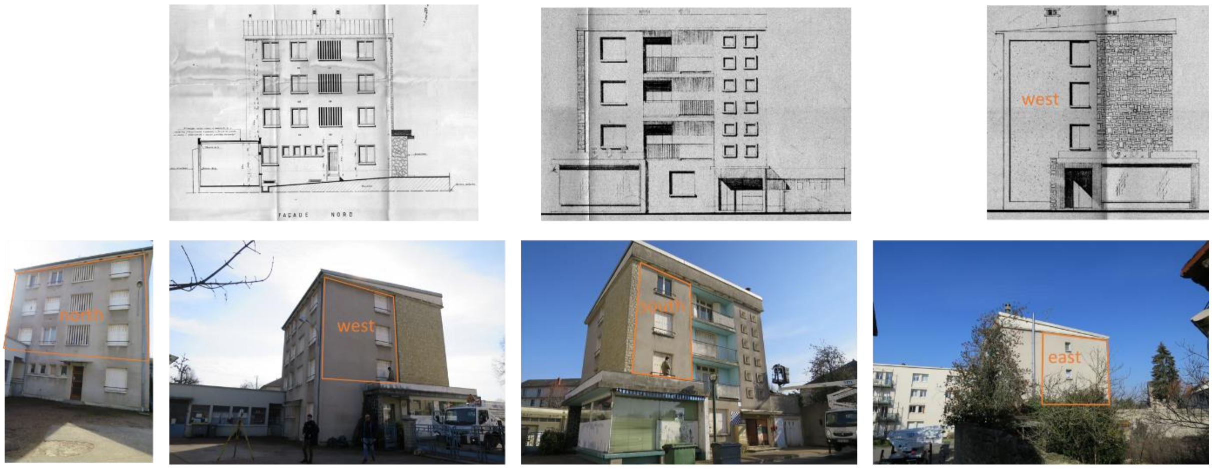


Figure 36: Façade segments selected for the project analysis.

The scanning of the building (SC 1.1) was achieved by a *Faro® Laser Scanner Focus Series X* [200], and the merge of different stations was achieved by SCENE®, also from Faro® (SC 1.2.1) (these tasks were not achieved by the author). Besides, this scanning was incomplete due to accessibility reasons, it was difficult to access all four façades and some data was missing.

Recap™ was used for achieving the tasks from SC1.2.2 to SC1.2.4 (see *Figure 37*). During the opening of the Point Cloud in Recap™, two-Point Cloud densities (SC 1.2.2) were tested:

- A low density of points with a grid of 100 mm by 100 mm.

- A higher density of points with a grid of 20 mm by 20 mm.

Once the Point Cloud was opened in Recap™, the origin was set up (SC1.2.3) and the unnecessary points from the cloud were removed (SC 1.2.4) (see *Figure 37*).

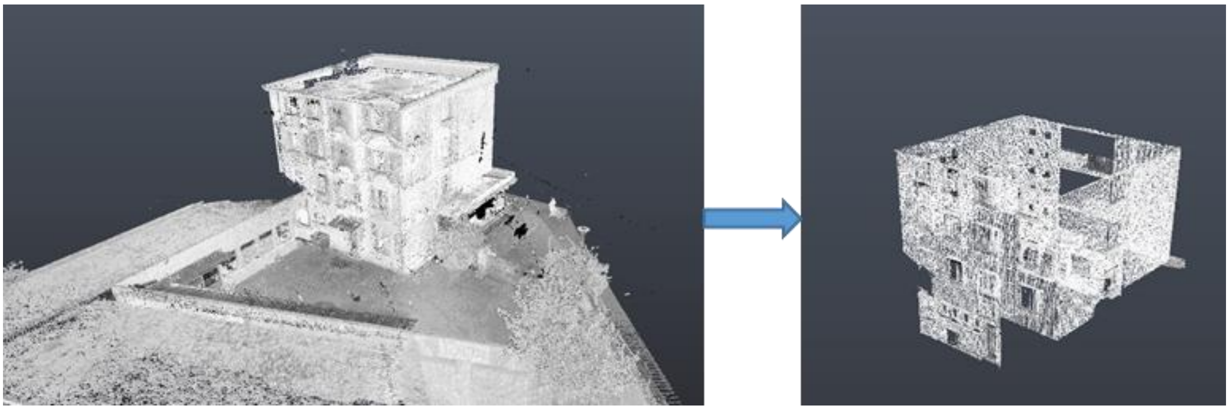


Figure 37: Left: Point Cloud received. Right: the façades are selected.

As a next step, four manageable working segments were defined (SC1.2.5) (see *Figure 38*) and, for that purpose, nine parts of segments were selected:

- Four manageable working façade segments without the interior of the window (SC1.2.6).

- The same four manageable façade working segments with the interior of the window (SC1.2.6).

- Slabs of a balcony used as a reference for horizontally dividing the module.

Each of the segments had a different number of points. These segments were first exported to a .pst file and then to Excel files.

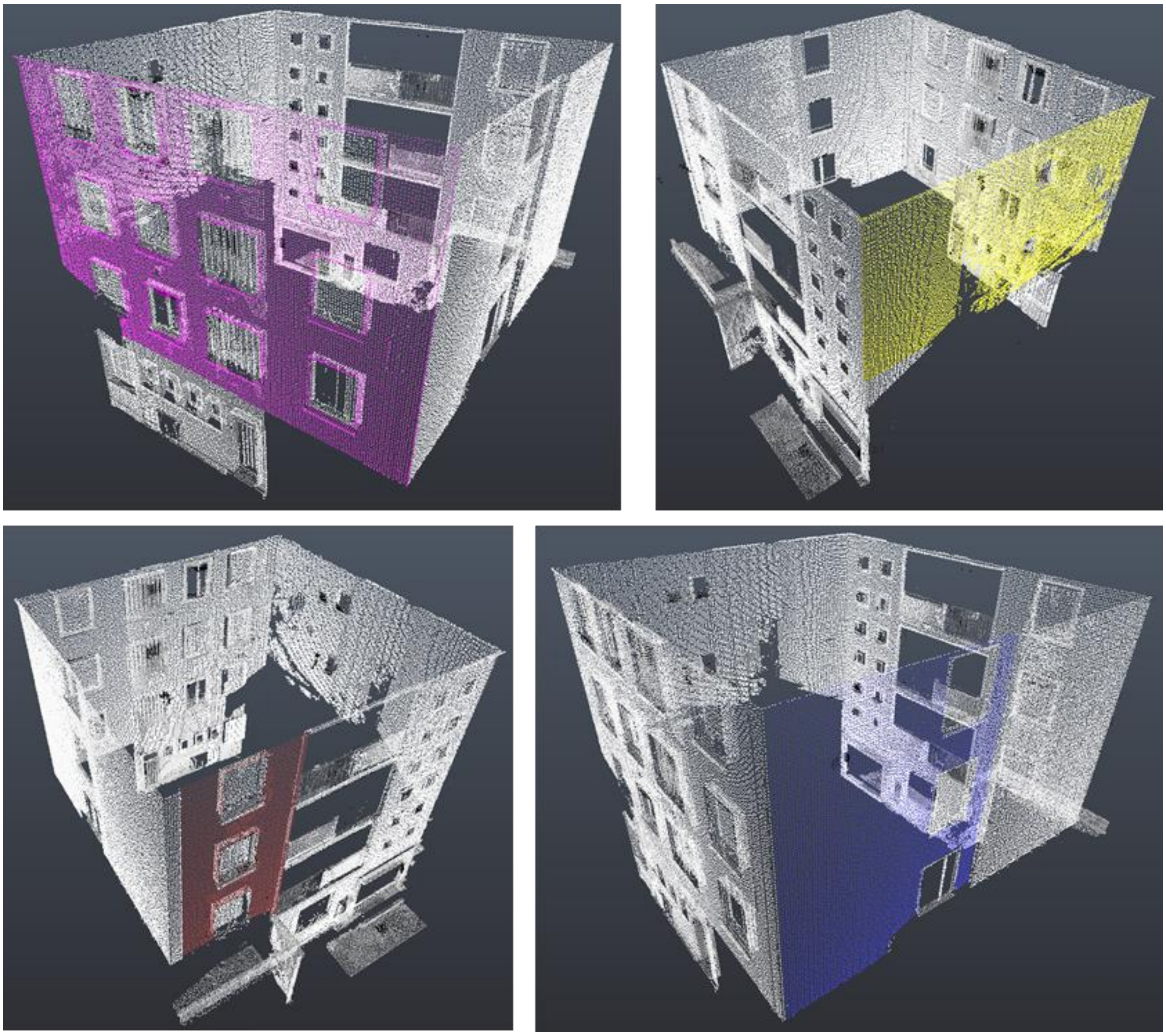


Figure 38: Selected façade segments: Top left: North. Top right: East. Bottom left: South and slabs. Bottom right: West.

Each segment was exported with two different degrees of density to check if that is a factor of influence on the final output of the modules as it can be observed in *Table 14*.

Table 14: Number of points for each wall segment.

100*100mm density grid				
	Segment	Window	Wall	Total
1	North		15997	19642
3	East		11969	12229
4	South		5297	7708
5	West		8212	8912
6	Slab	-	-	1461
20*20mm density grid				
1	North		173260	483150
3	East		30110	37766
4	South		72072	110683
5	West		100.971	215.728
6	Slab	-	-	44589

The Excel files were inserted to accomplish the algorithms in Dynamo™ and to carry out the solutions from DNS1.3.1 to DNS1.3.8.

After that, the code set up in Dynamo™ was executed. A geometry of lines was generated, which was exported to a CAD system (it could be exported directly to the Revit BIM (see *Figure 39*)).

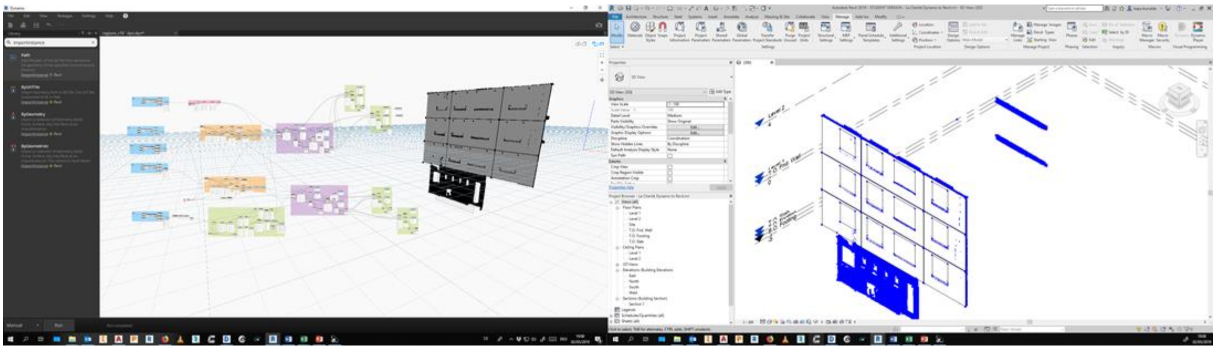


Figure 39: Excel file list with coordinates, processing in Dynamo™ and linking with Revit™.

The biggest issue was to define the perimeter of the windows. Different Point Cloud densities were tested. The point density of the wall was irrelevant. However, the density of the window hole had special importance.

5.4 Results

The two parameters, working time and output accuracy, were considered to evaluate the results:

Working time. The test was achieved on a computer with an Intel©Core™ i7-6700K processor with 4.00Hz ad with a RAM of 8,00GB. Regarding the necessary time for processing data, with the Point Cloud with a grid of 20 mm by 20 mm[24], time was reduced significantly to 4 hours. This means that 0,0017 hours were necessary per square meter (see *Table 15*). The SC1.1 (data acquisition) is a process that required up to 3 hours. By using the algorithms to process from DNS1.3.1 to DNS1.3.8. in Dynamo™, the processing time was minimized, as it is shown in *Table 15*. It must be noted that 40 hours[25] were needed for designing the analyzed case in chapter 4.3, therefore, the time reduction was significant.

Table 15: Approximate time for each step.

	Time	M²	h/m²
SC 1.1: data acquisition	3 h	234,85	0,0127
SC 1.2: data processing	0,5 h	234,85	0,0021
DNS 1.3: layout definition	0,5 h	234,85	0,0021
		Total	0,0017

<u>Output accuracy</u>. As estimated due to the tolerances of the Point Cloud, in overall, the accuracy of the output compared to the layout defined manually was still not as good as desired. In *Figure 41*, the results of the façades south, west and east are shown. The results gathered by the 20 mm by 20 mm grid are shown in red, while the results gathered by the 100 mm by 100 mm grid are shown in blue. In *Figure 41* and *Figure 40*, the layout of the manually-defined modules are in black. As shown in *Figure 41* deviations are up to 50 cm. However, due to the better Point Cloud definition in the North façade, the primary layout achieved by the novel solution had only deviations around 20 cm as it is shown in *Figure 40*. In this figure, only the results gathered by the 100 mm by 100 mm grid are shown in blue because the results of the 20 mm by 20 mm grid are poorer. Therefore, it can be considered that for the developed DNS, the density of the Point Cloud is not as relevant as the accuracy of the Point Clouds. Besides, another topic that needs to be considered is the corners of a module when the wall is not regular (see *Figure 40*). The algorithms developed did not consider this situation and “errors” appeared.

24 When using the Point Clouds with the grid of 100*100mm, the computer took too much time for processing.

25 That included the manual detailing of the materials and elements of the modules.

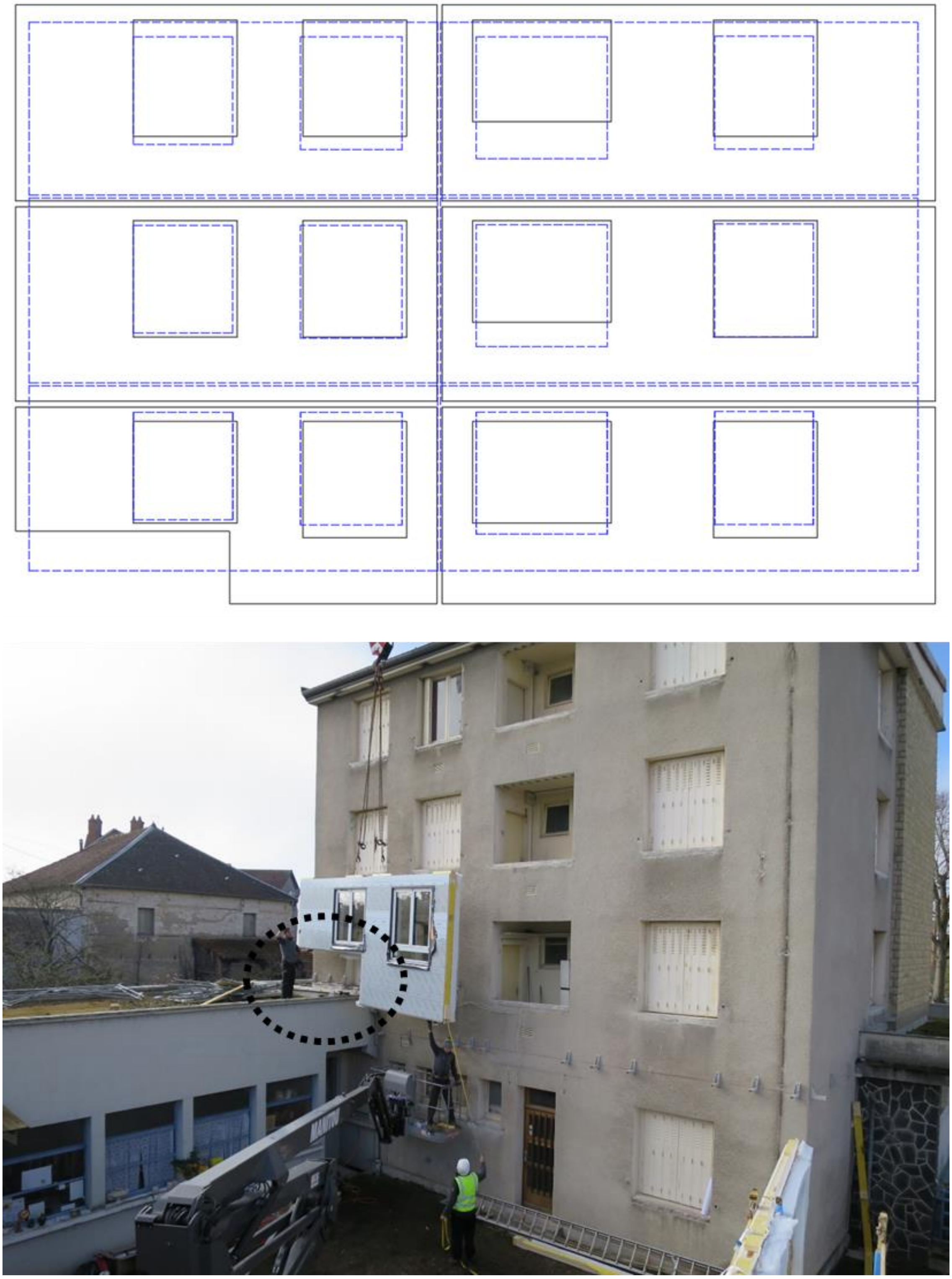


Figure 40: Top: comparison of manual (black) and automated procedures (blue). Bottom: picture showing the corner detail.

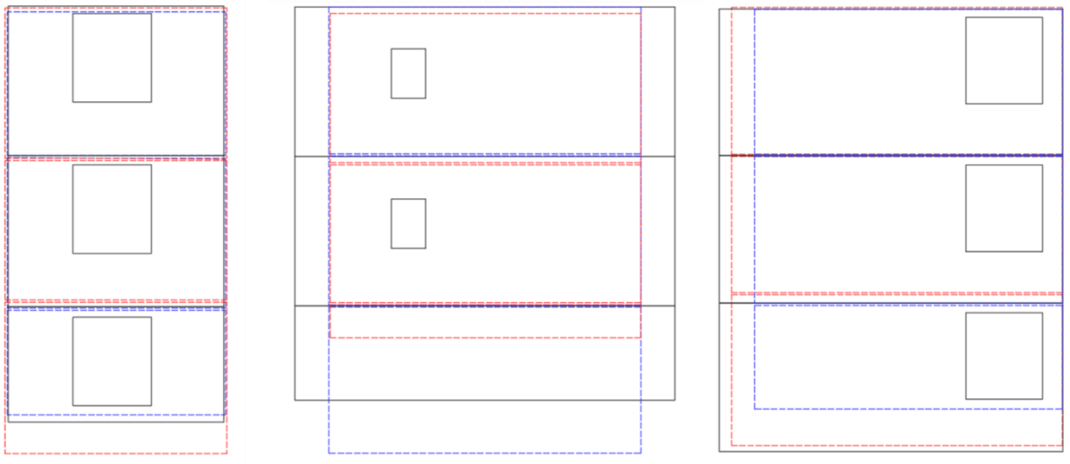


Figure 41: Comparison of manual (black) and automated (blue and red) procedures in facades south, west and east.

Finally, excessive noise of the selected segments generated an issue to define the shape of the windows. The windows were not detected by the algorithm if the definition of points around the window sill corners was not sufficient. That is what happened in all segments, except for the North segment. The reason for this issue might rely on the blind spots of the surveys in East-West, South and West (see *Figure 42*).

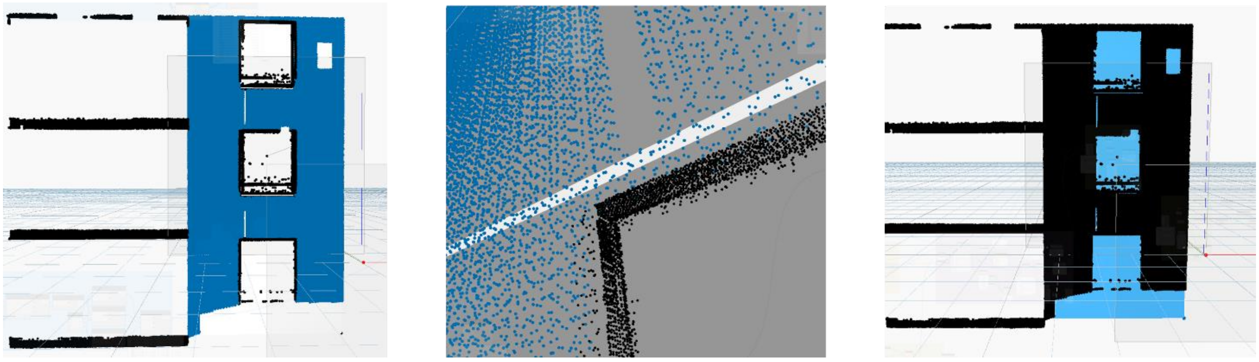


Figure 42: Insufficient window sill definition in segment South.

5.5 Future Needs

According to the results, it was concluded that spending more time achieving an accurate 3D laser data acquisition can be a good strategy for getting the primary layout with sufficient precision. However, as remarked in previous points some future needs were detected:

- **FN1.1**: Accuracy of the measuring device and the acquired data. The primary layout definition is dependent on the accuracy of the Point Cloud data acquisition. The limitations of the building measurement, lack of enough information, and blind spots are a major thread to put into practice the methods explained in this chapter.

- **FN1.3.1:** Accuracy of the selected segments. The Point Cloud does not offer a surface *per se*. Data processing and decision-making are necessary for selecting surfaces. Determining the working plan and section of the primary layout properly has primordial importance.

- **FN1.3.3**: This study is limited by the definition of the coordinates of the building slab. Without that data, it is difficult to know where to split horizontally the building modules layout and where to place the connectors. In future work, thermal camera images should be considered and matched with the Point Cloud to find the slab's position (see *Figure 43*). There was an interesting combination of thermal images and 3D laser scanning [201]. Unfortunately, the accuracy of the solution was not defined.

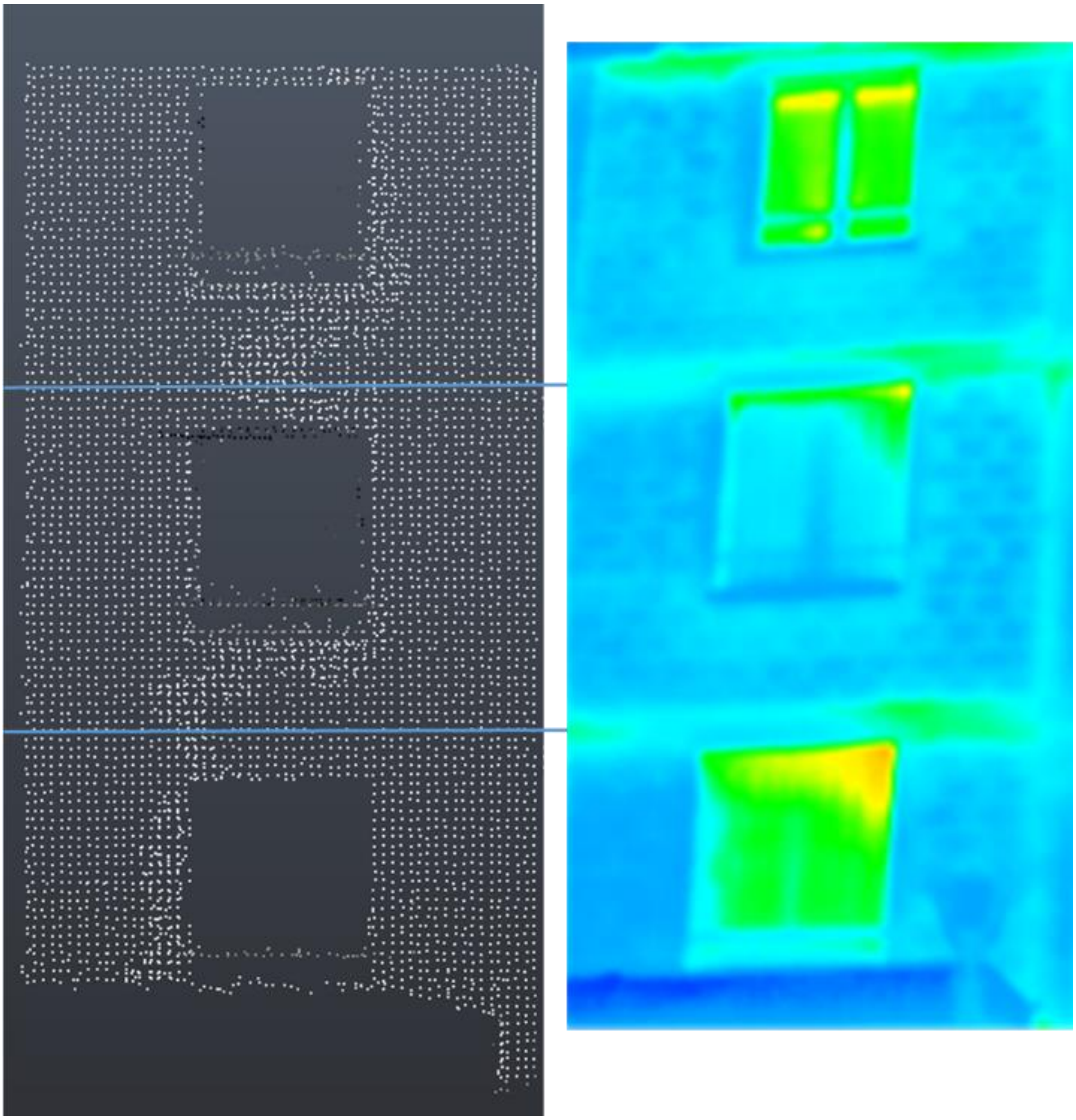


Figure 43: Thermal camera and Point Cloud combination for defining the position of the slab (Thermal picture by Dr Zaratiana Mardara, FCBA).

Apart from the FNs found to improve the research presented in this sub-chapter 5.5, it must be noted that two points need to be addressed in the future:

- Define the geometry for customized fire barriers. According to the latest research on the topic, each module should define a separate fire area [202]. That means that each module should have a fire barrier in the whole perimeter. As explained before, walls are not plumbed and are irregular, and it is necessary to remark that the panels need to be fireproofed and that areas of each module need to be protected with barriers or cavity barriers. Fire resisting barriers can be placed on top of the modules. Each module should be fireproof independent. Therefore, it is necessary to know the approximate thickness of the barrier to avoid gaps or excessive thickness. The depth of the perimeter varies depending on the irregularities of the wall (see *Figure 44*).

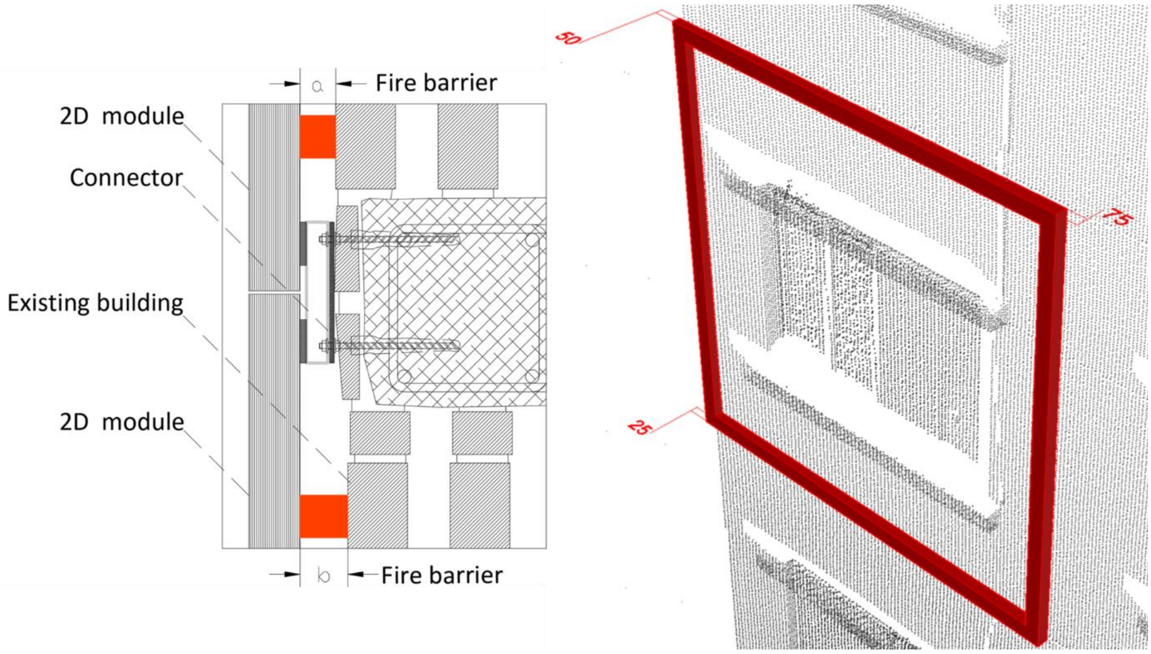


Figure 44: The fire barriers need to have a variable depth along the façade. Left: cross-section. Right: view with Point Cloud.

- Create a library for recognizing objects in complex façade elements. A more complex façade typology beyond the scope of this research should be taken into consideration for a broader market approach. To do so, development of different processing algorithms would be necessary.

6 PARTIAL ROUTING AND NOVEL ASSEMBLY SEQUENCE

As mentioned defined in chapter 4.1, there are two main strategies for manufacturing frames. The first strategy lacked accuracy and the second strategy consumed too much routing time. Currently, accuracy is dependent on the precision-routing-machining and the calibration of the elements that comprise the module. Moreover, in the analysis in chapter 4.1, it was revealed that the more complex a machining, the more difficult the assembly of the elements. This fact impedes automation assembly. To find a new strategy, the idea of *"routing the whole perimeter of each of the elements in order to get an accurate module*" must be questioned. Within this context, some questions arise. Can the accuracy of non-calibrated timber-frame manufacturing by using current assembly lines (explained in chapter 4.1) be improved by further routing/machining the joints while avoiding unbalancing the assembly process? Can full automation be approached within the current manufacturing and assembly lines? Which are the impediments for reaching that goal within the current assembly lines?

To evaluate the appropriateness of any type of improvement, two main assessment parameters needed to be considered. As mentioned marked before, the objective of this dissertation was to improve the accuracy of the prefabricated modules. But how to achieve that goal at the current off-site timber-frame manufacturing lines and factories? In other words, how to reduce the deviations of the frame by routing the studs partially and by using current "common" productive hardware and without disturbing the steps within the manufacturing process? Previous research determined that accuracy and time consumption might create contradictions [43]. Currently, timber-frame module's tolerances are not fulfilling the DIN 18203-3 standard regarding manufacturing tolerances; hence, changes are necessary. But where is the limit in order not to create a time-consuming operation? How much working time would be necessary for achieving that level of accuracy? Within this background, the objective of the study presented in this chapter was to gain accuracy by adjusting the machining level of the studs while avoiding overworking machines and buffers and reaching a balanced manufacturing line.

Moreover, fully automated assembly procedures were approached in this chapter. In this context, apart from the overarching parameters (accuracy and time), there were two other concepts that needed to be addressed:

- **Design for improving assembly sequence planning**. According to Bock [127], the assembly sequence is determined or interrelated by the design of the components used for the assembly and design changes are required to facilitate an automated assembly. In other fields such as aircraft component assembly, a designing software frameworks was developed for product structure engineering and assembly sequence planning where the contact relation of each of the elements and the source were analyzed [203]. However, with a prefabricated timber module, the joinery and its design or arrangement have special relevance since the timber profiles or studs are un-processed (meaning non-calibrated). Timber frame manufacturing requires producing (cutting and preparing) and assembling all elements on the same factory layout and any change in the design must consider this topic.

- **Line balancing**. The higher the accuracy, the bigger the prefabrication degree that can be achieved and, accordingly, the less installation time is necessary thanks to the less rework needed for sealing the modules. But if the effort for manufacturing the modules with high accuracy is bigger than the time spent on the installation with rework for getting a sealed waterproof and airtight solution, then there is a contradiction [149] [145]. It is, in the end, a line balancing issue that requires accuracy of the prefabricated module. The literature in line balancing is prolific and it is not the objective of this research to create a new method for calculating balanced manufacturing factory layouts. But in order to classify the object of this study, the timber-frame module manufacturing can be considered as a Generalized Assembly Line Balancing Problem (GALBP) with stoc*hastic task time* due to the variation of the product [204]. In this research, it is necessary to gather the input data of the current performance and test and compare novel concepts against that.

In the next sub-chapter, the current timber-frame manufacturing process is broken down and the different steps are analyzed. Moreover, a novel concept is proposed and tested.

Does excessive machining of the elements by including complex geometry virtually harm a future robotic assembly? Is it possible to foresee that? This issue was determined by the so-called Assembly Oriented Design which needs to be evaluated [205] together with the Design for Assembly [206] and Robot Oriented Design [127] for a smooth assembly because the routed profiles need to be easily assembled by human operators or by robots.

6.1 Research Gaps for full automation in the assembly of non-calibrated timber frames

Breaking down the process explained in chapter 4.1 was necessary to analyse in-depth the causes of inaccuracies bigger than the required in the DIN 18203-3 standard. For this purpose, a case study was chosen, namely the timber frame module similar to the scheme in chapter 4, *Figure 46*, that is, a module of 2.39 mm by 2.79 mm with a single-window hole of 1000 mm by 1250 mm (6.67 m² are considered as the area of the module). The test was carried out in a Weinnmann manufacturing line with a medium degree of automation (not a fully automated one as shown in [157]).

The materials used in the case of this analysis were pinewood studs 120 mm by 80 mm and an OSB board of 12 mm. Regarding the design and the configuration of the frame, there are two types of unions in the frame: a) a nailed butt joint (1, 2, 3 and 8 in *Figure 45* and *Figure 46*) and b) a trench joint (4, 5, 6, and 7 in *Figure 45* and *Figure 46*). The butt nailed joints were used for assembling the regular studs to the top and bottom plates or beams (1, 2, 3 and 8 in *Figure 45* and *Figure 46*). The regular studs are cut in a saw with numerical control (Workstation 1 in *Table 16* and *Figure 47*).

The window framing needs further precision and an embedded joint to better transmit the forces and ensure accurate placement and fixation. For this reason, the trench joints are used to assembly the sill and head trimmer (5 and 6 in *Figure 45* and *Figure 46*) to the jamb studs (4 and 7 *Figure 45* and *Figure 46*). For that purpose, the jamb studs were machined in a CNC with a trench shaped cut to host the sill and head trimmer (Workstation A in *Table 16* and *Figure 47*). In Workstation B, the window frame or any other type of openings, such as doors, were conformed, as shown in Workstation A in *Table 16* and *Figure 47*.

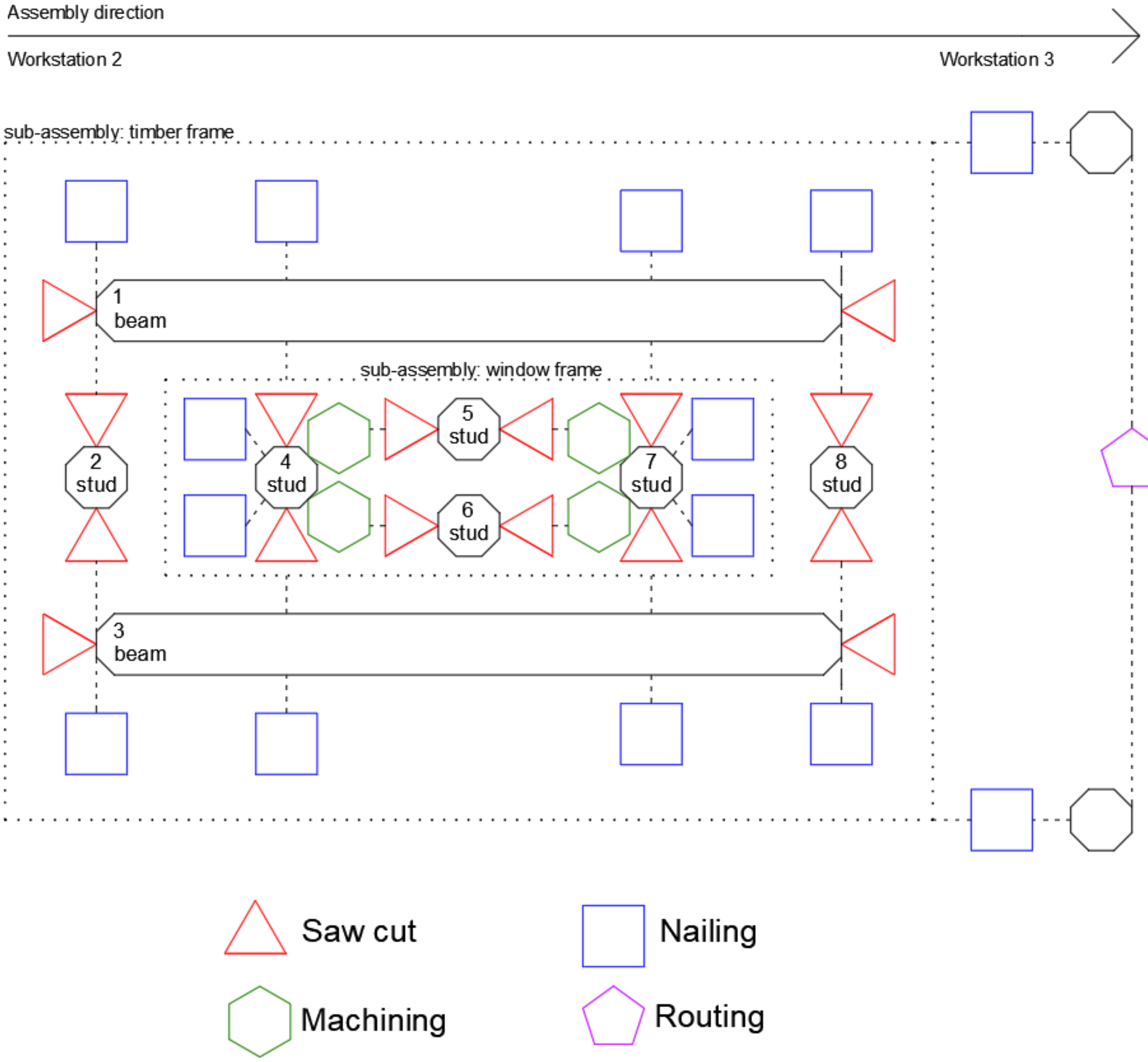


Figure 45: Necessary works for each of the studs and boards and the relation of contacts.

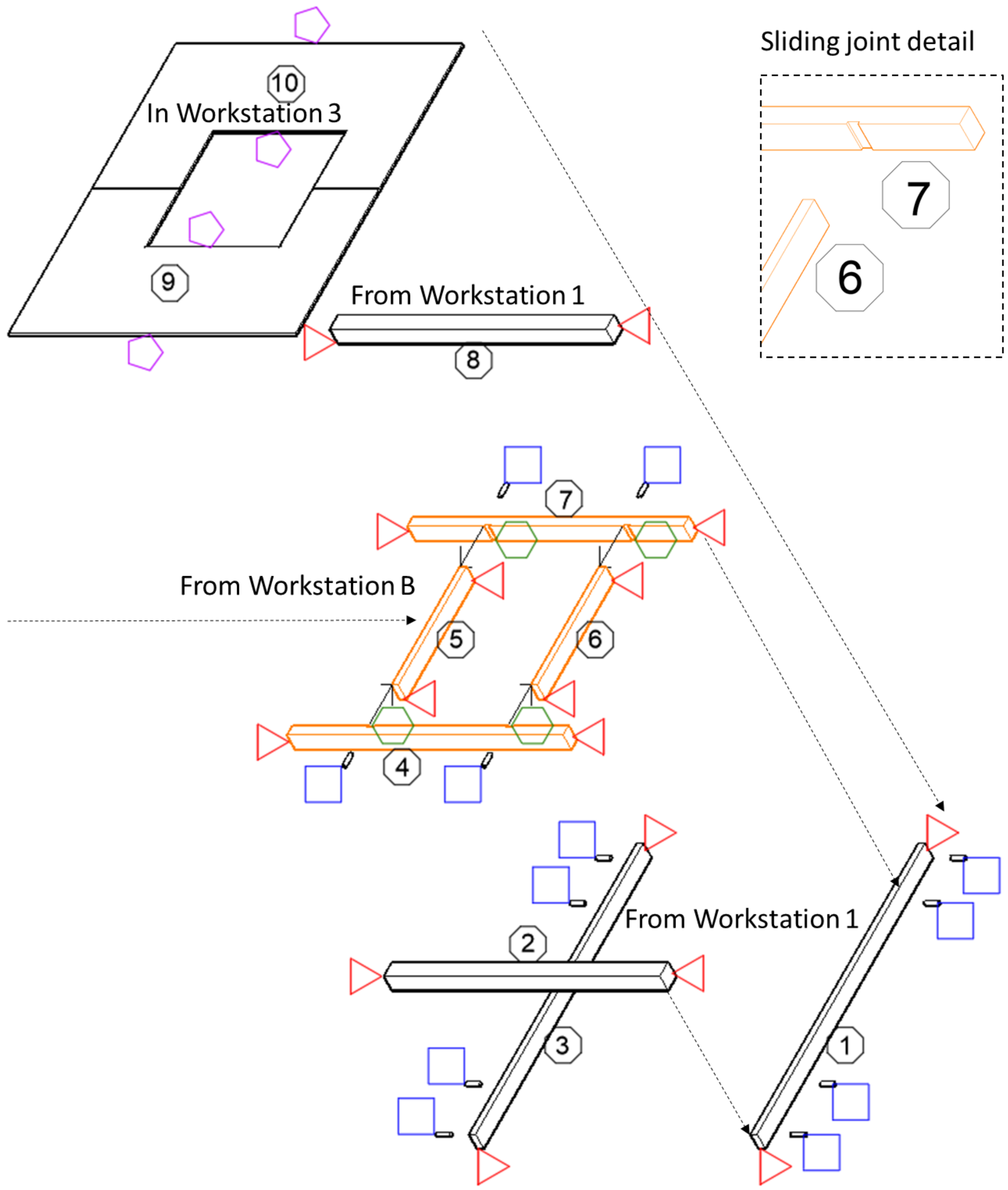


Figure 46: Scheme of the assembly process order.

This (simple) joint configuration implied a defined assembly sequence type and, as a consequence, a specific assembly line was determined. For accomplishing such joinery system, the current assembly sequence was performed in two parallel lines that merged in Workstation 2 (see *Table 16* and *Figure 47*). This parallel assembly configuration was implemented for both manual and robotic processes [157]. On next points, the two lines are explained:

For the regular studs and top and bottom plates, the assembly follows a logical line that starts in Workstation 1 and ends in Workstation 3 (see Line 1 in *Table 16* and *Figure 47*). This is a process that has already been automated and robotized to create an automated nailing station

[157]. The regular studs are held with stoppers and, after that, are nailed with nailing guns in Workstation 2 (*Table 16* and *Figure 47*). It is important to remark that the detected inaccuracies of the stud positioning happen during this process.

However, the window frame cannot be assembled in Line 1. The window frame (studs 4, 5, 6 and 7) needs to be assembled in a parallel workstation (Line 2 in *Table 16* and *Figure 47*) and, after that, is inserted in the nailing workstation (Workstation 2). The window frame is assembled manually regardless of the automation level of the assembly line. The reason for such manual assembly is that the nailing guns on the manufacturing line for the regular studs are aligned with the top and bottom plates and, therefore, they cannot reach the sill and head trimmers which are located in the interior and a perpendicular direction. This is a major issue for automating the assembly process.

Table 16: Assembly sequence I regular module.

Line 1: Regular studs and top and bottom plates (elements 1, 2, 3 and 8 in *Figure 46*)
The Arrival of Timber (M)
Workstation 1: Sawing machine
1.1-Adjust size in machine control (M)
1.2-Load timber to machine (M)
1.3-Cut to size studs and plates (A)
1.4-Unload from the machine (M)
1.5-Handle studs and plates to next workstation
Workstation 2: Stud-Plate nailing
2.1-Load program in the machine (M)
2.2-Place stud and plates (M)
2.3-Nail plates and studs (A)
2.4-Roll to next workstation (SA)
Workstation 3: Board placing, nailing and routing (elements 9 and 10 in *Figure 46*).
3.1-Load program in the machine (M)
3.2-Place board on top of the timber frame (M)
3.3-Fix accurately the timber frame (M)
3.4-Nail boards (A)
3.5-Route the boards (A)
End of the sequence

Line 2: Openings (elements 4, 5, 6 and 7 in *Figure 46*)
The Arrival of Timber (M)
Workstation A: machining CNC
A.1-Load program
A.2-Load timber to machine (SA)
A.3-Cut and rout (A)
A.4-Unload (SA)
A.5-Handle jamb studs to next Workstation B
Workstation B: window frame assembly station
B.1-Load studs and sill and head trimmers (M)
B.2-Assembly and nail studs and sill and head trimmers (M)
B.3-Unload
B.4-Move to **Workstation 2**:

(A) Automatic task
(M) Manual task
(SA) Semi-automatic task

As said before, the window jamb studs need to be machined in a CNC (Workstation A in *Table 16*). These jamb studs were moved to an assembly table (Workstation B in *Table 16*). The transition of the window frame from Workstation B to Workstation 2 was a horizontal movement that required human force and heavy loads need to be considered (see *Figure 47*). Moving such a window frame with a robot would be a difficult task because the 1) window frame size changes the end effector which should adjust its position to a different size all the time, and 2) Workstation B would need to be structured.

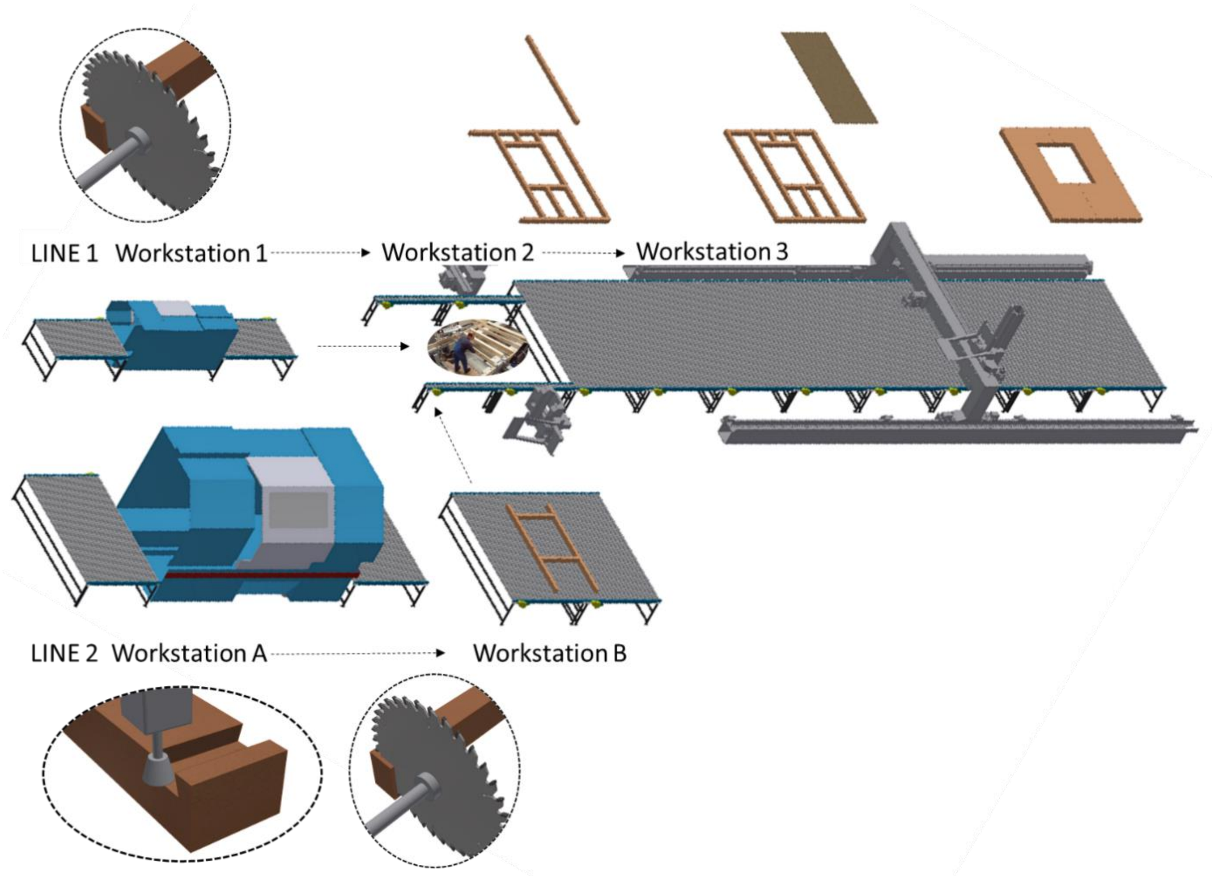


Figure 47: manufacturing and assembly line with current methods.

The process ends in Workstation 3 where the boards are placed on top of the timber frame and the CNC routes it.

The time spent in each work station for the manufacturing of the module is shown in *Table 17*. In total, 0,165 hours per square meter is needed for the whole process. This is the benchmark to consider in the next phases. The current Takt time [207] is between 10 and 20 minutes per module.

In summary, two reasons impede the automatic assembly of the window frame: a) nailing the sill and head trimmer to the jamb studs, and b) the need to move the window frame from one workstation to the other.

Table 17: Time for manufacturing the analyzed case.

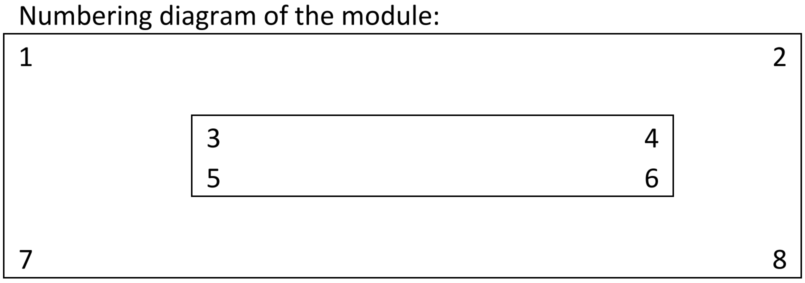
	Work-time	
Workstation 1: Sawing machine	0,267 h	
Workstation 2: Stud-Plate nailing	0,25 h	
Workstation 3: Board placing, nailing and routing.	0,15 h	
Workstation A: Machining CNC	0,267 h	
Workstation B: Assembly station	0,1667 h	
TOTAL	**1.1007 h**	**0,165 h/m²**

Regarding accuracy, the module was measured with a tape and presented deviations of up to 2 mm in the frame and 4 mm around the corners. As expected, the board routing had inaccuracies of up to 9 mm[26] (see *Table 18*).

Table 18: Accuracy deviation table.

Planned Points	Xn (mm)	Yn (mm)	Placed Points	xn´ (mm)	yn´ (mm)	Total deviation in mm
Point 1p	0	2785	Point 1p´	3	2780	6
Point 2p	2396	2785	Point 2p´	2394	2781	4
Point 3p	698	2350	Point 3p´	700	2354	4
Point 4p	1698	2350	Point 4p´	1703	2356	8
Point 5p	698	1100	Point 5p´	702	1105	6
Point 6p	1698	1100	Point 6p´	1705	1101	7
Point 7p	0	0	Point 7p´	0	0	0
Point 8p	2396	0	Point 8p´	2398	0	2

Numbering diagram of the module:



As a conclusion of this sub-chapter 6.1, it can be stated that:

- **RG2.1**: Accuracy of the elements must be achieved to ensure low tolerances of the modules without harming the assembly line.

[26] The module was considered as two dimensional

- **RG2.2**: There is a need for reducing the complexity and, if possible, avoid two parallel workstations and the subsequent window frame transfer. At this point, it is not relevant if the placement of the studs is done manually or by robots [208] but to optimize the assembly line and the sequence of the assembly. However, the sequence of a future robotic window frame assembly (or other highly-machined and bulky elements) need to be envisioned and, therefore, better solutions need to be proposed.

In the next sub-chapter, 6.2, these RG2.1 and RG2.2 will be addressed by DNS2.1 and DNS2.2.

6.2 Development of Novel Solution

Ideally, the movement for placing all the elements (boards, all studs, including the studs of the frame) should be made top-down as in Workstation 1. This way, different workstations would be avoided. In other words, it would be desirable to optimize the linear characteristics of the assembly line. Also, the idea of the linear process would be reinforced and time should be reduced. Further machining was necessary for achieving such situation.

A new concept was proposed to solve the research gap. The new concept was developed exclusively for the manufacturing context analyzed before but it could be applied to some other similar manufacturing lines. The new concept was conceived by considering the requirements of the assembly process and adapting the design for that purpose. The new concept was based on two main interrelated changes: new configuration of the joints that provide a new assembly sequence:

- **DNS 2.1:** Further machined joints that facilitate robotic positioning and assembly**.** The new concept was based on an assembly sequence-oriented machining which consists of machining of all timber stud joints to improve the manufacturing line assembly process, as well as the accuracy. The studs do not need to be routed as in options A and B in chapter 4.1 but only minor machining is necessary for the joints. For this test, it was decided to use the shape of the union by using *sliding dovetail joints*[27]*.* The dovetailed joints avoid the need for nailing in the axe of the stud, at least during the assembly process, because it provides a “temporary” union. Another objective was to check if the accuracy would improve by using a sliding dovetail and whether this would improve the assembly by facilitating a rigid temporary union before and while the nailing is achieved. One of the objectives of the test was to check if the sliding dovetail creates a more constrained joint and, therefore, more accurate timber frame (see *Figure 49*). In principle, the joints do not need to be nailed.

- **DNS 2.2:** Based on the previous point, a new assembly sequence was proposed within the existing assembly line. As defined in chapter 1, the manufacturing process and its

[27] This type of joint is not Robot Oriented Design friendly, but that was a limitation of the research. In the next chapter 7, a more friendly joinery is used.

steps are already set up. And the proposed assembly sequence needs to fit the current assembly line (see *Table 19*, *Figure 48*, *Figure 49* and *Figure 48*). The new sequence avoids a parallel workstation for the window frame because all the studs can be fed from one single feeder on top of the assembly line and all the movements for the assembly are top-down and all the elements can be placed. The window frames are not assembled in another workstation. This sequence is compatible with robotic or automated (future) assemblies and allows less operational paths (see *Table 19*, *Figure 48*, and *Figure 49*).

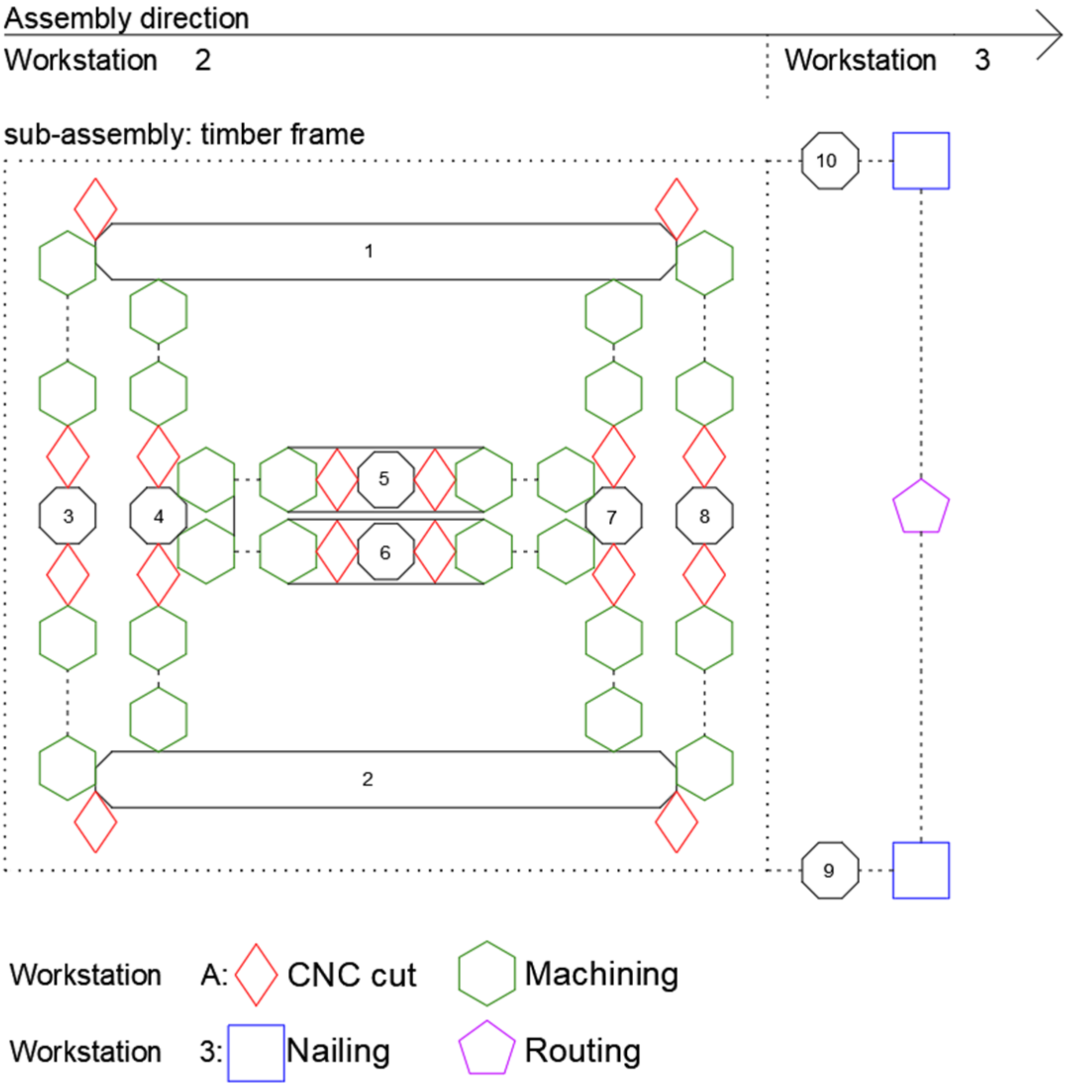


Figure 48: New Assembly sequence scheme.

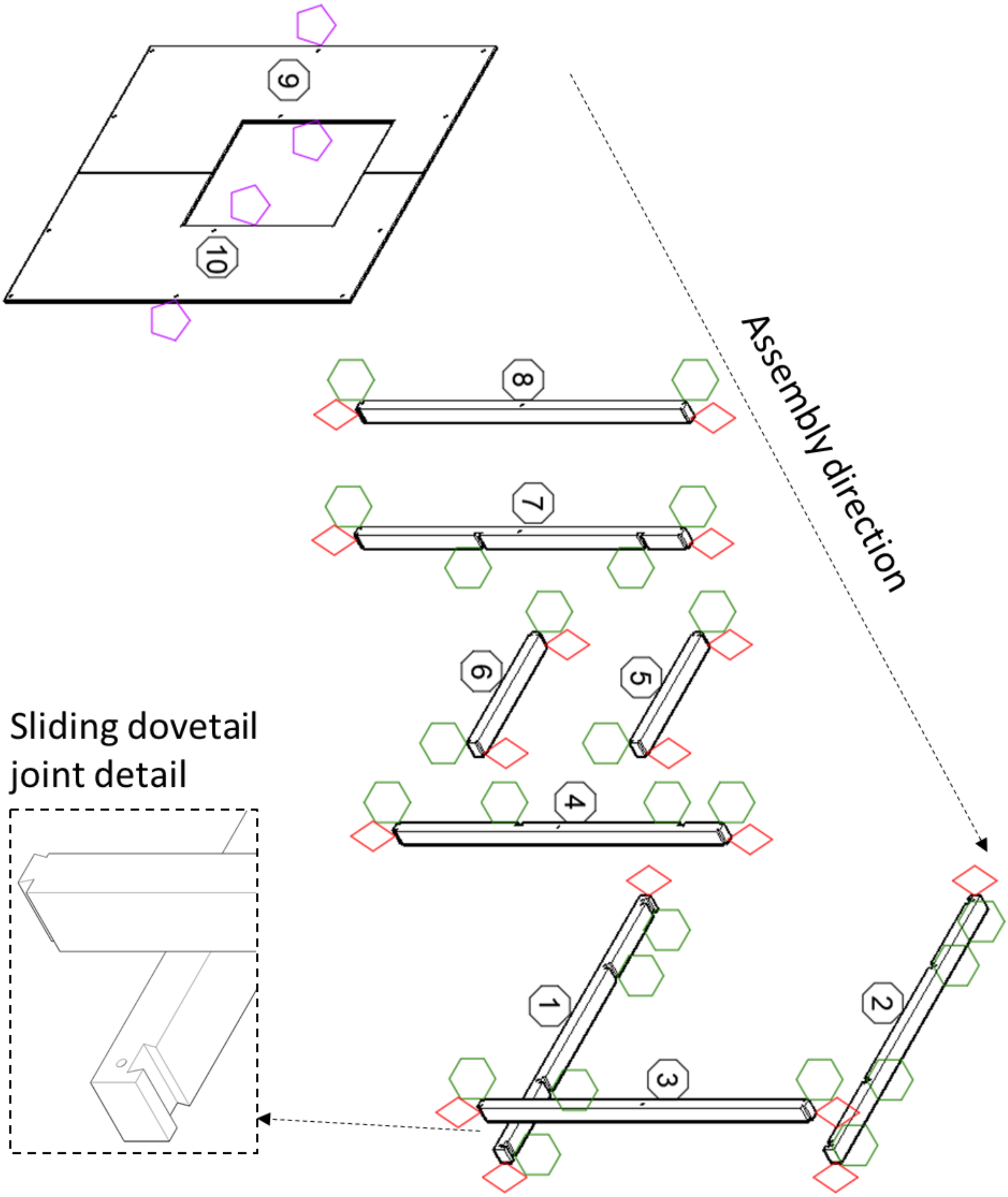


Figure 49: Unidirectional assembly of timber frame by dovetail joints.

To obtain such improvements, it was necessary to readjust the manufacturing and assembly processes. The current sequence has been changed. However, fFor fabricating such a module and to fulfil the pint in the previous point, the manufacturing line was still the same as the one specified in chapter 4.1. This new method would have the next steps.

It would be convenient to gain accuracy by routing the boards as well but the factory where the test was carried out did not have a CNC machine for that. The main limitations for achieving the experiments were the usability of the manufacturing line of POBI [33]. The experimentation was carried out during working hours, which means that the factory was cut for the realization of the planned tests.

The process started in Workstation A where the studs, plates and trimmers were cut to size and machined thanks to the CNC machine (see *Table 19*). The studs, plates, and the trimmers are not necessary to be routed as a board, but only the heads and butts. For the analyzed case, it was necessary to load the program for each of the elements to be machined on the computer of the CNC machine.

Table 19: Assembly sequence regular module.

Line 1: Regular studs and top and bottom plates (elements 1 to 10 in Figure 48 and Figure 49)
The Arrival of Timber (M)
Workstation A: machining CNC
Load program (M)
Load timber to machine (SA)
Cut and rout (A)
Unload (SA)
Handle studs and sill and head trimmers to next workstation
Workstation 2: Manual assembly
Load program in the machine (M)
Place stud and plates (M)
Nail plates and studs (A)
Roll to next workstation (SA)
Workstation 3: Board placing, nailing and routing.
Load program in the machine (M)
Place board on top of the timber frame (M)
Place accurately the timber frame (M)
Nail boards (A)
Route the boards (A)
End of the sequence

Once machined, the studs, trimmers, and plates should be moved to Workstation 2 which assembled all of them until the timber frame was configured. According to the current procedure, this process needed to be achieved manually but it could also be done automatically because the assembly path or movement is top-down with all timber-frame elements, therefore, a simple movement was necessary (see *Figure 49*).

After that, the timber frame was moved to Workstation 3. Here, the boards were placed on top of the frame. This process was currently done manually. Once achieved, the whole timber frame was set up in a known-coordinate system and the boards are nailed to the studs by the Weinmann CNC and route the boards afterwards.

There could be another variant to this option and avoid the routing in Workstation 3 of the boards in the Weinmann CNC and, therefore, avoid routing inaccuracies explained in chapter 4.1. However, this would imply routing the board in a CNC and such option could not be performed on the facilities where the test was achieved.

Comparing to the current procedure studied in chapter 6.1, some changes can be observed (see *Figure 50*). For instance, the manual saw was not necessary anymore because all cuts were accomplished at the CNC machine. Moreover, nailing the studs to the plates was not considered necessary because the sliding dovetail joints offer an embedded and rigid force transmission. Therefore, one step was reduced as well. The CNC for machining was more extensively used and, for this reason, it was necessary to test this novel concept to check the line balancing of the assembly process.

As it could be seen, this was somehow a third approach compared to the analysis made in chapter 4.1, which was between the total rooting and machining of the studs and the current method used by the assembly lines. The novel concept's objective was to facilitate the assembly but also to gain accuracy and to keep at least the current manufacturing line's takt time.

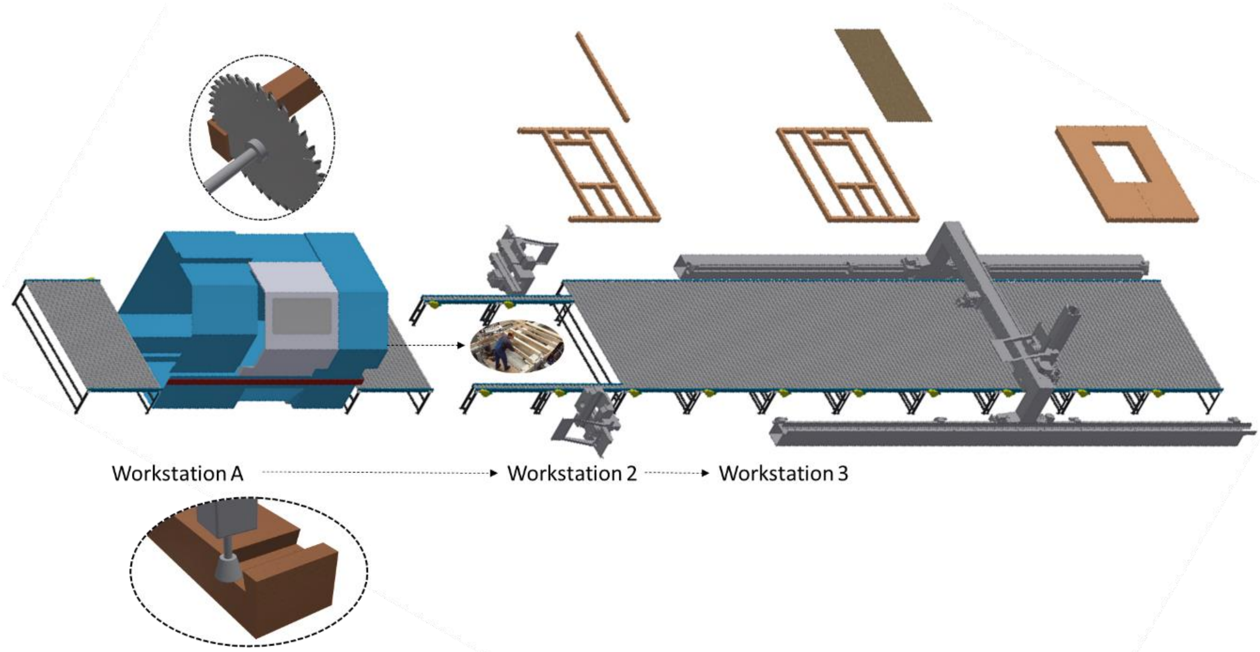


Figure 50: Assembly of timber frame by dovetail joints in one single line.

6.3 Proof of concept for the novel concept

The first proof of the novel concept was carried out in a test that was performed in the same industrial setting as the analyzed case in sub-chapter 6.1. Moreover, the materials used for manufacturing and assembling the module were the same as for the analyzed case in sub-chapter 6.1, that is pinewood studs 120 mm by 80 mm and an OSB board of 12 mm. The planned size and shape were the same as in sub-chapter 6.1.

For checking the manufacturing and assembling accuracy, holes were arranged in the same y and z coordinates both in the timber studs and also on the boards (see *Figure 51*). The objective was to evaluate differential deviations between the timber studs machined in the CNC and the boards routed on Workstation 3 (see *Figure 52*).

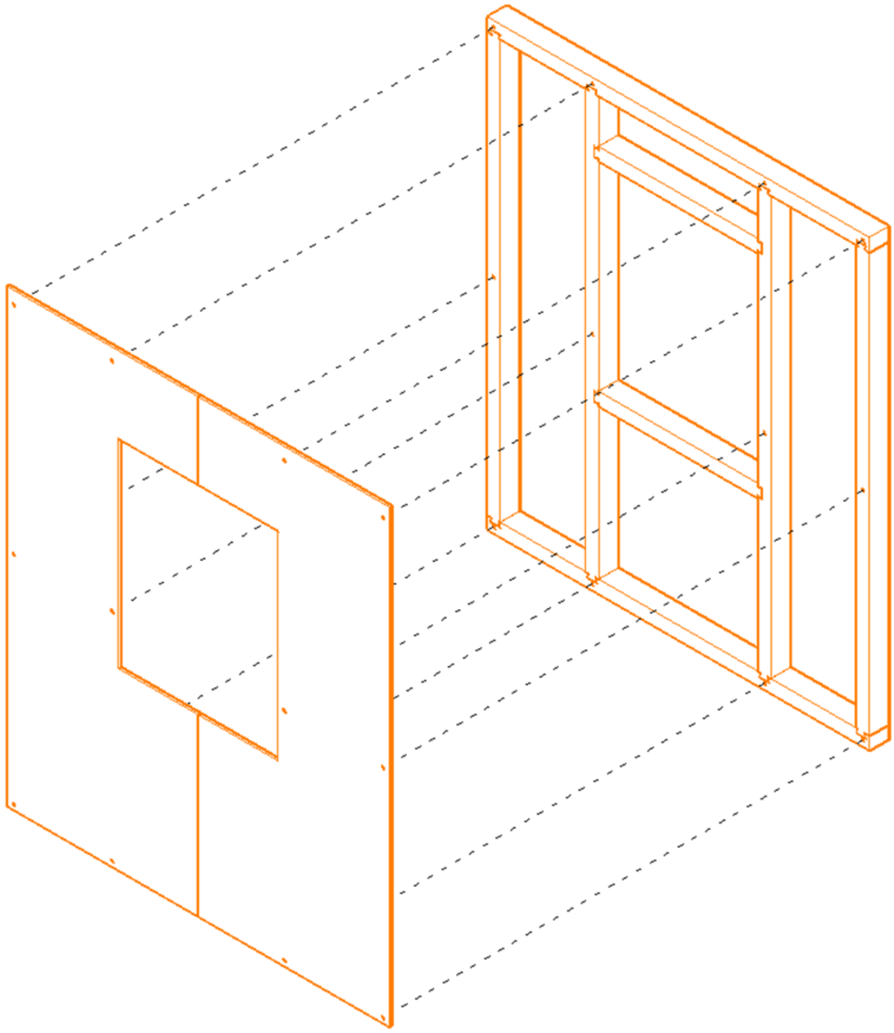


Figure 51: Scheme of the timber frame module and the location of the holes.

According to the previous analysis in sub-chapter 4.1, there are manufacturing and assembling deviation differences between the timber frame and the boards. It was considered necessary to assess if, with the novel method, the deviations increase or decrease.

The tools at the CNC was a Hundegger K2 [209] used for machining the female and male cuts of the dovetail. The tools were a circular drill bit for cutting the top and bottom of the studs and a shaped drill for machining the female and the male shapes (see *Figure 52* top).

Figure 52: Top: Machining of profiles.

Bottom: Sanding in Workstation A.

Sanding was necessary after the profiles were cut and routed to reduce chipped and non-sharped edges (see *Figure 52* bottom). The CNC machine by itself was not sufficiently accurate for shaping, as required. To avoid collisions of wood chips, the machined profiles needed to be ground, as it was done in the steel machining industry.

The previous paragraph is related to the deviations that the solid timber presents. Solid timber is more likely to be warped. There is the question of the warped wood when using a CNC. The aforementioned CNC machine does not press and hold the object locked but, on the contrary, the object is moved while the tools stay in an axe. The concept itself leads to inaccuracies. These inaccuracies are multiplied if the timber studs are warped.

Figure 53: Top: handling the profiles to Workstation 2 and assembly of the profiles in Workstation 2. Below: nailing in Workstation 3.

Once the studs, trimmers and plates were machined in Workstation A, these were transported to Workstation 2 and 3 and the operations were finished (see *Figure 53*). A hand nailing gun was used to better constrain the timber profiles but the time consumed can be neglected as it was very low.

6.4 <u>Results</u>

Similar to the rest of the chapters, for the assessment of the test, two parameters were measured, assembly accuracy and manufacturing and assembly time. The results of the new test were compared to the case studied in chapter 4.1the previous sub-chapter which uses the current technologies.

Accuracy

Once the timber frame was finished, it was measured by two means: total station and manual rulers. Both measurements were inserted in AutoCAD and compared to the original design achieved in Dietrich's software [84].

Different means of measurement offer different aspects and performances in building measurement [210], [211]. Combining two or more measuring techniques is a common procedure [212]. To acquire the dimensions of the assembled module accurately, two means of measurement devices were used and combined. On the one hand, an analogue system such as the measuring tape and measuring-rulers were used. These tools were used because it offers high reliability for measuring single linear objects in a close range (1-10 m) of distance. On the other side, a digital total station was used for measuring the distance between points or, better said, because it gives a referenced information in 3D, whereas the tape and ruler only measure distances. The total station can have errors up to 1.1 mm in a range of 60 mm in an indoor scene [213], especially if the measurement is carried out without any reflector [214]. It can be concluded that the combination of both techniques was justified. It was necessary to merge both results and to find the midpoint between the points taken by the analogue and the digital systems. The results show that, compared to the current methods explained in 4.1, accuracy was gained. Similar to chapter 4.1, the deviation was calculated in two module parts: the CNC Weinnmann routed boards and the CNC cut modules.

- The maximum deviation between planned and placed coordinates in the boards was registered at point 1b (with a deviation of 12 mm) while the lowest deviation was observed at Point 4b (with a deviation of 2.1 mm) (see *Figure 54* and *Table 21*). These high deviations were expected.
- The maximum deviation between planned and placed coordinates in the profiles was registered at point 6p (from profiles) (with a deviation of 1,5 mm) while the lowest deviation was observed at Point 7p and 8p, with no detectable deviation (see *Figure 55* and *Table 22*).

Comparing the accuracy of the profiles, results are better than in the case presented in chapter 6.1. Moreover, the tested model would fulfil the EN 13,380. However, the boards accuracy was still low.

It was relevant to the differences between the studs and the boards. While the studs were close to the limit deviations off lees than 1 mm, the assembled boards presented even higher deviations than expected.

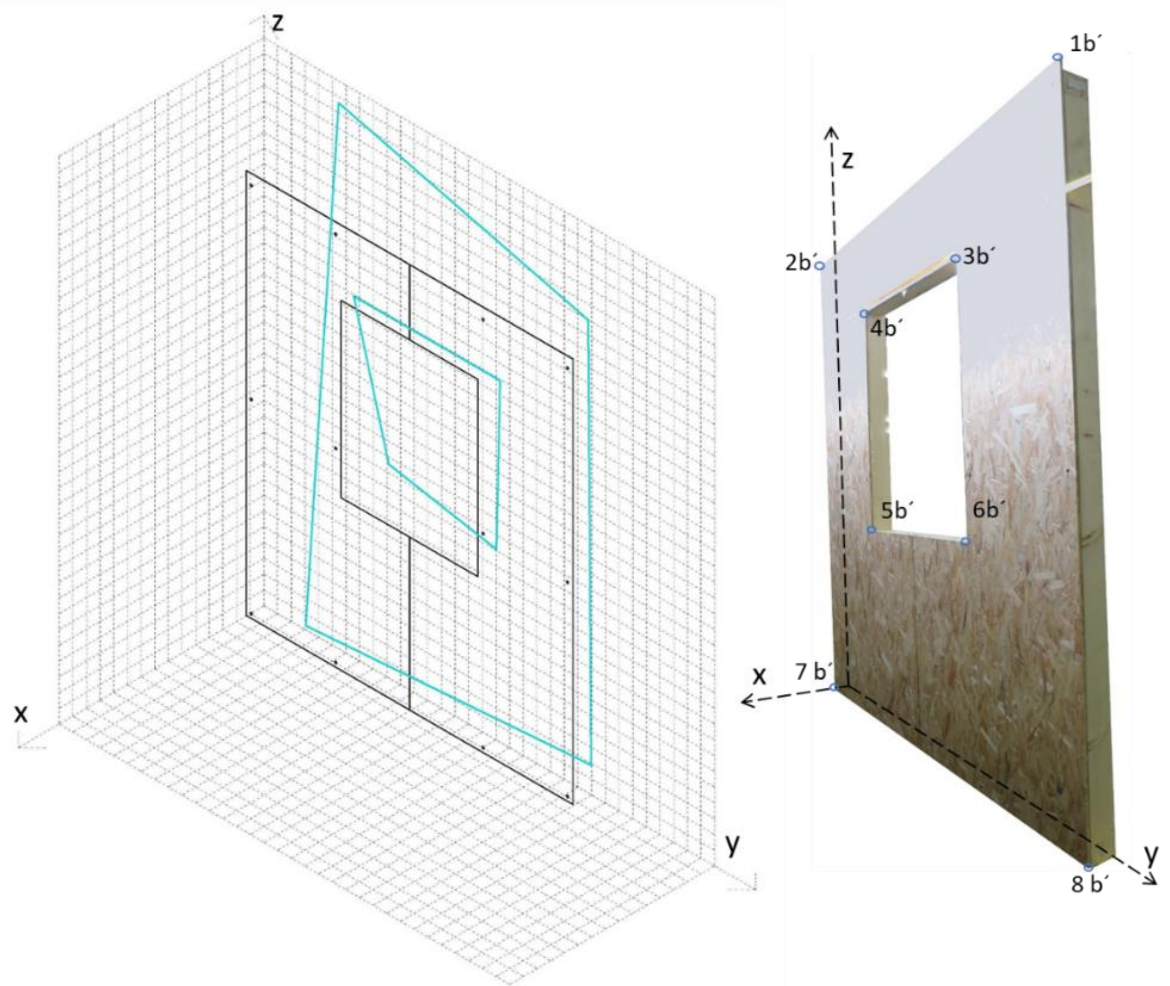


Figure 54: Planned and assembly deviation graph of the boards magnified by a factor of 80.

Table 20: Deviations (measuring deviation might be around 1 or 2 mm).

Planned Points	Xn (mm)	Yn (mm)	Zn (mm)	Placed Points	xn´ (mm)	yn´ (mm)	zn´ (mm)	Total deviation in mm
Point 1b	132	0	2827	Point 1b´	133,3	8	2836,1	12,1
Point 2b	132	2396	2827	Point 2b´	132,1	2396	2829,4	2,4
Point 3b	132	698	2350	Point 3b´	132,9	700	2351,8	2,8
Point 4b	132	1698	2350	Point 4b´	132	1700	2350,9	2,1
Point 5b	132	698	1100	Point 5b´	129,5	699.8	1102,3	3,8
Point 6b	132	1698	1100	Point 6b´	131,3	1699	1102,3	2,6
Point 7b	132	0	5	Point 7b´	131,3	4.8	6,2	4,9
Point 8b	132	2396	5	Point 8b´	131,3	2397	8,3	3,5

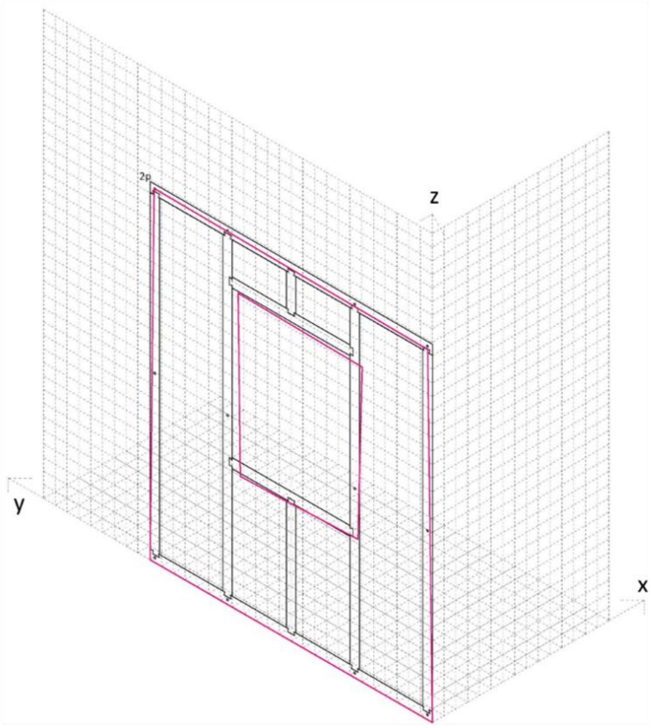


Figure 55: Planned and placed deviation graph of the profiles magnified by a factor of 80.

Table 21: Deviation of the profiles.

Planned Points	Xn (mm)	Yn (mm)	Zn (mm)	Placed Points	xn´ (mm)	yn´ (mm)	zn´ (mm)	Total deviation in mm
Point 1p	0	0	2785	Point 1p´	0	0,5	2784,3	0,8
Point 2p	0	2396	2785	Point 2p´	0	2395,6	2784,6	0,5
Point 3p	0	698	2350	Point 3p´	0	696,7	2349,6	1,3
Point 4p	0	1698	2350	Point 4p´	0	1697,4	2349,8	0,6
Point 5p	0	698	1100	Point 5p´	0	697,2	1099,2	1,1
Point 6p	0	1698	1100	Point 6p´	0	1697,1	1098,7	1,5
Point 7p	0	0	0	Point 7p´	0	0	0	0
Point 8p	0	2396	0	Point 8p´	0	2396	0	0

Figure 56: Left: Manual measurement of the module showing deviations between the frame and the board. Right: Deviation of the hole made on the board by the Weinnmann and the hole made on the profile by the K2 Hunddegger.

In *Figure 56,* it can be observed the comparative deviations between the studs (CNC machined and routed) and the boards (CNC routed). The differences are relevant in such a small piece of the module.

Time

All operations were recorded and noted. These are the outlined results (see also *Table 22*):

- Workstation A: The works started by loading each of the programs in the Hunddegger which took about 5 minutes. After executing the program, the CNC performed the loading of the profile, cutting to size the stud, machining the stud and unloading the studs. It took about 8 minutes on average at the CNC and 40 minutes (0,66 h) in total. Brushing the profile cuts and the machined parts was achieved in parallel as the CNC was working.

- Workstation 2: once in the module assembly line, it took about 15 minutes (0,25 h) to assembly the profiles. The profiles needed to be assembled manually, which took around 15 minutes. The first wWorkstation 2 (where all the profiles are were assembled and nailed together) had to be skipped because the assembly and nailing process is was dictated by the Weinnmann and does did not follow the logical sequence that our module required. This is was a major problem against automation, which would require a change. After that, insertion of the module onto the Weinnmann machine and the boards were placed on top, the boards were routed and the holes were made by the Weinnmann itself.

- Workstation 3: The routing and nailing were achieved in 9 minutes (0,15 h).

The total time used for the assembly of the timber-frame is slightly lower (1,06 h) than in the case explained in chapter 6.1 (1,107 h see *Table 17*).

Table 22: Time used for the novel approach.

	Time spent	Time spent B	Per m²	Per m² B
Workstation A: machining CNC	0,66 h	0,33h	0,098	0,049
Workstation 2: assembly and nailing of studs	0,25 h	0,25 h	0,037	0,037
Workstation 3: Board placing, nailing and routing.	0,15 h	0,15 h	0,022	0,022
TOTAL	**1,06 h**	**0,73 h**	**0,157**	**0,108**

However, the results in *Table 22* show an unbalanced situation since the time consumed in Workstation A is more than double the time necessary in Workstation 2 and 3. A solution would be to duplicate the productivity of Workstation A. If that would be the case, the time consumption could be reduced in 0,33 h in Workstation A and reach 0,77 h in total since one operator could control the two machines in Workstations A (case B in Table 22).

6.5 Future Needs

The results were positive but there is a need for further improvement to implement the new procedure in the current factory line. There are several reasons for stating that. The results achieved in the novel process show several different aspects:

- **FN2.1**: Adjustment in design to facilitate the assembly process.
  - **FN2.1.1** The design also needs to be considered as for rigidizing the module itself.
  - **FN2.1.2** Joints that facilitate the assembly are recommended.
- **FN2.2**: Adjust the manufacturing line.
  - **FN2.2.1**. As said before, add an extra CNC machining device, or duplicate the productivity of Workstation A. Organizational changes would be necessary, but that would require minor changes in logistics.
  - **FN2.2.2** Workstation 2 should be re-programmed depending on the new assembly sequence.
  - **FN2.2.3** The inaccuracies of the board when being routed by the CNC bridge should be solved. This is a topic that was not addressed in this research but future approaches must consider it.

The design affects and limits the accuracy degree and the manufacturing and assembly time. In future, any design strategy presented should appropriately consider the easiness and time of the assembly and the final accuracy result. If a CNC-based manufacturing is embraced, as a strategy to get more technical or machined elements that can host several services, this would imply more time consumption and several machines working in parallel.

In the following chapter 6, a new balanced line is proposed, and a robotic assembly is conceptualized and tested.

7 DEVIATIONS AND ADJUSTMENTS DURING ROBOTIC ASSEMBLY

For the research presented in this chapter, the main goal was to improve the robotic assembly of the timber-based prefabricated modules with calibrated and machined timber studs. A fully prefabricated façade module with highly machined elements requires accuracy when picking and placing the object. If the operation is achieved by hand, it can be controlled. But for achieving it with robots, some measures were necessary. Part of the content of this chapter was described in the paper for ISARC 2019 [215] [28].

Following the conclusions in chapter 6, an automated and robotized assembly line was configured for the assembly of calibrated and highly routed timber frames (see *Figure 57*). Testing such a manufacturing line would require a high cost. However, testing only the picking and placing during the assembly processes is achievable with limited resources.

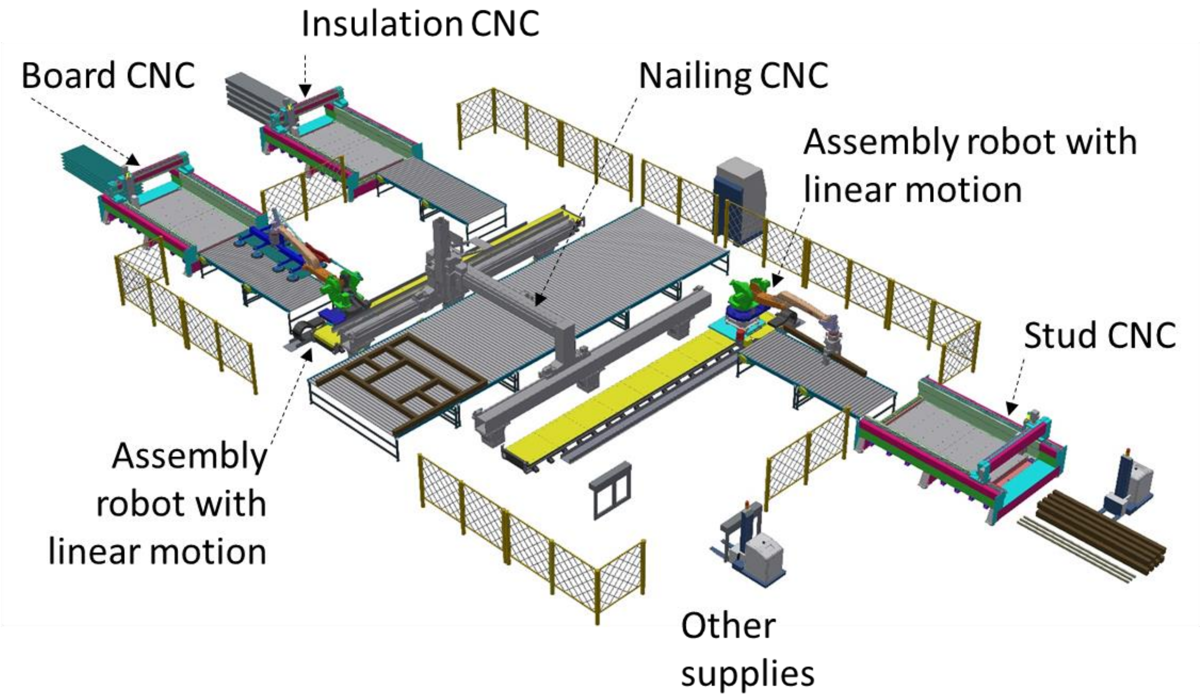


Figure 57: Scheme of an accurate frame manufacturing robotic assembly.

28 The research presented in this chapter might be published as a Journal article before or after publishing this dissertation

7.1 State of the art

The issue of accuracy and deviations in the assembly of construction modules was detected form the first experiments. 30 years ago, Kodama *et al.* [216] and Bock [127] reported deviations during the grasping and placing of construction blocks while building a wall. These blocks were specially designed for facilitating the assembly process following the robot-oriented design (ROD) concept [127]. However, the deviation of the wall built was considerable. Gambao also faced similar issues during the erection of a wall with robots during the ROCCO project [111]. To solve the issue, Arai *et al*. [217] defined a method for automatically calibrating the pose of the Robot Coordinates (not the grasped element) by using two cameras and LED Markers. The calibration error was around 0,2 mm and 0,6 mm depending on the workspace size but it took around 2 to 5 minutes in every case, which, for a simple assembly process is too long.

Recent studies were more focused on the accuracy of recognition of objects, rather than in the accuracy of grasping itself. The grasping quality was evaluated [218] by using the estimated probability of success or failure in the real environment. There has been visual analysis of the object to adjust the grasping position of the end-effector [219] but without considering the deviation of a grasped element and neural networks to better recognize the object [220].

In more recent research projects, ordinary bricks were used to build parametrically designed walls. Bonwetsch [221] reported deviations of up to 10 mm compared to the desired location. Eversmann [222] also identified deviations on the assembly were the “Orientation tolerances can, however, still cause failures”. Similar deviations happened in a research project that assembled timber profiles for building structures and, for this case, Willmann [223] suggested sensor feedback mechanisms to allocate the grasped object as well as the assembled module. This is quite important to remark because it is the core aspect of this chapter. Another point that should be remarked is that in the research conducted by Willmann [223] and that by Bonwetsch [221], the objects to be assembled do not present any special joining system to facilitate the allocation and assembly of the studs with each other, where the studs are only cut to the required angle.

On the other hand, some timber-framing machine builders offer the possibility of robotizing the assembly process of boards (not timber frame elements such as studs and mullions). Machine builders such as Weinmann [157] use robots for picking and placing studs. But, as far as the given information, the studs are repositioned after they are placed. The boards are routed with the accuracy that was specified in the previous chapter.

Moreover, as can be seen in reference [224] the grasped object tends to bend, which jeopardizes the exact placement of the object. Randek [225] also uses robots for picking and placing boards but these are routed afterwards, which can cause accuracy errors.

The accuracy of the robot’s grasping is not guaranteed when working in unstructured environments where the grasped objects are not placed in a known location. Besides, the variety of design of the prefabricated modules hinders automated programming of the robot’s grasp and path and pose planning.

As stated previously, it is necessary to recognize the location of the grasped or handled object to be assembled. In this sense, robotic assembly in construction can take advantage of concepts such as measurement assisted assembly (MAA). Maropoulos *et al.* [226] determined solutions that enable a more predictive and flexible assembly process by using active tooling and closed-loop control. This concept was mainly developed for complex and large-scale assembly processes such as in the aviation industry, but it can be used for the construction industry as well. Following these ideas, Druot *et al.* [227] applied the MAA for high accuracy aerospace assembly with robots with optimal results.

During the assembly process with robots, an adjustment of the robot's path and pose is necessary. There is already literature where robots' paths and poses can be adjusted depending on the feedback that the robot receives from different data acquisition and sensing devices and there are also some experiences in the robotic assembly that can be found in the literature. Nottensteiner *et al.* defined a system to recognize objects and plan the assembly process by using two robotic arms [228]. In the research carried out by Feng *et al.* [229] markers were used for localizing objects and defining a plan for the assembly of parametrically designed walls. Finally, an optical marker was used on top of the end effector to estimate the pose of articulated excavators [230].

The aircraft and automotive industries use jigs for structuring the environment and robotics, picking and placing are facilitated. Deviations are avoided by doing so. Moreover, advances have been made on the assembly gap control based on posture alignment [231].

7.2 Research Gaps

Industrial robotic assembly process normally requires high positioning accuracy of all elements before the assembly or a highly structured environment. But for the assembly of façade modules, due to the heterogeneity of the shape and the sizes of the modules, it is difficult to create a structured environment where all the elements are placed exactly in a known position for the robotic system.

The main problems of robotic assembly processes in unstructured environments such as the prefabricated module industry are the inaccuracies associated with picking and placing of objects. In the manufacturing industry, such as the automotive industry, grasping objects typically requires structured environments and accurate grasping end-effectors. However, due to the variety of objects, shapes, sizes, and weights in the construction industry, this premise might not always be possible in construction industry. In other words, due to the high variety of randomized products and objects in construction and, particularly in building renovation, it is difficult to generate a fully-structured environment. Therefore, the CNC machined elements of timber-frames need to be recognized before placing them in the module.

This has several implications in the grasping accuracy of the studs by the robot. Before the research of the method is explained in this chapter, some tests were already achieved [232] A simulation was defined and some problems were intercepted (see *Figure 58*). There are several reasons for inaccuracies that were pointed out in previous phases of the research [43].

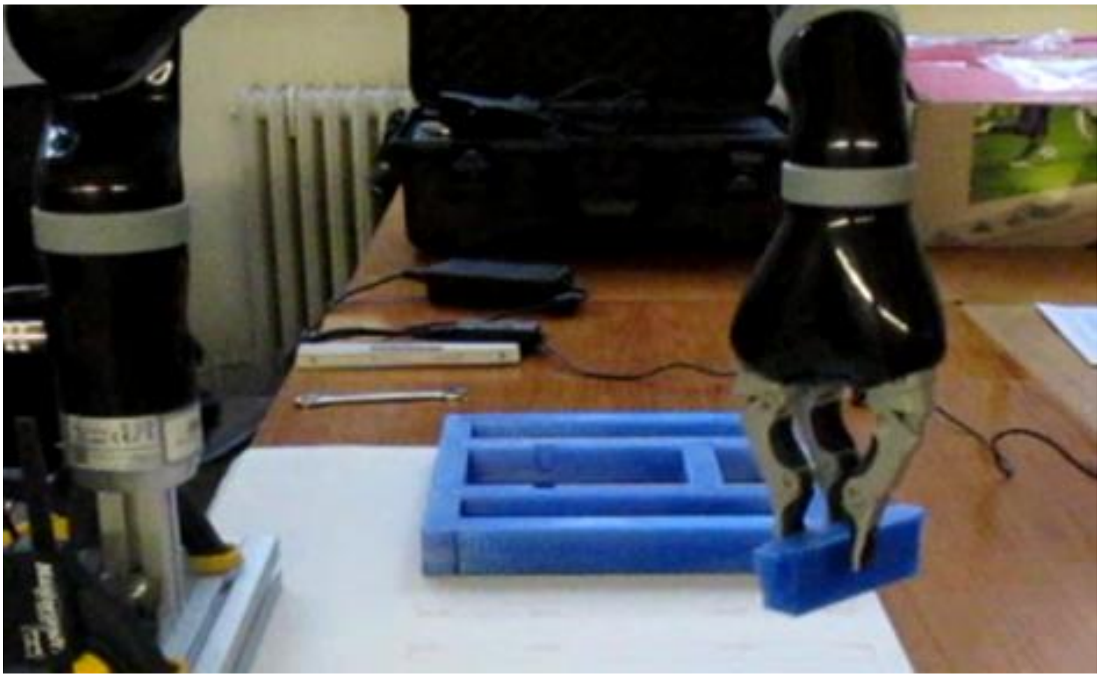


Figure 58: Assembly process carried out by the Kinova Jaco® robotic arm in previous research [232].

Besides some exceptions [223], the assembly of studs and boards is mainly achieved manually. The robotic assembly of prefabricated modules is still a process which faces some challenges related to accuracy as well. The remainder of this chapter focuses on defining and testing a solution related to overcoming accuracy issues with the robotic assembly processes. *Figure 59* shows a scheme based on CNC-routed elements that are robotically placed into an automated multi-function CNC bridge-crane for the assembly. In previous phases of the research, it was detected that deviations occur mainly while grasping and placing the timber elements by the robot. In the next points, the main research gaps are listed:

- **RG 2.1.1**: Lack of Robot Oriented Design for the assembled elements[29]. The joint system used by the current industry that is the nailed butt joint and the flat box union is not facilitating the robotic assembly. Moreover, the dovetail joint used in the previous chapter 0 needs to be amended to ease the placement of the stud in its planned location. In that case, the elements of the timber frame did not have any type of assembly-oriented design. Besides, as presented in chapter 6, the positioning and fixing of highly machined studs require accuracy and, sometimes, due to geometrical constraints, pushing and knocking is necessary. This procedure for robots is not correct and compliant joinery is necessary.

- **RG 2.2.1**: Deviations while picking and placing. There are several reasons for deviations to occur. The first reason is the incorrect placement of objects during feeding. The heterogeneity of sizes and shapes relies on difficulties of fixing the object

29 Note that the numbering is affected by the FNs defined in chapter 6.5

in a known initial position. If the initial position of the studs is not accurate, if these studs are not exactly in their “home” position, the initial deviations will be translated to the final pose. Moreover, due to the inaccurate initial position of the studs, the mass gravity point changes and that might cause major deviations while being picked by the end-effector. The end effector is not sufficiently structured for grasping the object. In the automotive industry, the grasping end-effectors hosts frames, fixtures and jigs that facilitate that positioning [233]. This is only possible when the object is always the same. Finally, in the case of some objects, especially boards, the object tends to bend and, therefore, the final position might not be adjusted. This is a recurrent topic in construction, especially with long span objects, which affects both off-site and on-site scenarios. For these reasons, deviations occur while grasping the objects (see *Figure 59*).

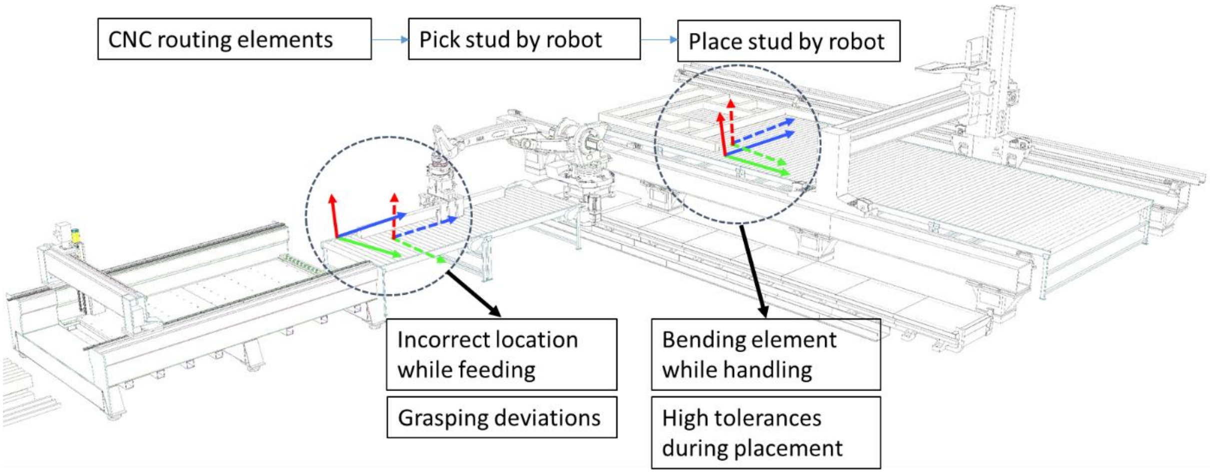


Figure 59: Issues while picking and placing.

For all these reasons, it was decided to create a novel method that focuses on the correction of deviations of the grasped stud and the posterior changes on the design based on the tolerances that can be absorbed by the robotic assembly.

7.3 Development of Novel Solutions

The main research objective presented in this chapter is to adjust the robotic assembly path and pose depending on the location of the grasped element. For achieving that goal, it was necessary to use visual systems that recognize the position of the grasped element and accordingly correct the deviation by adjusting the path and the pose of the robot. As a consequence of the change on the robot path and pose, the deviations and displacements generated while grasping the object should be corrected and the assembly should be carried out correctly.

The objective of the method presented in this chapter is to correct this deviation by:

- **DNS2.1.1:** Create connectors or joinery systems that facilitate the assembly by robots.

- **DNS2.2.1:** Localizing the stud's position once it is grasped by the end effector or grasping tool. Based on the location of the grasped stud, recalculating the initially planned path (or pose correction depending on the case) of the robot to correct the deviation of the grasped element. Applying this recalculated path and adjusting to the final pose of the assembly process. For localizing the deviated grasped object's location, an intermediate pose was planned just after the stud was grasped by the end effector tool. During this pose, the location of the grasped object was measured by two different means.
    - For the first solution, visual ArUco markers were placed on a known corner of the studs and these were recognized with a camera and a processing library named OpenCV (reference) in ROS environment.
    - For the second solution, the coordinates of the objects were measured manually by a digital theodolite and the data was transferred to the robot-controlling system also in the ROS environment.

As a resume, the location of the deviated object should be calculated and compared to the planned location so the robot could divert from its original path and adjusting the pose.

On the next sub-chapter, the measurable parameter in the experiments were the accuracy of assembly while the necessary time for processing was not considered as a measurable parameter because the processing time in all tests was far bigger than to be achieved by hand.

7.4 Tests

To prove the concept, a mock-up was used for the robotic assembly. The works carried out during the experimentation phase consisted of assembling a scaled mock-up that resembled a timber-frame. In this case, the joinery was specifically designed for facilitating a robot-oriented assembly. The idea was that the robot could just leave the stud when approaching the cavity. On this test, only the pick and place task of a relatively small and lightweight element was achieved and deviations occurred.

The objects of the mock-up were made or fabricated by a 3D printer (German RepRap X400©) using PLA filament (Polylactide PLA from German RepRap©) as an additive material. The objects were dovetailed, as can be seen in Figure 2, to facilitate the placement by the robot (*Figure 60*).

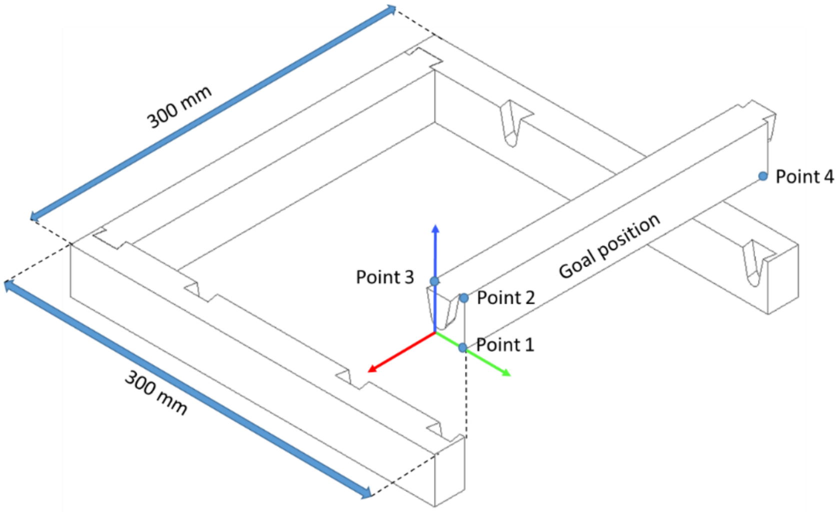


Figure 60: Prefabricated module mockup used for the assembly in laboratory environment experiments.

The size of the mock-up was 300 mm by 300 mm by 35 mm, which is about ten times smaller than a conventional prefabricated timber-frame module. The robot used for the assembly process was a Kinova Jaco® (6 Degrees of Freedom) robotic arm (see *Figure 58*). The robot was placed in a referenced or known location concerning the assembled module. The objects were also in known locations.

It is noteworthy that the scale of the mock-up and the functionalities of the robot do not appear to reflect the reality of the assembly of the prefabricated module or that of the building industry. However, the materials and the robot used for the test reflect a worst-case scenario regarding deviations. On the one hand, the accuracy of the end-effector (hand type) of the Kinova Jaco ® is not appropriate for grasping cubicle objects and, therefore, the deviations are considerable and appear exaggerated when compared to a gripper that is more adequate for such conditions. These “large” deviations are “good” and it is assumed that the robot and the mockup are suitable for this test and carrying out the adjustment of such grasping inaccuracies while picking and placing objects. However, the control of this robotic arm can be achieved by ROS [125] and, therefore, this opens the possibility of interacting with different devices such as cameras. On the other hand, the size of the mockup is 10 times smaller than a typical timber-framed module. In *Table 23*, the materials and devices used during the experimentation are defined.

Table 23: Equipment, materials and resources used.

Computer processor	Intel CORE i7 8th Gen
Robotic arm	Kinova Jaco®
Controller	ROS
Path planning	MoveIt!
Light source	LED lamp

Three tests were carried out during the experimentation phase. The first test was achieved without applying any deviation correction. The second test was achieved through the use of ArUco markers for localizing the grasped object's place. The third test was achieved by using a digital theodolite or Total Station for localizing the key point coordinates of the object. Each test was repeated five times. Once the grasped object's location was determined, the robot modified its position to get closer to the planned location of the object. All three tests were finalized with a goal position where the location of the grasped object was measured to define the accuracy obtained in each test. Four points were measured, as it is shown in *Figure 60* and *Table 24*: point 1, point 2, point 3 and point 4.

Table 24: Planned location for point 1, 2, 3, and 4 (mm).

	Position X	Position Y	Position Z
Origin	0.0	0.0	0.0
Point 1	0.0	25.0	0.0
Point 2	0.0	25.0	37.5
Point 3	0.0	0.0	37.5
Point 4	-250.0	25.0	0.0

In all tests, the robot was positioned relative to a reference coordinate, in other words, the position of the robot was independent of the location of the assembly module.

Even though the working environment was not structured, the experiment needed to have some references, a coordinate system for the robot, for the assembled element and the assembling unit. These three coordinate systems must be known at some point to detect the deviation and achieve the pose adjustment.

Test without any deviation correction

This experimentation was carried out to determine the benchmark or the "normal" capabilities of the robot. The protocol is a process without any iterative step, as shown in Figure 61, and no correction or adjustment was applied.

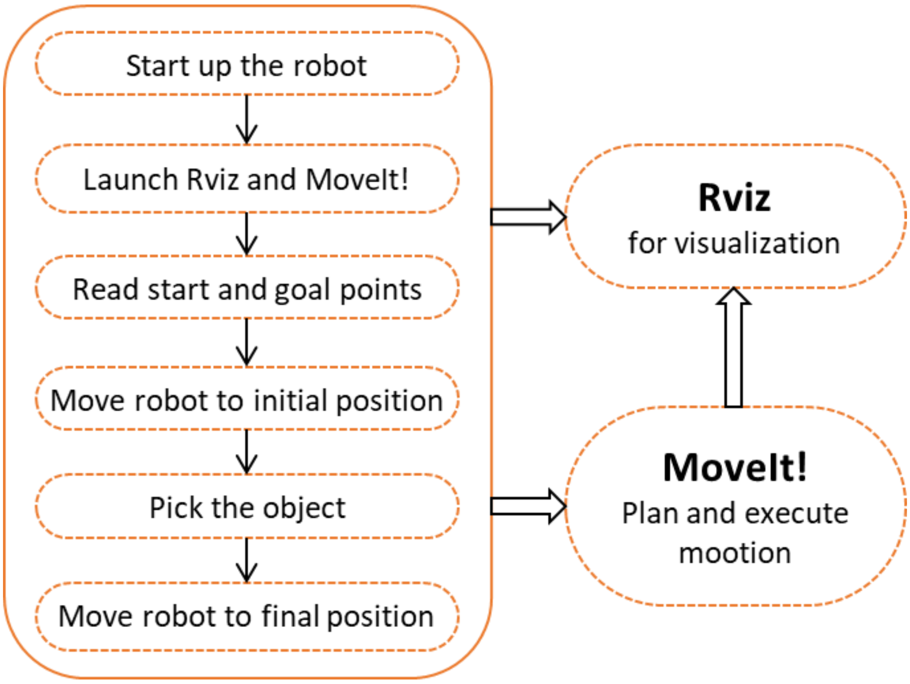


Figure 61: Protocol of the assembly process for the test without any deviation correction.

The path planning and the grasping were determined in advance by the data generated for the parametric software. In *Figure 62* the five different locations of the object on the final pose of the robot are shown in red. In green, the planned locations of the object are shown. In *Table 25*, the average point coordinates of the five different locations can be seen.

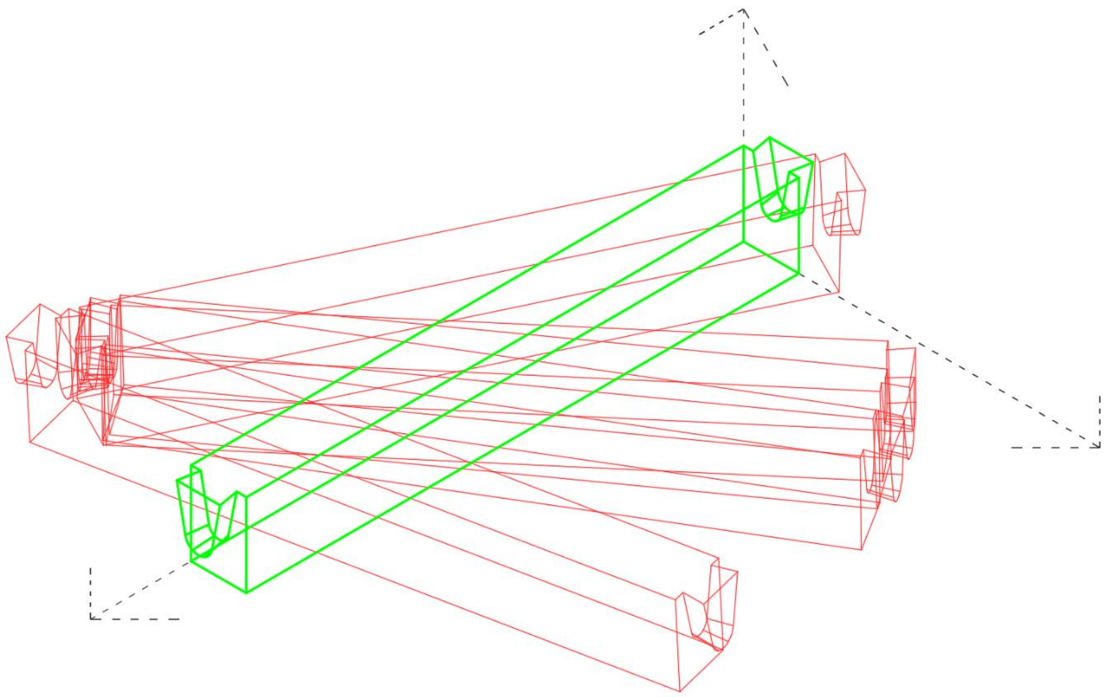


Figure 62: Goal position (in green) and results (in red) without using any deviation adjustment.

The results of the pose without any pose deviation, as expected, show a high deviation in comparison to the planned location of the object, where distances reach up to 136,86 mm in Point 2.

Table 25: Absolute location in the test without any deviation correction and distance from the planned location (mm).

Name	Position X	Position Y	Position Z	Distance
Point 1	-65,20	-106,50	14,90	147,53
Point 2	-47,70	-94,10	-10,10	136,84
Point 3	-47,10	-93,00	-1,80	111,41
Point 4	-188,60	99,20	-22,60	98,93

As it can be observed in Table 25, the results are considerably poor and impede the assembly of the mock-up with deviations higher than 100 mm. Therefore, these results show a worst-case scenario regarding deviations that need to be improved upon in the next two tests.

Test with Open CV and ArUco markers

This test was based on the capabilities of Open CV [234] for recognizing the so-called ArUco markers. It states on their official website "OpenCV (Open Source Computer Vision Library) is an open source computer vision and machine learning software library". In this test, two types of markers were used according to their functionality. First, a set of markers was placed onto the grasped element so that the pose on the center of it could be obtained if any of the markers were detected. The other marker was fixed on the working table as a reference for the coordinates of the robot and the assembled module. The marker on the working table was used as a reference for the positioning.

During this test, an iterative step was defined to check and correct the deviation as explained in *Figure 6*. This iterative step improved the adjustment of the goal position. The camera was calibrated by using OpenCV and the chessboard square placed in front of the Jaco robot. The corner of this square was used as a Reference coordinate, as it is shown in *Figure 7*.

The detection of the markers was not without issues, meaning that it was affected by insufficient lighting. Furthermore, the occlusion of the markers caused the grasped object to not be recognized. When the markers were inclined too much away from the camera, it was difficult to detect them. Besides, the z-axis flipping occurred sometimes [235]. This problem was prevented by using several markers and by accepting the average position.

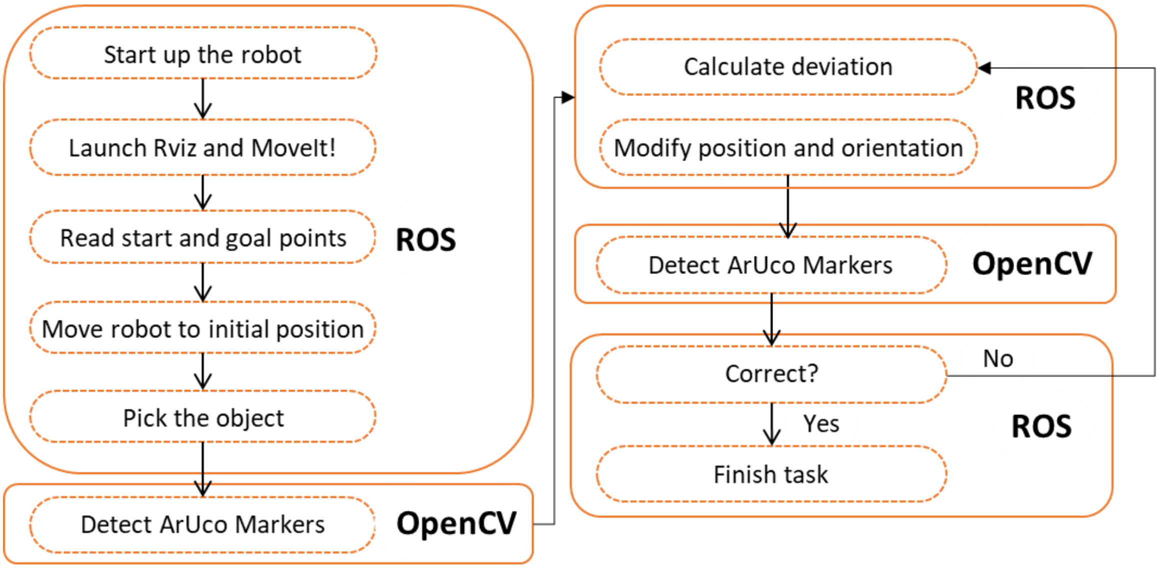


Figure 63: Protocol of the assembly process for the test with the ArUco markers.

However, due to specific conditions such as grasped point or brightness, only one marker was detected and z-axis flipping was found to occur. The camera used was a Logitech C170©.

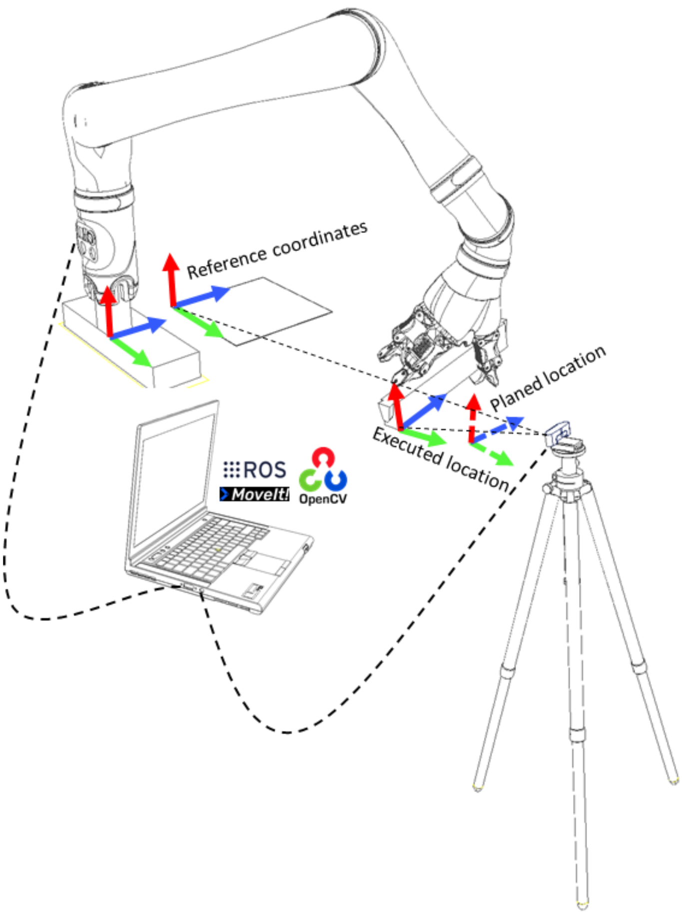


Figure 64: Scheme of the recognition of the grasped object by using the ArUco markers.

In Figure 64, the scheme on the left shows the relative simplicity of the system. The camera needed to be placed on the point where the markers on the object and the reference marker can be seen at the same moment. The results, however, considerably improve the final position location. In Figure 65, the five different locations of the object on the final pose of the robot are presented in orange. In green, the planned location of the object is shown.

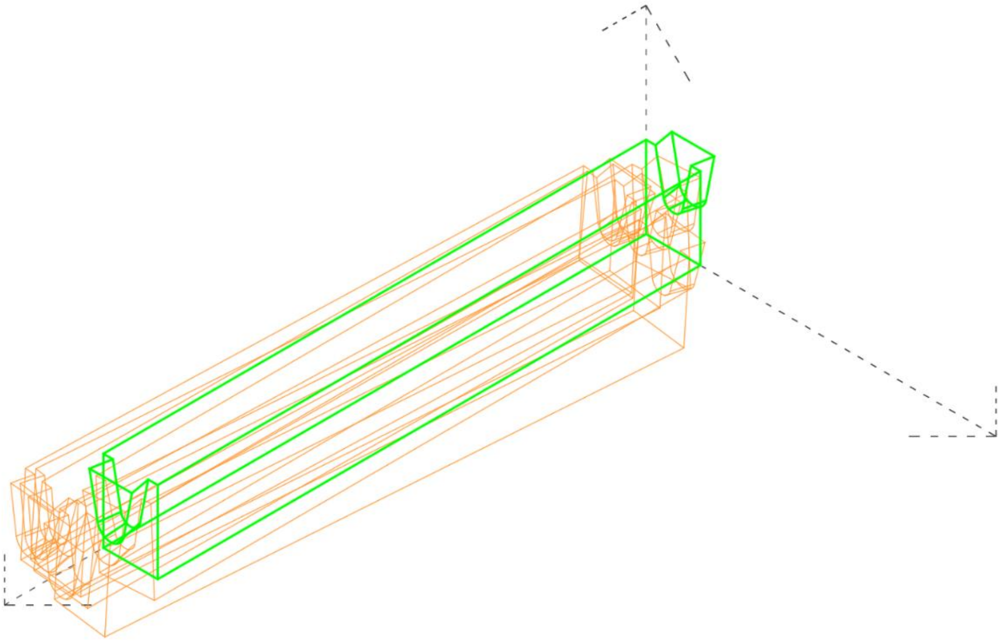


Figure 65: Goal position results using ArUco markers.

In *Figure 65*, the different poses of the robot are shown. The picture bottom left and right pictures in *Figure 66* show the deviated and corrected poses.

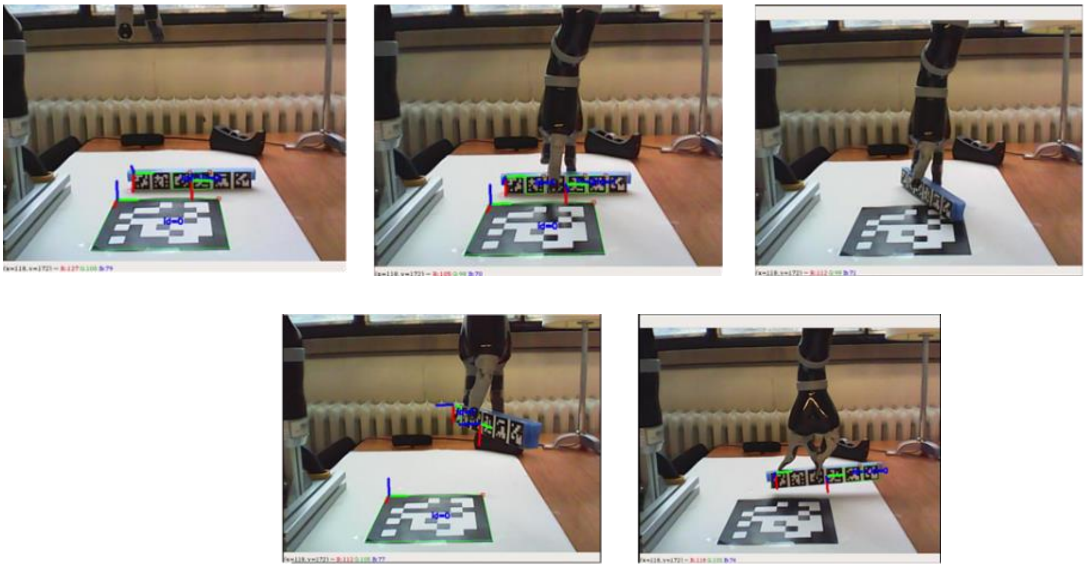


Figure 66: Correlation of the process with the markers, images from the ROS controlling interface.

In Table 26, the results show deviations smaller than those presented in the test in previous sub-chapter. Also, similar to the test in sub-chapter, Table 26 shows the average point coordinates of the five different locations.

Table 26: Absolute location in the test with the markers and distance from the planned location (mm).

Name	Position X	Position Y	Position Z	Distance
Point 1	11,50	11,80	9,40	19,87
Point 2	11,40	10,10	1,90	40,24
Point 3	13,20	-10,30	28,20	19,15
Point 4	-238,10	18,10	-14,20	19,77

Test with the digital theodolite

In this test, during the intermediate pose, the objects were recognized by localizing three points of each object by a digital theodolite (Leica 3D Disto©). This test further requires a human operator who recognizes the location of the grasped object points by the Leica 3D Disto©. This is not an automated procedure since the points were measured manually and the data were inserted on the ROS program manually as well.

During this test, an iterative step was defined as well as in the previous test to check and correct the deviation as explained in *Figure 67*. In all five tests that were accomplished, the same three points of the element's corner were measured in the same order.

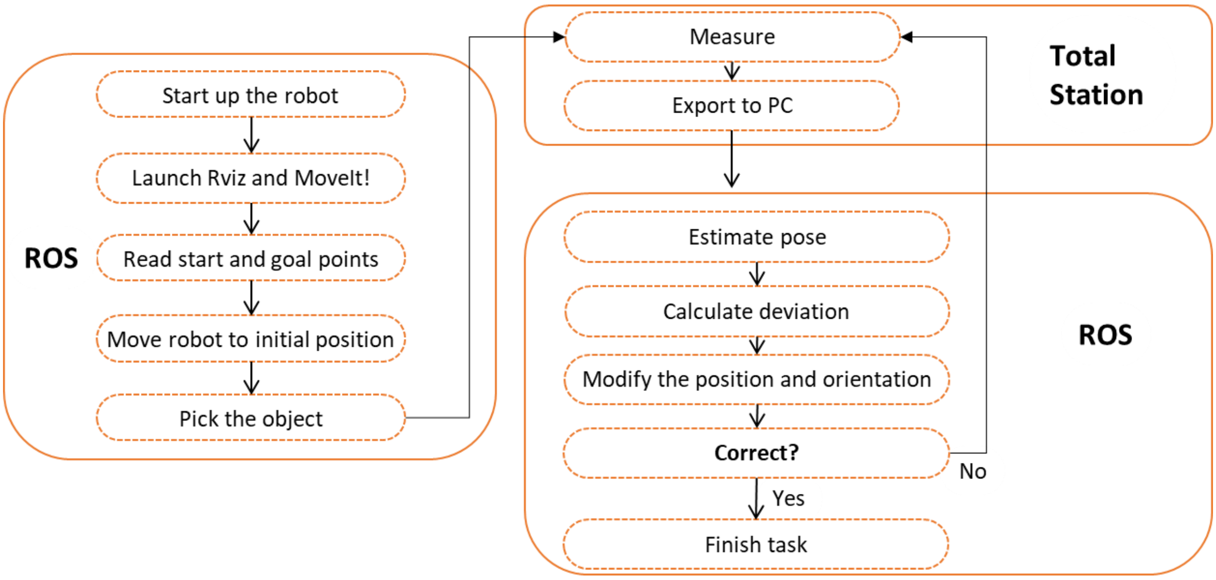


Figure 67: Protocol of the assembly process for the test with the digital theodolite.

For calculating the necessary robotic pose adjustment depending on the element's position, a series of algorithms were used. Then, the deviation of the position and orientation between the planned pose and the executed pose was obtained. As shown in *Figure 68*, the interfaces with the digital theodolite were not robust and, therefore, time-consuming.

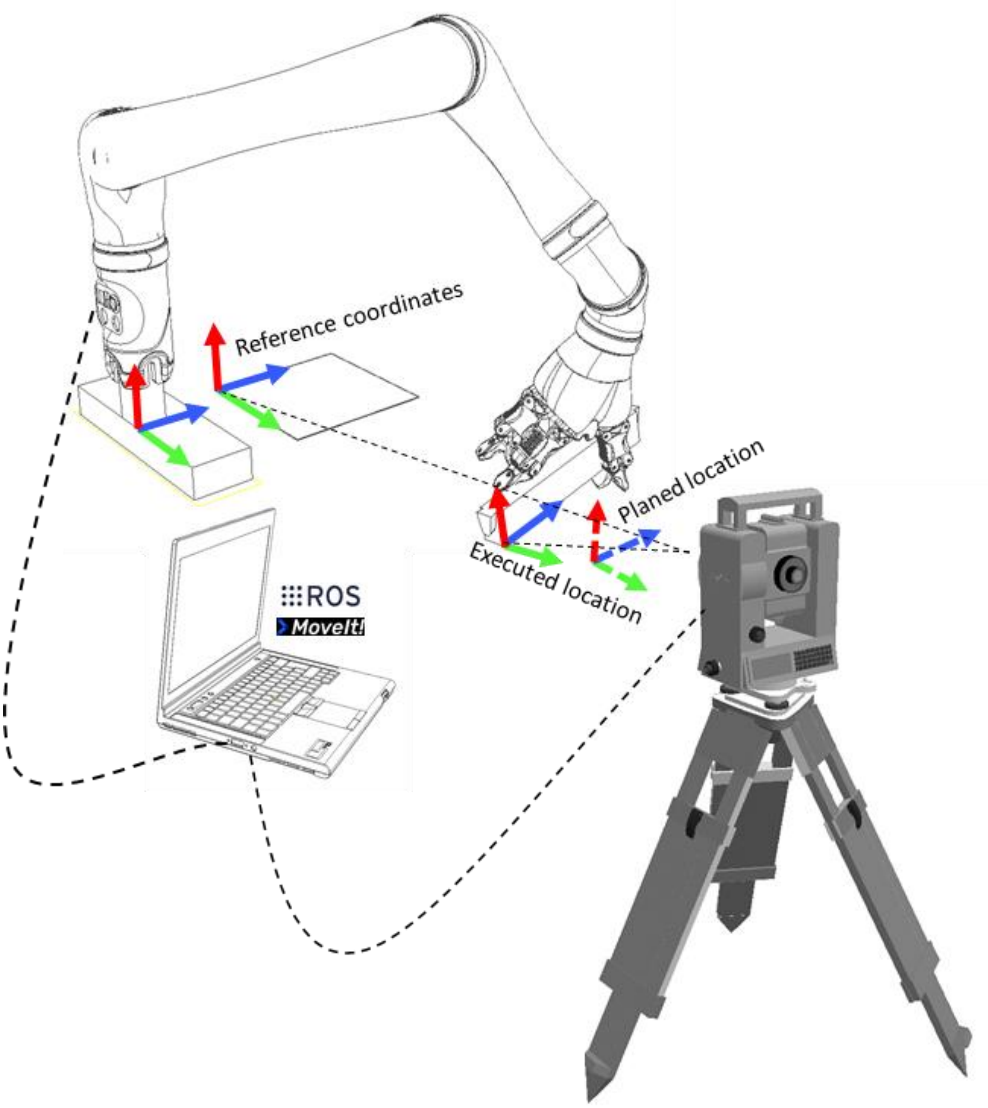


Figure 68: Scheme of the localization of coordinate recognition by using a digital theodolite.

In Figure 69, the five different localizations of the object on the final pose of the robot are shown in purple. In green, the planned location of the object is presented. Table 27 shows the average point coordinates of the five different locations.

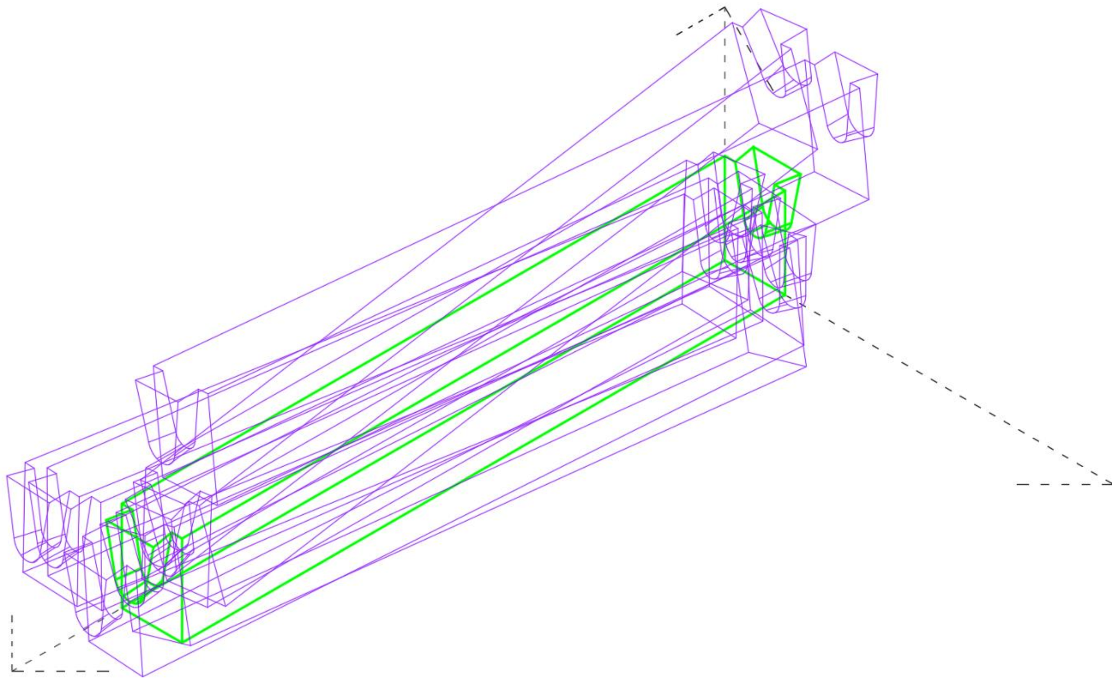


Figure 69: Goal position results by using a digital theodolite.

Similar to the test explained in previous sub-chapter, there were some issues while estimating the position of the grasped element. The points in this test were selected manually and, therefore, the obtained coordinates were subject to errors.

Table 27: Absolute location in the test with the digital theodolite (mm) and the distance from the planned location.

Name	Position X	Position Y	Position Z	Distance
Point 1	-6,10	10,60	6,90	17,09
Point 2	-7,90	-18,60	40,70	44,43
Point 3	-6,40	6,00	43,80	10,80
Point 4	-254,40	26,00	5,40	7,04

7.5 Conclusions and Future Needs

The objective of the research was accomplished, which was to adjust the deviations of the grasped objects by recognizing their location. However, future work is necessary to create a more robust solution. Time and accuracy parameters need to be considered to evaluate the results achieved during the tests.

Accuracy. The results differ considerably during the three tests. On the first test (without any deviation adjustment), the final pose deviations are too high to accomplish any type of assembly tasks. On the two tests carried out with adjustment operations, the final localization of the object improves considerably, as an average, around 70 mm were `corrected´. The experiments achieved with the guidance of the markers show the best and most accurate results compared to the final desired location of the object. The tests achieved by the coordinate's localization with the digital theodolite present higher deviations than the results gathered with the ArUco markers. Apart from the principal objective, some other issues need to be considered. It is assumed that the robotic system developed in the research will still have deviations due to the inaccuracy of the aforementioned method. For these reasons, the next FNs were determined:

- **FN 2.1.1**: Adjusted Robotic Assembly Oriented Design depending on Assembling Tolerances. The objects need to be conceived considering tolerances due to robotic devices calibration and accuracy during picking and placing. The robotic device repeatability and accuracy are constraints that need to be considered. There must be accordance between the robotic system used and its accuracy and the assembly tolerances of the elements. The design of the joint should be adjusted to the accuracy that is permitted by the robotic system in each case. In other words, it is necessary to adjust the design of the elements according to the tolerances admitted. The product should be adjusted to absorb the deviations of the robotic system. Therefore, design changes that facilitate the assembly are necessary to be considered and evaluated. As a result of the study, it has been concluded that the design of the joinery needs to adjust depending on the assembly tolerances achieved by adjusting the path and pose. Regarding the assembly of large-scale and bent objects such as plasterboards, the markers may be a better solution because the object moves while being handled[30].

Time. In this chapter processing time as a parameter was not considered because the time for processing the data gathered and adjusting the deviations was, by all means, very long. Among the methods presented in this chapter, the third test (recognition of coordinates) requires more attention from the human operator. However, it is not necessary to stick a marker on the object to be assembled which, in complex assembly processes where there are many parts, may be advantageous. For all cases, the next FN was determined:

- **FN 2.2.1***:* Agile robot path adjustment depending on CAD files of the prefabricated modules. A specific interface for processing the data gathered with the digital theodolite and linking it with the ROS controller would reduce the necessary time to complete the processing.

However, there might be some limits for a fully robotic assembly. The modules and its elements (boards and studs) are not standard; they change their geometry from case to case, therefore robotic path and poses for the assembly necessarily needs to change constantly. Apart from the boards and studs of the module, there is a multiplicity of objects and elements to be assembled in a prefabricated module. Not all of them are designed according to ROD and there is an important effort to make in this aspect. However, further studies have been made in that sense [236].

30 The preliminary study of this concept is being worked out currently.

Finally, the procedures for the recognition of objects and the adjustment of deviations can be applied to the on-site installation of fully prefabricated modules as well. The pick and place prefabricated modules at the construction site is a task that could benefit from it, as it is explained in chapter 8.2.

8 ROBOTIC INSTALLATION OF MODULES WITH A CDPR

This chapter presents the development based on the conceptual framework and first achievements of a system based on a cable-driven parallel robot (CDPR) that hosts a set of tools on its platform named Modular End Effector (MEE). This system was developed for the installation of unitized curtain wall modules (CWM) within the HEPHAESTUS project[31]. It was the first time to achieve such an activity in the construction sector by a CDPR and with such high payloads (see *Figure 70*).

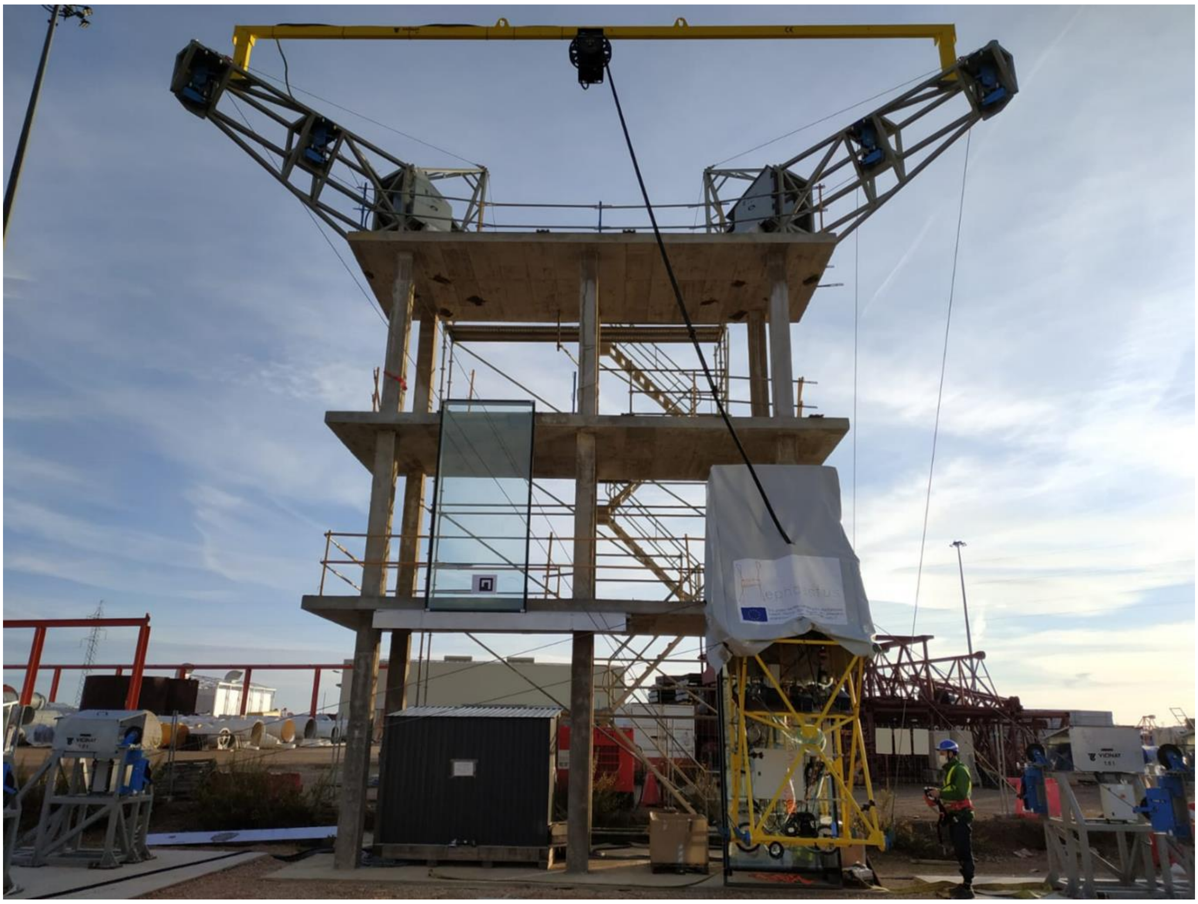


Figure 70: The author of the dissertation operating manually the HEPHAESTUS robot. Picture taken by Julen Astudillo (from Tecnalia), at Acciona facilities in Noblejas (Castilla la Mancha, Spain)

The method for arranging such a complex system in all development stages has special importance. For that reason, further decomposing the conceptual framework is necessary. The development of this complex system was based on certain requirements and needs. In

31 Content explained in this chapter are part of research project with many partners that are necessary to explain the context. All external contributions to the author’s research and dissertation are referenced and authored.

sub-chapter 1, the method and the conceptual framework for the development, which includes the simulation, the integration and the prototyping, are explained. The conceptual framework is valuable for the assessing and localizing contradictions and research gaps of the tested solution. This approach is valuable for future development, not only for assessing critically the aforementioned system but also for any other robotic device that might be achieved in the next years. Within the subsystems of the Conceptual Framework, one of the categories was developed in the context of this dissertation. This category is related to a stabilizer of the MEE (see APPENDIX 5: Stability of the cable robot platform).

A test in a close to a real environment as possible was carried out as explained in sub-chapter 8.2. Moreover, the first results of the cable robot regarding accuracy and repeatability, as well as time consumption of the working cycles are exposed in sub-chapter 8.2. Moreover, in sub-chapter 8.2 the data gathered during prototyping is extrapolated to a real case of a building and the feasibility of the proposed system was compared to the current traditional manual methods.

8.1 Development, simulation, and integration

The objective of such a system is to improve the current manual efficiency and conditions for the installation of CWM and avoid risky and hazardous operations, as explained in chapter 2 and chapter 1. Due to this, the research included in this chapter focuses on finding a solution to these issues.

The configured CDPR was the first prototype defined for achieving the installation of real curtain walls. This means that the CDPR was not validated before. Furthermore, a cable robot with a set of tools fulfilling such performance was not integrated into a CDPR with such characteristics. For these reasons, the whole robotic system, including the CDPR and the MEE needed to be tested to foresee the capabilities of the system. In this phase of the research, the main question relied on the next points:

- CDPR is feasible for the installation of the CWM with the required accuracy, that is, if it achieves the work as planned and expected by the designed plan. Within this context, here are the next sub-questions:
    - How accurate would the location of CDPR platform be? This topic is developed in DNS 3.1.
    - How accurate will the fine bracket (or connector) positioning be? This topic is developed in DNS 3.2.
    - How accurate will the placement of the CWM onto the brackets be? This topic is developed in DNS 3.3.
- Performing working-time of the CDPR system for the installation of CWM is less than the traditional manual methods.

In chapter 2, there was an analysis of different robotic systems for the installation of façade modules. As a further development of these concepts, the HEPHEASTUS[32] project consists of developing and prototyping a CDPR for the installation of CWM.

The development of such a complex concept depended upon multiple requirements and facts. Due to the complexity, an overall perspective was necessary that linked, synchronized, and coordinated all the different aspects of this system. At the same time, there was a need to breakdown of sub-categories to separately achieve the goals by different stakeholders that participate in the development of such a complex system.

Moreover, the definition and development relied on a concept that was not proved before. Therefore, the decisions adopted in every sub-system needed to be simulated and checked to ensure the suitability in regards to the rest of the sub-systems. To accomplish such objectives, this subchapter focusing on the Conceptual Framework structured the system and its sub-systems.

Precedent research and initial concepts

CDPR robots are based on a platform that is moved by cables that are tensioned by winches. These winches and the length of the cables are controlled and synchronized by a CNC-controlled system[33].

For the CDPR robots, at least 6 cables are required for controlling all 6 Degrees of Freedom (DOFs) of the platform, while often more than not 8 cables are used for better performance. CDPRs have been the subject of intensive research these past few years, and most of the theoretical issues, linked to the cables being only able to pull and not push. Cable-driven parallel robots are a subclass of parallel robots [237]. The cables are actuated by winches. Today, they have already proven their interest, in particular for large scale industrial applications [238], [239], [240], [241]. The principle of a CDPR can be adapted to move heavy payloads over large dimensions. For these same reasons, CDPRs have being theorized in the past for several construction applications, from manipulation of elements to contour crafting and building inspection [242], [243], [244]. Only a few related works involving cable robots in the field of construction can be found. In [245], a concept for a cable robot for large-scale assembly of solar power plants is introduced. In [246], a cable robot concept for a contour crafting system is described. In [247], [248] cable-robots for automated bricklaying can be found. Regarding the cable robots for installing façade elements, a CDPR was envisioned [249]. Frequently, the platform includes a set of tools that achieve certain tasks. In the case of the HEPHAESTUS project, this set of tools was named Modular End Effector (MEE).

In this context, before the HEPHAESTUS research project, an initial concept was drafted. At first, the concept was designed to use the so-called cable-driven parallel robot (CDPR) for

32 The results of this chapter were gathered during the research developed within the HEPHAESTUS project.

33 The contents of this sub-chapter are partially explained in the ISARC 2020 paper [253].

different tasks in the vertical envelope of a building [115]. Moreover, concepts were developed to use the CDPR for the installation of prefabricated modules onto existing buildings (see *Figure 71*). The initial concepts included renovation activities in façades. In the case where the existing building conditions would not permit it, such activity would need an independent supporting structure to hold the cable robot without relying on the existing buildings (*Figure 71* right).

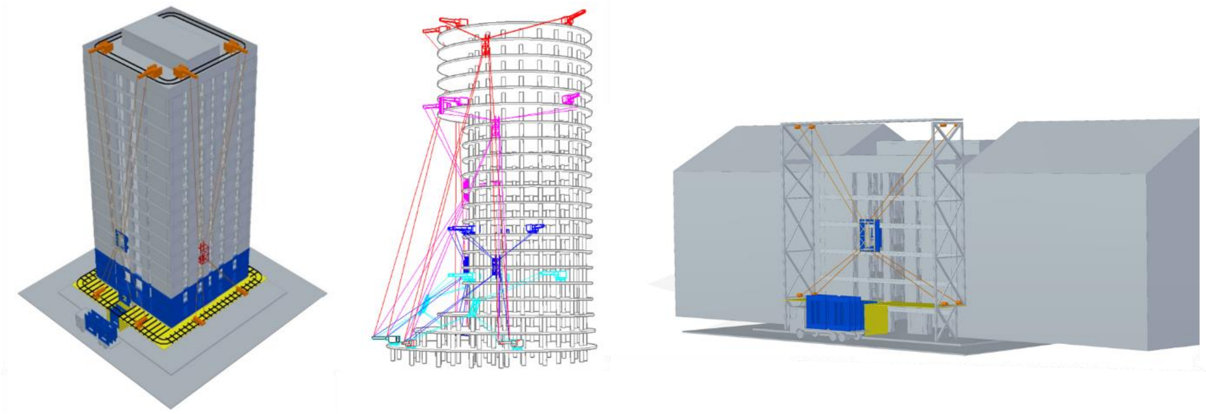


Figure 71: Left: Façade renovation with modules for a high-rise building. Middle: CDPR for high rise erection. Right: Façade renovation with modules for a low-rise building.

A more developed system consisted of two main sub-systems: the CDPR for the rough positioning and the MEE for the fine positioning. Both sub-systems that carry out each job need to be controlled by the same CNC system (see *Figure 72*).

The set of tools, the MEE for accomplishing the tasks, was initially a multipurpose Cartesian robot with 3 axes that performed several functions [115]. This concept was considered suitable for renovation processes since it was set up to work in vertical plans, meaning for placing brackets on existing vertical walls or the front of the slab.

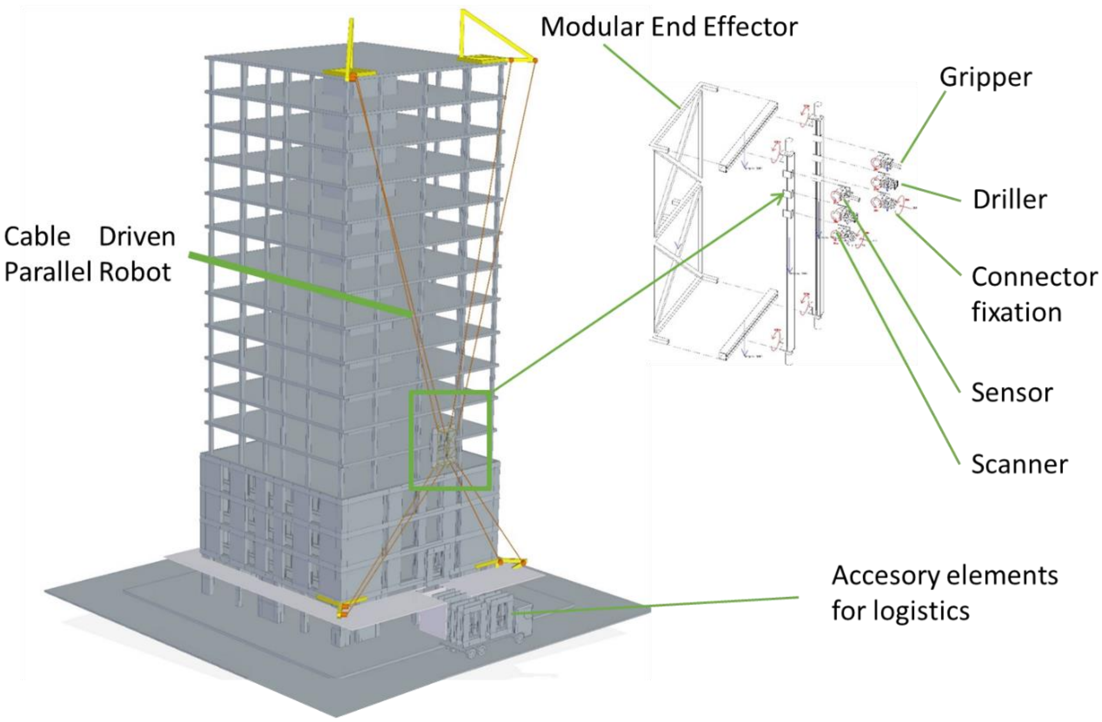


Figure 72: First development of the cable robot for installing CWM for the HEPHAESTUS project.

The concepts in *Figure 71* and *Figure 72* include devices that facilitate the unloading of the modules from the transportation truck. Moreover, according to these concepts, the modules would be faced in front of the set of tools and help to pick up the module. The carriage of the winches and poles would require to calibrate the CDPR whenever the workspace was changed, and with the current technology, that would be a considerable challenge for the system that was not developed in the HEPHAESTUS project.

Research Gaps (RG) and Developed Novel Solution (DNS) for a real test

The research explained in this chapter does not focus on building renovation but on new building erection[34] processes. The initial ideas evolved for the proposal and during the HEPHAESTUS research project. For the research projects within the H2020 framework [250], it is necessary to fit the concepts to given objectives by the EU Commission, and to the certain cost and time limitations. Besides, it is necessary to prove the capabilities of the overall system in real demonstrations, which requires rigorous simulation processes to foresee issues [250]. For these reasons, the tasks of the CDPR and the MEE were reduced and focused on the installation of CWM. The concepts explained in this sub-chapter needed to be prototyped, integrated, tested, and assessed. That induced a detailed definition of the requirements,

34 During the preparation of the proposal, the first idea was to use it mainly for building renovation, more precisely for the installation of prefab building modules, similar to the ones used in BERTIM. There was also a strategic decision of all the partners to focus for new building façades, more specifically with the so -called curtain walls.

research questions and developments of the system and a limitation of the scope of the research challenges. The solutions presented below are not necessarily the optimal situations, but it is rather constrained by the research project limitations and for these reasons, the solutions are open for future improvements. Moreover, the development process was achieved alongside decision-making under uncertainties of the performances of the CDPR. The election of most suitable solutions required a decision-making process accorded by the whole partners of the HEPHAESTUS project [120]. Within this context, the Conceptual Framework presented in chapter 1 was considered as an optimal framework to facilitate the development and to organize and assess every phase.

The main subcategories of the robotic system explained in this chapter are to install and fix the CWM onto the concrete floor with the required accuracy in a non-time-consuming manner. This is considered the generic objective of the system.

The installation of the CWM has specific requirements. A CWM is a prefabricated façade module that consists of a frame, normally in aluminum, which is enclosed with a glass panel. In the case of HEPHEASTUS, the CWM weighs about 300 kg. The CWM hangs from two brackets on the concrete building slab and some gaskets permit the waterproof and airtightness condition (see *Figure 73* and *Figure 74*) when the modules are placed beside each other. The brackets are fixed to the concrete slab by screws. Its manual installation process requires marking the location of the brackets with the use of Total Station theodolites.[35]

Once the characteristics of the installation process are determined, the Research Gaps (RG) that need to be determined for applying the Conceptual Framework, and more specifically, the RG3 sub-system was broken down in smaller categories depending on the operations that need to be performed, namely CDPR requirements (RG 3.1), bracket installation requirements (RG 3.2), and CWM installation requirements (RG 3.3).

35 The operations described in these phases don't exactly match with the current more trending manual curtain wall manual procedure. In the manual procedure, first, the manual procedure uses a cast-in-channel (reference) and therefore the screwing operations are different. But for the HEPHAESTUS project, it was considered more challenging to drill (also it was taken as a part for achieving building renovation projects). Moreover, it was seen as closer to renovation processes. Second, with the defined steps, the process would be incomplete. For completing the procedure, there would be extra gaskets that need to be placed in order to guarantee the waterproof of the curtain wall system once the module is fixed onto the brackets. But these operations were rejected for the robotic operation in the HEPHAESTUS project.

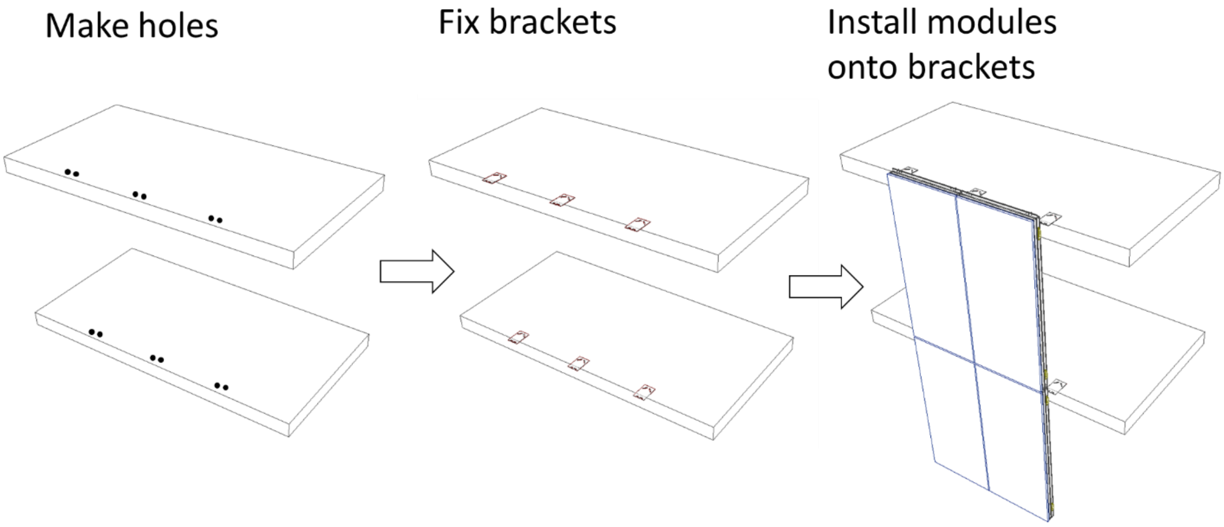


Figure 73: Installation process of the curtain wall, schematic process.

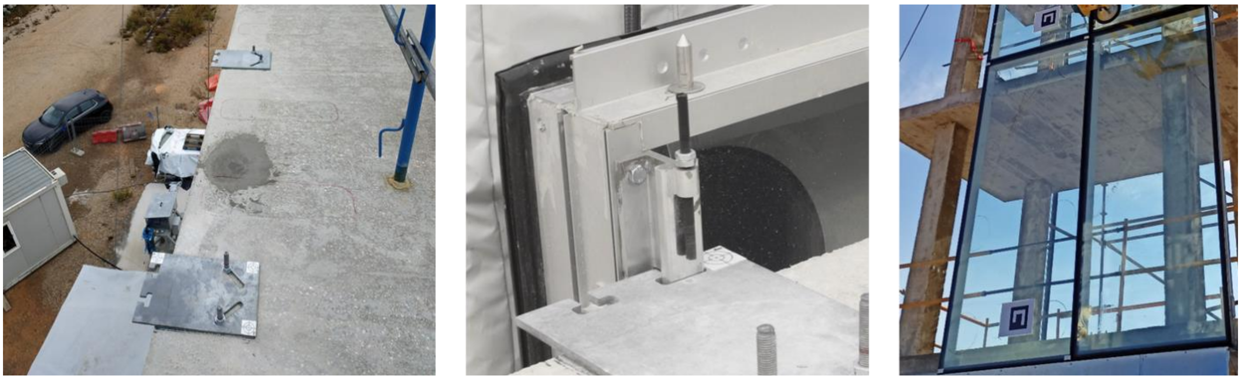


Figure 74: Left: Brackets installed (picture by José David Jiménez Vicaria, Acciona Construcción). Middle: CWM being installed onto brackets (picture taken from a video by Alex Iturralde). Right: CWM modules installed on top of the brackets. All pictures taken at Acciona facilities during the HEPHAESTUS demonstration.

The requirements of the CDPR workspace were named RG3.1[36]. Comparing to the initial concepts, the workspace, which was determined mainly by the location of the cranes, is fixed or not varaible. On-site construction is an unstructured environment where the size of the façade changes almost in every project. For this reason, it is necessary to create a specific workspace for each façade area that is being installed. The DNS 3.1 solutions are shown in *Table 28*. The RC3.1 hosts two other sub-systems, adjustment to the workspace (RG3.1.1) and installation of the CDPR (RG3.1.2). Besides, it is important to remark that it is necessary to transfer the data of the building's coordinate system to the control system of the CDPR, in

36 This topic was mainly developed by Tecnalia, IPA Fraunhofer, LIRMM and Cemvisa-Vicinay.

other words, a sub-system of the Data Flow (SC1.5) is necessary to calibrate the CDPR (see DNS1.1 in *Table 28*).

Table 28: RG and DNS of the CDPR.

RG3.1. set up the device.	**DNS3.1:** set up the CDPR.
RG3.1: Capacity to move the CDPR platform in automated mode, with a weight of 400 kg, that hosts several tools for the installation of the CWM (with a weight of 300 kg) in a workspace with 2 floors, 8,5 m by 10,6 m.	DNS3.1: A CNC controlled (with a Beckhoff PLC [251]) CDPR with anchored supports on the building structure that host the winches and pulleys (see Figure 77 and [252])
RG3.1.1: to adequate the configuration of the CDPR to a given workspace.	**DNS3.1.1:** Calculations and simulations are needed [253]. (see *Figure 75*)
RG3.1.2: install the CDPR and all its components in the real workspace	**DNS3.1.2**: use of mobile cranes to fix the anchored supports, to the concrete slabs.
RG1.5.1: Calibrate the CDPR in regards to the 0,0,0 point and coordinate axes of the building.	**DNS1.5.1** Measure the coordinates of the CDPR platform in regards to the building's 0,0,0 point. (see K0 in *Figure 75* left)

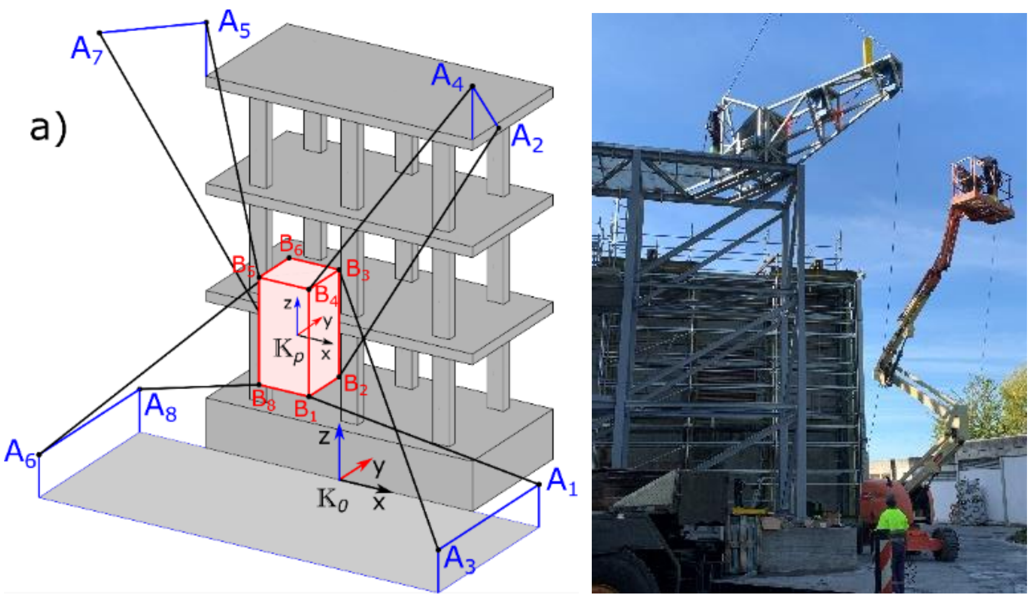


Figure 75: Left: DNS3.1.1 (adjustment of the workspace).
Right: DNS3.1.2. (installation of the CDPR)[37]

The requirements of the bracket installation were named RG3.2. The fixation of brackets was achieved by some of the tools on MEE, which were operated by a 6 DOF robotic arm (see *Table 29* and *Figure 76*). On the MEE, a PLC was implemented to control a ROS-PC which

37Both topics developed mainly by Tecnalia, LIRMM, IPA Fraunhofer and Cemvisa.

operated the robotic arm and the tool-system. The MEE IPC worked as a slave of the general control of the CDPR. *Table 29* shows the requirements and solutions for this purpose.

Table 29: Research Gaps and solutions for the bracket installation. [38]

RG3.2: fixation of the bracket automatically	DNS3.2: MEE based on the robotic arm
RG3.2 Fix the bracket on the required position with the required accuracy (DIN 18202) in regards with the 0,0,0 point of the building. The tasks need to be achieved with a relative accuracy of 1mm. To achieve such purpose, some other subtasks need to be performed:	DNS3.2: A 6 Degree of Freedom (DOF) robotic arm and the tools which are allocated in an aluminum frame that is supported/hosted on the CDPR platform. The environment of the robotic arm can be considered as structured: the tools are in a known position in regards to the origin of the robotic arm.
RG3.2.1: Get a stable and structured workspace for the MEE. The set of tools on top of the platform must perform steadily. Therefore, vibrations must be avoided and for that, the transmission of forces from and to the CDPR need to be considered and reduced. Previous solutions based on decoupling were rejected [254][39].	DNS3.2.1: A linear system that hosts a vacuum gripping system is used. The linear system and the vacuum gripping system are controlled by the Beckhoff PLC of the MEE. It is necessary to move the CDPR platform downwards to contact the vacuum cups with the concrete slab. Further explained in Appendix 5.[40]
RG1.5.2: Once the MEE frame is stabilized, localize the MEE frame in regards to the origin coordinate system of the building, in other words, calibration is needed.	DNS1.5.2: Measure the location of the MEE frame by using a Total Station and three-sphere reflector attached to the MEE.
RG3.2.2: Tool changing for the robotic arm	DNS3.2.2: The robotic arm uses different tools. A tool changing system works with a dedicated compressor.
RG3.2.2.1: Make holes on concrete slab	DNS3.2.2.1: Use a drill tool and pressurized dust removal to remove the dust.
RG3.2.2.2: Pick, place, and hold the bracket	DNS3.2.2.2: A gripping tool that is activated with a vacuum system
RG3.2.2.3: Fasten the anchors.	DNS3.2.2.3: Anchor driving tool with a hydraulic picker.
RG3.2.2.4: Torque the anchors	DNS3.2.2.4: Torquing tool.

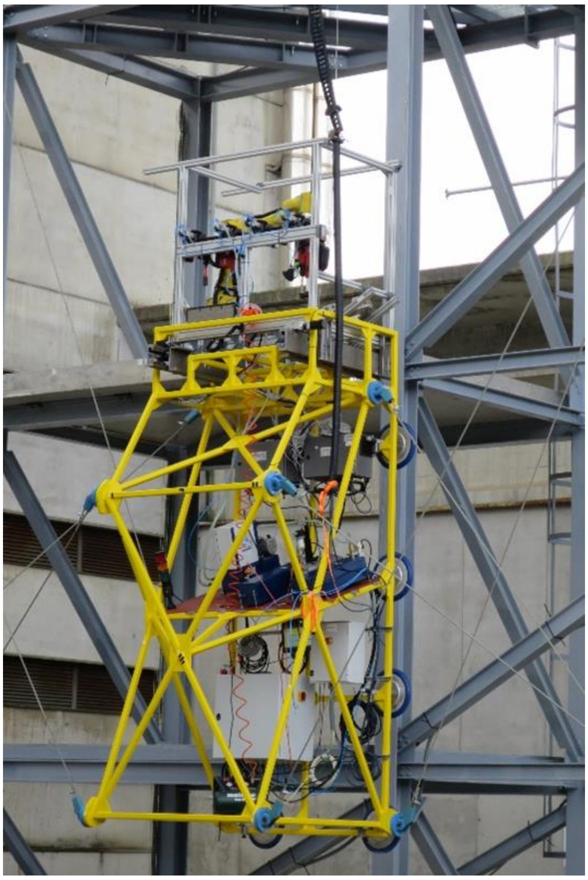
The drilling tool incorporated an air pressure device to clean the dust created during the drilling process. Besides, it is necessary to remark that the robotic arm repositioned automatically when hitting a concrete slab rebar. After that, the robotic arm picked the bracket with a gripper and placed it on the slab. Next, the robotic arm grabbed the anchor from a magazine and fixed

38 The initial concept was achieved by nLink and TUM members, including the author of this dissertation. The final achievement, except for the DNS3.2.1, was achieved mainly by nLink.

39 A solution was developed by Mr. Meysam Taghavi based on a hexapod-shaped active damper, but this solution was rejected due to its complexity [256].

40 This initial concept was developed by Mr. Meysam Taghavi and the author of this dissertation. The final definition of the mechanical devices was achieved by the author of this dissertation. The control of the mechanical devices was achieved by Mr. Malte Feucht.

it on top of the holes. The robotic arm used a screwdriver to fasten the anchor. After the task was finished the torquing tool was released (see the whole process in [119]).



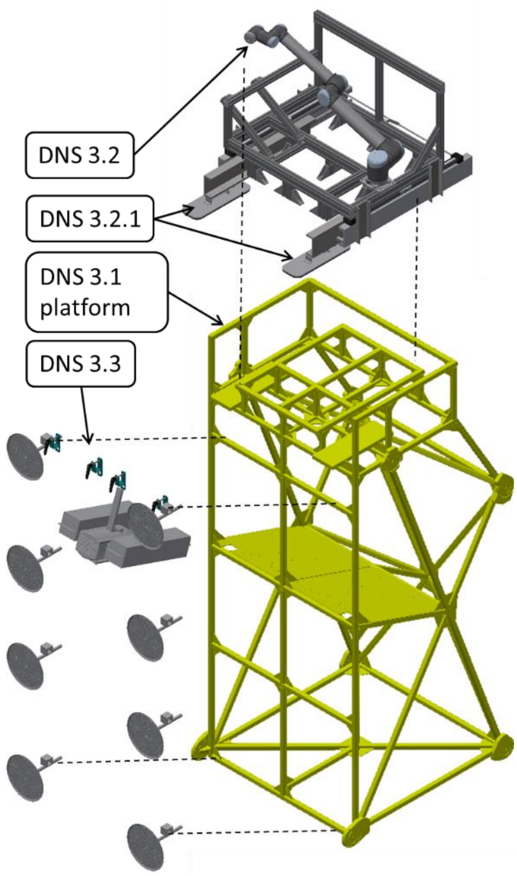


Figure 76: The MEE, its components (developed by nLink and TUM) and their location on the CDPR platform (platform developed by Tecnalia).

The requirements of the CWM installation were named RG3.3. For the prototype and test, the CWM installation onto the brackets was conceived in two modes: automated and manual control. In the manual mode, the operator in charge of the CDPR would move the platform and adjust the position to the location of the CWM, which is supported in an inclined rack, and activate the Vacuum Lifting System (VLS), which is part of the MEE, when ready[41] (see *Figure 77*). In both automated and manual mode, the activation of the tools was achieved through the slave Beckhoff PLC [252], [251]).

41 The curtain wall modules are transported from the off-site manufacturing factory in horizontal racks. The capabilities of the CDPR were not configured for permitting picking 300kg CWMs laying down horizontally. For this reason, it is necessary to pick the CWM from the carriers and place them in an inclined rack.

Table 30: Functional Requirements and solutions of the CWM installation (FR3.3)[42].

RG3.3: Install the module	DNS3.3: Vacuum Lifting System (VLS)
RG3.3: Pick and place the CWM onto the required position	**DNS3.3**: As a part of the MEE, the CDPR platform hosts a Vacuum Lifting System (VLS) that permits to grip the curtain wall which is manually controlled through the Beckhoff PLC.
RG3.3.1: Place Curtain Wall Module in vertical	**DNS3.3.1:** place the CM in a magazine with a crane
RG3.3.2: Pick up the Curtain Wall Module.	**DNS3.3.2:** activate the vacuum system
RG3.3.3: Install the curtain onto the brackets	**DNS3.3.3:** release the vacuum system

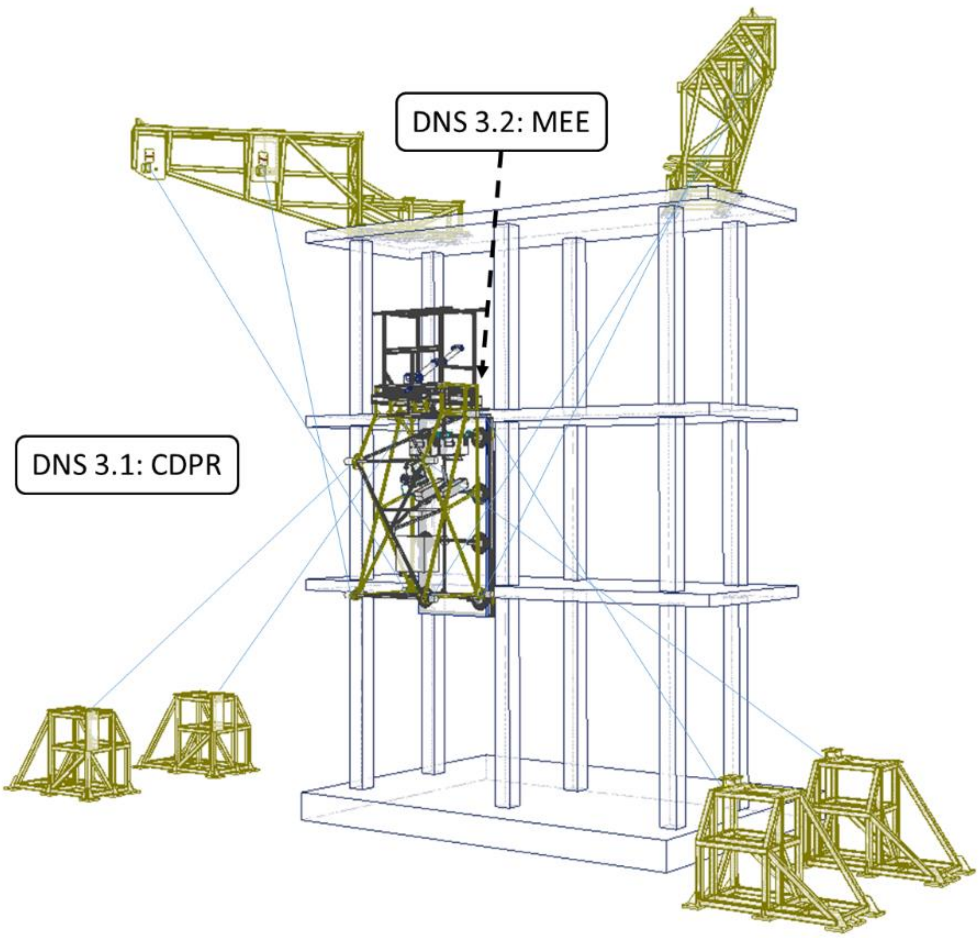


Figure 77: Simplified CAD of the CDPR and the MEE (developed by the HEPHAESTUS consortium).

The scheme of the CDPR and MEE followed to some extent the scheme defined in chapter 2.3, that is, a rough positioning by the CDPR and a fine positioning by the MEE. However, some contradictions prompted during the development process. For instance, it was decided

42 The initial concept was achieved by Cemvisa and TUM members, including the author of this dissertation. The final definition of the mechanical device was achieved by the author of this dissertation. The control of the mechanical devices devices was achieved by Mr Malte Feucht.

that the vacuum cups of the VLS should be attached to the CDPR platform with rigid fixtures. These means that there was no possibility for readjusting the position of the CWM in the probable cause that the CDPR picked the Curtain wall in an undesired position.

8.2 Tests in close to the real environment

The first demonstration tests were performed in Tecnalia facilities in Derio (Basque Country, Spain) from 09.12.2019 to 24.01.2020. Once all the components of the demonstrator were installed, the operation of all the components (motors, movement of the robot, positioning concerning the steel structure, sensor, etc.) was verified. This was the first time the different elements of the robot (winches with cable pulling on the platform/base) and the higher-level control of the robot that realize the coordination of the winches were put together. The bracket installation was performed successfully and the CWM was lifted appropriately.

The second demonstration was achieved at Acciona's facilities in Noblejas (Castilla-La Mancha, Spain) between 01.07.2020 and 20.11.2020. This was the second time the prototype was built with additional features than in the first demonstration. In this case, six brackets and 4 CWM could be installed.

Accuracy

Several tests were carried for testing the concepts in DNS3.1 (CDPR capabilities), DNS3.2 (bracket installation), and DNS3.3 (CWM installation).

Accuracy and repeatability of the CDPR (DNS 3.1). In overall, the repeatability and accuracy of the CDPR platform were optimal in both demonstrations. The results of the demonstration showed a better performance than expected in previous phases of the research project. The maximum position error of the CDPR was about 20 mm and the max orientation error about 0.8 degrees. Moreover, the preliminary results showed promising repeatability (with an accuracy of 1 or 2 mm, depending the location and wind) of the CDPR while repeating the poses. Issues regarding looseness and stiffness of cable tension appeared in the corners of the workstations but without harming the stability of the platform.

Accuracy of the bracket installation (DNS3.2). The deviations of the CDPR platform with respect to the desired position were planned to be adjusted by the MEE. During the first demonstration, for the FR3.2 (bracket installation) single brackets were installed according to planed locations (see *Figure 78*). During the second demonstration, six brackets were placed during the tests. However, it was noted that the repeatability of the bracket placement only presented deviations of about 1 mm, and therefore, the capabilities of the whole system were guaranteed[43].

During the second demonstration, the calibration of the CDPR and the MEE platform was achieved with more precision. This permitted the installation of the brackets as in planned situations. The accuracy of the bracket placement was dependent upon the calibration of the MEE in regards to the origin of the building and the CDPR platform. Moreover, the accuracy of the MEE depended on the accuracy of the Total Station.

It must be remarked that the MEE did not present any relevant disturbances while it was stabilized by the grippers and that the robotic arm could perform its activities with the necessary firmness and lack of vibrations transferred from the CDPR. However, the robotic arm itself and the tools presented some sort of vibrations while performing their work and in multiple drilling trials, deviations occurred.

Figure 78: The MEE in operation [119]*. Pictures by Julen Astudillo (Tecnalia).*

Accuracy of the CWM installation (DNS3.3). Some clarifications must be made to explain the results. The author of the thesis operated manually the CDPR for the placement of the CWM onto the brackets on the picking and placing[44]. The author of this dissertation never had a previous experience of installing such CWM modules and this lack of experience affected the positioning accuracy. Moreover, the lower profile (close to points 13, 14 and 15 in *Figure 79*) was fixed, after the brackets were installed. Finally, the height of the CWM was adjusted manually once it was supported on the bracket. For these reasons, the final location of the CWM was more inaccurate than expected. Therefore, in the analysis of the results, it was necessary to adjust the planned point coordinates (see *Table 31*). Moreover, it must be

43The author of this dissertation participated in all tests for bracket installation. It was controlled by nLink, TUM and Tecnalia and measured by Tecnalia and the author of this dissertation.

44 With the assistance of Tecnalia and Acciona.

considered that during the measurements, the Total Station was generating errors of up to 5mm.

Table 31: Deviation of the modules in the second Demonstration.

Planned Point	Xn (mm)	Yn (mm)	Zn (mm)	Placed Points	xn´ (mm)	yn´ (mm)	zn´ (mm)	d	d z
1	-2304	-295	10304	1´	-2300	-286	10303	9,90	9,85
2	-870	-295	10304	2´	-866	-279	10302	16,61	16,49
3	-804	-295	10304	3´	-802	-280	10315	18,71	15,13
4	629	-296	10304	4´	629	-284	10316	16,97	12,00
5	-2304	-295	6980	5´	-2294	-301	6968	16,73	11,66
6	-870	-295	6980	6´	-862	-295	6971	12,04	8,00
7	-804	-295	6980	7´	-800	-297	6982	4,90	4,47
8	629	-296	6980	8´	631	-303	6985	8,53	7,03
9	-2291	-295	6907	9'	-2283	-299	6916	12,69	8,94
10	-882	-295	6907	10'	-873	-294	6915	12,08	9,06
11	-804	-295	6904	11'	-799	-297	6926	22,65	5,39
12	629	-296	6904	12'	632	-302	6923	20,15	6,71
13	-2291	-295	3577	13'	-2286	-279	3577	16,76	16,76
14	-882	-295	3577	14'	-879	-274	3577	21,21	21,21
15	629	-296	3580	15'	629	-273	3593	26,42	23,00

The results in *Table 31* reflect all the aforementioned issues. The deviations (*d*) are low especially in points 1' to 12' but there are also significant errors in points 13' to 15' (see also *Figure 79*). In *Table 40*, *d z* refers to deviations without considering errors in z axe.

One issue must be outlined. *Figure 79* shows the picking rack that hosted the CWM before being handled by the CDPR platform. The piking rack was supported on the ground floor foundation and the first-floor slab. The position of the rack was unknown and the location of the CWM on it was not always the same (consider that the CWM weighs approximately 300kg and it was placed by a mobile crane operated manually). For these reasons, the CWM was not placed on a known and repeatable location. Due to aforementioned issues, it was necessary to recognize the CWM and its exact location before pick up from the rack and adjust the location of the CDPR platform accordingly. Instead, the lack of parallelism between the 8 Vacuum Cups of the VLS and the glass in the CWM would result in leaks and, therefore, the vacuum system would not perform correctly. For this reason, it was crucial that the CDPR platform adjusted its position or path depending on the deviations of the CWM on top of the rack. To solve this issue, and similar to the strategy presented in chapter 7.3, ArUco markers were placed on top of the CWM in a known position[45]. The position of the ArUco markers was detected by using the OpenCV libraries in a ROS computer and a high-resolution camera.

45 This study was made jointly with Mr Daniel Illner.

This allowed the adjustment of the position of the CDPR platform before picking up the CWM from the rack (see *Figure 80*).

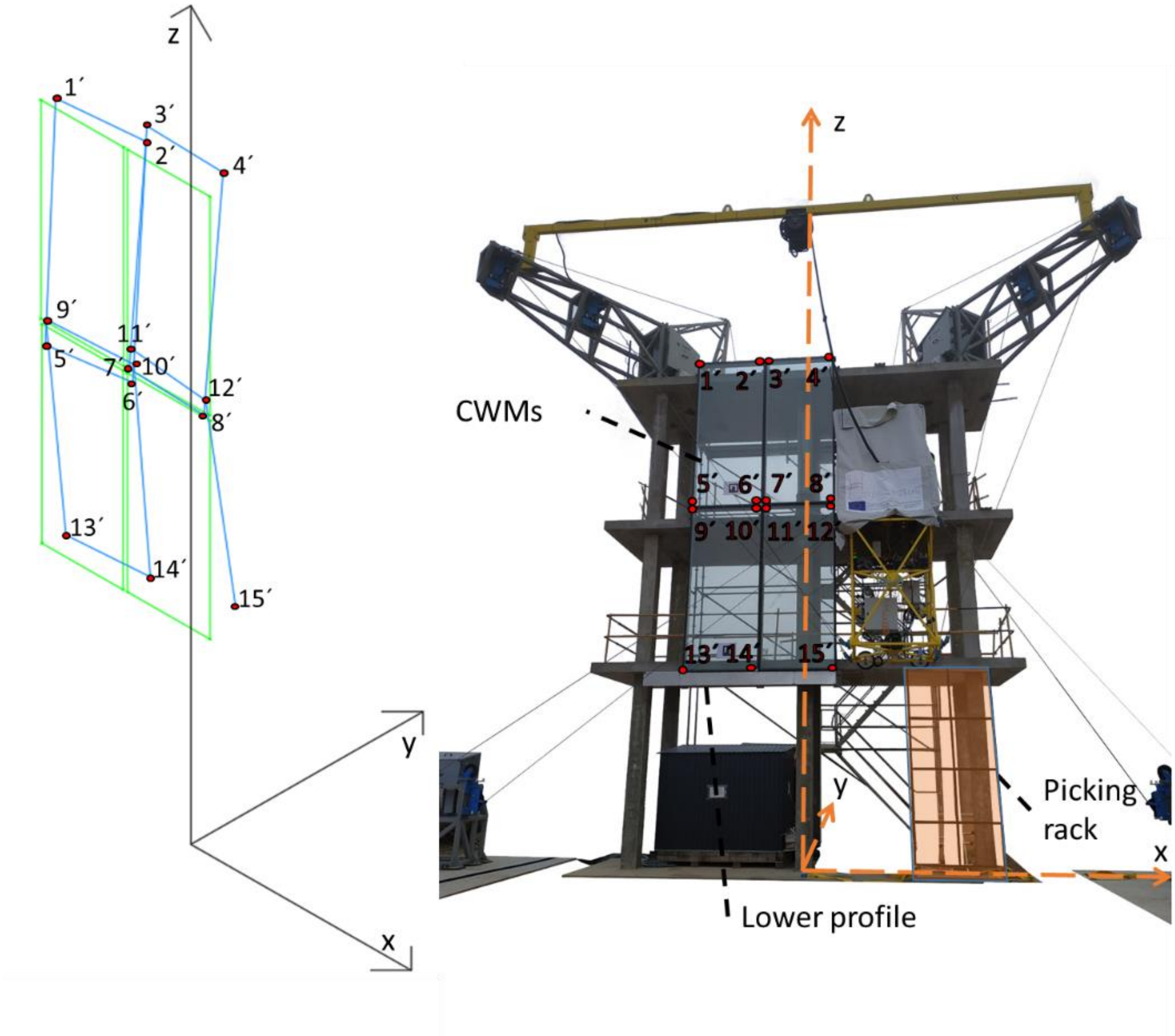


Figure 79: Planned (green) and placed (blue) deviation graph magnified by a factor of 80x in second demonstration at Acciona's facilities. Picture photographed by José David Jiménez Vicaria (Acciona Construcción).

The ROS computer had to be adapted to the existing network and connected to the main computer of the CDPR to enable the communication. This way, a GCode was generated and the adjustment of the CDPR platform could be achieved in an almost automated mode. The results of this approach are promising but still need further development[46].

46 During the writing of this dissertation, this topic was still under development.

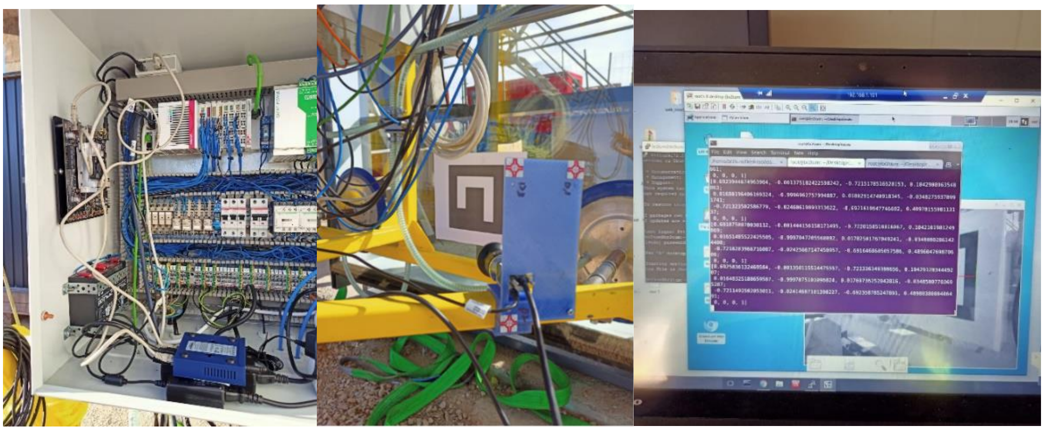


Figure 80: First approaches with the camera recognition of the CWM.

Time

With the tests carried out and the results achieved, the performance of the fully operational robotic system in real construction environments was foreseen. As in the rest of the chapters, time consumption was monitored and analyzed. With the monitored tasks, the foreseen performance of the HEPHAESTUS robot was deduced. The objective of such analysis is to compare it to the current manual methods for installing unitized curtain walls. It is important to differ the test realized in the context of the research project and the possible improved scenarios in the future. Construction sites differ from case to case and, therefore, the workspace of the cable robot needs to be adjusted to every case. Moreover, several workspaces are necessary to cover the whole building. This point needs to be considered in the case of the implementation in real cases. First, the unitary times were measured. In *Table 32*, the time for installing the CDPR and the MEE is shown.

Table 32: Worker hours for the installation of CDPR workspaces.

DNS3.1 setting up the CDPR workspace	hours	Op	T H	Cost
DNS3.1.1: define the workspace				
Task organization and define robot workspaces	0,5h	1	0,5	
Transform the coordinates of the brackets	0,5h	1	0,5h	
DNS3.1.2 Installation of the CDPR				
Install cranes and cables	40h	3	120h	3000€
Install electrical circuit	8h	2	16h	400€
Install platform, including the MEE	2h	2	4h	
DNS1.1: Calibrate the cable robot in regards with the building	4h	2	8h	
DNS3.1.2: Uninstall the CDPR when tasks are finished	8h	3	24h	3000€
TOTAL hours			173h	

The whole bracket installation cycle was accomplished in 0,18 hours (less than 11 minutes) and it is an operation that could be achieved by one operator (see *Table 33*). The question of using a robotic arm with so many tools changing is a topic that needs to be addressed in the future. The MEE could only host two brackets and its respective anchors. For this reason, the platform had to be fed with anchors every two operations, which would add about 1 minute to the overall account.

Table 33: Worker hours for a bracket installation.

	Time (hours)
DNS3.1 Move the CDPR to the bracket location	0,00833h
DNS3.2 Install one bracket with the MEE	
DNS3.2.1: Open linear actuators	0,025
Move platform downwards and activate the suction cups	
DNS1.2 or 1.5: Measure the location MEE by using a Total Station and calibrate	0,05h
DNS3.2.2: Install the bracket	
DNS3.2.2.1 Make holes in concrete	
Pick rotary hammer (drilling tool)	
Drill two holes in concrete with rotary hammer	0,0167 h
Clean holes	
Release rotary hammer	
DNS3.2.2.2 Pick, place, and hold the bracket	0,0167 h
Pick bracket with bracket clamper,	
Place bracket clamper and bracket on top of the concrete slab,	
DNS2.2.3 Fasten the anchor	0,033h
Pick the anchor setting tool	
Pick the anchor (twice)	
Fit the anchor in the hole (twice)	
Release the anchor setting tool	
DNS3.2.2.4: Torque the anchor	0,033h
Pick the torque tool	
Torque anchors, twice	
Release the torque tool	
DNS3.2.2.5: Release the bracket clamper and leave in the magazine	0,00833 h
	0,0167 h
TOTAL	**0,18 h**

Once all the brackets were installed, the CWM modules needed to be placed in a magazine to facilitate the suction cups in the platform to reach the CWM. This was an operation that required excessive logistic resources and operating-time in demonstrations (see *Table 34*).

Table 34: Worker hours for CWM installation

DNS3.3 Install the curtain wall	Time (hours)	Operators
DNS3.3.1. Place the CWM in the rack	0,0833h	2
DNS3.3.2: Pick up the Curtain Wall Module.	0,0833h	
Move the CDPR platform to the magazine		1
Adjust CDPR platform to the CWM		1
Grip the CWM in a desired or known position		
DNS3.3.3: Place curtain wall onto the brackets	0,0833h	1
Localize the brackets' position.		
Place the CWM onto the brackets		
TOTAL	**0,33 h**	

The future usability of the system will rely on the efficiency, productivity and suitability to the installation process of CWM. The DNS3.1, and especially setting up the CDPR workspace, is the biggest time-consumer among different DNSs. Therefore, it is necessary to maximize the use of the workspace. With the data gathered in *Table 32*, *Table 33*, and *Table 34*, the minimum size of workspace can be estimated to ensure competitiveness by using *Equation 1* (where W is the current installation time per m² with manual techniques, T_i is the installation time of the CDPR workspace, T_b is the installation time of the bracket, T_c is the installation time of the CWM, f is the number of floors, c_f is the number of CWM per floor and A is the area of each of the CWM[47]).

Equation 1

$$W = \frac{T_i}{A \times f \times c_f} + \frac{T_b \times f(c_f + 1)}{A \times f \times c_f} + \frac{T_c \times f \times c_f}{A \times f \times c_f}$$

To apply this equation to the same case studied in chapter 4.2, where W is 0,48 h/m², and A is 4,8 m², and c_f is 20, f (number of floors) would be 4,8. This means that with a Workspace of more than 5 floors and 20 CWM in each floor, the time spent by the CDPR and the MEE would be less than with manual methods. This data is significant for considering the integration of the cable robot in a construction site (see *Figure 81*).

47 The number of brackets is normally one more than the number of CWMs.

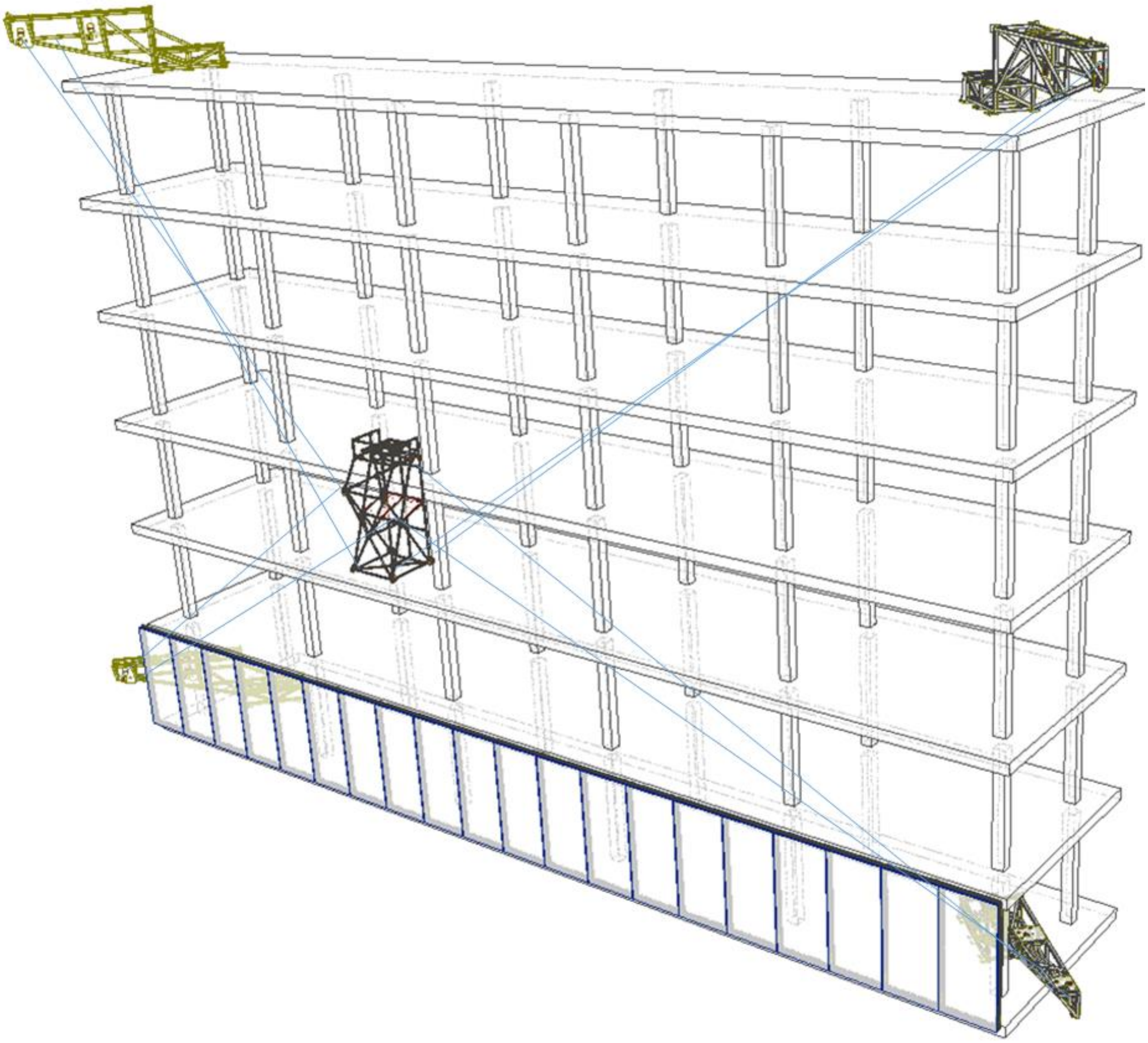


Figure 81: Minimum optimal workspace size.

8.3 Future Needs

During the demonstrations, issues aroused. Future Need should be solved in the next research phases:

- **FN3.1**. Faster set up of the robotic device is necessary.
- **FN3.2.1.** The slab's non-planar situation has been ignored. However, this is a topic that needs further consideration. Distance sensors would facilitate recognizing the planar situation of the slab.
- **FN3.3.1**: Improve recognition and localization of the CWM to be more accurate.
- **FN3.3.2**: Recognition of the bracket before placing the CWM onto it. A compliant connector that facilitates the placement of the connector would be necessary.

Studies about robotic in-situ fabrication have faced similar issues [255]. Apart from these points regarding the research achieved in this dissertation, some topics are foreseen for future development. For instance, a 3 Axe Cartesian robot for the placement of the bracket that would permit a more stable and reliable solution than the robotic arm (see *Figure 82*).

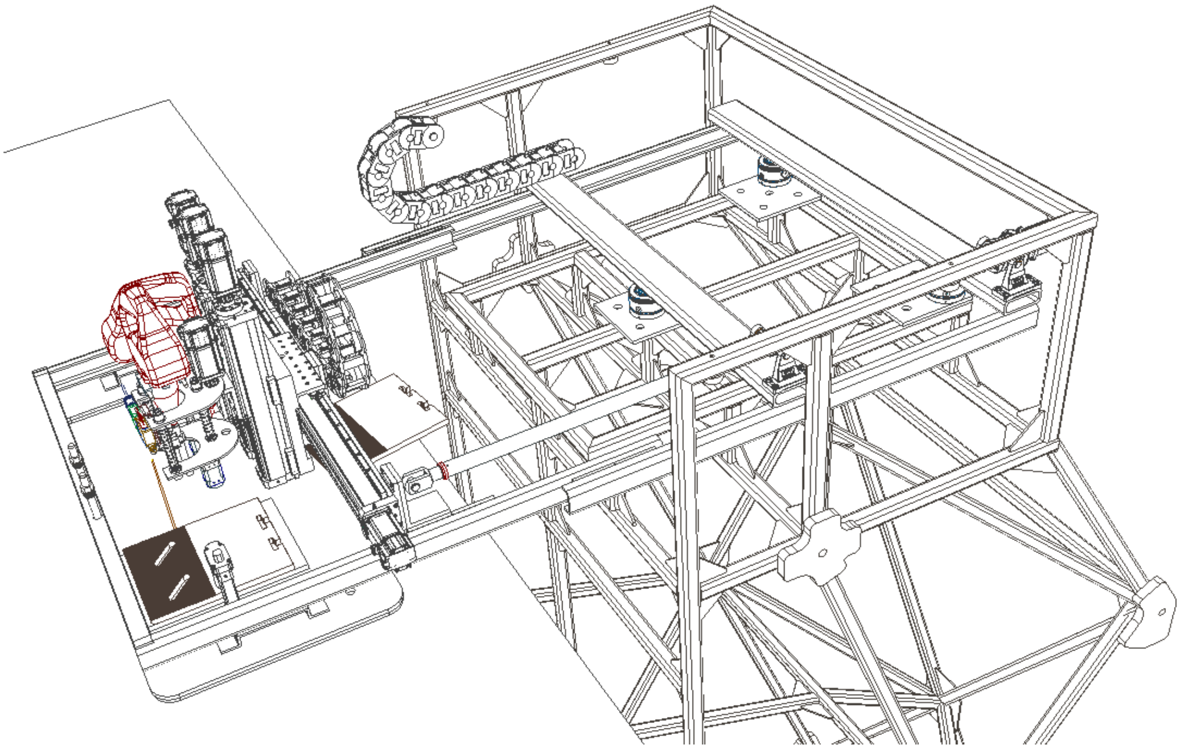


Figure 82: Developed Cartesian system for bracket installation that avoids tool changing.

9 MATCHING KIT CONCEPT

In chapter 0, the layout of the façade was automatically gathered. The module can be accurately prefabricated according to this layout by using the correct manufacturing and assembly tools off-site. But on-site, how to place the module with such high accuracy on the existing wall? Currently, modules are installed onto existing walls through two pieced connectors which are fixed partly on the module and partly on the existing façade (see *Figure 83*). To avoid unmatched connecting and placements and ensure proper fitting, these connectors need to be accurately fixed, both on the wall and on 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.

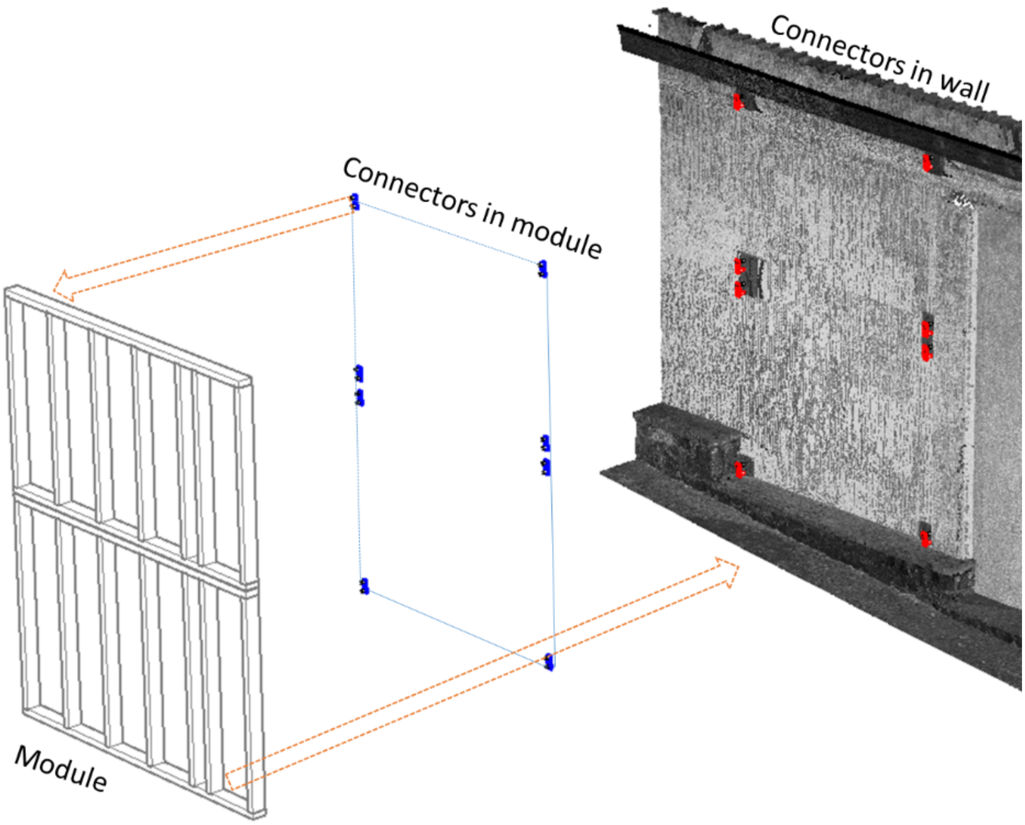


Figure 83: Exploded view of a module being placed in a wall with connectors. Point Cloud made in BERTIM project.

Furthermore, if the modules have embedded services or renewable energy sources (RES) 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 it can be observed in *Figure 83*, 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 up to 50 mm, walls and floors do not fulfil planar geometric requirements that are necessary for placing accurately prefabricated 2D modules. In a previous phase of this research, several façades were measured using 3D laser scanning tools (see *Figure 84*).

- Errors during the transfer of data from the wall to the design and *vice versa*. A façade and a wall are not regular and known geometries. Surfaces have complex and unperceivable 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 the lack of marking during the measurement of the façade 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 its 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 deviations too. The operator (or robots, see chapter 8.2 and *Figure 85* right) working with a drill bit in heights and with high wind is likely to perform the task with an error. Besides, there might 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 explained in chapter 8.2.

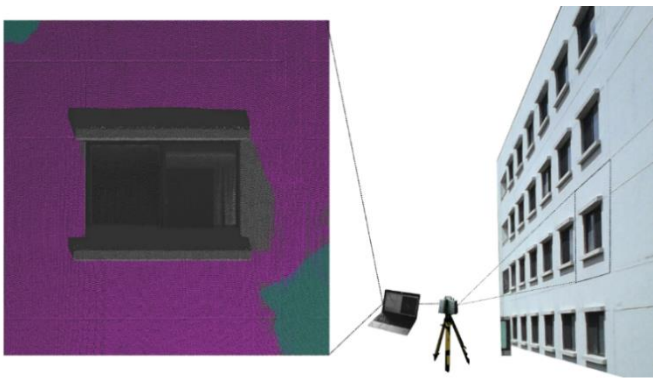


Figure 84: Data from a 3D laser scanner shoeing non-planar situation of a segment of a wall[48].

48 The Point Cloud and the images used in this figure were gathered during the stay of the author at SKKU at the chair of Prof. Kwon.

All the points explained before refer to an information workflow. How to transfer the data from the layout to the existing wall while placing the connector? And in case of deviations while placing the connector, how to transfer the data from the connector in the wall to the module? If this information workflow is missed or not considered, the connector in the module will not match the connector in the wall and the installation process would fail.

Previous studies have developed concepts to solve this situation with partially prefabricated elements adjusted to the required geometry [53] and prefabricated modules [55], [90], and interfaces [256] but it is only focused on a proposal for using a cost-effective laser scanner [257]. Unfortunately, these developments did not explore further the question of fully prefabricated walls. Two strategies can be adopted for placing the connector in the wall:

- **Strategy 1**: Place very accurately the connector in 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 for placing the connector in its location. Besides, this method does not consider possible deviations when the connector is being fixed. This strategy was used in the case presented in chapter 1 (see *Figure 85* left).

- **Strategy 2**: Place the connector in the wall with some tolerances, measure the location and make adjustments for achieving the desired location. In the tests explained in chapter 08, it was observed that installing rigid robotic supports and cranes for placing connectors very accurately onto buildings are 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 the foundation marking with patterns to accurately fix the connectors in a Japanese construction [258] or the rain-screen installation process (see *Figure 85* left).

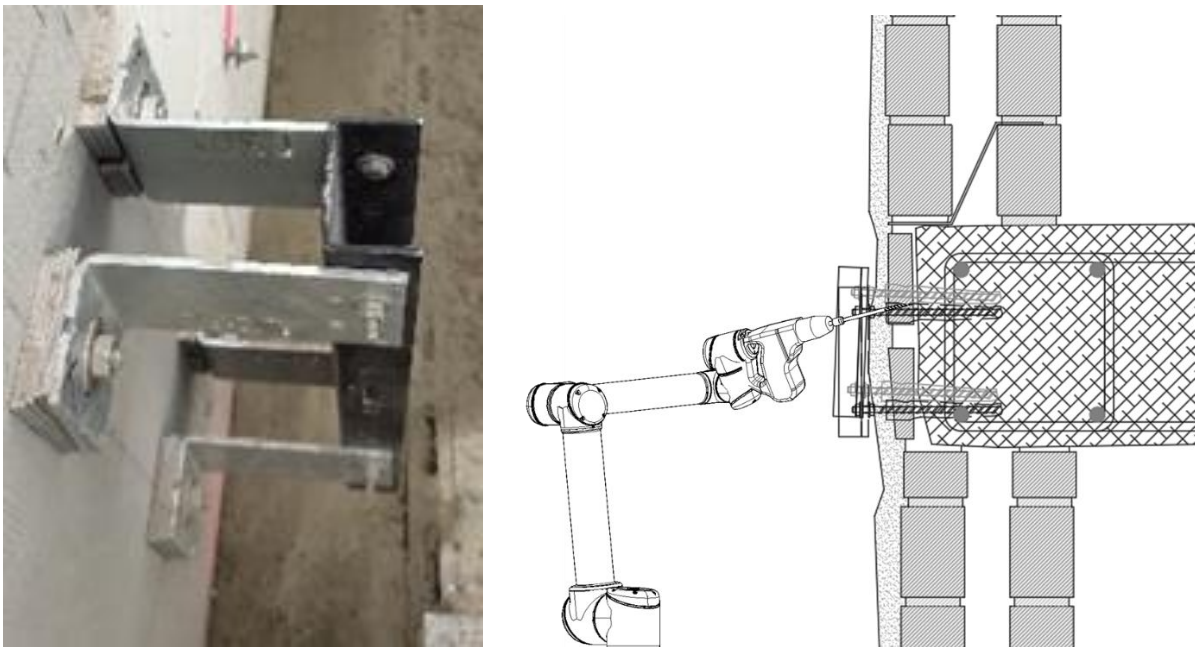


Figure 85: Left: accurately placed connector for rain-screen by using several wedges. Right: deviations occur while drilling and placing.

On the other side, Strategy 2 is often used for the insertion of the technology of medical implants, where deviations of the placed implants are adjusted and corrected [259], [260], [261]. 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 [262].

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 [156]. In the next sub-chapter, this solution, named Matching Kit, is further explained.

9.1 The Concept of Matching Kit (MK)

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 [156]. This MK is not based on a certain connector type, but on a concept that defines the interface between the façade 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 (see *Figure 86* right):

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

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 (see *Figure 86* left).

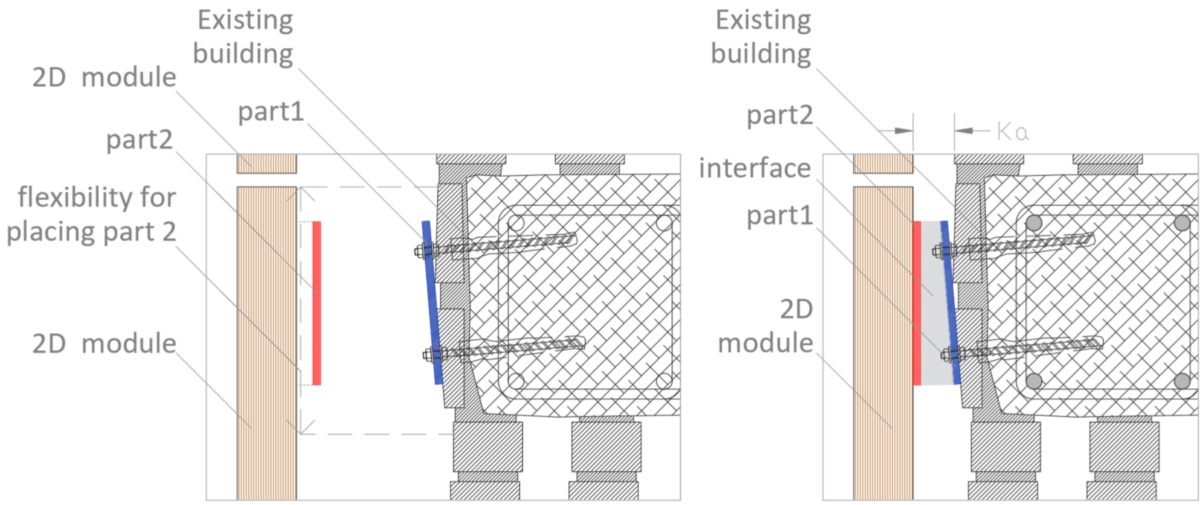


Figure 86: Left: flexibility for placing Part 2. Right: The shape of the interfaces.

The position of Part 1 can be determined by at least three coordinates (x_n, y_n, z_n) concerning a given origin point (0,0,0) of the facade. Besides, there are two equations, namely the line equation (Ln, Equation 2) and the distance equation (Dn, Equation 3), linking Part 1 and Part 2 (*Figure 87*). In *Equation 2* and *Equation 3*, K_a is the constant distance between the outer surface of the existing wall and the inner surface of the 2D module (*Figure 86* and *Figure 87*). This constant distance is defined by the designer of the refurbishment process. With these, sufficient information is available for defining the MK geometry. In *Figure 86* and *Figure 87*, 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 grey.

Equation 2

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

Equation 3

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

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

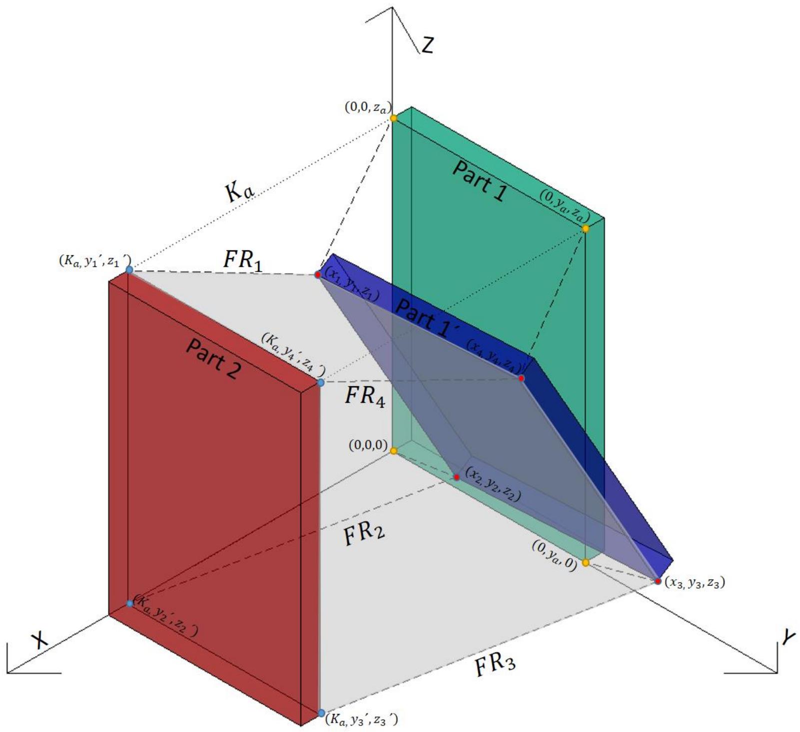


Figure 87: Geometric definition the MK.

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:

- Fixation of Part 1s on the building façade 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 and that the actual Part 1s position differs from that predicted in the design.
- Accurate measurement of the location of Part 1s.
- 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.
- Manufacturing of the interface MK by using digital techniques (CNC cut or additive).
- Installation of the interface on top of Part 1s. Once the MK was accurately manufactured and installed in its designated location, a planar situation was achieved.
- Place Part 2 onto the module depending on the location of Part 1s.
- 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 next sub-chapters. This scheme was used for the previous tests explained in the next sub-chapter 9.2.

9.2 Summary of previous tests with the MK

To validate the aforementioned MK concept and its process, three tests were carried out. 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 get results in different scenarios. The parameters or measurable variables for validating the procedure include the installation time and placement accuracy of the 2D modules. The questions before proofing such concept were:

- Would a customized interface improve the installation process without harassing the rest of the steps?
- Would accuracy be gained by doing so?
- Is the Matching Kit a better solution than the Strategy 1 presented in sub-chapter 9.1?

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 35*.

Table 35: 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©	Hundegger K2© and Weinnmann©
Point acquisition	Leica, MS-60©	Leica, MS-60©	Leica, Disto©
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©	120*80 mm pine-wood Marker stickers from Dietrich´s©.
Reflector	Rothbucher Systeme©	Rothbucher Systeme©	-
Mechanical connection Screwing system	Unicon-Basecon® Maytec®	Sherpa_XS5® 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 length	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 fully routed in a CNC as well 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: standardly produced timber framed modules were used. Due to manufacturing tolerances of the module, the contour of the 2D modules was rectified manually after the manufacturing process was finished (the modules were manually routed to gain accuracy of around 2 mm). The MKs were produced manually with a hand sander.

Figure 88 and *Figure 89* illustrate the concept used in Test 3. Two modules were installed onto an existing building mockup.

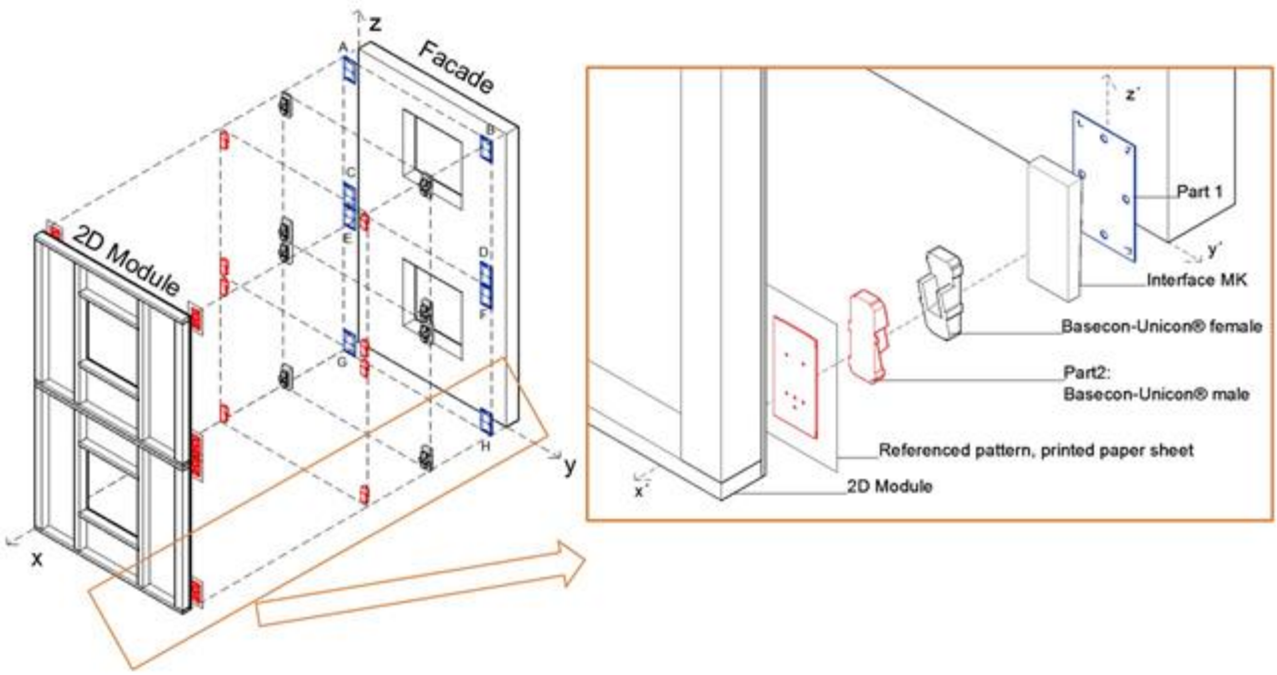


Figure 88: Exploded view of the 2D module in Test 3.

Figure 89 shows the exploded view of the real components of Test 3. Part 2s were placed thanks to a printed pattern.

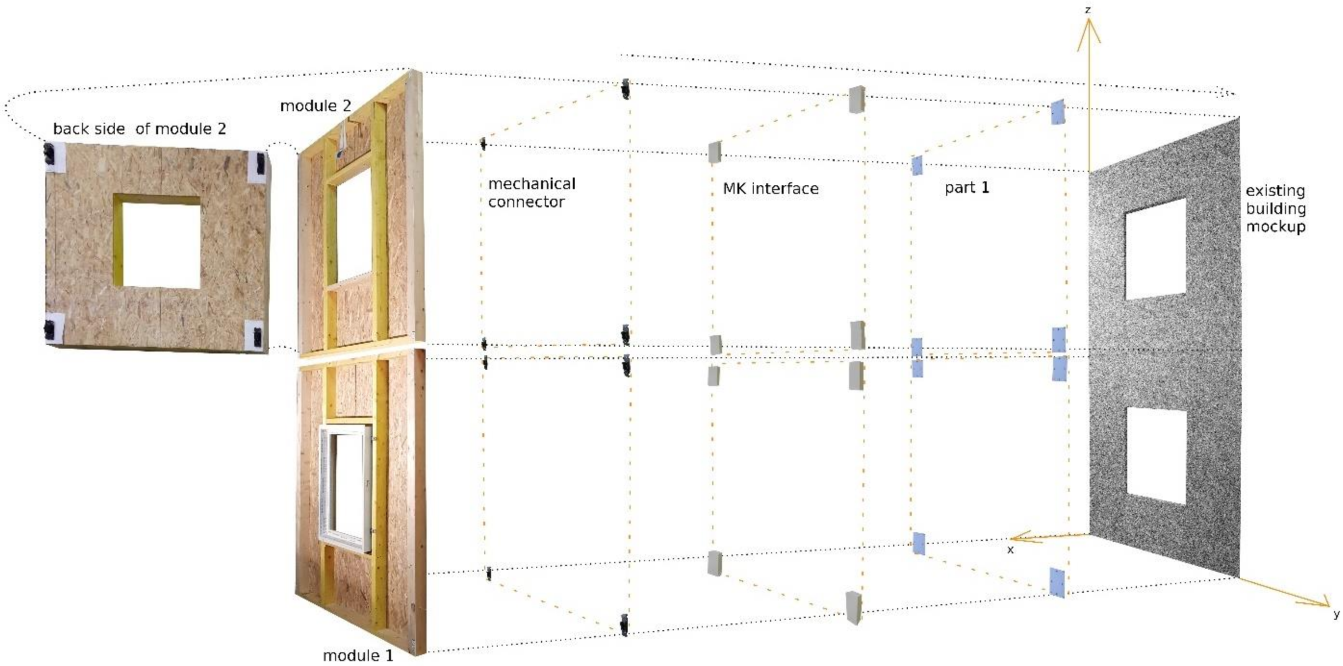


Figure 89: Exploded view of the 2D module in Test 3.

The installation sequence of Part 1 and the MK interface in Test 1 are shown in *Figure 90*. The MK interface in Test 1 had laser cut bed (see *Figure 90*).

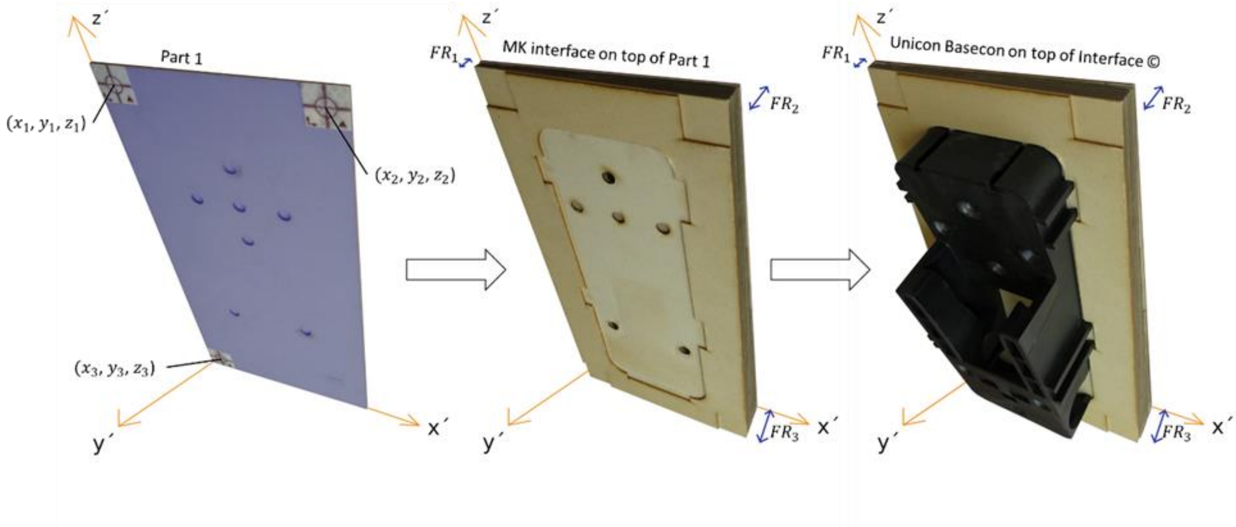


Figure 90: Three phases for installing the MK on top of the building façade.

Holes (see *Figure 90*) 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 regards to the 0,0,0 (shown in *Figure 88* and *Figure 89*) point of the existing building.

Installation time

The measured time was from the initial placement of Part 1s onto the “existing wall” until the 2D module installation. The time marked in *Table 36* 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 (see *Table 36*). In task *g*, the necessary operators varied depending on the 2D module size. The entire process comprised the following tasks.

Table 36: Installation time recorded from tests 1, 2, and 3.

		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	2.00	1.00	4.00	3.30 m²
Test 2	1.32 h/m²	0.10 h	0.16 h	0.16 h	0.10 h	0.08 h	0.01 h	0.07 h	1.00	2.00	3.00	1.50 m²
Test 3	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	3.00	1.00	4.00	5.30 m²

a: Placement of part1; **b**: Measuring of part1; **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.

The total time for installation per square meter (T) was calculated using *Equation 4*. 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.

Equation 4

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

At this point, it can be stated that the installation time in these tests was reduced considerably compared to the demonstration carried out at the “Kubik” building (1.72 h/m², see chapter 4.2) but not with that much difference with the demonstration in La Charité which was 0,5 h/m² of which 0,15 for data acquisition and 0,35 for installation without considering finishings (see chapter 4.3). 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. Besides, as it is explained on the next section, the accuracy achieved in the tests was higher which means that full prefabrication could be guaranteed.

Placement accuracy of 2D modules

Two parameters must be validated regarding the accuracy of the MK system. Firstly, the mechanical connectors in Part 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 (see *Figure 91*).

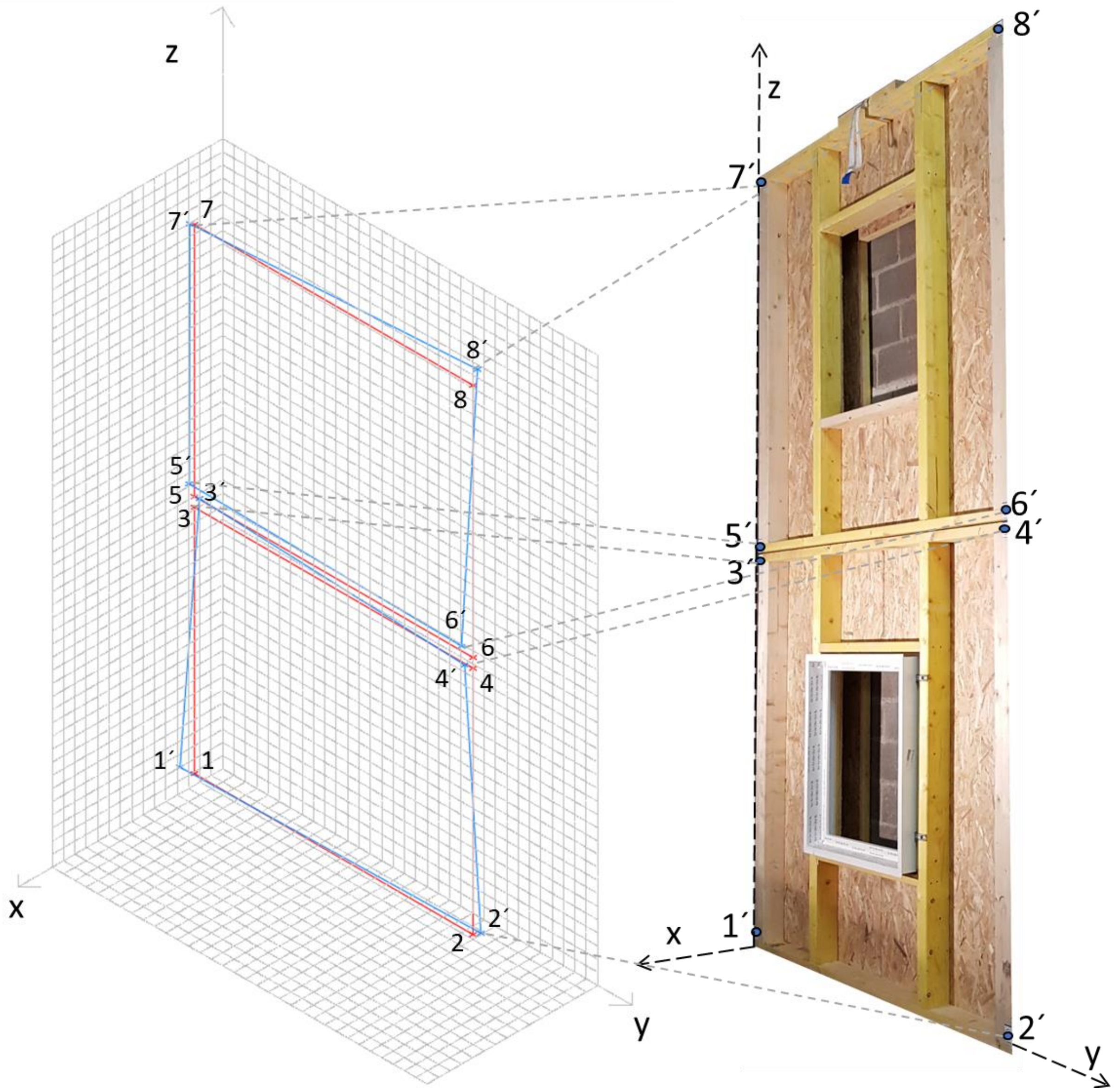


Figure 91: Results of test 3 (see also [156]*).*

In conclusion, it can be stated that the 2D modules that were routed in a CNC in Test 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[49].

49 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.

9.3 Research Gaps found during previous tests

The 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:

- **RG 1.1a** 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.

- **RG 1.1b** Reduce redundant measurement. If the scheme for getting an automated layout in chapter 0 and the process for the MK concept are combined, contradictions and redundancy of measurements appear. It is necessary to define the low level of detail layout of the modules 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.

- **RG 1.1c** 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 that 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.

- **RG 1.3a** 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 (as seen in chapter 0). It is necessary to compare both approaches.

- **RG 1.3b** 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 improve the these concepts, these points were implemented in the test explained in chapter 9.4.

9.4 Improved concept and semi-automated sequence

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 92*:

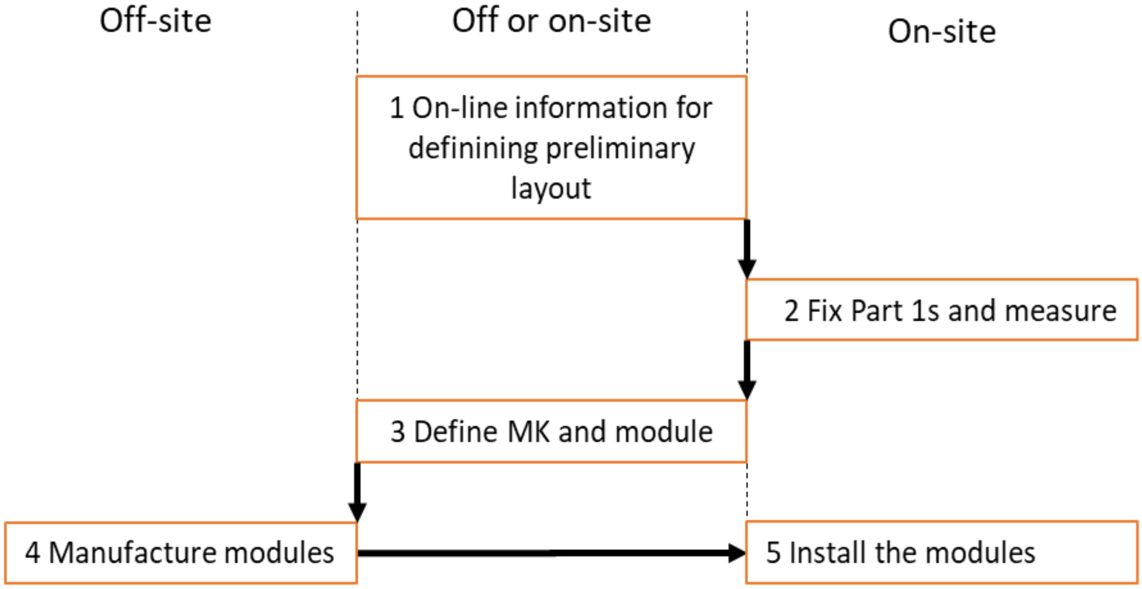


Figure 92: Process scheme.

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 façades, Part 1s is also placed in each corner of the window, as a reference target and not necessarily as a spot for a mechanical connector (see *Figure 93*).

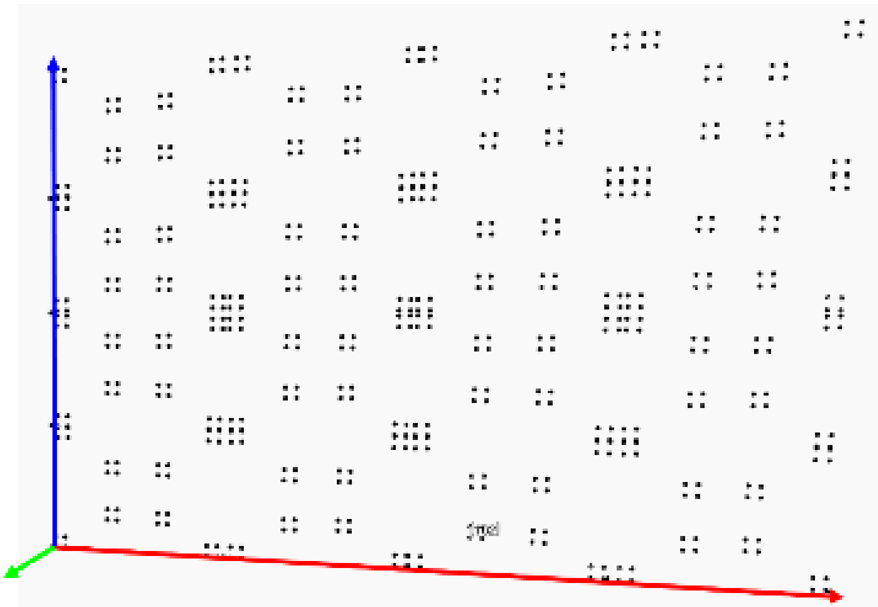


Figure 93: Location of Part1 coordinates.

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 as in chapter 0 to automatically create the layout of the modules. A new flowchart was created which includes the data from the Point Cloud (see *Figure 94*) and create the shape of the interfaces with developed Python™ [263] nodes within Dynamo™ [199].

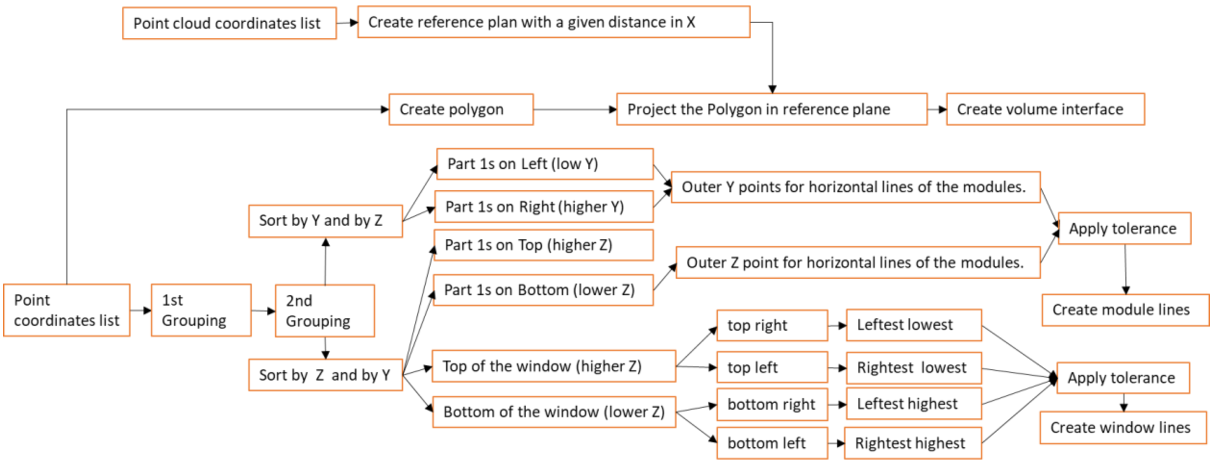


Figure 94: Process flowchart.

The procedure defined by the flowchart in *Figure 94*, foresees to use either the Point Cloud or Part 1s 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, needs to be recognized. To achieve this, each of the points in every Part1 needs to be clustered. For doing so, two groupings need to be accomplished. First grouping consists of the points that are in a range of 100 and 170 mm.

The second grouping consists of separating Part 1s in the same cluster of four. The first and second grouping 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.

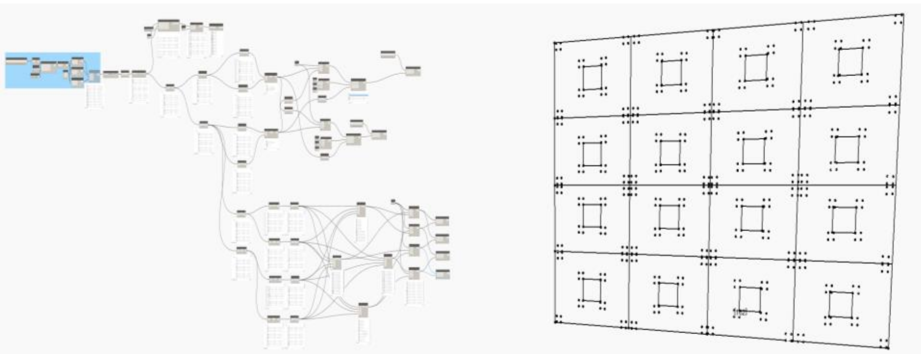


Figure 95: Definition of the layout by Matching Kit.

It is necessary to locate the line, to avoid overlapping and to cover the borders of the façade correctly. Part 1s of the Matching Kit is put with high tolerances and, therefore, there might be overlapping of points. As it can be seen in *Figure 95*, the whole process explained in previous chapters is reduced to a few algorithms and scripts in Dynamo™ (that include Python™ codes).

9.5 Outdoor test of the MK with the improved concept

To validate the concepts presented in sub-chapter 9.4, Test 4 was performed outdoors, in a wall at Egoin's factory[50] [34] with materials and elements that are part of the standard 2D module of the company (see *Table 37*). To configure the 2D module, 12 mm width OSB boards and 62x140 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© [157] manufacturing line. Two modules were manufactured and installed in this test. The CAD software used for the layout design was CADWorks© [264]. The insulation, 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. Therefore, all the capabilities of the research explained in chapter 9.4 could not be implemented. 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 37: Devices and materials used in test 4.

SOFTWARE	
Design of module	Recap™, Dynamo™
Digital fabrication CAD	CADWorks™ for transforming the data from Dynamo™
MK interface	Biesse© CAM for transforming the data from Dynamo™
MANUFACTURING	
Module element cutting	Weinnmann©
Module element routing	Weinnmann©
Interface MK cutting	Biesse Rover© CNC
MEASURING TOOLS	
Point acquisition	Leica©, MS-60©., provided by Infolur
Laser scanner	Leica©
MATERIALS AND ELEMENTS	
Modules	
Frame	62x140 mm
Board	12mm OSB
Interface MK	Oak solid wood
Reflector marker	Rothbucher Systeme©
Mechanical connection of the MK	Knapp Walco®40
Anchor	Mechanical Anchor with a plastic cap
MODULE SIZE	
Module height	1998 and 2219 mm
Module length	3342 mm

43 This test was achieved within the BERTIM project.

As in medical reports and papers, this sub-chapter gathers the outcome of an experiment or test. The test was carried out as an experiment in progress or a proof of concept of the scheme (*Figure 94*). 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 reproducibility of methods and results and further improve the MK concept.

Phase 1: Using geographic information systems in 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 travelling to the site. This phase consisted of preliminary data definition of the layout with online services**.** Today, there is no 3D cadaster available [265], although this is a topic that needs to be discussed further. Preliminary information of the existing building façade was gathered by using GIS and online data. For this test, Google Street Maps™ [266] and GeoEuskadi (Basque GIS portal) [267] 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 (see *Figure 98*).

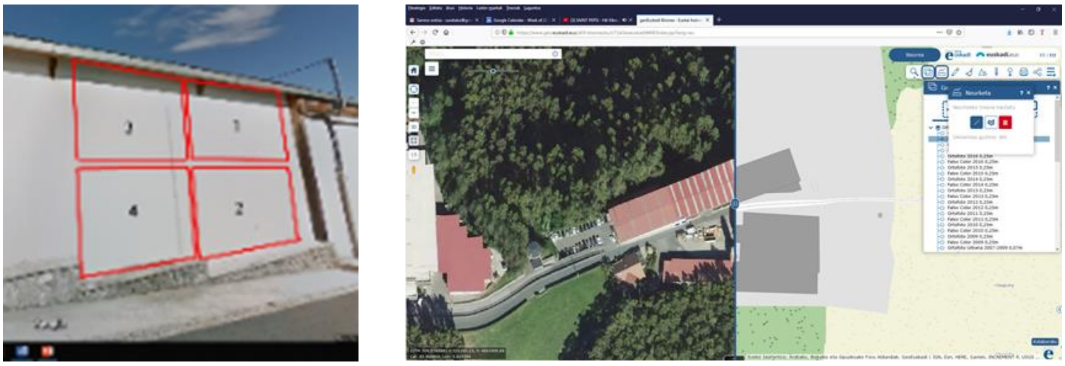


Figure 97: Definition of the modules in Egoin using Google Streets™ and GeoEuskadi (Basque GIS portal) cadastral information.

This is a very simple wall and this method should be improved. In future, potential clients could complete the data and use photogrammetry for measuring the façade. Ideally, from a marketable point of view, these steps would not require any cost to the company, and the client would not need to hire, since they would only be used as an approximation. It is also a plan for risk mitigation for various reasons. On the one hand, in this phase the contracts are not still signed with the costumer and travelling there would require an economic loss if the contract did not go further.

Phase 2 and 3: Part 1 placement, data acquisition, data processing, layout and MK definition.

Following the scheme in *Figure 94*, the fist on-site task fulfilled several steps. Part 1s was previously prepared and cut in squares of 200 mm by 200 mm and markers were placed on it (see *Figure 96*). At this point, the facultative engineers could also prescribe any type of solution that the façade renovation requires:

- Step phase 2.1: Part 1 placement and fixation. With the information gathered in the previous phase and with the help of the physical references on the wall, it was possible to place each Part 1, within about 0,09 hours. As it can be seen in *Figure 96*, no marking device was used, only simple tape measures.

- Step phase 2.2: Data acquisition**.** After placing Part 1, it was possible to start with the data acquisition. For the test, data acquisition of 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 (see *Table 38*). Besides, the Point Cloud was surveyed with a 3D Leica laser scanner. The 3D density of the Point Cloud grid was 5 mm.

Figure 96: Top left and right: fixation of Part 1.Bottom left: Point survey by Total Station. Bottom right: laser scanner at work.

- Step phase 3.1: Data processing. Following data acquisition, it was necessary to reduce the density of the Point Cloud™ [199] to around 8.000 points, instead of the millions of points harvested by 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.

Table 38: Part 1 target's coordinates in mm georeferenced.

Position X	Position Y	Position Z
993899	4997544	102807
993900	4997545	102600
993901	4997540	102986
993901	4997542	102779
993904	4997493	100796
993905	4997725	102604
993905	4997723	102812
993905	4997719	102992
993906	4997721	102783
993911	4997673	100795
993911	4997522	104604
993911	4997492	100616
993914	4997527	104782
993915	4997702	104598
993915	4997672	100616
993918	4997707	104778
993975	5000200	103019
993975	5000197	102839
993976	5000197	102811
993976	5000192	102633
993982	5000375	102836
993982	5000371	102627
993983	5000379	103016
993983	5000376	102807
993984	5000178	100803
993991	5000358	100804
993991	5000178	100624
993996	5000237	104555
993998	5000358	100624
993999	5000417	104555
993999	5000237	104735
994005	5000417	104733

- Step 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.

- Step phase 3.3. This output was inserted in AutoCad and compared with the manual process. There were only minor deviations compared to 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 (see *Figure 98*).

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 97* 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 manufacturing and installing processes (see *Figure 98*)

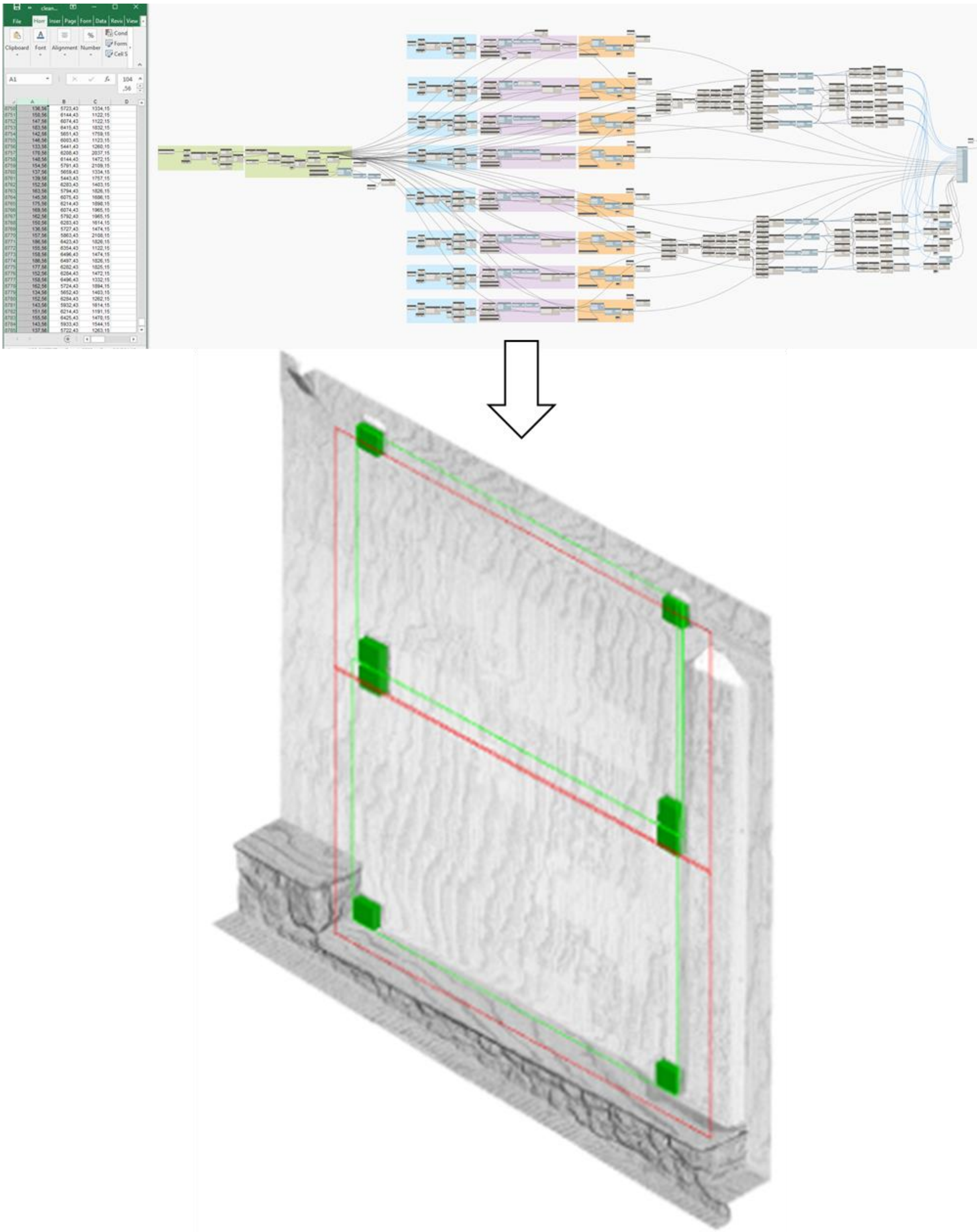


Figure 97: Automated process from the Excel file to the layout and MK definition.

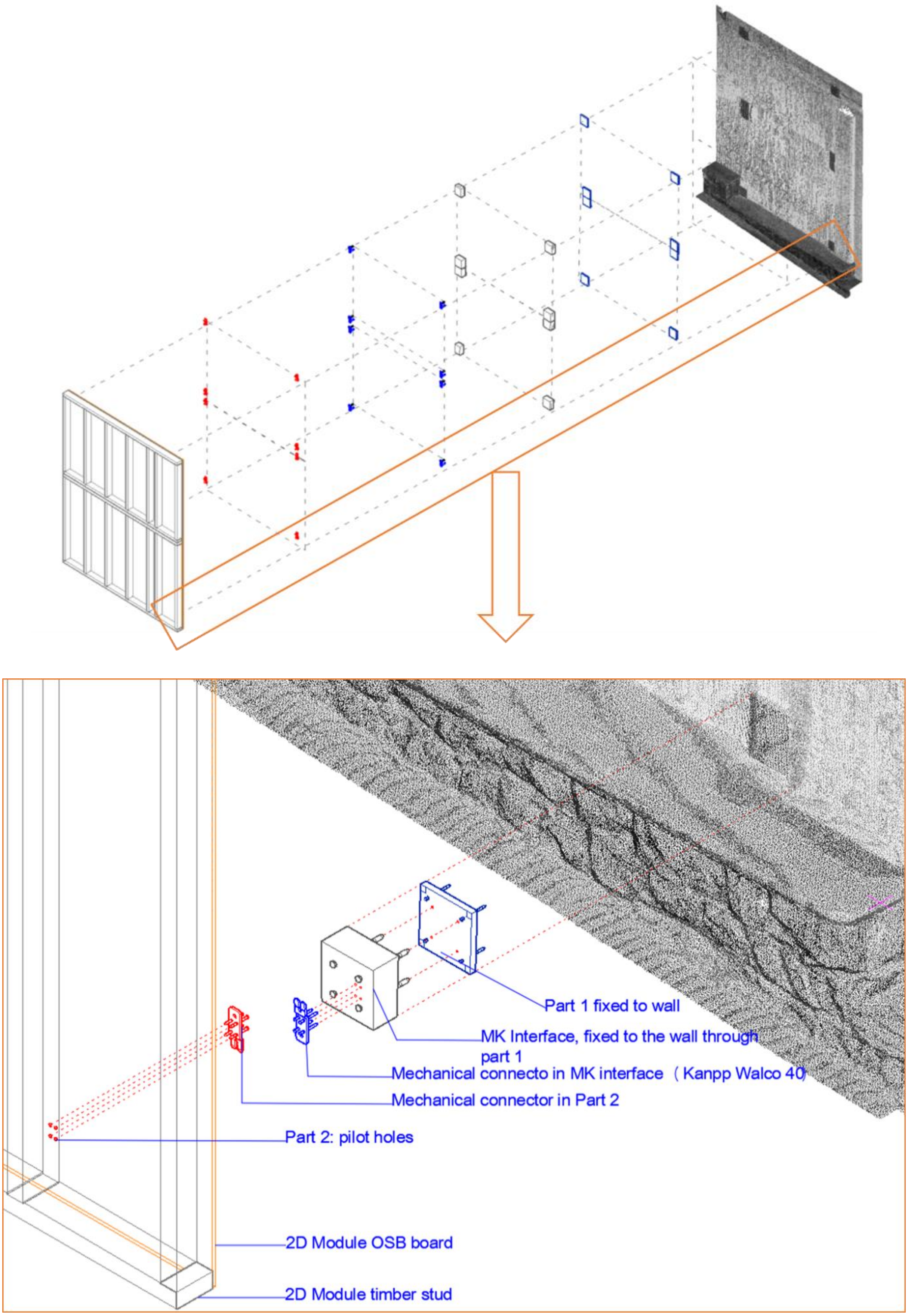


Figure 98: Installation process of the Matching Kit at Test4.

Phase 4: Manufacturing

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

Figure 99: MK manufacturing process.

The MK interface shape was drafted in the Biesse CAM software and produced at the Biesse CNC [268] (see *Figure 99*).

Phase 5: On-site Installation

Two means for 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 hole accurately by 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 (see *Figure 100* and *Figure 101*).

Figure 100: Installation sequence of the modules. The module below installed with a crane.

Figure 101: Installation sequence of the modules.

Necessary working time

Table 39 shows the time spent in each step. Comparing to previous tests explained in sub-chapter 9.2, the time consumed in Phase 1 was not considered because it is an extra step that previous tests did not achieve.

Table 39: Installation time recorded from tests 4.

		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	0.45 h/m²	0.09	0.09	0.05	0.19	0.15	0.08	0.10	3.00	2.00	4.00	7.15

a: Placement of part1; **b**: Measuring of part1; **c**: MK shape and layout 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.

The total time for installation per square meter (T) was calculated using Equation 3. For test 4, T was 0,45 h/m².

Equation 5

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

The existence of four connectors for each module is an issue that must be reduced. Besides, machining the interfaces in an industrial CNC was time-consuming when comparing to the 0,10 in Test 2.

Accuracy of the final position

In Test 4, the maximum deviation between planned and placed coordinates was registered at point 8 (7.2 mm) while the lowest deviation was in point 1 (2.9 mm) (see *Table 40*). In *Figure 102*, the deviation is magnified by a factor of 20.

Table 40: 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
1	0,00	0,00	0,00	1´	2,23	0,90	1,50	2,90
2	3342,00	0,00	0,00	2´	3337,20	-2,20	1,50	5,40
3	0,00	0,00	2219,00	3´	2,72	-1,50	2216,50	4,00
4	3342,00	0,00	2219,00	4´	3338,20	-2,20	2215,50	5,50
5	0,00	0,00	2239,00	5´	4,59	2,40	2242,50	6,30
6	3342,00	0,00	2239,00	6´	3337,20	-0,05	2241,50	5,40
7	0,00	0,00	4237,00	7´	-0,30	0,30	4230,50	6,40
8	3342,00	0,00	4237,00	8´	3335,30	-1,20	4234,50	7,20

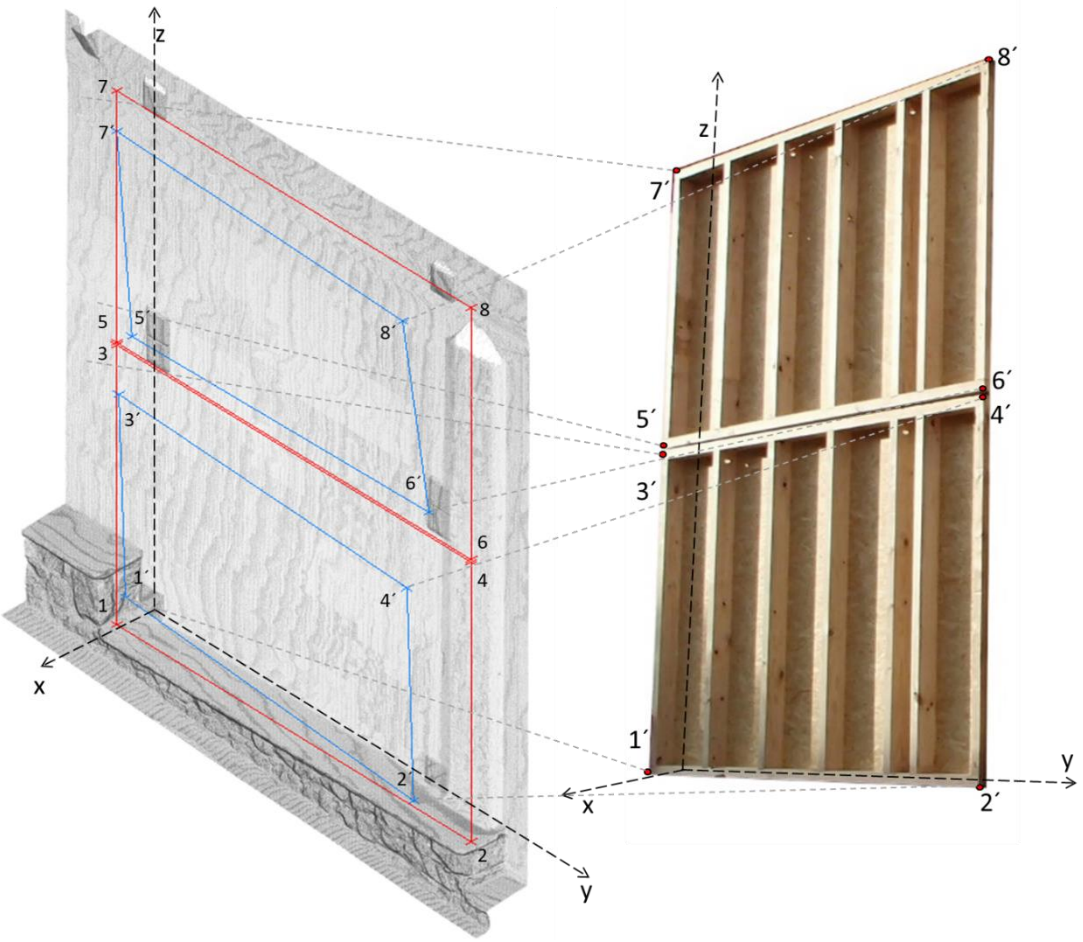


Figure 102: Planned and placed deviation graph magnified by a factor of 20 in test 4.

The results show that the DIN 18202 was fulfilled. However, the DIN 18203-3 could not be achieved, given the maximum deviations of 5 mm. The reasons behind that are, probably, the inaccuracies of the manufacturing process.

Issues while performing the test

The results show a larger installation time per square meter than in La Charité (see chapter 4.3). However, the total time per module installed is less.

Compared to Test 1,2, and 3, Test 4 gradually gained complexity and got closer to real cases. The manufacturing procedure of the MK was one challenge. Besides, the measuring time with the Point Cloud was still a question to be solved. However, as explained before, several issues happened during this test:

- **Issue 1.** Measuring deviations of Part 1s. Part 1s were CNC routed with high accuracy. Therefore, the geometry of Part1s was known. On the first survey, the measurement offered a deviation of 20 mm. Due to that, a second survey was carried out and the required accuracy was not achieved neither. For the third survey, with markers on top of Part 1s, an accurate measurement was achieved.

- **Issue 2**: The MK interface should be developed towards a more lean and on-site reproducible technique. The part does not need to be screwed necessarily; it can be stick. The mechanical connector on top of the MK in buildings could be tested for its resistance to forces or not.

- **Issue 3**: Just behind the two modules installed with the set of MK components, two other modules were installed with the conventional method or Strategy 1, that is, placing the connector without tolerances. However, during the installation process, the information workflow of this Strategy 1 failed and a connector was placed with major deviations. Therefore, the modules were not placed accurately and the comparison could not be achieved.

It is important to highlight that the subject refers to a single case studied; hence, further studies would be necessary.

9.6 Future Needs

Some concepts need to be improved in future work:

- **FN1.1.1** Potentialities of 3D cadaster should be explored to maximize the online data acquisition.

- **FN1.1.2** The use of a Total Station is tedious; therefore, using devices for the recognition of Part1 automatically should be enhanced by:

  - Use of a dense Point Cloud for recognizing automatically Part 1s. Additionally, in Dynamo™, as part of the process developed, the possibility to use only the input of the coordinates of the Point Cloud to automatically generate the geometry of the MK was explored by using the iterative closest point and Bayesian estimation. Unfortunately, the Point Cloud density needs to be higher for this purpose.

  - Use of photogrammetry for recognizing Part 1s. Software such as Photomodeller [195] offer point coordinates in a rather close range as well as target-based recognition [269].

- **FN3.2**: A leaner production of the MK interface is necessary.

Other topics which might need to be considered apart from the use of the Matching Kit include:

- Only 2 connectors might be better instead of 4, like in the curtain wall (see sub-chapter 8.2) in order of the time spent with the manufacturing of the MK.

- The MK set of components and its procedure can be used for either manual or robotic installation processes. Chapter 1 pointed out the calibrating efforts of on-site robots for reaching the accuracy needed for the installation of façades. Therefore, installing the connector with high tolerances with an MK interface might be a solution for facilitating the robotic system. Is the Matching Kit interface a faster solution than calibrating an on-site robot? That is a question that further research should achieve in every case.

- The MK could be used only in key modules, meaning corners, and to use them as a ruler. In this sense, windows would be an issue, though.

Finally, the MK concept, its set of components and its process were implemented in a real building refurbishment (see *Figure 103*). Phases 1 and 2 (not placing the interface) were achieved by the author of this thesis, phase 3 was achieved by a manufacturing company and phase 4 by installing companies. This was the first real case using MK and without the assistance of the author during manufacturing and installation. The results could not be monitored due to issues related to on-site urgencies at the end of the research project BERTIM. Moreover, the first trials for using photogrammetry for automatically measuring Part 1s was accomplished.

Figure 103: First achievements with photogrammetry and a module installed with an MK concept in a real project. Bottom picture by Mr Hervé Coperet (POBI Industrie).

10 COMPILATIONS AND CONCLUSIONS

As determined in chapter 1, the different DNSs have addressed two main parameters, namely the working time for achieving a task and the accuracy for achieving such tasks. In line with the objectives chapter 3, a reduction of 30% of the working time was realized compared to current procedures. To fully answer whether the objectives of this dissertation were reached, chapters 5 to 9 gathered a set of DNSs that solved the initial needs to some extent. However, in terms of how the set of DNSs can be evaluated with a holistic perspective of the renovation process, 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/m^2) of all the DNS defined in chapters 5, 6, 8, and 9 was considered first (see *Table 41*)[51].

Table 41: Time spent in the selected DNSs.

	Working time per square meter (h/m^2)			
	Set 5 Point Cloud	Set 6 Assembly	Set 8 Cable robot	Set 9 Matching Kit
SC1:Data flow				
SC1.1: Data acqusition	0,0127			0,05
SC1.2: Data Processing	0,0021			
SC1.3: Layout definition	0,0021			0,05
SC1.5: Transfer On-site data			0,0208	0,18
SC2:Manufacturing				
SC2.1: route elements				
SC2.2: assembly				
Analysis in chapter 6		0,108		
SC3:Installation				
SC3.1: Setting up device			0,36	
SC3.2: brackets fixation			0,0542	0,18
SC3.3:module installation			0,06875	0,084

Some notes on the data in *Table 41* 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 [84]. Besides, the data need to be considered in different contexts.

- Set 5 (Semi automated Primary Layout Definition with a Point Cloud): In regards to Set 5, data from *Table 15* in chapter 0 was taken into consideration. The DNS in chapter 0

51 The DNS presented in chapter 7 is not a reliable solution regarding time, and that is why is not considered in Table 40. However, the study shows a method for adjusting the geometry of the elements in order to be assembled by robots.

is fast at defining the layout of the module but it requires a considerable effort around data acquisition to generate reliable and accurate data.

- Set 6 (Partial Routing and Novel Assembly Sequence): For the calculation of Set 6, data in Table 22 was considered. The data gathered in chapter 6 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 manufacturing process. However, it shows a strategy, albeit a minor CNC machining of elements that might be a solution to some issues in the future.

- Set 8 (Robotic installation of modules with a CDPR): Regarding the installation robot presented in chapter 1, the biggest handicap is the set-up of the robotic system (173 hours that for an optimal workspace shown in *Figure 81* would be 0,36 hours per square meter). The rest of the operations are work-time efficient and accurate enough according to the first tests. For the calculation of Set 8, *Table 33* and *Table 34* were analyzed with the following remarks:

    - The data transfer to the CDPR and the MEE of the robot takes 0,05 h for each bracket. Considering that two brackets[52] 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, 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, therefore, 0,06875 h/m² are necessary.

- Set 9 (Matching Kit concept): The solution in chapter 1, the MK, 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. For the calculation of the Set of solutions 9, data (a, b, c, d, e, f, g, j, and k) from *Table 6* was taken. To calculate SC1.1, SC1.5, SC3.2 and SC3.3, *Equation 6* to *Equation 9* were used.

52 This is not totally exact, normally in a CWM façade, one bracket per module +1 is necessary in each row.

Equation 6:

$$T_{sc1.1-9} = \frac{(a) * j}{k}$$

Equation 7:

$$T_{sc1.5-9} = \frac{(b + c + d) * j}{k}$$

Equation 8

$$T_{sc3.2-9} = \frac{(e + f) * j}{k}$$

Equation 9

$$T_{sc3.3-9} = \frac{g * h * j}{k}$$

The sets 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 Sets 5 (Semi-automated Primary Layout Definition with a Point Cloud), 6 (Partial Routing and Novel Assembly Sequence) and 8 (Robotic installation of modules with a CDPR).

- Combination 2: It combines Set 6 (Partial Routing and Novel Assembly Sequence) and 9 (Matching Kit concept).

- Combination 3: It combines Set 6, Set 8 and 9. In this case, the Matching Kit concept is combined with the robotic installation of the modules. Combination 3 overlaps differently since the robotic installation with the MK was not approached.

In all combinations, for the manufacturing subcategory (SC2), the data achieved in chapter 6 is multiplied by 5 (as the data gathered represents only 20% of the manufacturing process) to represent the manufacturer of the whole prefabricated module. This is only an estimation.

Data in *Table 42* show 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). In both cases, less time is necessary than the combination of the lowest records in the analysis in chapter 1,*Table 13*, 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 13* (3,60 h/m²).

Table 42: Time spent in each of the combinations.

	Combination of Lowest records	Combination of Highest records	Combination 1	Combination 2	Combination 3
SC1:Data flow					
SC1.1: Data acqusition	0,09	0,15	0,0127	0,05	0,05
SC1.2: Data Processing		0,34	0,0021		
SC1.3: Layout definition	0,17		0,0021	0,05	0,05
SC1.5: Transfer On-site data	0,04	0,13	0,0208	0,18	0,18
SC2:Manufacturing					
SC2.1: route elements	0,21	0,45			
SC2.2: assembly	0,40	1,74			
Analysis in chapter 6			0,108*5	0,108*5	0,108*5
SC3:Installation					
SC3.1: Setting up device			173h=0,36		173h=0,36
SC3.2: brackets fixation	0,03	0,08	0,054	0,18	0,054
SC3.3:module installation	0,34	0,71	0,068	0,084	0,068
TOTAL	**1,28 h/m²**	**3,60 h/m²**	**1,06 h/m²**	**1,08 h/m²**	**1,30 h/m²**

But are the results in *Table 42* enough 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 [270], [271] model 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 43*) which is based on the lowest and highest records and the combinations from *Table 42*. 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 43*). 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, the data in *Table 7* shows a maximum deviation of 7 mm, which has been considered as highest record. For all Combinations 1 to 3, data from *Table 21* shows 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 43*). The initial objective of this dissertation was that installation tolerances must be lower than 5 mm, as the DIN 18203-3 specifies (see chapter 4.1). 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 chapter 4.3), and this value is taken as the highest record. For set 8 and, therefore, Combination 1, the installation accuracy in *Table 31* shows absolute deviations of up to 11,66 mm in regards to the planned position. For set 9 and, therefore, Combinations 2 and 3, the installation accuracy in *Table 31* shows absolute deviations of up to 7,2 mm. The W weight for this indicator is considered as 25% (1/4).

In *Table 43*, 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 10 is used and applied for getting Normalized Indices ($\bar{I}_{ij}$).

Equation 10:

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

Table 43: 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

By applying *Equation 11*, the Normalized Indices' $\bar{I}$ values are summed and the Combination's significance Rj is achieved (see R in Table 44). Finally, the Combination´s degree of efficiency in 0-100 scale is achieved by applying Equation 12 (see N in Table 44).

Equation 11:

$$R_j = \sum^j (\bar{I}_j)$$

Equation 12:

$$N_j = \frac{R_j - R_{min}}{R_{max} - R_{min}} * 100$$

Table 44: Final assessment.

	Lowest	Highest	Combination 1	Combination 2	Combination 3
Total sum of normalized indices ($\boldsymbol{R_j}$)	0,12	0,45	0.15	0.13	0.14
Combination‘s degree of efficiency ($\boldsymbol{N_j}$)	100	0	90.57	96.73	93.49

The results show that the objectives have not been reached 100%. As remarked in chapters 5 to 9, future research should solve the remaining issues. Therefore, some points must be improved, as highlighted before in chapters' 5 to 9 Future Needs. The FNs are compiled and their numbering re-adjusted in *Table 45*.

Table 45: Compilation of future needs.

SC	
1	FN1.1.1: Accuracy of the measuring device (Set 5)
	FN1.1.2: Potentialities of 3D cadaster (Set 9).
	FN1.1.3: Recognition of the Part1 automatically (Set 9).
	FN1.3.1: Accuracy of the selected segments (Set 5)
	FN1.3.2: Recognition of slab. (Set 5)
	FN1.5.1: It is necessary to correct possible deviations of the CNC (Set 8)
2	FN2.1.1: Adjustment in design to facilitate assembly process (Set 7).
	FN2.1.2: Design should consider rigidizing during the assembly (Set 6)
	FN2.1.3: Joints that facilitate the assembly are recommended (Set 6)
	FN2.1.4: Adjusted ROD depending on Assembling Tolerances (Set 7)
	FN2.2.1: Adjust the manufacturing line (Set 6).
	FN2.2.2: Include CNC machining devoices Organizational changes (Set 6).
	FN2.2.3: re-programming depending on the new assembly sequence (Set 6).
	FN2.2.4: Inaccuracies of the board routing (Set 6)
	FN2.2.5: Agile robot path adjustment depending on CAD of the modules (Set 7)
3	FN3.1.1: Faster set up of the robotic device is necessary. (Set 8).
	FN3.2.1: A leaner production of the MK interface is necessary. (Set 9).
	FN3.2.2: Consider uneven surfaces (Set 8).
	FN3.3.3: Accurate Recognition of the modules. (Set 8).
	FN3.3.4: Recognition of the bracket. (Set 8).

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 in Chapter 1 show that reaching absolute accuracy in a façade workspace leads to time-consuming setting up of the robotic device.

The data gathered in this dissertation can be used as a basis for future business plans. However, the Technology Readiness Level (TRL) of the Developed Novel Solutions (DNS) 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 [272].

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, where this dissertation 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 [273] will address some of the aforementioned needs.

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APPENDIX 1: Decision Making Process, a scheme

The scheme in *Figure 104* shows the decision making process for the research development used in the research presented in this dissertation.

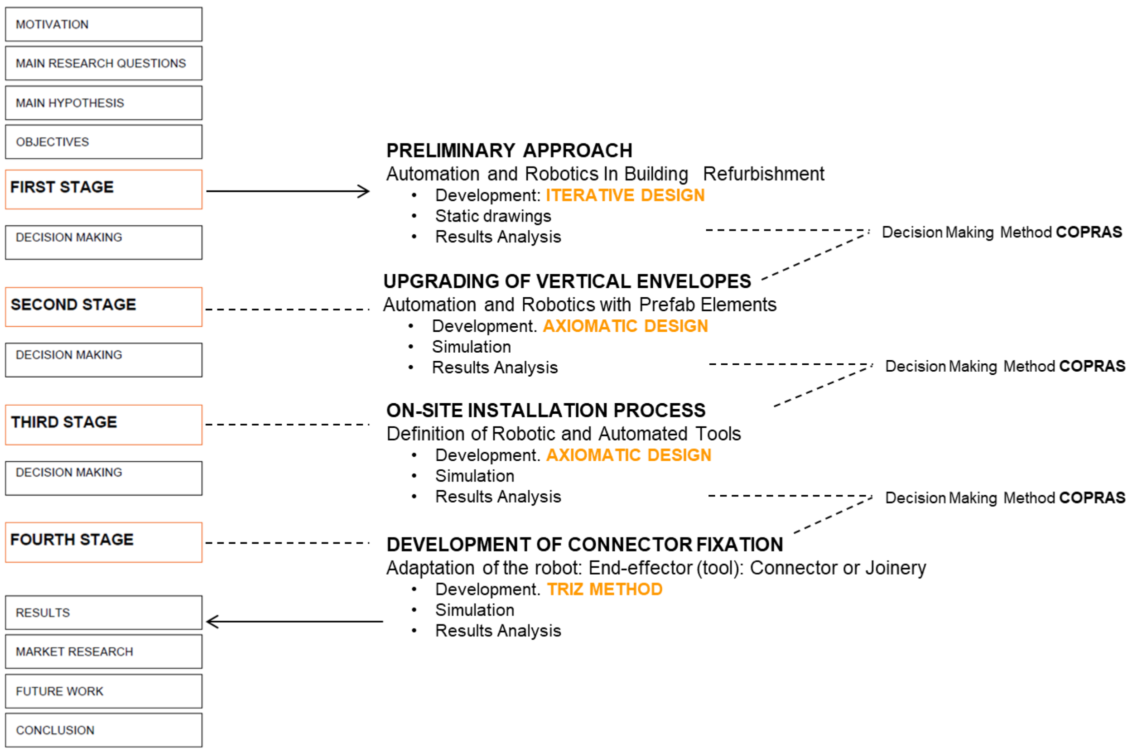

Figure 104: Decision making process for the research development.

APPENDIX 2: European Projects for Management

Name	Year	Topic
Sureuro	2000-2004	Provide housing companies with practical management tools for integrating sustainable development and tenant participation in their refurbishment management.
Surefit	2007-2009	Tailor-made process models and implementation guidelines of sustainable roof-top extension retrofit.
Cetieb	2011-2014	Develop innovative solutions for better monitoring the indoor environment quality and to investigate active and passive systems for improving it.
EASEE	2012-2016	Developing a tool-kit for energy efficient envelope retrofitting of existing multi-storey and multi-owner buildings.
HERB	2012-2016	Develop and demonstrate energy efficient new and innovative technologies and solutions for retrofitting and performance monitoring of a number of typical residential buildings in EU countries.
Nezer	2014-2017	Promote the implementation and smart integration of Nearly Zero Energy Building Renovation (NZEBR) measures and the deployment of Renewable Energy Sources (RES) in the European renovation market.
BuildHeat	2015-2020	- Elaborating systemic packages for the deep rehabilitation of residential buildings; - Developing innovative technologies facilitating the implementation of the renovation measures; - Developing financial tools enabling large public and private investments; - Involving the construction chain from the very beginning and all along the building life cycle.
Buildupon	2015-2017	Changing the way of working together will lead to strong, well implemented renovation strategies over time. Establishing and maintaining innovative platforms for cross-sector collaboration and partnership.
Gorefurb	2015-2018	Bridging the gap between the supply side (building construction sector) and demand side (homeowners) by developing dedicated renovation packages for different market segments within the residential sector.
Newtrend	2015-2018	Improve the energy efficiency of the existing European building stock and to improve the current renovation rate by developing a new participatory integrated design methodology targeted to the energy retrofit of buildings and neighborhoods, establishing energy performance as a key component of refurbishments.
Refurb	2015-2018	Provide private homeowners with overview, advice and local one-stop-shop solutions.
Optimeemal	2015-2019	Improve the energy behavior of a district – will be achieved through a mix of development and testing activities.
Dreeam	2015-2019	Show that renovating at a larger scale opens the opportunity for a better integration of renewable energy and is generally more cost effective.
Abracadabra	2016-2019	Demonstrating to the key stakeholders and financial investors the attractiveness of a new renovation strategy based on AdoRe, intended as one (or a set of) Assistant Building unit(s)
Opteemal	2015-2019	Development of an Optimised Energy Efficient Design Platform to improve the energy behavior of a district – will be achieved through a mix of development and testing activities.
Exceed	2016-2019	Create a European database for measured and qualitative data on beyond the state-of-the-art buildings and districts.
4RinEU	2016-2021	Provide an answer to these challenges, providing new tools and strategies to encourage large scale renovation of existing buildings, fostering the use of renewable energies, and providing reliable business models to support their applications.
Stunning	2017-2019	Identify and promote innovative packages for renovation to accelerate their acceptance by the market players and consumers and increase the renovation rate in Europe.
iBroad	2017-2020	Lifting these barriers by developing an Individual Building Renovation Roadmap for single-family houses.
Novice	2017-2020	Develop and demonstrate a new business model in building renovation to better monetize energy efficiency by consolidating services and subsequent revenue streams from both energy savings and demand response.
Qualitee	2017-2020	Increase investment in energy efficiency services in the building sector within the EU and improve trust in service providers.
HEART	2017-2021	Incorporates different components and technologies, which cooperate to transform an existing building into a smart building.
Renozeb	2017-2021	Unlock the nZEB renovation market leveraging the gain on property value through a new systemic approach to retrofitting that will include innovative components, processes and decision-making methodologies to guide all value-chain actors in the nZEB building renovation process.
Rezbuild	2017-2021	Creating a collaborative refurbishment ecosystem focused on the existing residential building stock.
Envision	2017-2022	Energy harvesting of the façade, and works by absorbing the invisible part of the solar radiation (the near-infrared (NIR) part, roughly 50% of the solar energy spectrum) allowing visible aspects to be retained.
Triple a reno	2018-2021	To foster new consumer and end-user centered business models and decision support tools, using evidence-based performances that facilitate Improving performances of deep renovation by enhanced quality control
Reco2st	2018-2021	Residential Retrofit assessment platform and demonstrations for near zero energy and CO2 emissions with optimum coST, health, comfort and environmental quality.
TURNKEY RETROFIT	2019-2021	A home-owner-centric renovation journey, which will transform the complex and fragmented renovation process into a simple, straightforward and attractive process for the home-owner.

APPENDIX 3: European Projects with prefabrication

Name	Years	Topic
Annex 50	200x-200x	Use prefabricated systems to reach the set energy targets.
GEDT	2004-2007	Large element insulation technology with vacuum insulation.
TES and smarTES	2008-2014	Prefabricated timber modules for gaining the efficiency of the building.
MPPF	2008-2013	Integration of different multifunctional appliances, especially RES, on a plug-and-play-type façade. It is not focused in renovation processes, but mainly in new buildings.
BEEMUP	2011-2014	BEEM-UP will demonstrate the economic, social and technical feasibility of retrofitting initiatives, drastically reducing the energy consumption in existing buildings, and lay the ground for massive market uptake. In one of the demonstrations, use high prefabrication degree.
Retrokit	2012-2016	RetroKit will develop and demonstrate multifunctional, modular, low cost and easy to install prefabricated modules, integrating efficient energy use systems and RES for systemic retrofitting of residential buildings.
MEEFS	2012-2016	Develops an innovative, energy efficient, multifunctional façade system for retrofitting geared towards the residential building sector. Partial prefabrication.
Adaptiwall	2013-2017	Focuses on developing a multifunctional and climate adaptive lightweight prefab panel suitable for cost-efficient, rapid and energy efficient retrofitting of façades and eventually also suitable for roofing, inner walls or entirely new buildings.
A2PBEER	2013-2018	Retrofitting methodology for public buildings. Vacuum Insulated Panels. Partial prefabrication.
MF Retrofit	2014-2017	The project aims to deal with the numerous requirements of facade panel retrofitting by developing a light-weight, durable, cost effective and high-performance panel.
Insiter	2014-2018	The key innovation of INSITER is the intuitive and cost-effective Augmented Reality that connects the virtual model and the physical building in real-time. Point Clouds are used and combined with BIM.
MORE CONNECT	2014-2019	Objective is to develop and to demonstrate technologies and components for prefabricated modular renovation elements in five geo-clusters in Europe.
E2VENT	2015-2018	External thermal refurbishment solution with external cladding and air cavity. Partial services, mainly.
Rennovates	2015-2018	The Ren(n)ovates proposal focuses on the deployment and demonstration of an innovative systemic, 4-step holistic approach comprising state-of-the-art renovation with state-or-the-art smart ICT control. Deep renovation of residential buildings will be carried out including the installation of a standardized pre-fabricated energy module equipped with communication technology converting the buildings into Net Zero Energy Buildings.
BERTIM	2015-2019	Holistic building renovation with timber prefabricated modules and development of software that integrates data acquisition and manufacturing.
Bresaer	2015-2019	BRESAER will design, develop and demonstrate an innovative, cost-effective, adaptable and industrialized envelope system for building refurbishment. This system will include combined active and passive pre-fabricated solutions integrated into a versatile lightweight structural mesh.
Impress	2015-2019	Reducing installation time of prefab panels by more than 30% // Improving precision of formworks for irregular shapes by 50%.
Heat4Cool	2016-2020	Heat4Cool proposes an innovative, efficient and cost-effective solution to optimize the integration of a set of rehabilitation systems in order to meet the net-zero energy standards.
VEEP	2016-2020	To develop and demonstrate a series of technological solutions for the massive retrofitting of our built environment, aiming at cost-effectively reducing building energy consumption. Combination of concrete and superinsulation material manufactured by using, at least, 75% (by weight) of C&DW recycled materials, as raw materials.
Eensulate	2016-2020	To bring existing curtain wall buildings to “nearly zero energy” standards, while complying with the structural limits of the original building structure and national building codes.
P2ENDURE	2016-2020	Plug-and-Play systems in combination with on-site robotic 3D-printing and Building Information Modeling.
Re4	2016-2020	To promote new technological solutions for the design and development of structural and non-structural pre-fabricated elements with high degree of recycled materials and reused structures from partial or total demolition of buildings.
Plug n harvest	2017-2021	Adaptable/Dynamic Building Envelopes (ADBE) - such as Multifunctional Façade Modules - has been proposed towards overcoming many of the shortcomings of CR and BA.
Progetone	2017-2021	One of the barriers of implementing safety measures regarding earthquakes is the high cost of a structural renovation. ProGETonE proposes a pre-fab approach to reduce these costs significantly.
EnergyMatching	2017-2022	EnergyMatching aims at developing adaptive and adaptable envelope and building solutions for maximizing RES (Renewable Energy Sources) harvesting.

APPENDIX 4: Scheme of the Questionnaires

The scheme in *Figure 105* shows the technologies gathered for the BERTIM project [42].

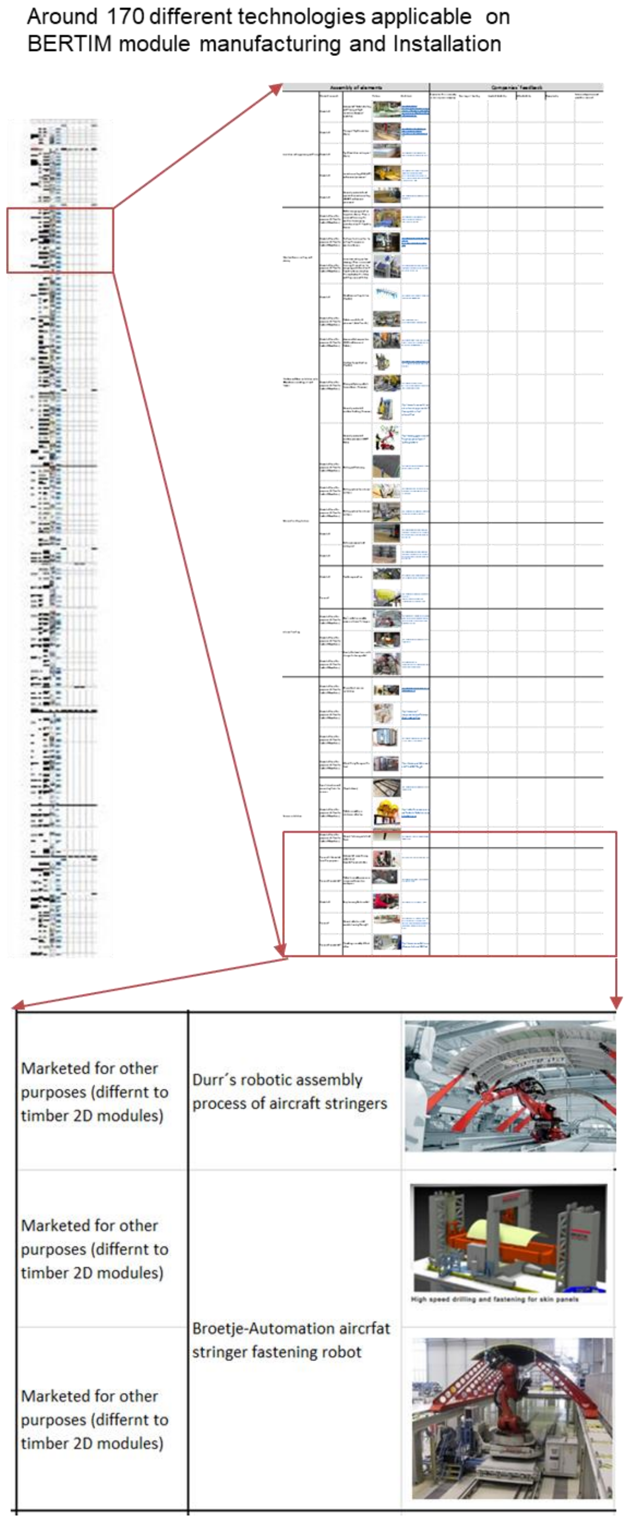

Figure 105: Technologies gathered.

APPENDIX 5: Stability of the cable robot platform

This appendix[53] deals with Research Gap RG3.2.1 and the development criteria for solution DNS3.2.1. Moreover, it focuses on calculating the maximum force that the CDPR can apply to the MEE platform while the stabilizers are applied.

During the development phase, one of the uncertainties of the cable robots was related to the stability of the CDPR and its platform while accomplishing the bracket installation. In the development and prototyping phases, it was unclear what forces would be transmitted from the CDPR platform to the MEE. In the previous stages, three solutions were considered:

- A solution was developed by Mr. Meysam Taghavi based on a hexapod-shaped active damper, but this solution was rejected due to its complexity.
- Another solution based on uncoupling the whole MEE frame was proposed by Mr.Meyam Taghavi (see *Figure 106*, left). However, this solution was rejected due to the imprecision of the CDPR to couple again to the same position accurately once the bracket was installed. This option was rejected because the repeatability of the CDPR during the development was unknown and the stabilization capabilities of the suctioners were supposed to be extremely high.
- Passive dampers were also considered (see *Figure 106*, right). However, experts on the field (which included dumper manufacturers) rejected this option.

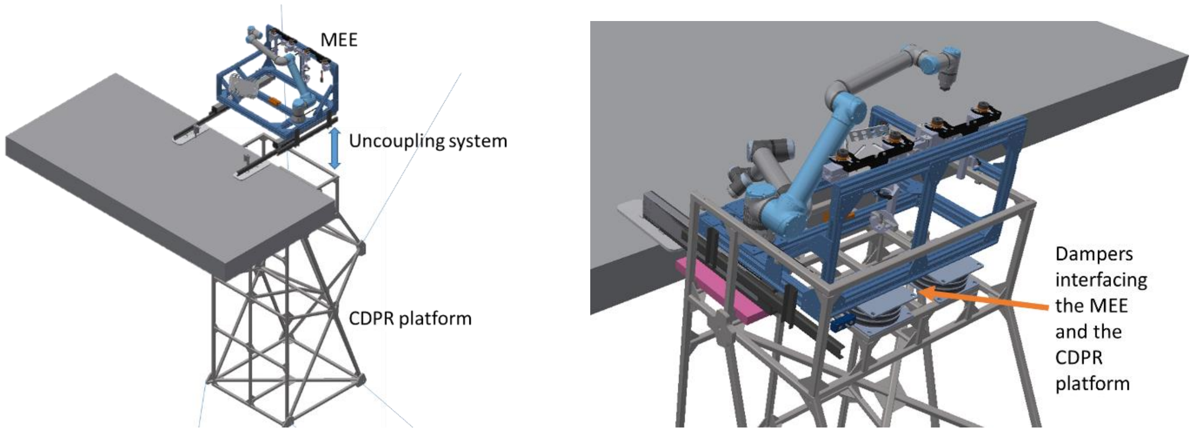

Figure 106: Left: Uncoupling system.
Right: Passive dampers, both rejected versions.

53 It is an adaptation of a chapter that was written by the author of this dissertation for a Deliverable in the HEPHAESTUS project. The calculations shown in this Appendix 5 are just an approximation during the definition process of the stabilizers. Currently this calculations are being redefined and might be published in a Journal.

As an alternative solution, a rigid fixture between the MEE frame and the CDPR platform was proposed by the author of this dissertation. The fixture was defined by using extruded aluminum profiles system similar to the one used in the MEE frame (see *Figure 107*). In order to realize the fixtures, holes had to be made on the CDPR platform. A pattern was used to position the holes with accuracy. Some deviations were made but, in general, the fixtures were placed correctly.

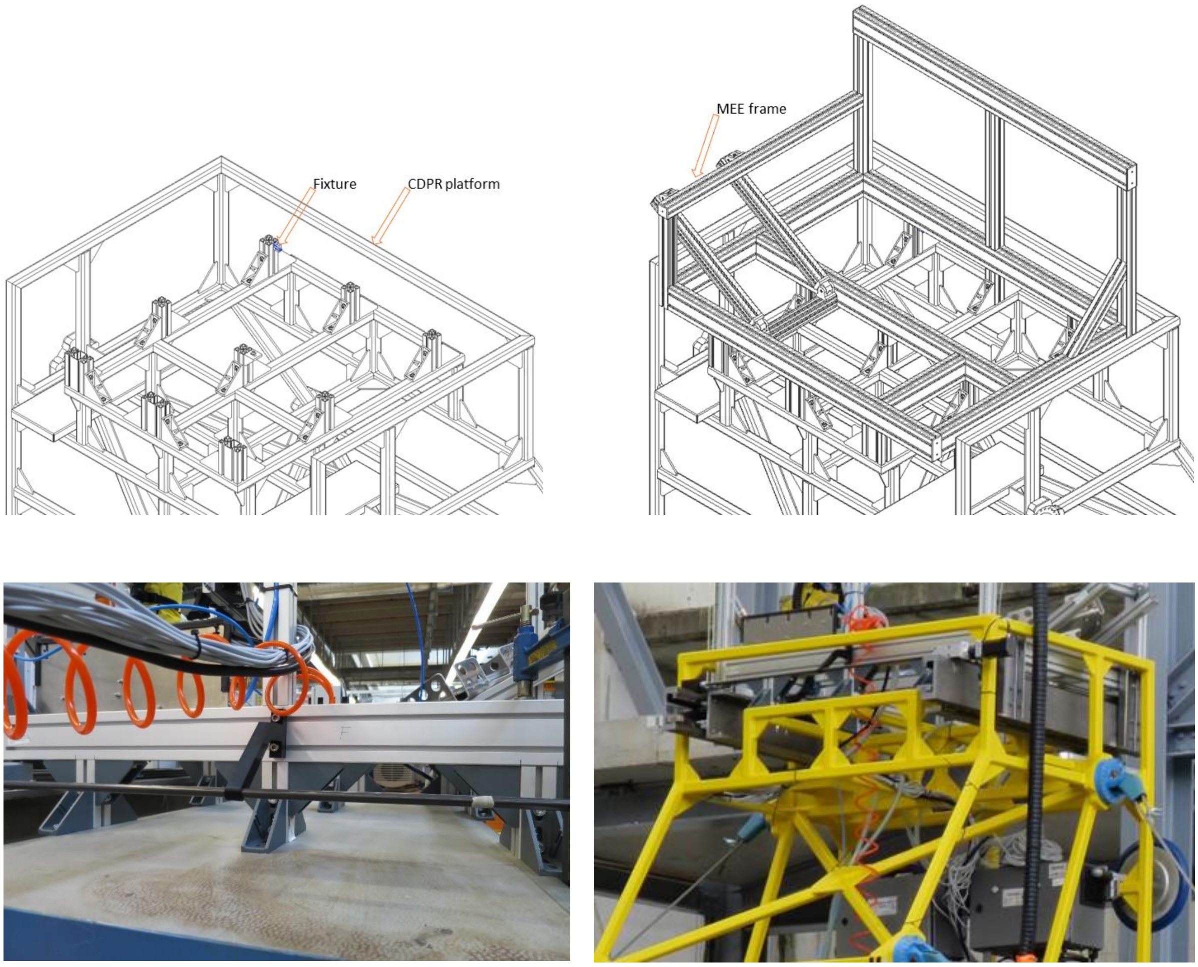

Figure 107: Top: CAD file of the fixture between the MEE frame and the CDPR platform. Below left: Fixed fixture in the laboratory environment. Below right: fixed fixtures on the final prototype.

Within this context, the stabilizer should support the forces transmitted by the CDPR platform to the MEE (and vice versa) during the robotic arm's performance. In previous phases, it was decided that the stabilizer would be based on two linear actuators with rails that would extend two profiles that hosted a vacuum gripper, each being connected to a vacuum system, as shown in *Figure 76*.

Calculation justification for adopting a rigid fixture

The linear axes that carry the gripper work under considerable stress when it is extended and gripped to the building as shown in *Figure 108*.

The linear actuator functions as a composed cantilever beam when it is gripped to the building structure as shown in *Figure 107*. The profile that is hosting the suction cup receives the moments of the load of the MEE's platform. It was calculated that the MEE as a whole will be about 150 kg. For calculating such number, the following loads were considered:

- 30 kg for the aluminum frame.
- 30 kg for the robotic arm.
- 40 kg for the operating tools (drill, hammer, fastener) and devices (sensors).
- The previous points sum to 100 kg.
- A considerable safety coefficient must be taken into consideration because elements can be changed during the purchasing and prototyping process. This coefficient should be c=1,5, which makes the total weight 150 kg.

That means that, in a balanced situation, each of the actuators needs to support 75 kg with its respective moments.

For the calculation, the scheme in *Figure 108* was used.

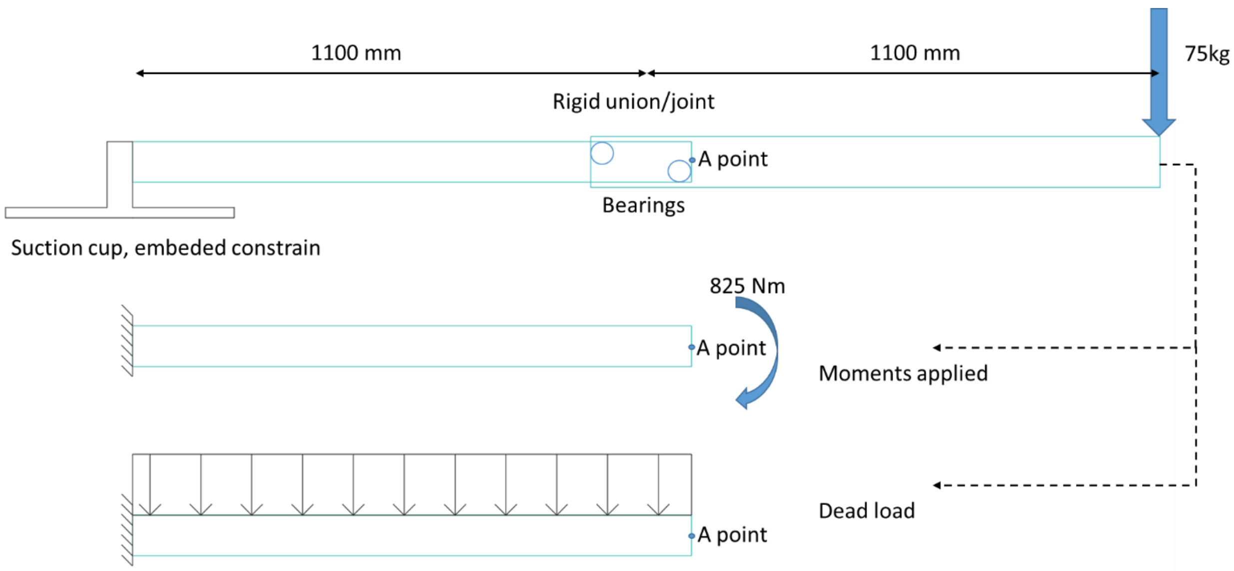

Figure 108: Loads to be supported by the linear actuator system.

In the end, the part of the linear actuator that is hosting the gripper is working as a cantilever beam with an embedded constrain. That beam, profile or guide, should have a deflection smaller than 0,25 mm at point A (see *Figure 109*). The calculation of the deflection is done as in next equation:

$$\delta_{max} = \frac{ML^2}{2E\ I_x}$$

Where, δ_{max} is the deflection (0,25 mm), M is the moment applied (825 Nm), L is the length of the beam (1100 mm), E is Young's modulus (of steel profile) and I_x is the inertia of the profile. According to this formula, I_x should be greater than 998,25 cm^4, just to support the moments, without considering dead loads of the profile. Therefore, a steel profile was selected.

The profile was simulated by using a FEA plugin within Inventor™ and the results were satisfactory as it is shown in *Figure 109*.

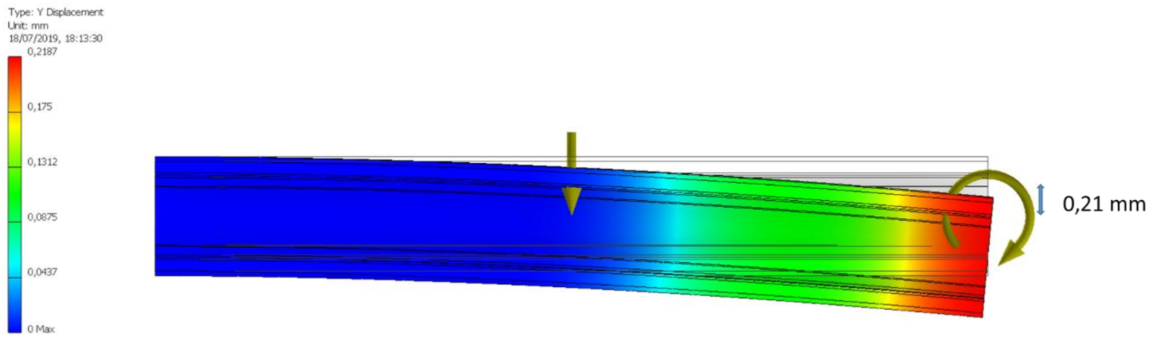

Figure 109: FEA simulation of the selected guide/profile.

However, this simulation and calculation should be integrated into the general MEE platform.

Going further on the detail of the linear actuator, the next step was to integrate the bearings and the profile that supports the MEE platform. *Figure 110* does not show optimal results, with displacements up to 1,5 mm.

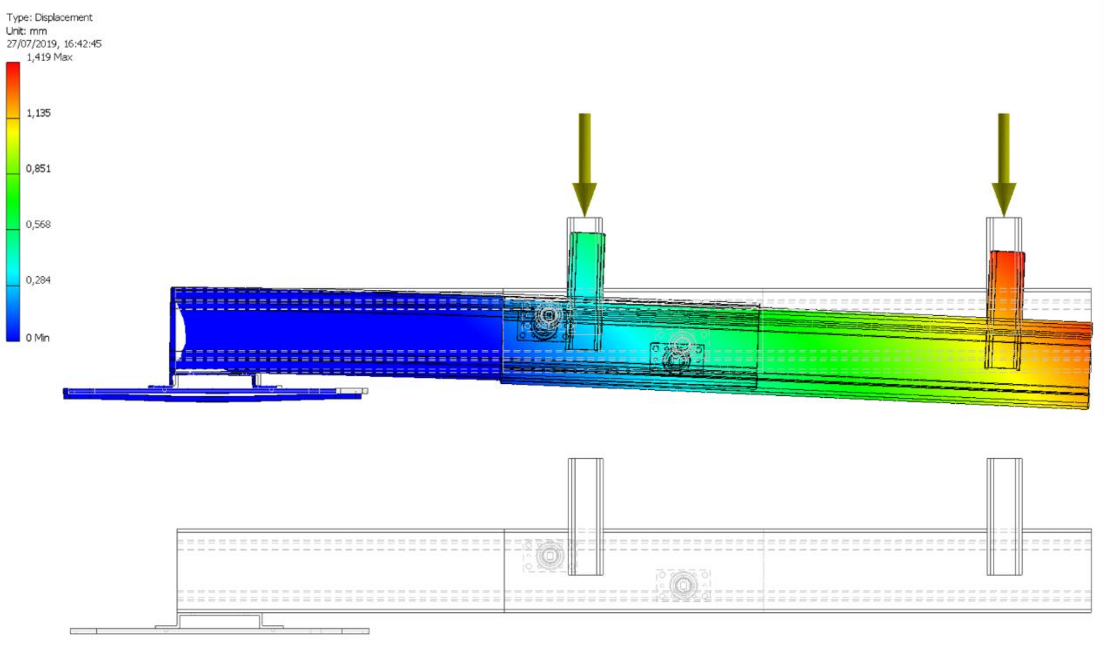

Figure 110: Integrated linear actuator.

However, these results should be considered carefully as the linear actuator in this simulation is not working jointly, with other elements, but alone. Therefore, it is necessary to consider the whole MEE as it is explained in chapter 8.1. The MEE frame and the stabilizers, once built, will be a complete, joint structure. Therefore, it was considered necessary to simulate structural behavior. Two cases have been simulated:

a. The dampers below the MEE do not support the MEE.

b. The dampers below the MEE offer elastic support.

The objective is to check if the dampers could be suitable for the interface between the MEE and the CDPR platform. For case a), the displacement reaches up to 1 mm, as shown in *Figure 111*.

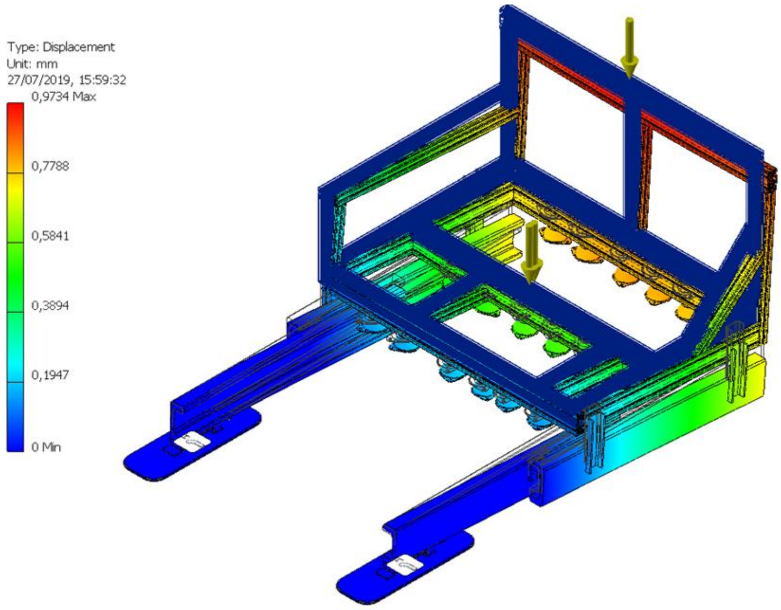

Figure 111: MEE without the support of the dampers.

For case b), the results are better (*Figure 112*). The dampers offer, even though elastically, support to reduce the displacements and the displacements are reduced to half compared to case a), which is an optimal situation. The simulations include the dead load of each of the components.

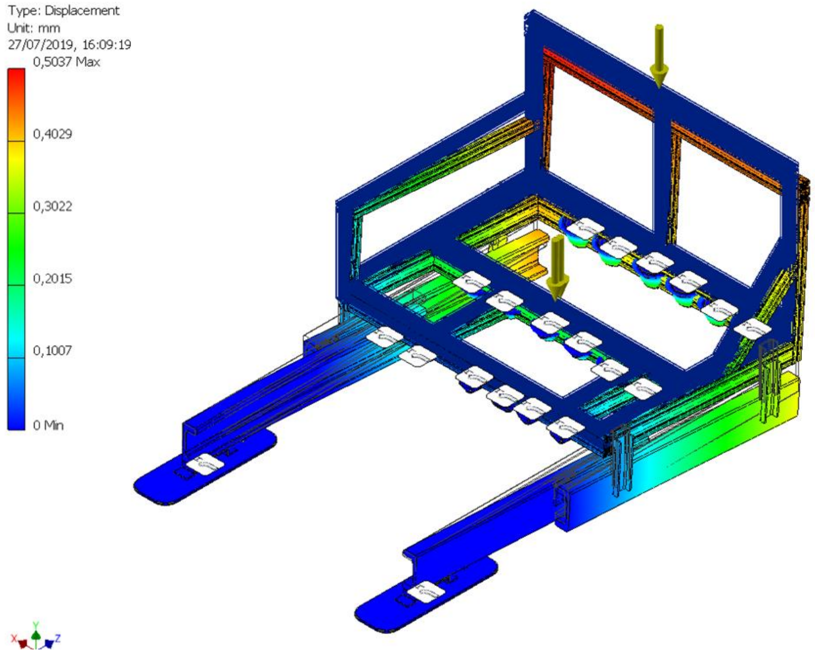

Figure 112: MEE with the support of the dampers.

The decision, in principle, shows that the dampers should be placed as elastic supports. However, this decision should depend on the results of the first demonstrator at Tecnalia's facilities. The idea would be to test several dampers that better fit the requirements and the possible unexpected forces generated by wind and loss of stiffness of the cables. Force sensors will be included between the MEE platform and the CDPR platform. Based on this simulation, there were still some points to be considered. The transmission of forces when the linear actuators were under maximum forces had to be solved.

Design definition of the stabilizer

In order to improve the linear actuator, a more robust solution was developed. This solution included rails and carriers as shown in *Figure 113* and *Figure 114*. The purpose of using rails and carriers was to support the moments and the axial forces that could be generated during the gripping to the building. The rails need to be supported in a machined hosting profile. The hosting profile needs to be machined in order to keep the rails in parallel. The rails need to be placed on parallel plans so the carriers can run along the rail smoothly. Besides, the profiles needed to be rigid enough in order to support the forces and reactions of the profile. The profiles needed to be machined with low tolerances (0,5 mm) in order to host the rail with accuracy. For this solution, a single NEMA23 motor and a 5-1 gearbox were used. For actuating two gearboxes, a shaft was used (*Figure 115*). The solution was mounted on the MEE and used for test in the lab (*Figure 116*). The solution performed properly in all cases. Some load tests were carried out and the profiles apparently supported loads up to 150 kg each.

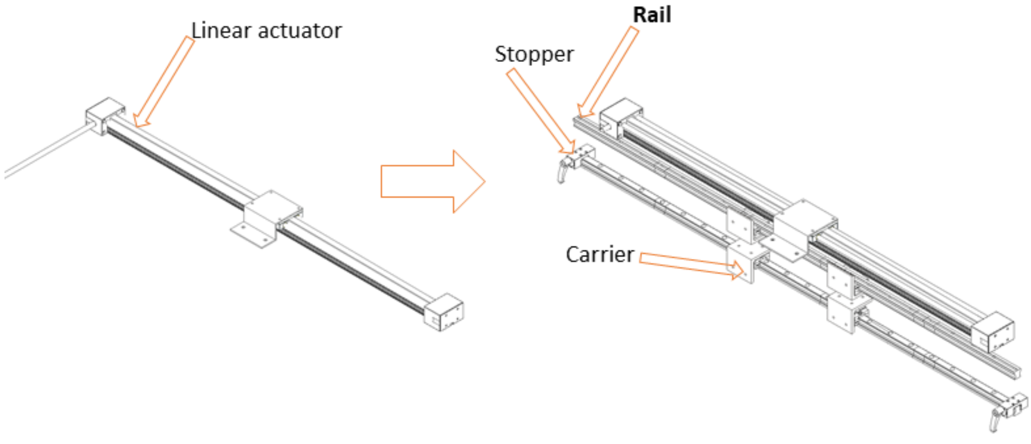

Figure 113: Left: the linear actuator. Right: the rail, the carrier and stopper.

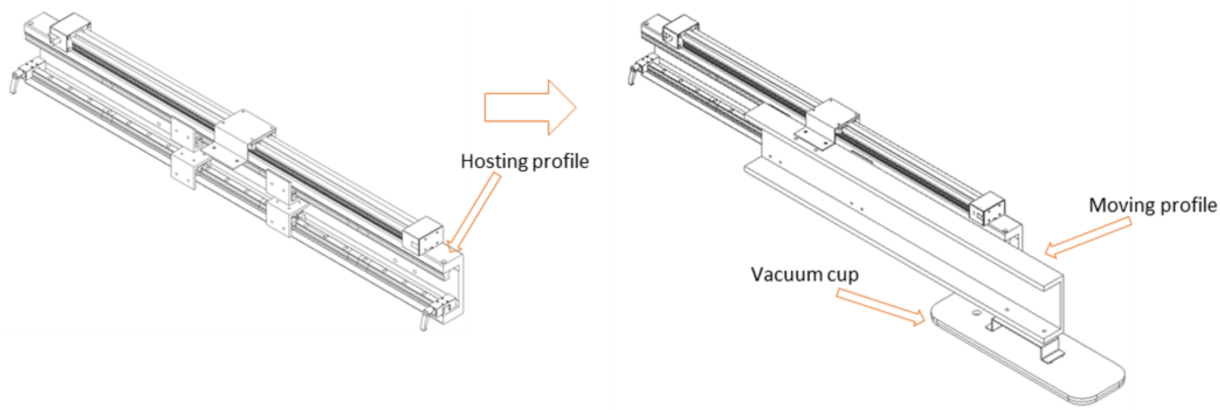

Figure 114: Left, the hosting profile. Right, the moving profile and the vacuum cup.

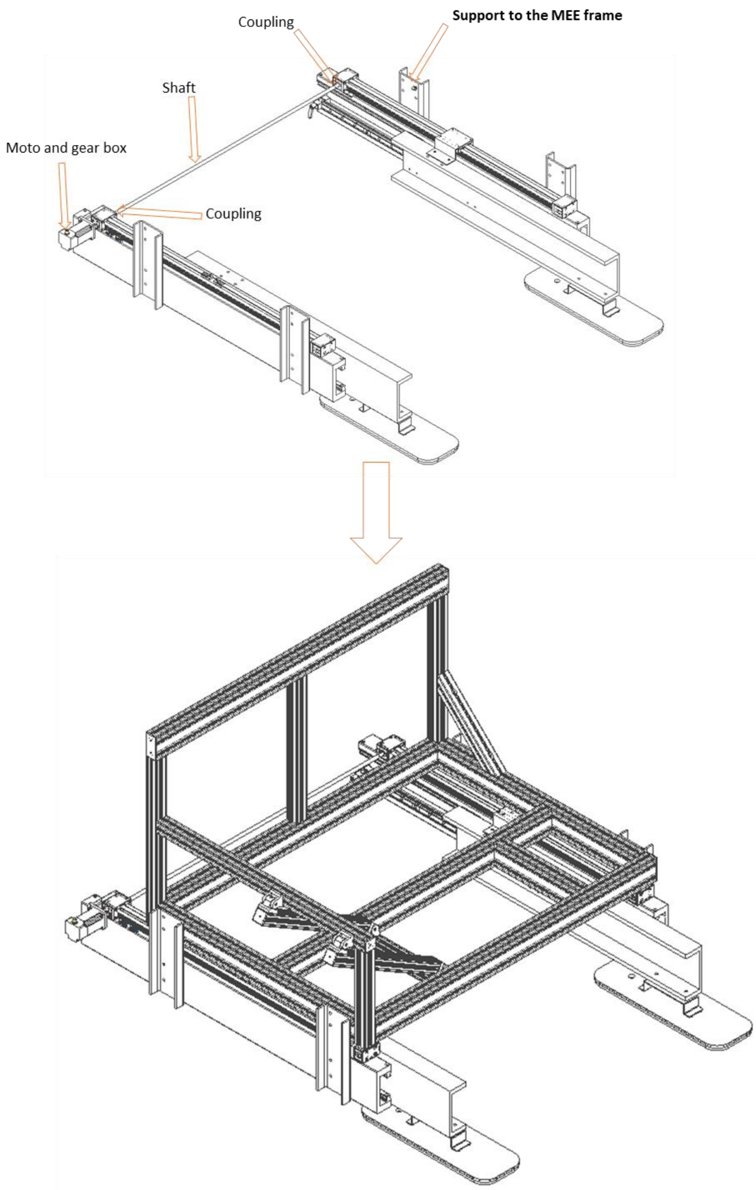

Figure 115: Top: the two actuators linked by a shaft.
Bottom: the two actuators mounted on the MEE frame.

Figure 116: Left: the linear actuator solution in the lab. Right: the linear actuator performing on the prototype.

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SHORT CURRICULUM VITAE

Kepa Iturralde Lerchundi / 28th of August of 1979 / Donostia (Basque Country, Spain)

Higher Education

- From January 2014, PhD candidate at Technische Universität München.
- From January 2011 to December 2014, PhD candidate at University of the Basque Country.
- June 2010, Studies in Doctoral Programme (equivalent to Master's degree) at the University of the Basque Country.
- February 2007, Master Engineer-Architect, University of the Basque Country.

Professional background

- From October 2015, Research Associate at Lehrstuhl für Baurealisierung und Baurobotik Technische Universität München, Germany.
- From February 2015 till August 2015, Visitor researcher at Sungkyunkwan_University, Seoul, Republic of Korea, thanks to AUSMIP program.
- From February 2014 till February 2015, Visitor researcher at University of Tokyo, Japan, thanks to AUSMIP program.
- From October 2012 to December 2013, Visitor researcher at Lehrstuhl für Baurealisierung und Baurobotik at Technische Universität München, Germany
- From January 2011 to December 2014, Researcher at the University of the Basque Country, Department of Architecture, Donostia, Spain
- From 2007, Founding-partner at Metak Arkitektura Tailerra Bilbao, Spain. www.metakarkitektura.net
- From 2007 to 2008, Architecture Project director at Katsura SL, Bilbao, Spain. www.katsura.es
- From 2005 to 2006, Project coordinator at Okile DDM S.L., Bermeo, Spain. www.okile.com
- Year 2002, Carpenter at Atari, Anoeta, Spain. https://www.carpinteriatari.com/

Research Projects

- BERTIM H2020 project (From October 2015 to May 2019)
- HEPHAESTUS H2020 project (From January 2017 to August 2017 and from June 2019 to December 2020)
- ENSNARE H2020 project (From February 2021)