DELIVERABLE 2.5

Method for implementing an efficient, integrated, modular and customized manufacturing and installation process of the BERTIM modules

CHAPTERS 1, 2, 3, 4, 5 and REFERENCES

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1. Table of content

Glossary

Assembly process: within the manufacturing process, once the base frame or platform is configured, several elements or sub-components are added to this base-frame.

Base frame: Support body of a module

Common platform: The BERTIM modules will be based on Common Platforms that include the support body (CLT or timber-frame), the fixture and connector.

Connector (also known as Fixture): it is the element that connects the existing building and the 2D or 3D module.

Degree of automation: it refers to the percentage of human-manual works performed while the manufacturing and the installation process.

Installation (process): It comprises the period of preliminary tasks on the building, the arrival of modules to the site, the necessary logistics, fixation of the modules and final rework.

Work-station: Environment, Location or Space where production tasks are performed. A work-station can be single-task or multi-task and can offer different degrees of automation.

Manufacturing process: It comprises the period from the production of single elements, through the assembly of components and modules and final shipping and transport preparation.

Methodology: in the case of this Task 2.5 it´ll refer to the strategy for applying a solution or a set of solutions, that is the system.

Modular: In this research, there are two types of Modular concepts.

2D and 3D timber based modules: These refer to the Timber based 2D and 3D modules. These modules share a common platform which is made out of timber-frame or CLT.

Modular work-station: Linked to the previous concept, the work-station

System: a set of solutions or concepts that are part of a whole. This System is applied through a specific methodology.

Sub-system: a set of solutions or concepts part of a higher system. In the case of BERTIM we have three Sub-systems, the 2D module, the manufacturing process and the installation Process.

List of figures

List of tables

1. INTRODUCTION AND OBJECTIVES

This Deliverable 2.5 is the output of the development achieved on Task 2.5 within the Work-Package 2 of the BERTIM Research Project. Prior to the Task 2.5, it has been found that the manufacture-installation of prefabricated modules for the refurbishment market needs to be lifted to a more integrated, systemized and automated level, in order to transform the existing buildings stock towards near zero energy consumption at reasonable cost. In building renovation, prefabricated modules have to be industrially customized to each building, and therefore, standard prefabrication and refurbishing approaches have to be re-conceived. In that sense, the automotive industry is a good example of combining modular products and manufacturing processes.

In this research project, the goal of a dedicated **Task 2.5** is to ameliorate the existing holistic renovation process, by a combination of an integration of robotic, automation and augmented reality technologies. In that sense, it has to be pointed out that **this Deliverable 2.5 collects most of the output presented on a paper ISARC congress (Iturralde et al., 2016), which is specialized in Automation and Construction**.

Basically, one of the main final objectives is to **reduce time and cost** of the current process of the **manufacturing and installation** of 2D and 3D modules significantly (by 30% or more). For the development of this research, the Axiomatic Design method has been used, which is a matrix based method. Here, the main requirements and design parameters are expressed mathematically. The objective of applying this method is to define a scientific approach to the re-conception of the prefab modules and the manufacturing and installation processes, and therefore find an optimal solution for every decomposed requirement.

The BERTIM project scopes the use of timber-frame based 2D and 3D prefabricated modules for the building refurbishment. The research project´s main goals have been pointed out as:

1. ``define a **general methodology** for the efficient mass (*customized*) manufacturing process of prefabricated modules in the timber manufacturing industry´´
2. ``The methodology will allow installation time reductions of at least 30% compared to typical renovation´´

This ``general methodology´´ can´t be based on a single solution, it must be a System that approaches several Building renovation needs bespoke solutions all the time, and therefore it is necessary to conceive a highly customizable module that can be adapted to the majority of the targeted building typologies. Besides, the Off-site manufacturing process needs to be (re)adapted to this circumstances as well as the On-site installation process. Therefore, there can be defined three main **Sub-systems**:

- **Sub-system1**: 2D and 3D modules configuration
- **Sub-system2:** the manufacturing process
- **Sub-system3:** the installation process

For achieving these goals, it is necessary an overall perspective, it cannot only be based on product improvement, or only in the manufacturing process or only in the installation process. It must be a general solution, but also flexible for being implemented in different situations [1]. A key question is also how to accomplish this objective in several prefabrication companies, which act in different environments and markets and currently employ different degrees of prefabrication and automation. Therefore, the final solution needs to be adaptable to various construction scenarios, existing manufacturing/installation and automation levels and investment capabilities. In that context, the manufacturing-installing process has to be co-adapted with the design and modularity of the prefabricated high-level components. Besides, it will be considered the insertion of new technology such as manufacturing workstations with variable automation degrees, module installation with cooperative robots, object recognition, assistive devices (e.g., smart glasses) and other data acquisition and tracking solutions. This adaptation process is carried out in collaboration with the industry partners (companies), as well as with the more research-oriented partners. In a first phase of the project, the proposed solution for the manufacturing-installation process will be tested by simulation, small-scale usability tests and expert inclusion. In a later stage of the project the key aspects of the proposed will be tested and evaluated in operational environment (3 real world use cases for buildings to be renovated). For all these reasons, the achieved system needs to be:

1. Highly Modular system. The system is organized in solution-kits that cover the three main Sub-systems: the module, the manufacturing process and the installation. Each solution-kit can be implemented independently within each of the Sub-systems.
2. Integrates the product, manufacturing and installation.
3. Linked processes suppliers and other works such as building preparation, data acquisition, BIM…
4. Common platform for all BERTIM 2D and 3D modules.
5. Adaptable to various manufacturers. Degrees of automation, facilities, investment
6. Product adaptable to various buildings, defined within the range

On the first 10 months of the research project three different manufacturers have participated. The manufacturers are from three European countries located in different climatic regions (Company 1, Company 2 and Company 3). The first two companies have participated actively on the research project. The third company participated only on the very first phase. And a fourth will start working in month 11 (Company 4). **Different information has been received from the companies, either because they don´t have enough time for answering or either because the required data hasn't been monitored**. This situation can be considered as uncertain, since a very marked company profile isn´t defined. Therefore, it must be taken a decision under an unclear definition of the manufacturer companies. Dealing with this uncertainty in principle is good, as the BERTIM system should be adaptable to a high variety of manufacturers. In other words, the three Sub-systems must be designed with incomplete information. For all the reasons explained, it is necessary to define a clear modular system that integrates aspects of the prefab module, manufacturing and installation processes. In

Deliverable 2.3 it has been pointed out the need for using a specific method for handling this complex situation where many issues need to be achieved. Therefore, the reminder of this **deliverable** is to explain the development of this complex and multi-aspect system by applying a matrix based methodology such as Axiomatic Design [2].

In this **chapter there are 5 main parts**. First, methodology is explained. Second, there is an Analysis of the participant companies. Following, a common background of the companies has been subtracted where the main similarities regarding to product, manufacturing and installation have been pointed out. After that, Axiomatic design is implemented into the main three Sub-systems. And finally, one aspect within one of the Sub-systems is further detailed. This aspect is related to the placement of the connectors within the buildings. Regarding to the primary Research Proposal, some of the concepts have been modified and reorganized.

2. RESEARCH METHOD

In this complex situation, it is a must to avoid subjectivity when adopting a design decision and criteria. Therefore, a step-by-step methodology that guides the research has been defined:

1. Preliminary Conception based on previous experiences.
2. Analysis of the Modules, Manufacturing and Installing system of the participating companies. For this purpose, a questionnaire has been provided to the companies. They could define and quantify the manufacturing and installation Providing factory layouts, product details, and the direction where the research should be directed to. The analysis has been completed with a visit to the factories and some other resources.
3. Analysis of solutions in some other industries, such as car manufacturing, for gathering and **identifying suitable technology** that could be applied to the production and installation process. Questionnaires have been handed out to the companies asking about the suitability of the identified technologies
4. Definition of Functional Requirements and Design Parameters.
5. First prototypes and tests.
6. Final definition for implementing the proposal.

In phase 4, and 5, it´ll be applied the so called Axiomatic design method for reorganizing the whole proposal. The Axiomatic Design is being used mainly by developing and manufacturing companies which need to improve or create products.

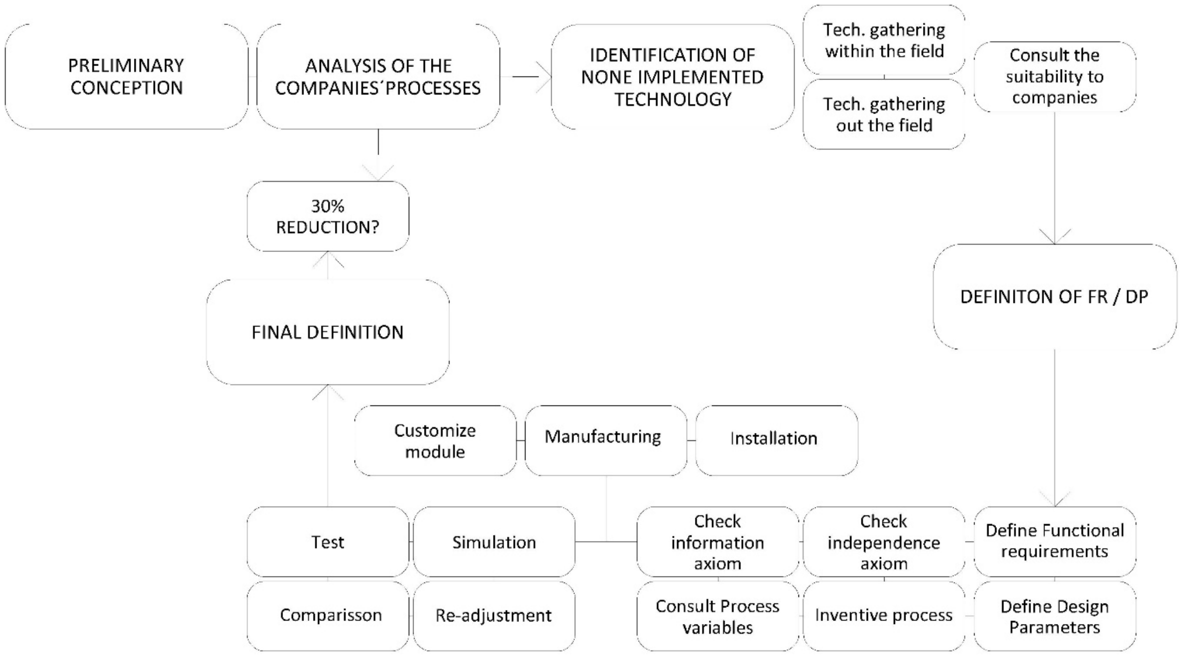

Figure 1 Brief scheme of the research method.

2.1 Axiomatic Design

As a short explanation of the axiomatic design, it can be said that there are four main domains: Customer domain, Functional domain, Physical domain and Process domain. These domains are strongly interconnected. In the Customer domain, the Customer Attributes or needs are defined (CA). The Functional Requirements (FR) are part of the functional domain. In this domain, constraints such as economic feasibility are also underlined. Once it is known what to achieve, it must be asked how to accomplish it. The Physical domain is for conceiving the Design Parameters (DP) or physical artefacts. But is it feasible the adopted solution regarding to achievability with existing technologies? On the Process Domain the Process Variables (PV) are defined in order to assure that the Design Parameters are realizable. The Axiomatic Design offers a Design Matrix for interrelating the CAs, FRs, DPs and PVs. Moreover, for such complex research developments as in our case, the CAs, FRs, DPs and PVs have been decomposed into smaller units and hierarchized in order to make the problem solving issue affordable and achievable. Also, each of the decomposed CAs, FRs, DPs and PVs must remain independent (Independence axiom).

For the interconnection of the higher degree of DPs and lower degrees, a zigzagging procedure must be carried out. In this very moment, the research will enter the phase E. For now, the companies have agreed on modifying and adapting the modules, the manufacturing process and the installation process within some limits. Here it´ll start the approach of the solutions for the decomposed FR.

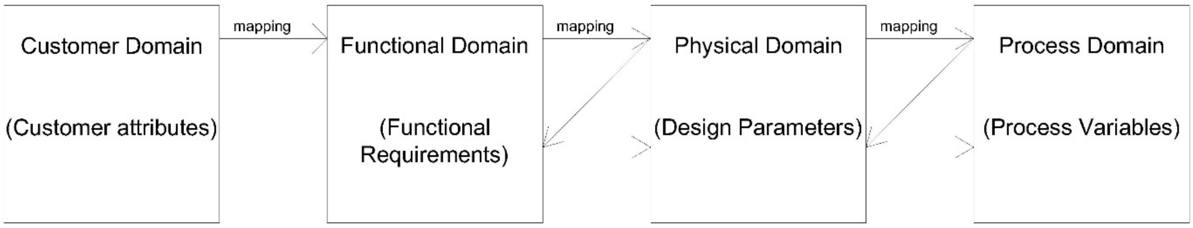

Figure 2 Scheme of the different domains, attributes, requirements, parameters and variables.

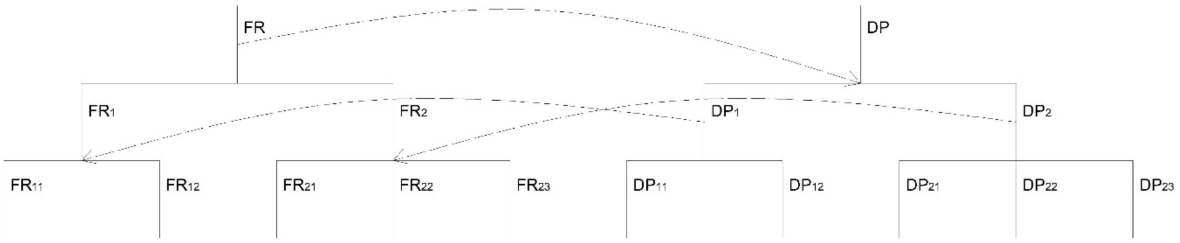

Figure 3: Scheme of the Decomposition and Hierarchy of the different FRs and DPs and Zigzagging development approach.

The research process hasn´t advance till this point yet, but it must be considered that the best solution will be always the one with higher probability of success (Information axiom). For that purpose, on Work-Package 3 prototypes will be conceived and tested in order to gather the most optimal solution. It has to be said that whereas the DPs of the sub-system 1, related to the module, will be implemented; the sub-system 2 and sub-system 3 are still being discussed the possibilities to execute the solutions.

2.2 Complementation with other methods

The Axiomatic Design is not the only method for solving every single problem within this complex situation. Actually, for solving single and particular elements, there are some other matrix based methods that might suit better. The inventiveness of each decomposed problem would also need to be guided by specific methods that facilitate the problem solving during design and development phases such as TRIZ [3]. This option will be taken into account on the next Work-Package 3.

2.3 Related research and projects

Previous to BERTIM, there has been already some research on all three Sub-systems. On the first Sub-system, there is some experience the usage of prefabricated 2D Modules for building prefabrication, the research projects such as TES, MPPF, Annex 50 and GEDT [4,5,6,7] are relevant and must be taken into account, especially considering the modularity. On the manufacturing sub-system; the SME Robotics (European Union 7th Framework Programme) project where Human-Robot Cooperation was achieved for the case of wooden house production [8]. Finally within the Installation process there have been some other studies where the installation process has been gathered [9,10]. For this purpose, existing procedures and devices have been adapted for a faster connector and module installation process as seen in Figures 4, 5, and 6.

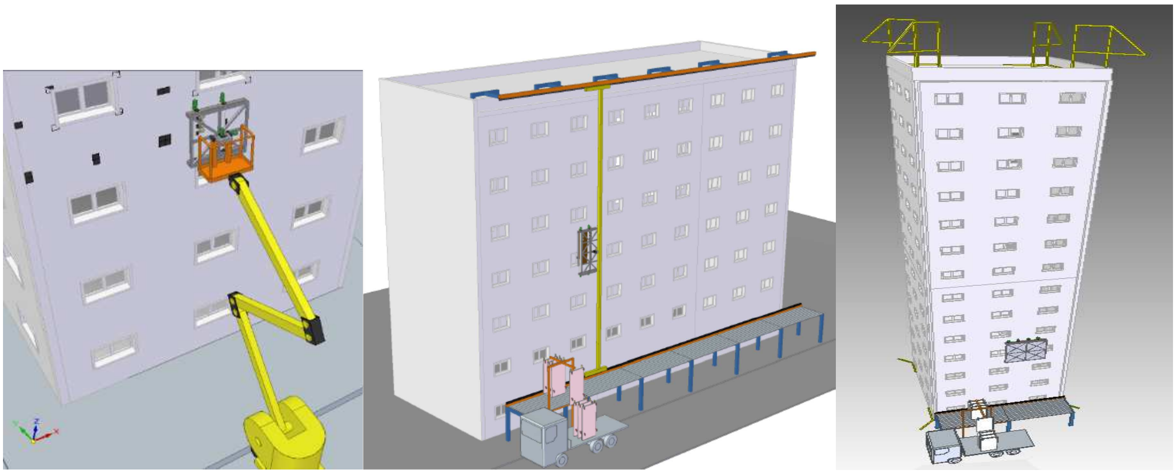

Figure 4 (left) Connector installation system based on an Aerial Work Platform.

Figure 5 (middle) Installation of modules by a vertical bridge crane

Figure 6 (right) Installation of modules using a cable robot.

Examples: Linner, Iturralde, br2 TUM]

For the installation of lightweight sandwich panels, the company Trimo has developed a robotic system. This system picks, places and fastens with rivets the sandwich panels onto previously installed guides [10]. Besides, it must be pointed out the façade glass installing technique used at the Apple Campus. The used crane system was conceived and fabricated by the Italian company Cimolai. Here the apparatus of the system is very big and requires a big free area, suitable for new building erection, but the approach might be interesting for the BERTIM modules.

Besides, it has to be pointed out that there has been a preliminary development prior to the companies´ analysis. On Task 2.1, several ideas and concepts have been developed and based on a lean manufacturing process and a rapid installation procedure (Figure 7).

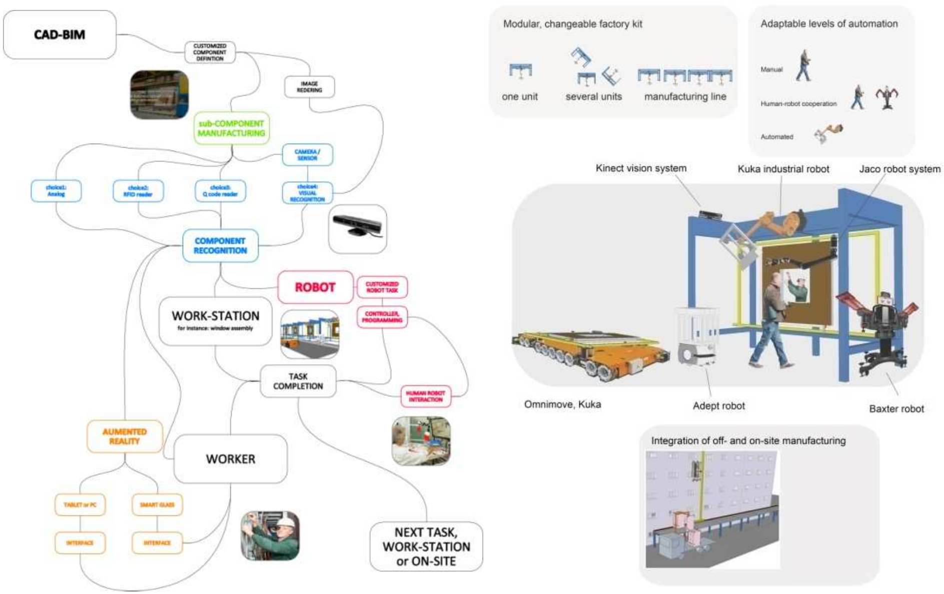

Figure 7 Scheme of the preliminary developments[Examples: Linner, Iturralde, br2 TUM]

3. ANALYSIS

For the analysis of the companies´ 2D modules, manufacturing process and installation process three main resources have been used. For one side, a questionnaire, Visits to Factories, Interviews with different Expertise within the companies, catalogue analysis, videos of the manufacturing and installation process

3.1 First questionnaire and Information Request

This first analysis has been based on a **Questionnaire and Information Request**. (See Annex1), which has been used as a first survey for analysing the manufacturing, assembly and installation process.

The information gathered by the Questionnaire itself has presented some limitations. First, the companies tend not to provide all the information at first, sometimes because the question or request was not properly formulated, and some other times because the companies haven´t taken into consideration some issues. Second, the companies do have their own monitoring, tracking and measuring methods. For instance, some companies are more focused on man/hour productivity whilst some other is more focused on factory production. Normalizing and unitizing the gathered information has to be checked again. Finally, some companies tend to give more information about manufacturing, some others about installation etc.

The three participant companies´ facilities and factories have been visited in order to have a closer contact of the manufacturing process. Besides the factory visits, the uploaded information in websites and the information given by the partners has been used in order to achieve this analysis.

Prior to the System Development, the information about the companies' characteristics has been gathered. This was apprehended by structured questionnaires and overall information request, interviews with experts, and factory visits.

3.2 Identification of suitable technologies

After the first Analysis of the companies, we have identified some suitable technologies that could be implemented within the **Manufacturing and Installation** processes of the companies. Some of the identified technologies are **already marketed** and used within the **manufacturing of the timber based prefabrication** of building elements. Those are probably known by the members of the companies. Some other identified technologies are originally used in **some other industries**, such as aircraft industry or furniture industry. And finally, there are some technologies that have been developed only in **research phase**.

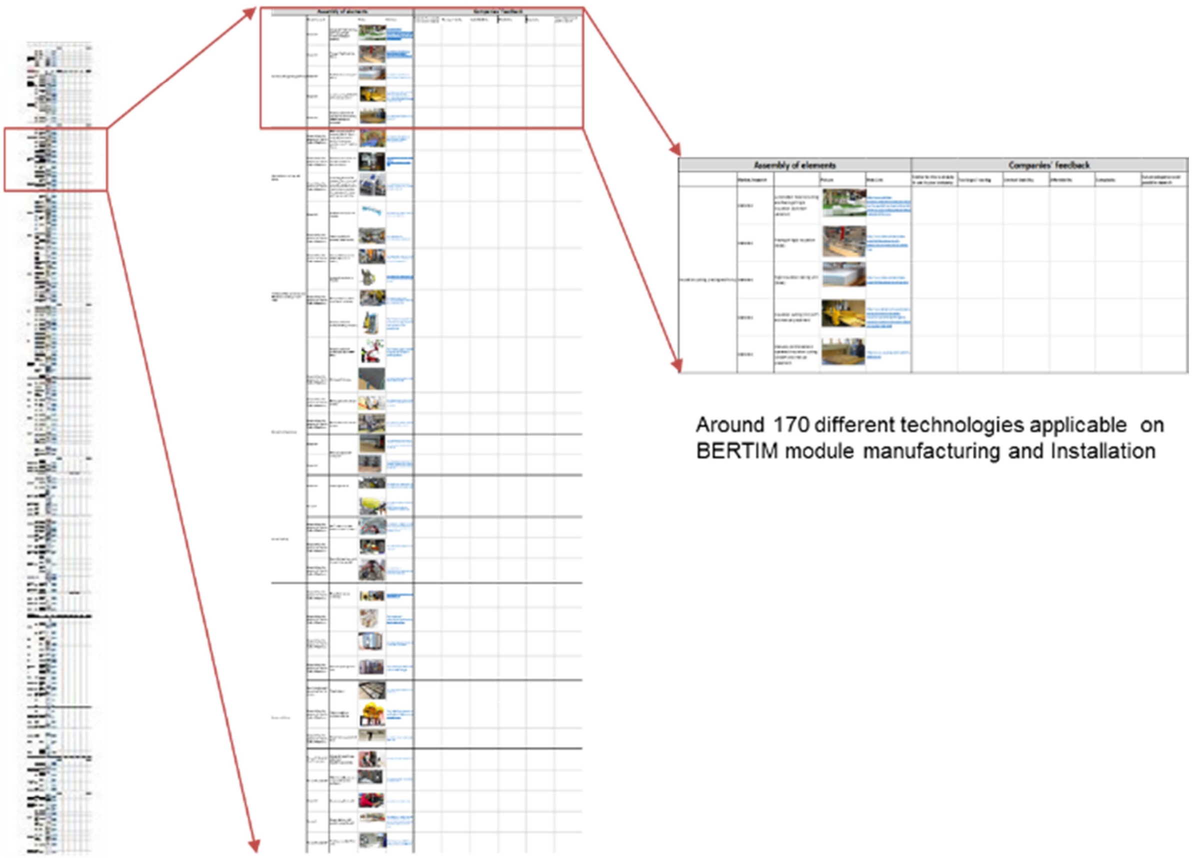

Figure 8 Scheme of the identified technologies

In total 170 different examples have been gathered, divided in these fields (more info in **Annex 2**):

- Automated 2D module manufacturing lines
- Manufacturing of main element:
  - Beams
  - Timber Frame
  - CLT
- Assembly of elements:
  - Insulation cutting, placing and fixing
  - Moisture barrier cutting, placing and fixing
  - External finishing fixation
  - Internal finishing
  - Service installation
- Inner-logistics and handling
  - Conveyor
  - Handling
  - Truck
  - Bridge-crane
  - 2D module Carrier
  - 3D module Carrier
  - Cable-robot
  - Tilting stations
  - Buffering systems
  - Temporary storage
- Platforms, Work-stations
- Quality Control
- Shipment-Logistics
  - Palletizing of boards
  - Specific carrier for hosting 2D modules
  - Specific truck for transporting the 2D modules
  - Temporary storage on-site
  - Off-loading of the modules
- Connector or Joinery
  - Placement of the connector
  - Placement of element or module
  - Compliant connector
  - Precision guiding references on the 3D modules
  - Connector for the CLT panels. Tracing reference holes.
  - Connector that also connect services
  - Existing wall, new 2D module connector
  - Linear connection between the 2D modules
- Measurement
  - 3D Laser Scanning
  - From images, Photogrammetry
  - Reflector-target.
- Support bodies
  - Hanging scaffolding
  - Mast climbing
  - Tower crane
  - Forklift
  - Aerial Work Platform and mobile crane
  - Lift
  - Shuttle system
  - Several Robotic systems

Uploading systems
On-site handling
Cabinet installation at ships
Suctioning balancer
Uploading carrier
Maintenance and upgrading
Rail based maintenance system
Maintenance and upgrading after sales
Inspection of tile exfoliation
Information workflow
Assistance to the operator for the assembly process
Nesting
Augmented reality
Object recognition, Traceability
Define the necessary parts and elements for each 2D or 3D module

3.3 Qualitative aspects

With qualitative aspects it is meant the characterization of the companies that define their three Sub-systems; 2D modules, the manufacturing process and installation process. As a résumé, the main qualitative aspects are pointed out in the next table.

Table 1: Main qualitative characteristics of companies

	Company 1	Company 2	Company 3
Product standardization	High degree of standardization, Catalogue based products	Low degree of standardization	
Production system	Manufacturing line	Non connected work stations	Non connected work stations
Main product	Timber-frame	CLT and Timber frame	CLT and Timber-frame
Installation process	No	Yes	Yes
Customization	Limited	High	High
Adaptable manufacturing process	Limited	Highly adaptable	Highly adaptable
Manufacturing automation degree	Medium	Low	Medium
Building refurbishment	No	Yes	Yes
Prefab degree	70%	30-90	30-90%
Manufacturing range	Sawed timber-> prefab wall	Lumber->3D module installation	Forest -> Building finalization
Main handling device during manufacturing process	Rolling table +Hanging conveyor	Bridge crane + Forklift	Bridge crane. Conveyor in the future

3.4 Quantitative aspects

If we look for quantitative aspects, the main data obtained for the manufacturing process and installation process of 2D modules are shown in table2. The data in this case refer to the manufacturing and installation of new buildings. In the case of Company 1´s installation process, the data are given by the subcontracted company. Besides, some companies don´t work with 3D modules; in this phase of the research we will focus on 2D modules.

The productivity of the processes shows that there is a big difference between companies 1-2 and 3 referring to the installation process.

Table 2. Main quantitative characteristics of companies

Company	Production staff	2D module manufacturing	2D m. production	Installation staff	2D module installation	Time for Rework
Company 1	26	17,04 m2/hour	0,65 m2 /worker-hour	9 operators	1,6 m2 /worker-hour	?
Company 2	18	10 m2/hour	0,55 m2 /worker-hour	4 workers	2,2 m2 /worker-hour	0,08 m2 /worker-hour
Company 3	9	11,25 m2/hour	1,25 m2 /worker-hour	5 workers	7,6 m2 /worker-hour	?
Company 4	No info	No info	No info	No info	No info	No info

The big gap between companies 1-2 and 3 referring to the installation process might be due to the special installation system used by Company 3, which consists of a similar on-site factory as used by NCC Komplett and Skanska´s Flying factories [10]. Anyhow, this system wouldn´t be usable for Building Renovation and therefore we can´t take this data as a benchmark.

In order to broaden the sample about this issue, a request has been made to a none-participant company. This company states that they install 60m2 per day with 3 workers. Therefore, they have a ratio of 2,8 m² installed per worker-hour. In this example the test has been monitored with a low building and using one aerial work platform, one mobile crane and one forklift crane.

Therefore, we consider that as an average, the current companies' m²/ worker-hour ratio for manufacturing and installing 2D modules are:

1. 0,55 m²/ worker-hour for manufacturing
2. 2,5 m²/ worker-hour for installation.

This means that if we sum both Off and On-site time in for every finished square meters:

$$\frac{1}{0{,}55}+\frac{1}{2{,}5}=\frac{1}{a}=2{,}21\ hours/m^2$$

This leads to 0,45 square meters installed per worker hour:

$$a=0{,}45\ m^2/h$$

It is interesting to consider some other examples of façade installation processes [12, 13]. For instance, if we compare the task of **adding a new isolating finished layer** to the building envelope, we can see that there are some differences from manual to prefabricated procedures. Let's check the **worker hour per square meter** in these variants. For manual procedures, (in this case a common EIFS) we need two people working for around 0.8 hours (1.6 hours in total) for installing the layer, including the external finishing. That makes 0,625 square meters installed per worker-hour. For the case of the semi-prefab rain-screen, this is reduced to 1.3hours, or in other words, 0,769 square meters per worker-hour.

Table 3. Installing time of different façade installing systems in building renovation.

	Average Placement and fixation time	Manual manufacture On-site
Manual procedure (EWIS // EIFS)	0,625-0,707 m2 /worker-hour	Yes, total
Semi Prefab withrain-screen)	0,61-0,769 m2 /worker-hour	Yes, partial

Sources: Baukosten Gebäude Altbau 2014 – BKI and http://www.generadordeprecios.info

Here we have a considerable difference comparing the EIFS or to the rain-screen installation process. If we focus on the m²/ worker-hour ratio, we can see it is 42% times faster, regarding. We need to take into consideration that the time measured for the installation of both EIFS and rain-screen doesn´t include the necessary re-work for the finishing in the corners, window sills and similar.

Besides, it has to be pointed out the less and most time consuming tasks within Manufacturing and Installation process. In all three companies, the most automated tasks are conforming the base, either in CLT board or Timber-frame. Depending on the factory assets, between 5 and 20 square meters of the base frame can be produced in one worker-hour. Once the main element of the module is already produced, the assembly takes

The different degrees of Quality and complexity of the 2D modules that the companies offer is also a parameter must be taken into account. Company 2 and 3´s product quality and complexity is higher than Company 1´s.

3.5 Similarities and common background

As said before, this research will define a timber based 2D and 3D module type that will be adopted by the companies. We have considered bringing out the main similarities of the modules that are produced in the companies, in order to define the common platform [1] that the future BERTIM module must have. This very simple scheme will be the base of the **BERTIM module**:

1. Base structure: timber-frame with infill insulation (Alternatively CLT).
2. Rigidizing board (alternatively CLT).
3. External insulation placed onto the board.
4. Services will run through the timber frame.
5. Flexible finishing system.

It must be said that within this similarity there are still some peculiarities in each company, for instance, the dimension of primary elements (stud and raster dimension, profiles, insulation types, windows…) that uses each manufacturer.

If we focus on the Similarity of the **manufacturing process**, we can see that for obtaining the final highly prefabricated 2D module, between 25 and 35 different tasks (e.g. stud cutting, timber-framing, insulation placement, window fixation etc.) must be carried out for the production of elements and the assembly of the modules at the factories. This 25-35 task do not include the simultaneous works needed in parallel production lines for the manufacturing of supplies such as windows. The proposed product needs to be adapted to this line and manufacturing timing. For instance, one of the Functional Requirements of the Company 1 is that any of the proposed Design Parameters must be limited to the Time-Tracking of the production line which means to produce a 2D module every 9-22 minutes.

1. Preparation of documents for the production of the modules. In one side, we have graphic information files such as CAD, production information files such as CAM and Order Lists. Those files are used either for the internal manufacturing process or handed out to external suppliers.
2. Arrival and temporary storage timber boards. Once the boards arrive form the saw-mill, they are temporary stored. Inspection of the boards. This is done either with naked eye or there are visual systems for the detection of knots.
3. Cutting the boards in its proper length.
4. Manufacture process of the timber-frame or the CLT panel.
5. Assembly of different elements on the timber-frame or CLT panel.
6. Preparation for the transport.

Regarding to the similarities of the **installation process,** there is a higher variety of solutions. Only Companies 2 and 3 perform directly installation activities. Company 1 doesn´t install their modules, the client directly contracts an installer company. Company 2 is the one that works more for building refurbishment. Company 1 hasn´t ever worked in building renovation and Company 3 has worked only in the installation of 3D modules on the top of buildings. About the equipment and support devices, mobile cranes, aerial work platforms and even scaffolding are mainly used.

4. METHODOLOGY FOR IMPLEMENTING A MASS CUSTOMIZED MANUFACTURING AND INSTALLATION PROCESS

As said in the beginning, we´ve determined three main Sub-Systems: the 2D and 3D modules configuration (A), the manufacturing process (B) and the installation process (C). These three different sub-systems must be interrelated and therefore integrated in a unique system. But there must be the choice to implement independently. The issue here is that what traditionally has been considered as PVs (Manufacturing + Installation process) are part of the FR. But the primary goal of an efficient manufacturing and reduction of installation time directs as to consider as FR. Due to the heterogeneous type of manufacturers, the adopted solution must be adapted to any type of company. Even more, each company can be flexible and decide either they use the whole set or only some of the decomposed FRs and DPs. Therefore, the independence axiom is really a must in this case.

In other words, there is uncertainty if the DPs certainly will be implemented totally or independently. We need to assure that they remain independent. So, applying the axiomatic design to our system and A, B and C sub-systems we can have the next matrix:

$$\boldsymbol{FR} = \boldsymbol{A} * \boldsymbol{DP}$$

$$\begin{Bmatrix} \boldsymbol{FR_1} \\ \boldsymbol{FR_2} \\ \boldsymbol{FR_3} \end{Bmatrix} = \begin{Bmatrix} \boldsymbol{x} & \boldsymbol{A_{12}} & \boldsymbol{A_{13}} \\ \boldsymbol{A_{21}} & \boldsymbol{x} & \boldsymbol{A_{23}} \\ \boldsymbol{A_{31}} & \boldsymbol{A_{32}} & \boldsymbol{x} \end{Bmatrix} * \begin{Bmatrix} \boldsymbol{DP_1} \\ \boldsymbol{DP_2} \\ \boldsymbol{DP_3} \end{Bmatrix}$$

(A) $\boldsymbol{FR_1} = Customize\ the\ existing\ 2D\ modules\ for\ building\ refurbishment$
(B) $\boldsymbol{FR_2} = Maximize\ the\ offsite\ manufacturing\ process\ of\ existing\ facilities$
(C) $\boldsymbol{FR_3} = Minimize\ onsite\ Installation\ time\ and\ cost\ of\ the\ modules$

(A) $\boldsymbol{DP_1} = Adaptable\ 2D\ modules$
(B) $\boldsymbol{DP_2} = Modular\ assembly\ workstation\ kit$
(C) $\boldsymbol{DP_3} = Rapid\ installation\ system$

By decomposing and hierarchizing the FRs and DPs, we can get the matrixes explained on the next sub-chapters.

In this first step of the definition of the FRs and DPs, there has been an iterative and collaborative process with the companies to check that the offered preliminary DPs are correct and suitable for a further definition and decomposition process. Furthermore, on the matrix besides the diagonal elements the rest should be zero in order to gain a robust solution, or at least the elements on the upper part should be zero to keep no interference among the FRs and DPs.

4.1 Decomposed FR1 and DP1: Customization of the 2D modules by conceiving an adaptable module.

As said before, the modules need to be highly adaptable. The modules that produce the companies should be reconfigured in order to obtain easily customizable modules to a high variety of Building typologies that have been already defined within the BERTIM project: concrete or steel structure buildings where the modules could be supported hanging from the building. In principle, self-supporting modules will be avoided as there would be a need for inserting dedicated foundations.

The next matrix shows the definition on the first decomposed Functional Requirements and Design Parameters of the modules:

$$\boldsymbol{FR_1} = \boldsymbol{A_1} * \boldsymbol{DP_1}$$

$$\begin{Bmatrix} FR_{11} \\ FR_{12} \\ FR_{13} \\ FR_{14} \\ FR_{15} \\ FR_{16} \\ FR_{17} \end{Bmatrix} = \begin{Bmatrix} x & A_{12} & A_{13} & A_{14} & A_{15} & A_{16} & A_{17} \\ A_{21} & x & A_{23} & A_{24} & A_{25} & A_{26} & A_{27} \\ A_{31} & A_{32} & x & A_{34} & A_{35} & A_{36} & A_{37} \\ A_{41} & A_{42} & A_{43} & x & A_{45} & A_{46} & A_{47} \\ A_{51} & A_{52} & A_{53} & A_{54} & x & A_{56} & A_{57} \\ A_{61} & A_{62} & A_{63} & A_{64} & A_{65} & x & A_{67} \\ A_{71} & A_{72} & A_{73} & A_{74} & A_{75} & A_{76} & A_{77} \end{Bmatrix} * \begin{Bmatrix} DP_{11} \\ DP_{12} \\ DP_{13} \\ DP_{14} \\ DP_{15} \\ DP_{16} \\ DP_{17} \end{Bmatrix}$$

$FR_{11} = Adapt\ to\ existing\ building\ configuration$
$FR_{12} = Adapt\ to\ existing\ building\ minor\ elements (cornices, friezes\ \dots)$
$FR_{13} = Adapt\ to\ different\ manufacturers\ common\ elements$
$FR_{14} = Adapt\ to\ different\ climatic\ regions$
$FR_{15} = Adapt\ to\ different\ aesthetic\ options$
$FR_{16} = Adapt\ to\ variable\ services$
$FR_{17} = Adapt\ to\ structural\ needs\ (hanging\ modules, self\ supported\ etc.)$

$DP_{11} = Convex\ and\ concave\ and\ vertical\ and\ horizontal\ corner\ solutions$
$DP_{12} = Separate\ module\ from\ the\ facade\ in\ order\ absorb\ minor\ elements$
$DP_{13} =$ *Module System based on common interfaces (connectors, plugs...) and ``geometries´´ instead of particular elements*
$DP_{14} = Variable\ thicknes\ of\ Insulation$
$DP_{15} = A\ system\ that\ allows\ variable\ finishings$
$DP_{16} = Flexible\ Criteria\ for\ placing\ the\ services\ within\ the\ 2D\ modules$
$DP_{17} = Adaptble\ timberframe\ and\ connector\ configuration$

In principle, and within this decomposition level, we can state the independence axiom of the matrix. Besides the proposed FRs, we might need to include more such as Airtightness, Moisture Barrier and Economic Feasibility of the proposed solution. But these would maybe be included as generic Constrains. Finally, it´s being discussed if the module could be dismountable. Taking into account all the requirements, there has been a preliminary approximation on the Design Parameters. For further development, some simulation and prototypes will be accomplished.

4.2 Decomposed FR2 and DP2: Maximize off-site manufacturing process of the modules within the existing facilities by a Modular assembly workstation kit

The goal here is to improve the Off-site Manufacturing process. The proposed solution should all the time implementable to any kind of manufacturing facilities, providing agility and to fulfil the needs of the costumer of BERTIM modules. The modular workstation kit must accomplish some decomposed requirements. The design matrix is solved like this:

$FR_2 = A_2 * DP_2$

$$\begin{Bmatrix} FR_{21} \\ FR_{22} \\ FR_{23} \\ FR_{24} \\ FR_{25} \\ FR_{26} \\ FR_{27} \\ FR_{28} \end{Bmatrix} = \begin{Bmatrix} x & A_{12} & A_{13} & A_{14} & A_{15} & A_{16} & A_{17} & A_{18} \\ A_{21} & x & A_{23} & A_{24} & A_{25} & A_{26} & A_{27} & A_{28} \\ A_{31} & A_{32} & x & A_{34} & A_{35} & A_{36} & A_{37} & A_{38} \\ A_{41} & A_{42} & A_{43} & x & A_{45} & A_{46} & A_{47} & A_{48} \\ A_{51} & A_{52} & A_{53} & A_{54} & x & A_{56} & A_{57} & A_{58} \\ A_{61} & A_{62} & A_{63} & A_{64} & A_{65} & x & A_{67} & A_{68} \\ A_{71} & A_{72} & A_{73} & A_{74} & A_{75} & A_{76} & x & A_{78} \\ A_{81} & A_{82} & A_{83} & A_{84} & A_{85} & A_{86} & A_{87} & x \end{Bmatrix} * \begin{Bmatrix} DP_{21} \\ DP_{22} \\ DP_{23} \\ DP_{24} \\ DP_{25} \\ DP_{26} \\ DP_{27} \\ DP_{28} \end{Bmatrix}$$

$FR_{21} = Adapt\ to\ different\ degrees\ of\ automation$
$FR_{22} = Perform\ different\ assembly\ tasks$
$FR_{23} = Support\ the\ 2D\ module\ Vertically\ and\ Horizontally\ during\ assemly$

$FR_{24} = Adapt\ to\ various\ Handling\ systems\ (hanging\ conveyor, carrier,$
$FR_{25} = Adapt\ to\ various\ assembly\ processes\ configurations$
$FR_{26} = Adaptble\ factory\ reconfigurations$
$FR_{27} = Adapt\ to\ various\ supplying\ systems$
$FR_{28} = Operators\ must\ reach\ easily\ the\ parts\ of\ the\ 2D\ module$

$DP_{21} = Adaptable\ ergonomic\ framework\ where\ either\ manual\ processes\ or\ robotic\ activities\ can\ be\ carried\ out$
$DP_{22} = Possibility\ to\ Host\ different\ tool\ types\ for\ assembly$
$DP_{23} = Possibility\ to\ Host\ 2D\ module\ supporting\ elements$
$DP_{24} = Integration\ of\ the\ exisitng\ handling\ system\ within\ the\ workstation$
$DP_{25} = Rejoinable\ workstation\ kit$
$DP_{26} = Movable\ workstation\ kit$
$DP_{27} = Dedicated\ area(s) or\ passes\ for\ supplies$
$DP_{28} = Posibility\ to\ include\ various\ (mobile) platforms$

The preliminary conception of the workstation has already been presented to the companies and the feedback has been positive (Figure 2). But some issues need to be solved, the Information axiom is not fulfilled. For instance, it affects directly to the FR1 since the work-station is not appropriate for a variable size of 2D modules (it can´t host longer modules than 6 meters) and it is neither usable for the assembly of 3D modules. This has been considered and on the second phase and the problem has been solved. The solution was a more open work-station, with higher degree of flexibility and possibility for being joined in order to create production lines (Figure 4).

4.3 Decomposed FR3 and DP3: Minimize on-site Installation time and cost of the modules by a Rapid installation system

How to accomplish a rapid installation process? Nowadays, too many support devices are needed during the installation of these panels. On the next matrix, we have pointed out the Functional Requirements and Design Parameters that reach the installation process to a rapider task.

$$FR_3 = A_3 * DP_3$$

$$\begin{Bmatrix} FR_{31} \\ FR_{32} \\ FR_{33} \\ FR_{34} \end{Bmatrix} = \begin{Bmatrix} x & A_{12} & A_{13} & A_{14} \\ A_{21} & x & A_{23} & A_{24} \\ A_{31} & A_{32} & x & A_{34} \\ A_{41} & A_{42} & A_{43} & x \end{Bmatrix} * \begin{Bmatrix} DP_{31} \\ DP_{32} \\ DP_{33} \\ DP_{34} \end{Bmatrix}$$

$FR_{31} = Avoid\ time\ comsuming\ settingout\ of\ the\ connectors$
$FR_{32} = Minimize\ time\ during\ the\ placement\ and\ fixation\ of\ modules$
$FR_{33} = Minimize\ duration\ of\ the\ accesory\ support\ devices\ on\_site$
$FR_{34} = Minimize\ rework$
$DP_{31} = Connector\ with\ interface\ that\ offers\ higher\ tolerances$
$DP_{32} = Fast\ placement\ and\ fixation\ system$
$DP_{33} = Easy\ and\ stable\ handling\ system$
$DP_{34} = Fully\ or\ Highly\ prefabricated\ modules$

The BERTIM project considers that previous to the Installation process there would be a 3D data acquisition of the existing building that would provide enough data to define the location of the connectors and the accurate size of the panels. This rapid installation process will gather the use of fewer handling and support devices.

On the very first attempts, we´re considering the use of only one single device and no other support system, similar to the handling of cargo containers. For that purpose, the joinery system must be accurately positioned. Once we have defined tall the decomposed FRs and DPs, we can check the independence axiom and if there is any interference between them.

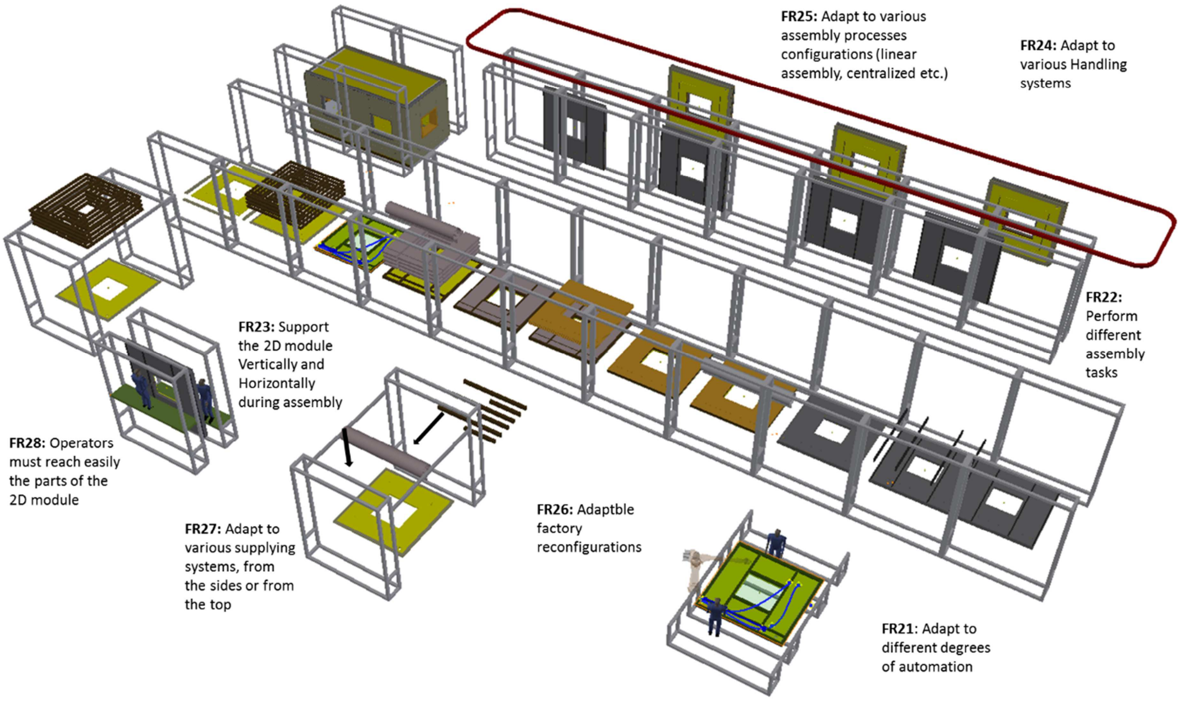

Figure 9: Second development of the work-station modular kit, implementation of the FRs.

4.4 Master matrix and information axiom

A master matrix has been configured to check the independence axiom of each of the decomposed FRs and DPs of every Sub-System. As said before, it is non-accurate to state that the decomposed FRs and DPs don´t interfere with each other, more detailed and decomposed solution are needed. In next sub-chapter 2.5 one decomposed FR and DP will be further decomposed in order to gain more definition of the solution.

4.5 Detailed FR31 and DP31 development

The FR31 refers to ``Avoid time consuming setting out of the connectors onto existing building´´. How traditionally have been set out the connectors? For none prefabricated solutions such as the installation of rain-screen (or ventilated facade), the procedure is normally as follows:

Fixation of the connector plate into the existing wall. The plates are placed with a laser alignment system, normally separated every 600 mm vertically.

Vertical guides are placed onto the connectors. Onto this, we might need an extra horizontal guide, depending on the product type. This way, we get a planar situation and the guides are located in a known range of distance.

The external envelope modules are cut to the right measure and placed onto the guides.

For the installation of prefabricated elements onto existing buildings, first, a data acquisition of the geometry is necessary. This Data acquisition of the existing building is carried out using 3D laser scanning, photogrammetry or/and theodolites. This data acquisition is normally considered as sufficient for manufacturing the prefab modules. But, in this research, it will be considered that after this overall measurement, we must accomplish strategies for assuring the exact location of the connector. During the installation of any prefabricated element, the accuracy of the joinery system is primordial [4, 5, 6, and 7]. Some prefabricated timber based modules are being installed following the traditional procedure. Besides, in some other proposals [7] the connector is ``punctual´´, there is no guide or rail for obtaining a planar situation.

In principle, this process using punctual connectors is faster than the previous process. But the connector must be fixed very accurately. For this case, the connector is composed by at least two elements: the part onto the existing building, Part1, and the part that goes within the module, Part 2. The position on the module is dictated by the position on the wall and vice versa, their coordinates need to be coordinated. The irregularities of a wall might be 50 mm in a concrete and rigid structure building, which means that the joinery system must absorb these irregularities.

Normally, the process of manufacturing the modules and the installation process is carried out in parallel or at least in a subsequent process. This means that when part 1 is being fixed on the wall of the existing building, the 2D modules are being manufactured off-site. Besides, we are considering to use a fast clipping system with latches or similar techniques; that means we have an extra constrain, the maximum tolerance between the connector part in the wall and the module must less than 5 mm. This tolerance must be defined as the allowable variation of DP31Δ.

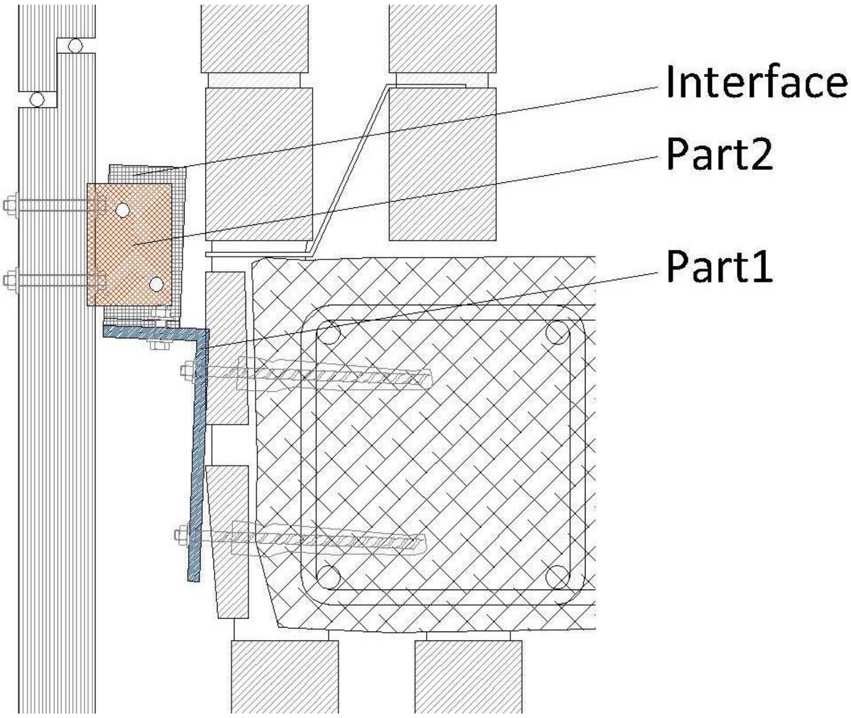

Figure 10 :First approaches regarding the connector type. Cross-section of the module and the existing building. We can see that Part 1 is not parallel to the vertical plan. Here, an interface was chosen in order to absorb the irregularities.

We will consider that the Companies manufacture the 2D modules also with that tolerance. On the first approach, we found out two main strategies.

Strategy 1: Place Part 1 of the connector with low tolerance

This means to obtain accuracy on-site, placing the connector part1 on its exact position, based on a given position of the connector by the designer. For achieving this highly accurate placing, we have two main options:

DP3.1a-Use of a multi-hole pattern that would allow us to place the connectors accurately with a degree of flexibility in case of impossibility of making a hole due to a rod bar or some other inconvenience. This way, we could achieve the necessary accuracy for placing the module on its place. The pattern can be physical or laser-made:

DP3.1.aa-Using a physical pattern. This technique has been traditionally used in the Japanese construction procedure due to the need of using prefabricated and rigid solutions. Disadvantage: This solution would mean to work with large physical elements on a vertical plan and therefore either scaffolding or an Aerial Work Platform would be needed.

DP3.1.ab- Using Laser Spatial Positioning system. Disadvantage: it can be used only at night or during cloudy days. Besides, the system might not be appropriate for tall buildings.

Both solutions wouldn't take into account the none-planar irregularities of the existing wall and the part1 might be placed on a non-parallel to vertical plan.

Strategy 2: Place Part 1 of the connector with high tolerance

With this approach, we can place the connectors with a traditional laser alignment system, taking into account that the whole set of connectors might not be in the same plan, meaning parallel with the same distance to the existing wall. After that, we must measure their accurate location. For facilitating this purpose, target-reflectors should be embedded on the connector. Once we know the exact position of the part 1, we can accurately correct the, or better said, modify some parts within the module. Within this strategy 2, we have two main options. One is to use an interface, and the other is to mill accurately some parts on a CNC mill.

DP3.1b- Adapt the connector´s interface by using a modifiable element. For this case we have two options.

DP3.1.ba- Using a 3D printed peg or dowel. The dowel needs to be hard enough to absorb the forces on the connector. Disadvantage: This solution might be very expensive and even time consuming.

DP3.1.bb- Making holes in different positions in a standardized interface. Disadvantage: The interface must be hold in an accurate location while doing the holes.

DP3.1c.- Modify the 2D modules connection point or surface by milling accurately in a CNC the placement of the part 2 within the module.

DP3.1.ca- Mill the stud (a single element) where the connector will be placed. Disadvantage: if the stud is milled before the assembly process of the module, any variance on the position of the stud within the module during the manufacturing process might create inaccuracies.

DP3.1.cb- Once the module is finished, insert the whole module into the CNC and make the necessary milling. Disadvantage: The Company must have a large CNC milling station.

As a result of this first research, we have found six different DP31 variants for satisfying FR31. We can see that all solutions present an impediment that should be solved on the next decomposition and zigzagging step. So far, we have gathered several Design Variables. How to validate Design Variables? In the following phase of the research, we must keep the independence axiom; each of the FRs needs to be satisfied without affecting any other. Only this way we will gather a robust solution, an ideal uncoupled design. It has to be pointed out that within this detail level, it cannot be stated if the future solution will fulfill the independence axiom since the definition is still vague. About the Second axiom, we know that the design with highest probability of success is the best design. For choosing the best design variables, we might need to take into consideration the different requirements of the companies. We have entered a phase where a prototyping of the solutions will be needed. The companies will provide the choice of proving some of the DP31 variants. We can still foresee some risks, for instance, due to timber´s unstable physical properties in differential humidity and temperature situation, the module´s geometrical properties might vary and therefore the location of the Part 2 might move. This might jeopardize the installation process; Part1 and Part2 might not fit.

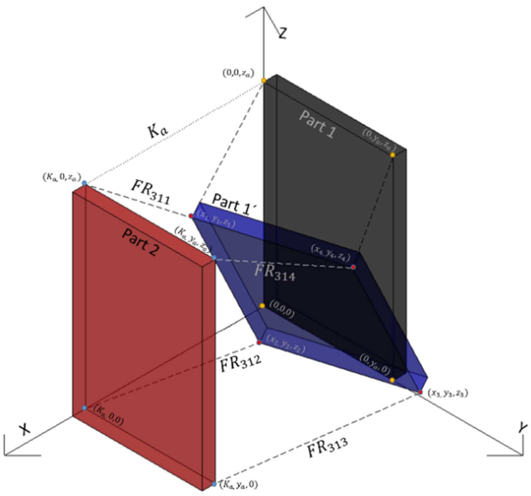

Figure 11: Abstract geometrical definition of FR31n.

Currently, the research is focused in Strategy 2, placing the connectors with high tolerance and specifically using an interface to absorb the variation. This decision has been taken co-ordinately with the expertise in the companies. In that sense, as guidance to future work, we can decompose the FR31 in equations that relate Part1 and Part 2. For that purpose, we will only need to measure the coordinates in Part1 and generate FR311, FR312 and FR313 by gathering the line´s equation (FRL31n) and the distance (FRD31n). After that, the DPs will be adapted accordingly.

$$FRL_{31n} = \frac{(x - K_a)}{(x_n - x_a)} = \frac{(y - y_a)}{(y_n - y_a)} = \frac{(z - z_a)}{(z_n - z_a)}$$

$$FRD_{31n} = \sqrt{(x_n - K_a)^2 + (y_n - y_a)^2 + (z_n - z_a)^2}$$

We will suppose Ka as constant, assuming that this constant will depend on the thickness of interface type. Either we use a custom made dowel or a customized hole locating system, with three decomposed FR311, FR312 and FR313 we could allocate Part2. In principle, with these equations the independence axiom is fulfilled, but as said before, it will depend on the final taken solutions, the DPs.

4.6 Manufacturing and Installing Protocol

All three Sub-systems must be interconnected, and therefore a specific step-by step working protocol must be defined. Depending on the final definition of the Sub-systems, the protocol will be defined in a way or another.

4.7 Feasibility for Implementation of the Method

The partners will need to choose which aspects they want to improve. Within the Sub-system, some of the Functional requirements might be more urgent for being accomplished than others. Thanks to the Independence Axiom, single sub-FRs and DPs can be applied, regardless the rest of the issues are managed or not.

5. CONCLUSIONS

The decomposition of the main Sub-system can be very broad and may lead to a broad list of FRs; some of them can´t be solved within this research process. In this phase of the research, we have gathered the main method or design frame for achieving the goal of the project. The Axiomatic Design approach has been applied and the complexity of the overall process has been handled. On the next phases and within the Axiomatic Design method, issues such as Weighting factors, Uncertainty, Reduction of variance and System analysis will be analysed. For that purpose, prototyping and testing will be necessary. The need of a modular and integrated system for achieving the goals in all three main Sub-systems is a complex task and therefore the use of a matrix based method has been justified. Gathering a solution for a modular and integrated product-manufacturing-installation system kit is a complex process and therefore it needs to be decomposed in affordable and multiple sub-systems. Besides, we must remember that the approximation made on this step will be valid for a robotic installation system of modules onto existing buildings. It must be taken into consideration that the biggest technology gap in terms of automation is within the installation process of the modules and therefore, main time reduction could be achieved on this phase.

REFERENCES

[1] Waltl H, Wildemann H., Modularisierung der Produktion in der Automobilindustrie, TCW, Transfer-Zentrum, 2014.

[2] Suh, Nam P. "Axiomatic Design: Advances and Applications, The Oxford Series on Advanced Manufacturing, 2001.

[3] Altshuller, G., 40 Principles: TRIZ keys to innovation, (Vol. 1). L. Shulyak, & S. Rodman (Eds.). Technical Innovation Center, Inc., 1997.

[4] Larsen, K. E., et al., "Surveying and digital workflow in energy performance retrofit projects using prefabricated elements", Automation in construction, 2011.

[5] Web page visited on the 04-07-2016: http://www.mppf.at/

[6] Web page visited on the 04-07-2016: http://www.ecbcs.org/annexes/annex50.html

[7] Various Authors, "Großelement-Dämmtechnik mit Vakuumdämmung", Institut Wohnen und Umwelt GmbH, Endbericht, Germany, 2007

[8] Web page visited on the 04-07-2016: http://www.smerobotics.org/demonstrations/d2.html.

[9] Iturralde, K., Linner, T., Bock, T., Development and preliminary Evaluation of a concept for a Modular End-Effector for automated/robotic Facade Panel Installation in Building Renovation, 10th Conference on Advanced Building Skins. 4-5 October 2015, Bern, Switzerland

[10] Bock, T. ,Linner., T., Volume 3: Site Automation: Automated/Robotic On-Site Factories, Cambridge Handbooks on Construction Robotics, Cambridge University Press, 2016

[11] Činkelj, J., Kamnik, R., Čepon, P., Mihelj, M., & Munih, M. Closed-loop control of hydraulic telescopic handler, Automation in Construction, 2010, vol. 19, no 7, p. 954-963.

[12] BKI, Baukosten Gebäude + Positionen Altbau, Fachbücher - Statistische Kostenkennwerte für Gebäude + Positionen im Altbau, 2015

[13] Web page visited on the 04-07-2016: http://www.generadordeprecios.info/