Development of a modular and integrated product-manufacturing-installation system kit for the automation of the refurbishment process in the research project BERTIM

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Abstract

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. Within the research EU-funded research project BERTIM, research institutes and companies are developing an interdisciplinary, cross-country approach for this challenge. In this research project, the goal of a dedicated work package is to ameliorate the existing holistic renovation process, by a combination an integration of robotic, automation and augmented reality technologies. Basically, the final objective 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.

Keywords: refurbishing, customization, automated, installation, prefabrication, axiomatic design

1 INTRODUCTION and PROBLEM STATEMENT

Achieving a zero energy consumer building stock is a goal of the European Union [1]. For that purpose, there have been several publicly financed projects [2,3] that have been working with several solutions in order to ameliorate traditional way of gathering a holistic energetic building renovation. This paper presents some of the achievements made within the BERTIM project [4] that was launched in June 2016. The BERTIM project scopes the use of timber-frame based 2D and 3D prefabricated modules for the building refurbishment. This research will be carried out in 48 months. 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´´*

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: the (A) 2D and 3D modules configuration, (B) the manufacturing process and the (C) 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 [5]. 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).

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. The reminder of this paper is to explain the development of this complex and multi-aspect system by applying a matrix based methodology such as Axiomatic Design [6].

2 DEVELOPMENT OF THE MODULAR PRODUCT AND PRODUCTION KIT SYSTEM

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 furtherly detailed. This aspect is related to the placement of the connectors within the buildings.

2.1 Methodology

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. Analysis of the 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.
2. 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.
3. Questionnaires have been handed out to the companies asking about the suitability of the identified technologies
4. Preliminary set of solutions for the Proposal of the manufacturing process. This proposal must be adapted to each case, it has to be flexible and modular.
5. First prototypes and tests.
6. Final definition.

In phase 4, and 5, it´ll be applied the so called Axiomatic design method for reorganizing the whole proposal. 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 these 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 haven 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 zig-zagging 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. 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. This method has already been used in previous and parallel research phases [7]. 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).

2.2 Analysis of the Existing Systems

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. As a résumé, the main qualitative aspects are pointed out in the next table.

Table 1. Main qualitative characteristics of companies

Company 1	
Product standardization	High degree of standardization, Catalogue based products
Production system	Manufacturing line
Main product	Timber-frame
Installation process	No
Customization	Limited
Adaptable manufacturing process	Limited
Manufacturing automation degree	Medium
Building refurbishment	No
Prefab degree	70%
Manufacturing range	Sawed timber-> prefab wall
Main handling device during manufacturing process	Rolling table +Hanging conveyor
Company 2	
Product standardization	Low degree of standardization
Production system	Non connected work stations
Main product	CLT and Timber frame
Installation process	Yes
Customization	High
Adaptable manufacturing process	Highly adaptable
Manufacturing automation degree	Low
Building refurbishment	Yes
Prefab degree	30-90
Manufacturing range	Lumber->3D module installation
Main handling device during manufacturing process	Bridge crane + Forklift
Company 3	
Product standardization	
Production system	Non connected work stations
Main product	CLT and Timber-frame
Installation process	Yes
Customization	High
Adaptable manufacturing process	Highly adaptable
Manufacturing automation degree	Medium
Building refurbishment	Yes
Prefab degree	30-90%
Manufacturing range	Forest -> Building finalization
Main handling device during manufacturing process	Bridge crane. Conveyor in the future
Company 4	
NO INFO	

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

Manufacturing	Production staff	2D module	2D m. production
Company 1	26	17,04 m2/hour	0,65 m2 /worker-hour
Company 2	18	10 m2/hour	0,55 m2 /worker-hour
Company 3	9	11,25 m2/hour	**1,25 m2 /worker-hour**
Company 4	No info	No info	No info
Installation	**Staff 2D module**	**2D module**	**Time for Rework**
Company 1	9 operators	1,6 m2 /worker-hour	?
Company 2	4 workers	2,2 m2 /worker-hour	0,08 m2 /worker-hour
Company 3	5 workers	**7,6 m2 /worker-hour**	?
Company 4	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 [8]. 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 [9] 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 reasonable benchmarks for 2D modules therefore are:

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

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.

2.3 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 to bring out the main similarities of the modules that are produced in the companies, in order to define the common platform [5] 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.

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.

2.4 System Development

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:

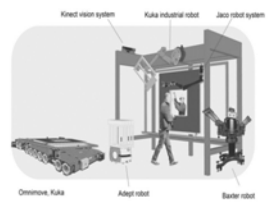
$$\boldsymbol{FR} = \boldsymbol{A} * \boldsymbol{DP}$$

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

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

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

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

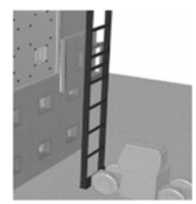


Figure1(left). Definition of the adaptable module(A).
Figure 2(middle). Preliminary idea of the WorkStation (B).
Figure 3 (right). Rapid installation system, a first proposal (C).

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.

2.4.1 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:

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

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

FR_{11} = *Adapt to existing building configuration*
FR_{12} = *Adapt to existing building minor elements(cornices, friezes ...)*
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.

2.4.2 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:

$$\boldsymbol{FR_2 = A_2 * DP_2}$$

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

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).

2.4.3 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.

$$\boldsymbol{FR_3 = A_3 * DP_3}$$

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

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.

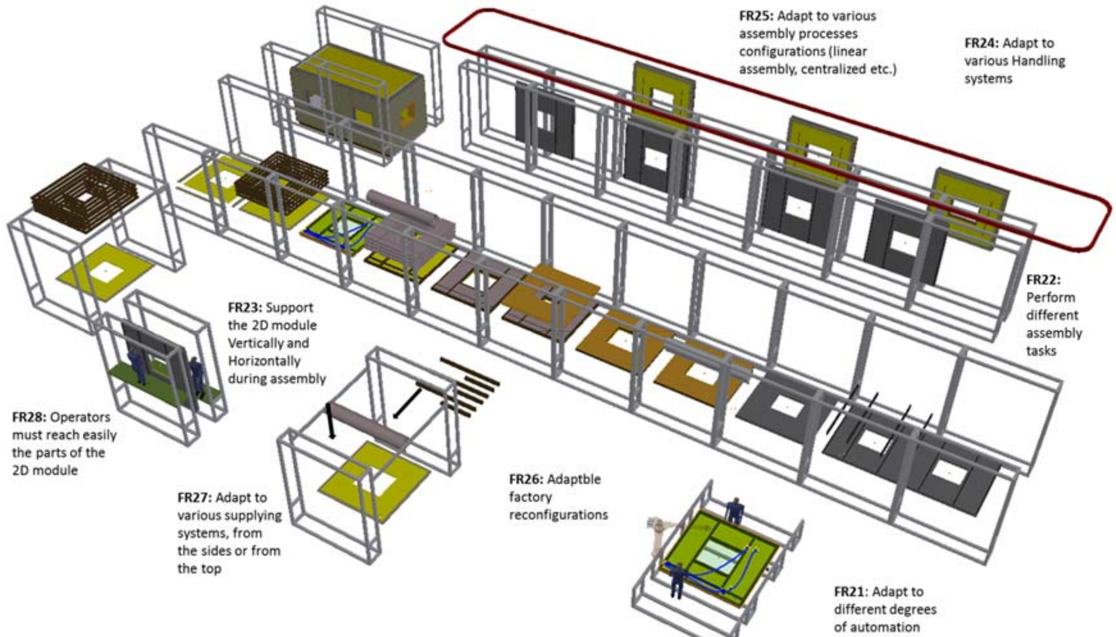


Figure 4. Second development of the work-station modular kit, implementation of the FRs.

2.4.4 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 furtherly decomposed in order to gain more definition of the solution.

2.5 Detailed FR31 and DP31 development

The FR_{31} 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:

1. Fixation of the connector plate into the existing wall. The plates are placed with a laser alignment system, normally separated every 600 mm vertically.
2. 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.
3. 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 [2,3]. Some prefabricated timber based modules are being installed following the traditional procedure. Besides, in some other proposals [10] 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 cases, 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 are 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 $DP_{31}\Delta$.

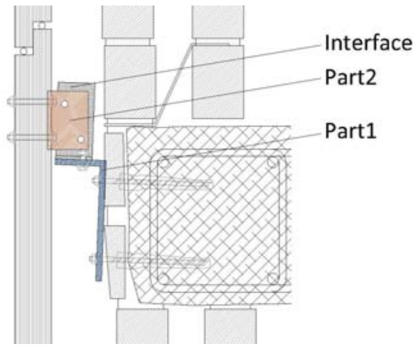


Figure 5. First approaches regarding the connector type. Cross-section of the module and the existing building. We can see that Part 1 is not parallel to the vertical plan. Here, an interface was chosen in order to absorb the irregularities.

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 patter 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 a 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 DP_{31} variants for satisfying FR31. We can see that all solutions present an impediment that should be solved on the next decomposition and zig-zagging 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 fulfil 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 DP_{31} 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.

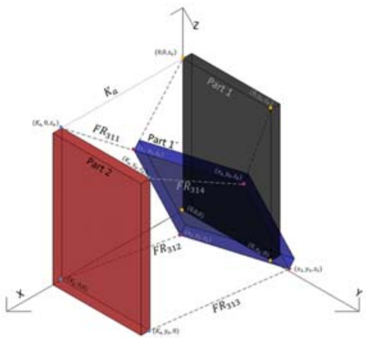


Figure 6. Abstract geometrical definition of FR_{31n}.

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 FR_{31} in equations that relate Part1 and Part 2. For that purpose, we will only need to measure the coordinates in Part1 and generate FR_{311}, FR_{312} and FR_{313} by gathering the line´s equation (FRL_{31n}) and the distance (FRD_{31n}). 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 FR_{311}, FR_{312} and FR_{313} 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.

3 CONCLUSION

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. 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. 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. 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, the main time reduction could be achieved on this phase. For that purpose, prototyping and testing will be necessary. Following the FR31 and DP31 development, the different connector solutions are being tested currently. The authors believe that this is a key issue for achieving a more automated robotic installation process of prefabricated modules for building refurbishment.

Acknowledgments

This paper has been drafted thanks to the funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No 636984. The content of this paper does not reflect the opinion of the European Union.

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