Monitoring and analysis of the manufacturing and installation process of timber based 2D modules used for building envelope upgrading

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Abstract –

The BERTIM Research Project is funded by the European Commission in order to develop a System for an efficient building envelope upgrading. The main goal of this envelope upgrading consists on adding a new 2D or 3D module onto the building external layer. The modules are made out of timber, thermal insulation and waterproof layers. These modules can also host some functionalities, mainly hot water and air services. In a previous phase, a Method for implementing an efficient, integrated, modular and customized manufacturing and installation process of the BERTIM modules has been conceived. This Method was achieved based on Axiomatic Design. The goal of this method was to generate and to coordinate three main sub-systems: the design and configuration of the 2D and the 3D modules (1), the manufacturing process (2) and the installation process (3). The idea is that the industrial partners within the BERTIM consortium can apply this method with enough flexibility, depending on the current economic and technical limitations. In this previous phase, specific solution weren't given, at least in the lowest hierarchy of the sub-systems; particular and disaggregated requirements weren't solved. The Axiomatic Design was mainly used in order to detect the possible interferences of the disaggregated Functional Requirements regarding the Independence and Information Axiom and the main risks of a Coupled Design. The first demonstration of the manufacturing and installation process has taken part at the KUBIK experimental building at Tecnalia´s facilities in Bilbao. The solutions taken for carrying out this demonstrator included new features, but it didn't differ relevantly with the traditional techniques that are used by a industrial partner within the BERTIM consortium. It has to be said that this demonstration was carried out as a relevant environment test and some results were marked and analysed. Basically, it was clear that the manufacturing and installation process and the module itself still needs to be re-adapted in order to improve the timing of the whole process. The Axiomatic Design matrix has been reviewed and upgraded. According to the Axiomatic Design Functional Requirements and the main Design Parameters defined in the previous phase, the demonstrator puts in evidence that the solutions taken don't fulfil the Independence and Information Axioms. The current System can be considered as a Coupled Design. In order to uncouple the System, the TRIZ inventive method has been used, focused on improving loss of time in all sub-systems. The TRIZ method facilitates the identification of the so called Contradictions that a System might have. These contradictions block or obstruct the possibility of improvement of a System. But thanks to the TRIZ Parameter Matrix and the 40 Inventive Principles, the problems are detected and diverted to find an optimal solution. It has been seen that especially on Sub-System 3, the installation process, the issues related to the connector are very relevant for diminishing the working hours on site. Before the end of the BERTIM research project, the modules will be manufactured and installed in three different operational environments, in real building refurbishment projects. The solutions defined with TRIZ methods will be implemented in this three case studies carried out by three different industrial partners.

Keywords –

refurbishing, customization, automated, prefabrication, axiomatic design, TRIZ

1 Introduction

A novel method of the manufacturing and installation process of prefabricated timber modules is being developed in the BERTIM [1] research project. As in every European Project, the research is based on

Work Packages (WP) that are organized correlatively in a calendar. Within these WP there are Tasks (T) that focus on specific matters. The overarching technical objective of the BERTIM research project is to define a holistic building renovation process, based on digital data workflow. For that purpose, a general implementation methodology for the manufacturing and installing industry must be defined. Once this methodology is applied in the industry, there must be a reduction of 30% on the In the BERTIM project, a **Set of Solutions** has been defined in Task 3.1 of Workpackage3, that included:

- Generic design of the modules according to the requirements such as insulation, wind force and structural purposes.
- The RenoBIM software will allow a repository of models.
- Definition of the manufacturing and installation processes and procedures that can be adapted to each manufacturer

On these previous task 3.1, a generic and standard solution was defined. But when applying this solution to each **specific building-case**, some other steps must be considered.

- Measurement of the existing building-case. The main purpose of the measurement is to accurately adapt to the existing building. For now, we haven´t specified in which phases this measuring(s) must be accomplished.
- Re-design or adapt the BERTIM modules to the building-case using a CAD first and with RenoBIM after
- Manufacture the modules according to CAD or BIM
- Prepare the building before installing the modules. With preparing the building it is meant the removal of unnecessary elements from the building
- Install the modules. In principle, the ideal scenario is to

In the Task 3.2 of Work-Package 3 of the BERTIM research project, a Demonstrator was carried out at the ``Kubik´´ building in Tecnlia's facilities in Bilbao, Basque Country (Spain). The Kubik building was built for carrying out there tests, it is a test building. The test consisted in installing five 2D modules onto the existing building façade. The re-designing, manufacturing and installation process where defined previously. The whole process was monitored and the results, considering specially time, was discussed.

Once the installation was carried out, the members form Tecnalia monitored the thermal performance of the modules and the building. Comparing to the previous Timber based research projects, the BERTIM modules can include services, generally hot water and ventilation ducts. This gives extra complication to the design, manufacturing and installation processes, the services need to be fit among each other an with the ones in the interior.

2 Methodology

The research methodology is based in two design methods or procedures. The first is Axiomatic Design [2] and the second is TRIZ [3].Previous to this paper, in task 2.5 of Work-Package 2, the Axiomatic Design was drafted as a core for defining the Methodology of Implementation of the BERTIM project. In Task 5.1, this methodology must be implemented but after the Demonstrator in task 3.2, some of the concepts that were drafted need to be reviewed since the beforehand ideas haven´t meet the reality. The ongoing research was carried out according to a methodology that is based in the next steps:

- Define the re-design, manufacturing and installation process. This was already carried out in Task 3.2, previous to the Demonstrator case.
- Implementation of the Kubik case study.
- Monitor the re-design, manufacturing and installation process of the case study.
- Get the results and analyze every break down form the monitoring process.
- Compare the results with the ETICS, Rain-screen and Kubik BERTIM ant o OMM.
- Adapt the previously used Axiomatic design process for the case of Kubik BERTIM. Break every single task down based on the sub-systems of the Axiomatic Design proposed in previous research [4] focusing on the Design Process, Manufacturing process and Installation process. The Functional Requirements naming have been modified according to the TRIZ matrix
- Allocate the points that can be improved.
- Find possible applications according to the TRIZ contradiction matrix and the 40 Inventive Principles to these points.
- Discuss the Design Parameters or solutions for these points.

After the discussion, the next steps of future research have been defined.

3 Description of BERTIM modules

The criteria for the design and the detailed design of the BERTIM modules have been defined in Task 3.1 of WP 3 according to the Requirements specified in Task 2.3 of

WP 2 of the Research project. For the façade 2D modules the next point were specified:

- Criteria Energy Efficiency Criteria For Modules' Design: insulation, Thermal performance, Condensation, HVAC energy consumption
- Criteria 2D Envelope Modules with and without Services Design: Structural design,3 support systems, Fire resistance, Insulation requirements for building outdoor ducts and pipes, Quick fit of water pipes.
- Detailed Design Of 2d Modules Without Services. Dimensions of the modules, Insulation type and finishes, Manufacturing process, Transport of the modules Particular case: 2D modules with embedded windows.

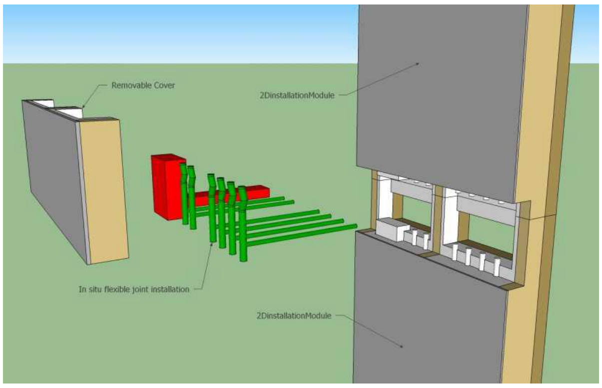

Figure 1. Definition of the module with services. The connecting system.

4 Traditional methods: EIFTS and rain-screen. Setting a benchmark to overtake

The benchmark in BERTIM refers to the traditional methods for the installation process. In this research process two main types have been considered. The so called ETICS (External Thermal Insulation Composite Systems) and the Rain-Screen

Table 1Installation of ETICS

On-site ETICS at Kubik				
Task	Kh	NoW	Ku	h/m²
Insulation	5,09	2,00	23,34	0,22
Rendering	30,63	2,00	23,34	1,31
Painting	7,10	2,00	23,34	0,30
Perimeter	20,20	2,00	20,49	0,99
Services	2,58	2,00	12,00	0,22
TOTAL h/m² WITH SERVICES				**3,04**
TOTAL h/m² WITHOUT SERVICES				**2,82**

In order to verify the data provided by the databases there has been an analysis of two different renovation projects.

Table 2Installation of Rain-Screen

On-site Rain-Screen at Kubik				
Task	Kh	NoW	Ku	h/m²
Insulation	6,44	2,00	23,34	0,28
Rain-screen	43,09	2,00	23,34	1,85
Perimeter	20,20	2,00	20,49	0,99
Services	2,58	2,00	12,00	0,22
TOTAL h/m² WITH SERVICES				**3,32**
TOTAL h/m² WITHOUT SERVICES				**3,11**

These data need to be reduced by 30% according to the preliminary objectives. With these data, we can therefore set as a benchmark,

- 2wh/m² for the modules with services.
- 1,75wh/m²for the modules without services.

The installing time could be considered as a 1wh/m².

5 Implementing the BERTIM 2D modules to the Kubik case study

The Kubik building is a test building. It has to be said that the Demonstrator at the Kubik building it is not a standardized procedure, and therefore it is more prompt to errors than traditional and already tested, proofed and commercialized techniques and procedures.

The modules used in the Kubik Demonstrator were manufactured by the industrial partner Egoin.
As said before, there were five 2D modules installed onto the building´s facade:

- Three of them didn´t have any services,
- the rest two, included services, such as hot water and a ventilation duct. The purpose of placing services in the Kubik module was purely for testing the easiness of the installation process and monitoring the heat loss through the installation itself.

The method used for manufacturing and installing a prefabricated module in the as follows the chronological :

On-site

2016-10-03 Dismantle previous façade element,. This façade was from a previous project
2016-10-18 Measure the existing building with total station. The criteria for measuring is based on localizing the perimeter.

2016-10-19 Making holes for connecting services

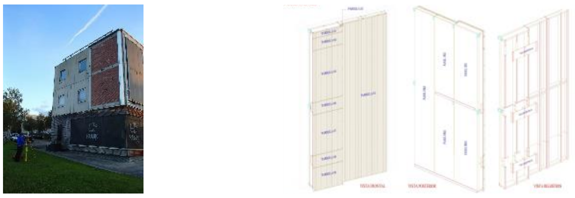

Figure 2. Measuring the building strategic points. Define the modules in CAD.

Off-site

2016-11-14 Define the modules in CAD according to the measurements.

2016-11-15 Manufacture the modules according to the CAD files. The process consisted on cutting studs, mill the studs, conform the frame and place the board. Next, they placed the vapor barrier and insert insulation. If the module had services, these were inserted at this point. Finally, the moisture barrier and the raster were assembled. The finishing grid was manufactured separately.

Figure 3: Manufacturing process of the modules.

On-site

2016-11-22 and 23: Download the modules from the truck. After that, the first structural profile was placed. Next, the insulating layer was fixed, and finally the modules were placed and fixed.

2016-11-24 and 25. Service fitting.

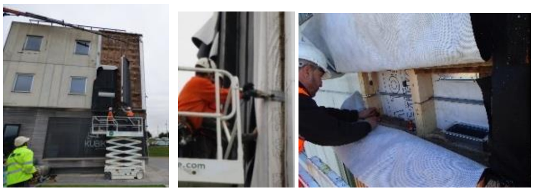

Figure 4. Installing the panels. Fixing the connector. Joining and fitting services

2016-11-28 Perimeter cladding and some other finishing.

Figure 5. Finishing placement and fixation. Final enclosure and perimeter finishing.

Table 3

BERTIM at Kubik				
Task	Kh	NoW	Ku	Kh/m²
RE-ENGINEERING PROCESS				**0,43**
Data acquisition	2,00	1,00	23,34	0,09
Re-design	8,00	1,00	23,34	0,34
MANUFACTURING PROCESS				**1,61**
Battens	2,00	1,00	23,34	0,09
2DM	4,00	2,00	14,13	0,57
TF+I+MB+VB	4,00	2,00	14,13	0,57
2DMWS			9,07	2,48
CLT	2,00	1,25	9,07	0,28
TF+I+MB+VB	5,00	2,00	9,07	1,10
Services	5,00	2,00	9,07	1,10
Finishing	2,00	2,00	23,34	0,17
Transport l.	0,50	2,00	23,34	0,04
INSTALLATION PROCESS				**2,24**
Transport u.	0,30	2,00	23,34	0,03
Connector	0,30	2,00	23,34	0,03
Insulation	1,50	1,00	23,34	0,06
Place fix modules	5,50	3,00	23,34	0,71
Finishing a	1,00	3,00	23,34	0,13
Finishing b	1,00	2,00	23,34	0,09
Services	6,00	2,00	23,34	0,51
Perimeter	8,00	2,00	23,34	0,69
TOTAL h/m² WITH SERVICES				**4,27**
TOTAL h/m² WITHOUT SERVICES				**3,21**

5.1 Comments about the data gathering.

In previous data gathering, the authors detected that 1,18 hour/m² were necessary for the manufacturing process; this shows the data are quite correct to the 1,29 h/m2The manufacturing process differs quite a lot from one partner to the other, depending on the facilities and assets they have for producing the modules. One of the analyzed partners showed that the 0,8 h/m² would be reached.1,25 m2/man-hour. Therefore, it can be said that there is already technology for automating and improving the manufacturing process.

An inaccuracy of around 10 mm has been found in the final positioning of the modules. The errors might be produced by:

- Inaccuracy of the manufacturing process
- Inaccuracy of the positioning of the support
- Inaccuracy during the placement of the modules
- Un-rigidness of the timber modules, that during transportation can be bended. Also, the modules can expand or shrink due to hydrothermal changes

Due to this inaccuracy, the tubes are not ready to fit and they need a rework at the construction site.

Figure 6. The connecting system with inaccuracies that can be detected visually.

5.1.1 Re-engineering process. Design adaptation

The re-engineering process for nesting and drawing the modules takes 0,34 h/m².

Without the RenoBIMtool this is a time consuming task that in the case of the Kubik case study, it took around 8 hours to re-design the modules. Besides the RenoBIM, the use of some other Parametric design would be necessary in order to automated the process.

5.1.2 Place and fix the modules

The installation of the modules takes 0,71 h/m2. This is The finishing's do not take much time, but if there was a fully prefabricated module, the finishing would be integrated. The same happens with the insulating layer that is placed on the wall.

5.1.3 Fitting of services on-site

The fitting of the services consisted on joining together the water and air ducts in a registrable box .it consisted in a manual operation and the whole box needed to be insulated and covered after that. The joining tubes where flexible in order to have bigger tolerances in case of big accuracy errors. The tubes form different modules and also from the inner services.

5.1.4 Finishing perimeter

This task requires major study definitely, since 0,69 h/m2 were necessary for that purpose. It can be considered even a bigger problem if there were windows involved. In the Kubikdemonstrator there was no window within the modules. This is already an issue that was covered in the Retrofirt project. In the BERTIM KubikDemonstrator there was no window. This issue can be a problems in the future.

5.2 The Axiomatic Design matrix

The H2020 EE-01-2014 call named ``**Manufacturing of prefabricated modules for (energy) renovation of buildings**´´, defined the next main Functional Requirements:

- Use **prefabricated** modules. It must be said that there is an underneath objective to integrate energy efficiency devices and **renewable energy sources** in the prefabricated multi-functional modules.
- Use of **advanced computer based tools** for integrating the value chain over the life cycle of the project
- Move from individual manufacturing to mass production. A more accurate term would be **mass-customization**.
- **Reduce the installation (and manufacturing)** time by at least 30%, compared to a typical renovation process for the building type. This term must be defined more accurately. In this research, we compute or determine the total time of Re-design, Manufacturing and Installation processes. And that time should be lower than the traditional methods.

Other minor objectives that can be considered also as a Constrains are:

- Reduce costs. This is related to the manufacturing and installation processes.
- Ensure quality
- Facilitate dismantling and re-use
- Improve on-site health and safety during manufacturing and installation.

In the BERTIM project, in previous approaches, the Functional Requirements and the Design Parameters related these previous points were defined as:

- Sub-system 1: Customize the prefabricated 2D modules for specific building refurbishment.
- Sub-system 2: Information workflow based on advanced software.
- Sub-system 3: Maximize the offsite manufacturing process of existing facilities of the industrial manufacturers.
- Sub-system 4: Minimize onsite Installation time and cost of the module

The Design parameters where considered the next:

- Sub-system 1: Use of highly prefabricated and adaptable timber-framed modules

- Sub-system 2: Use of RenoBIM for the integrated Product LifeCycle Management.
- Sub-system 3: Use of a Manufacturing Modular Kit that can be adapted to the manufacturers
- Sub-system 4: Define a Rapid Installation System

But on the Kubik Demonstrator, these Sub-systems were not fully implemented, and the primary hierarchy of the axiomatic Design was modified as follows:

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

$$\begin{Bmatrix} FR_1 \\ FR_2 \\ FR_3 \\ FR_4 \end{Bmatrix} = \begin{Bmatrix} x & A_{12} & A_{13} & A_{14} \\ A_{21} & x & A_{23} & A_{24} \\ A_{31} & A_{32} & x & A_{34} \\ A_{41} & A_{42} & A_{43} & x \end{Bmatrix} * \begin{Bmatrix} DP_1 \\ DP_2 \\ DP_3 \\ DP_4 \end{Bmatrix}$$

(A) $FR_1 = Definition\ 2D\ prefabricated\ modules\ for\ building\ refurbishment$
(B) $FR_2 = Information\ workflow\ based\ on\ digital\ Data\ \ CAD - CAM\ systems$
(C) $FR_3 = Maximize\ the\ offsite\ manufacturing\ process$
(D) $FR_4 = Minimize\ onsite\ Installation\ time\ and\ cost$

(A) $DP_1 = Adaptable, medium - prefabricated\ modules\ with\ limited\ acuracy$
(B) $DP_2 = Use\ of\ conventional\ CAD\ systems\ for\ the\ definition\ pf\ the\ modules$
(C) $DP_3 = Exisitng\ factories$ *with limited flexibility and no dedicated workstations*
(D) $DP_4 = Conventional$ *fixation process with a mobile crane and a platform*

Previously, it was defined an axiomatic matrix with higher hierarchy levels, but since the Kubik Demonstrator was carried out, it has been considered necessary to redefine the whole matrix back again.
But if we check this primary hierarchy in a matrix table, we can see that the independence axiom is not fulfilled fully. There are interferences between the different FRs and DPs is considerable as it is shown in Table 4.

Table 4: interference matrix

	DP1	DP2	DP3	DP4
FR1	x	x	0	0
FR2	x	x	x	0
FR3	x	x	x	0
FR4	0	x	0	x

For instance these are the points that need to be taken into consideration:

- Sub-system 1: In the case of the Kubik building, the adaptable prefabricated modules had a medium degree of prefabrication, around than 50% of the tasks were carried out at the factory. This adaptation , as seen before, had repercussions on the CAD redesign process. But also in the manufacturing process, the works need to be guided. But basically, the adaptable module needed special rework after being placed and fixed on to the wall; the finishing was necessary and the services need to be fit.
- Sub-system 2: The manual of adapting the CAD information, slows down the process of customization of the modules. Besides, there is no direct link with the manufacturing process and the information needs to be given in paper.
- Sub-system 3: If the existing manufacturing Time reduction in the installation processprocess needs to be maximemized, and we use the existing tools, the cuntinous customized modules and its bespoken process can diminishes the productivity of the factory.
- Sub-system 4: The installation time can be seen geopardized if the product needs an constant on-site customization such as perimeter enclosure. The accuracy of the modules needs to meet the geometry of the existing wall precisely.

Therefore, the strategies need to be re-defined. On the next sub-chapters, some broken down parts of the process will be analyzed. The main issue on this paper and question here is how to decrease time in all sub-systems.

5.3 Applying TRIZ to the Kubik Demonstrator and the BERTIM modules

In order to reduce time, the manufacturing, but specially the installation process needs to be fast. If we take as a primary objective to reduce time, we can organize the TRIZ strategy as follows.

5.3.1 Time reduction in the installation process

The **time reduction** in installation will come from a higher prefabrication and accuracy of the modules in order to obtain a fast fitting process.

Table 5: Principles 4 (asymmetry), 28 (replace mechanics), 10 (prior action and pre-arrange objects) and 34(discard and remove)

	Ease of operation(32)
Loss of time (25)	4,28,10,34

But a fast installation process and a high accuracy leads to lack on the ease of operation. The connectors on the wall need to be aligned with low tolerances in order the module and services fit. The TRIZ matrix provides the principles 4,28,10 and 34 for this situation. The principle 10, preparation of the alignment of the wall has been used already in some other similar research projects [5][6], but that leads again back to a loss of time.

Besides, the module might change its configuration during transportation due to heat and humidity changes, and therefore, the accuracy can be lost during logistics operations. This issue must be taken into consideration on next phases.

5.3.2 An accurate module for rapid processes

The defined module needs to be highly prefabricated, and therefore, highly defined in order to lose time. In consequence, a **highly prefabricated** module with services needs **high accuracy** in order to be fit rapidly.

For a higher accuracy of the modules, there must be an accurate **data acquisition** of the existing building in order to customize and bespoke the modules.

Table 6: Principles 35(parameter change) and 28 (replace mechanics)

	Adaptability (35)
Loss of time (25)	35,28

But the biggest contradiction of the highly prefabrication relies on the lack of adaptability of the module, that the module is so tight that no change is possible. TRIZ offers two principles for these situation, 35 (parameter change) and 28 (replace mechanics). This is related to the module materials and configuration; the module needs to be reviewed.

5.3.3 Time reduction in the re-design and digital workflow

Once the **re-design** process is ready, ease of manufacturing must be accomplished, with a clear digital information and material workflow. And it takes time in the manufacturing process and installation process if the elements, specially the services are not clear for the operator. The biggest harm is therefore , Customization of the module takes time on the **manufacturing process**, specially if no parametric or computational design feature is used and the elements are drawn in CAD manually.

Table 7: 24(intermediary), 26 (copying), 28 (replace mechanical system), 32 (change color)

	Los of information (35)
Loss of time (25)	24,26,28,32

In this situation TRIZ offers principles 24, 26, 28 and 32. Among them, the `` copying´´ principle is the most adequate for our case, basically, what needed is a clear parametric library of solutions that will `` copy´´ the module's configuration successively on the next cases. At BERTIM-Kubik Demonstrator that was not the case, since it was the first time implement and the process was manual

5.3.4 Manufacturing accuracy in the manufacturing process

The **accuracy** leads to a **loss productivity** in manufacturing process. Every single part of the module needs to be produced and assembled according to the previous design.

Table 8: 35 (parameter change), 28(replace mechanics), 34 (discard and remove), 4 (asymmetry)

	Productivity (32)
Manufacturing accuracy (25)	32,26,28,18

Among the principles proposed by TRIZ, the ``discard and remove´´ might be the most interesting. This principle would lead to use of patterns that can facilitated the insertion of services onto the modules.

5.3.5 New axiomatic design matrix

In theory, if the Inventive Principles are implemented the Axiomatic Design matrix should be uncoupled.

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

$$\begin{Bmatrix} FR_1 \\ FR_2 \\ FR_3 \\ FR_4 \end{Bmatrix} = \begin{Bmatrix} x & A_{12} & A_{13} & A_{14} \\ A_{21} & x & A_{23} & A_{24} \\ A_{31} & A_{32} & x & A_{34} \\ A_{41} & A_{42} & A_{43} & x \end{Bmatrix} * \begin{Bmatrix} DP_1 \\ DP_2 \\ DP_3 \\ DP_4 \end{Bmatrix}$$

(A) $FR_1 = Minimize\ onsite\ Installation\ time\ and\ cost$
(B) $FR_2 = Definition\ 2D\ prefabricated\ modules\ for\ building\ refurbishment$
(C) $FR_3 = Information\ workflow\ based\ on\ digital\ Data\ \ CAD - CAM\ systems$
(D) $FR_4 = Maximize\ the\ offsite\ manufacturing\ process$

(A) $DP_1 = Rapid\ placement\ and\ fixation\ process\ using\ interfaces$
(B) $DP_2 = Accurate\ andfullyprefabricatedmodule$
(C) DP_3 =Parametric definition of the modules using computational design
(D) DP_4 = *Dedicated workstations for services integrated on existing factories*

Table 9: interference matrix

	DP1	DP2	DP3	DP4
FR1	x	0	0	0
FR2	0	x	0	0
FR3	0	0	x	0
FR4	0	0	0	x

In this case, comparing to the BERTIM-Kubik case, the strategy is more focused on time reduction during the installation process, and the Functional Requirement 1 is placed first.

6 Conclusions

TRIZ has been useful for uncoupling the Axiomatic Design matrix in the case of BERTIM. But a broader study is necessary to reach specific solutions.

Strategies for a future robotized and automated manufacturing process.The next options can be re-marked:

- The higher the prefabrication, the lower the need of module installation time, fitting services and perimeter enclosure
- The higher prefabrication, the more accuracy is needed, and the more time is necessary in measuring and maybe, but not necessarily, manufacturing.

On future works, other Functional Requirements should be analyzed and researched. The authors will follow working on that direction. Currently they are studying fitting the Axiomatic Design objectives with the 39 Parameters on the Contradiction Table of TRIZ. The discussion is if one or more parameters need to be used in the finding a solution.

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