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Assessment method for developments in building envelope renovation with prefabricated modules

Kepa Iturralde [a*], **Nagore Tellado** [b], **Thomas Bock** [a], **Ignacio Gomis** [b]

a Chair for Building Realization and Robotics. Technical University of Munich.
b Fundación Tecnalia Research and Innovation

*corresponding author e-mail: kepa.iturralde@br2.ar.tum.de

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Abstract

Building envelope renovation with prefabricated modules (BERPM) is a concept that implies multi hierarchized requirements and sub-systems, where socioeconomic, environmental and technologic aspects are related. Several private and public organizations are willing to implement BERPM into the building stock. Besides, technology developers are willing to market their output into the building renovation. How different stakeholders can achieve that goal successfully in a coordinate manner, considering aspects such as environmental and socioeconomic perspectives? When developing a technology, it is often necessary to contextualize the approach with the existing policies. The aim of this paper is to stablish a framework for guiding the appraisal of novel technology achievement on different stages. This assessment is aimed mainly for technology developers. Moreover, any member from the field of policymaking and built environment could take advantage of using it. According to the novel method, there are two kind of assessments. First, there is a qualitative evaluation, which is based on an adaptation of Axiomatic Design. This is carried out on early stages. Second, there is a quantitative rating based on an adaptation of Complex Proportional Assessment (COPRAS). This second evaluation is only performed when measurable results and indicators are gathered. Such assessing methodology was applied on the BERTIM project as a case study. The results of this case study showed the main challenges to be improved within the research project.

1 Introduction

Achieving a zero-energy consumer building stock is a goal of the European Union [1]. In order to achieve this goal, existing buildings must be adequately insulated. Traditionally, this has been a manual and time consuming procedures [2]. There have been several research projects [3] such as Timber Based Element System (TES) [4], Annex 50 [5], and Großelement-Dämmtechnik (GEDT) [6] that were focused on different solutions. In the aforementioned studies, methods involving the use of prefabricated 2D modules to cover the building envelope were presented. This type of *Building envelope renovation with prefabricated modules (BERPM)* are complex systems such as the shown in the BERTIM research project [7] that cover many aspects, from manufacturing processes to energy consuming reduction of the building. These research projects need to be evaluated before launching the product into the market. How to assess the ongoing research projects related to BERPM in order to create a more cohesive and robust system? The methodological approach presented on this paper is meant to be a tool for the technology developers and companies, and also for the public administrative bodies. The technology for the *BERPM* is not developed by a single centralized stakeholder, but by multiple and independent developers that push for their achievements. Therefore, the technology developers need to know if their proposed solutions meet the needs of the so called *BERPM*. On the other hand, by using this method, the public administration has the choice to contextualize each of the possible solutions and its aspects and relate them while defining policies and strategies.

For all the reasons explained, the reminder of this paper is to define a clear methodology for assessing that research projects fulfil the requirements of the client within the context of the *BERPM*. This methodology was verified in a case study for the research project named BERTIM.

2 Assessment method

The assessment method is divided in two main steps. On the first step, the project is assessed qualitatively. For that purpose, the Axiomatic Design [8]is used. This qualitative assessment is meant to be achieved in the preliminary phases of the research project. On the second step, the multiple criteria Complex Proportional Assessment (COPRAS) method [9]is used for the quantitative evaluation of the technology. The quantitative assessment is more focused to intermediate phases.

The Axiomatic Design is based on two principles: the Independence Axiom and the Information Axiom. The first axiom ensures that each of the solutions developed within the project doesn´t interfere with any other solution. Besides, according to the Information Axiom, it is considered that the best solution is always the one with the highest probability of success while minimizing the information content. As a first step of the of the Axiomatic Design, some attributes (or objectives) are presented. These attributes are normally defined by the client and cover generic objectives without defining specifically the tendency. In the case of BERPM, the European Commission defined some needs in the EE01 2014 call [10] regarding the objectives of the research projects with prefab modules. Those can be taken as preliminary Customer Attributes (CA) of the *BERPM* . It must be taken into account that that these CAs can be subject to changes, depending on the major ongoing tendencies within the definition of what a *BERPM* is. Following the Axiomatic Design method, these CA are transformed to more specific Functional Requirements (FR), within the Functional Domain. Once the FRs are defined, the Design Parameters (DP) are developed.. The Design Parameters can be considered as a set of solutions that fulfil the Functional Requirements. The Design Parameters belong to the Physical domain. For relating the Functional Requirements and the Design Parameters (DP) or solutions a Design Matrix is used. The objective of the matrix is to prove that the Independence Axiom is fulfilled, which means that each of the Design Parameters can´t interfere with the rest of the DPs and FRs. In the case of the assessment method, the Axiomatic Design will be used for defining that the Proposed solution and sub-solutions don´t interfere or that are not contradictory with each other. A Main Matrix collects and interrelates all the FRs and DPs. All the CAs, FRs and DPs can be decomposed and hierarchized until a final, concrete and feasible solution is set. This *BERPM* Functional Requirement Matrix must be flexible depending on the novel socioeconomic and technological improvements. New Requirements and Constraints could be added (such as the current mainstream gender equality issues) and removed. Depending on the analysis of the needs and lacks of each moment and region, this system is subject to change. Once the technology has been assessed qualitatively, and if the Technology fulfils this step, on the next step there will be a quantitative evaluation.

Once the qualitative assessment is achieved and the results are positive, the qualitative assessment method is carried out. A Multi-Criteria Decision Making (MCDM) model such as COPRAS guides the evaluation of technology development. For this purpose, measurable indicators are chosen. The quantitative research gap is evaluated in a 0-100 scale. The objective of BERPM is mainly to improve current manual technologies for the building renovation. The indicators of existing traditional procedures are marked as 0. Besides, the indicators of the objective and idea system are marked as 100. The objective is formulated as an ideal solution which ameliorates all indicators.

3 Case study: BERTIM project

The BERTIM project was chosen as a case study for applying the assessing methodology. This project was suitable to be assessed since it deals with the issue of BERPM. The BERTIM research project is focused on ameliorating the renovation process of buildings in order to minimize energy consumption. For that purpose, prefabricated timber based modules are added on the external surface of walls. There are two types of modules, standard modules that have insulation for the envelop and installation modules that include hot water distribution and ventilation services inside the modules. The Technology Readiness Level (TRL) defined in the research project is considered quite high (TRL 7 at the finalization). The implementation of the solutions developed during the project is limited by the existing capabilities of the participant industrial companies.

Figure 1: Some aspects of the BERTIM project: layout-planning, manufacturing and installation.

3.1 Qualitative assessment on preliminary phases

First it was needed to check that the Independence Axiom was fulfilled and that the Functional Requirements remained without any interference. There have been previous experiences for defining mainly process from layout planning to final module installation processes[11], but these studies focused only in the mass customization and installation processes and therefore lacked the socioeconomic aspects that are required in an overall perspective. The Customer attributes were given by the European Comission on the EE-01 call. But the main objectives need to be transformed into more approachable objectives, or Functional Requirements. The objectives in such calls are often not listed and the ideas can be overlapped. Therefore, a new list was drafted by the authors. First the higher hierarchy levels (FR 1 to FR 4) were gathered which were: energy consumption reduction, increase resource efficiency of the construction sector and arise refurbishment sector to a more efficient level. The solutions given to these concepts were generic, and therefore, the main given solutions (DP1 to DP4) were also generic. Though, in the next hierarchy level (i.e. FR1.1, FR1.2…), the solutions (DP1.1, DP1.2…) were more specific and tangible as shown in the next list:

- **FR1: Building energy consumption reduction.**
- **DP1: Development of prefabricated modules to renovate the existing building into a more energy performant building**
  - **FR1.1**: Passive measures for improving envelop energy performance
    - **DP1.1**: High insulated modules including windows allow increasing envelop insulation and air tightness and reducing thermal bridges reducing building energy demand.
  - **FR1.2**: Better quality standard and performance guarantee for the installed prefabricated modules and their integrated components, while enhancing indoor air quality.
    - **DP1.3** Prefabricated solutions that allow high level of accuracy, which enable high airtightness. The incorporation of mechanical ventilation systems assures correct ventilation of dwellings.
  - **FR1.3**: Efficient building services to reduce building energy consumption.
    - **DP1.2**: Old inefficient individual HVAC systems are replaced by efficient community HVAC systems. Installation modules integrate hot water distribution (for heating and DHW) and ventilation system with heat recovery. Solar and thermal panels are incorporated to the 3D modules in the roof.
- **FR2: Reduction of consumption of resources in the building refurbishment sector.**
- **DP2: Use of low primary energy demand materials and efficient processes.**
  - **FR2.1**: Use of low embedded energy materials.
    - **DP2.1**: Use of local timber with low primary energy demand from cradle to cradle and carbon footprint.
  - **FR2.2**: Use of recyclable materials
    - **DP2.2:** All materials used in BERTIM are recyclable materials.
  - **FR2.3**: Resource efficient manufacturing processes.
    - **DP2.3**: In principle, the prefabrication of elements with timber modules is more effective than manual process with current materials since the waste material is minimized.
- **FR3: Upgrade and arise building renovation towards an efficient industry.**
- **DP3: Implementation of mass customization** [12]**.** This concept has been widely used within the manufacturing industry that is being directed from massively produces goods towards a more tailored product for the customer. However, in building renovation, all the output is individualized, it is adapted to the existing building. Therefore, the next step is to move towards a higher degree of production. In Mass-customization there are several approaches. For the case of building renovation with prefabricated elements, two main premises are necessary (FR 3.1 and FR3.2)
  - **FR3.1**: Prefabricated Solutions to a wide range of building typology.
    - **DP3.1**: Adaptive standard but customizable modules. This solution was further developed by the Iturralde et al.[13]
  - **FR3.2**: Collaboration among involved stakeholders during the construction process through a digital information workflow among them from data gathering to installation phase.
    - **DP3.2**: Development of RenoBIM decision support tool that allows a holistic renovation process. The tool allows information flow based on BIM from building data gathering and development of building BIM mode.the assessment of more cost-effective solution, and it

is interoperable with energy efficiency calculation software, structural calculation software, the layout software and manufacturing CAM and CNC.

- **FR3.3**: Maximize off-site manufacturing process.
    - o **DP3.3**: Adapt existing workstations to achieve a more efficient manufacturing procedure and a higher prefabrication level in the final product. This topic is more developed by Iturralde [13]
- **FR3.4**: Reduction in installation time by at least 30%, compared to a typical renovation process for the building type.
    - o **DP3.4**: This topic is more developed by Iturralde et al. [13]. The installation time of the proposed renovation process by prefabricated modules is shorter than the traditional systems.
- **FR 3.5**: Adaptability of the solutions to the end-users or customers.
    - o **DP3.5**: Ensure low intrusiveness and impact during renovation works for building users. During the installation of the modules the building users can live in their dwellings with minor disturbances since the renovation system installation only needs to lift the modules with a crane to its position in the building envelope. The new distribution system for HVAC and DHW is integrated in the façade modules, so no rehabilitation work inside the building is necessary. Besides, the new windows and balconies are also integrated in the new façade modules, so once the self-supporting modules are installed, only minor works to integrate the old building and the new modules are needed.

Taking into consideration all this points, and following the Axiomatic Design method, it can be stated that the BERTIM project meets the requirements of the BERPM concept, and that the given solutions fullfil the Indepencence Axiom. However, the solutions given in these points are generic and therefore need a deeper and more quantitative evaluation that is developed in next sub-chapter.

There are some other requirements that weren´t addressed in this first evaluation. In that sense, the EU call reminds that there must some points addressed:

- Cost reduction comparing to current traditional renovation systems.
- In line with that, the provided BERTIM solution must enable a maximum return on investment of less than 10 years for end-users.
- Another requirement is related to the safe working environment. In principle, the BERTIM project is seeking for the automation of risky tasks and therefore . Create safe and dedicate work-environments off-site in the factory and on-site.
- Creation of high-skill jobs for workers who could master innovative construction tools. Incorporation of laser scanner, use of drones for the creation of BIM model, use of tools in BIM and use of energy calculation software. New tools that increase the efficiency of the process are introduced in the traditional renovation process.

For now, the research project hasn´t developed enough data for validating such concepts, but in the near future these points will be addressed. Besides the Functional Requirements and the given solutions or Design Parameters, there are Process Variables or constrains that limit the possibilities. In that sense, some of the aforementioned points, such as cost reduction, can be moved to this domain.

3.2 Quantitative assessment on intermediate phases

Once the Key Functional Requirements and the Design Parameters were verified as independent, the next step was to define measurable indicators. At this point, the Design Parameters achieved in previous step were transformed to measurable indicators. In the case of BERTIM, the goals were defined on the research proposal. These objectives can be defined as Ideal Solution or Objective (Objective in Table 1 and Table 2). Besides, we have the current or existing situation´s indicators (Existing in Table 1 and Table 2). These have been gathered in a previous analysis [11] based on the data mining of the participating companies and statistical data [13]. The main results of the current BERTIM research project were gathered in several Tests and Demonstrations achieved until now [11]. As a brief explanation of the indicators and its characteristics the next list is presented:

- **Indicator 1** (FR1.1): Reduction of the building façade U-value. The thermal performance of a façade will be characterized by calculating its U-value. A demonstration was realized at the Kubik building[11] [14]. The pre-existing brick façade, which was thermally characterized within [cross reference], had a U-value of 1.35 W/m^2K and the objective, considering design material properties, was to achieve a post-retrofitting U-value of 0.21 W/m^2K. After the installation of the BERTIM prototype in KUBIK, the experimental campaign analysis showed that the post-retrofitting U-values measured by the equipment were in vicinity of the design value, between 0.197 and 0.301 W/m^2K (average 0,249 W/m2K)
- **Indicator 2** (FR1.2): Ventilation rates that assure correct air quality without reducing energy efficiency. Current old building stock was not supplied with mechanical ventilation which assures correct air quality, space air renovation depends on the infiltration through façade and external openings. The objective in BERTIM is to reduce the non-controlled air renovation flows (infiltrations) by the retrofitting of the building façade and its corresponding openings, and assure the air quality by supplying the minimum air flow required, which means the minimum energy consumption, to assure the space air quality using centralized mechanical ventilation systems which include heat recovery. Different scenarios for different climates where simulated to validate this objective. Baseline scenario is an apartment block with medium or high permeable constructions, where the considered infiltration rates were assessed according to EN 13465:2004. The results showed that the improvement of the infiltration rates and the use of centralized mechanical ventilation with heat recovery achieve the objective of assuring space air quality without increasing energy consumption, even the primary energy consumption has a potential reduction range between 35% and 65% depending on the climate and pre-retrofitting façade. Therefore from a 100% baseline consumption, the proposed BERTIM scenario achieved an average 50% baseline consumption.
- **Indicator 3** (FR1.3): Reduction of building energy consumption. BERTIM project covers not only passive measures (retrofitting of the façades and openings with 2D modules, 3D modules to be installed in the roof) but also the integration of different active measures (RES integration, centralized building services). The objective is to reduce by at least a factor of 2 with respect to the current situation of the target buildings. Simulations carried out in the project for different scenarios, which consider all these possible passive and active measures, showed that the objective of reducing the current consumption is achievable, giving a potential energy primary consumption reduction range between 45% and 70%. Therefore from a 100% baseline consumption, the proposed BERTIM scenario achieved an average 42,5% baseline consumption.
- **Indicator 4** (FR2.3): Reduction of wasted material during manufacturing and installation process. To measure this, there have been several studies [15] that show that the regional construction context has its relevance. According to Llatas [15] [15]the refurbishment works require an on-site waste of 338,7 kg per floor square meter. The specific case of envelope energetic renovation, the data is not defined. In order to gather this data, an extrapolation was made: if it is considered a floor-area-to-perimeter-ratio of 1.2 and a inner distribution-envelope ratio of 1,6, the , the façade renovation should generate a waste of 89,13 kg/m^2. This is only an estimation. The objective should be to reduce this parameter to half (44,56 kg/m^2). In the analyzed case study, the waste calculation was calculated, which included the waste generated off-site (65 kg/m^2) The strategy in BERTIM is to keep the existing building envelope, and therefore this generates less waste than removing it.
- **Indicator 5** (FR3.1): Adaptability degree of the BERTIM process to existing building typology. There can be four main features in a façade: opaque wall, window, outer balcony and inner

terrace, that is the objective of BERTIM, to scope all 4 typologies. Existing manual processes can scope all these features, but current fully prefabricated modules can´t be placed as easily, there are no experiences without any after rework, therefore the current situation is 0. In BERTIM project, opaque walls and walls with windows have been only gathered, that is two façade types.

- **Indicator 6** (FR3.2): Number of stakeholders involved in a common platform information flow. With traditional methods, in the renovation projects the information is not shared digitally among different stakeholders. As an objective, it is meant that the building owner, the manufacturer, the architect and the energy engineer share a common platform. Thanks to the RenoBIM software developed within the BERTIM project, this objective is already achieved.
- **Indicator 7** (FR3.3): Prefabrication degree of the final product. Current techniques such as ETICS require fully manual and on-site procedures, therefore the prefabrication degree is 0. The objective of this research is to reach 100% of prefabrication degree. In the demonstrator carried out at Kubik, the modules weren´t prefabricated, it only reached 44% [Iturralde 2016].
- **Indicator 8** (FR3.4): Time reduction on installation time. With current techniques, in the case of ETICS and rain screen the data vary from 2,82 to 3,11 h/ m², therefore there can be a settled media of 2,97 h/m². The objective was to reduce this time 30%, therefore 2,079 h/m². In Kubik, the installation time was 1.73 h/m², but it must be considered the off-site manufacturing process for the fabrication of the modules is not accounted in this time.
- **Indicator 9** (FR3.5): Number of intervention inside the dwellings during renovation works. Currently, it is assumed that the As an objective, it is foreseen that all operations related to the envelope and the general supply of energy and ventilation is carried out without any intrusive activity. However, in the BERTIM project there was one activity indoors, because the service-room was not installed in a separate 3D module in the top as foreseen.

Besides these indicators, there are at list another two could be listed. But for now, in the BERTIM project, these data weren´t monitored. One indicator that is missing is the embedded energy of timber modules and its comparison to main trend materials for façade renovation. Another indicator that could be inserted is the percentage of recyclable materials. If we compare the current traditional renovation methods such as ETICS, we see that mainly these are conformed of expanded polystyrene (EPS) where recyclability ratio is quite low. Meanwhile, with the BERTIM modules, the recyclability is higher, but still these data needs to be gathered.

Table 1: indicator

			Attributes				**Normalized attributes**		
	W	**D**	**Unit**	**Existing / Current**	**Objective**	**BERTIM**	**Existing / Current**	**Objective**	**BERTIM**
I1	1/12	min	W/m²K	1,35	0,21	0,249	0,17	0,03	0,03
I2	1/12	min	percentage	100	50	50	0,11	0,06	0,06
I3	1/12	min	percentage	100	50	42,5	0,12	0,06	0,05
I6	1/12	min	kg/m²	89,13	44,56	65	0,10	0,05	0,07
I7	1/12	max	façade types	0	4	2	0,00	0,15	0,07
I8	1/12	max	stakeholders	0	4	4	0,00	0,11	0,11
I9	1/12	max	percentage	0	100	44	0,00	0,15	0,07
I10	1/12	min	h/m²	2,97	2,079	1,71	0,10	0,07	0,06
I11	1/12	min	intrusive acts	2	0	1	0,15	0,00	0,07

In Table 1 all the indicators of the Current situation (E), the Ideal Result (O) and the current BERTIM project´s situation have been gathered. The weight for each of the indicators was same on this paper. The direction means which value is optimal for the referred indicator, maximal or minimal. In order to normalize the indicators value, the Equation 1 is used and applied. Once we have normalized values, this can be transformed to the total sum of minimized and maximized normalized indices by applying Equation 2 and Equation 3. With this values it can be achieved the Alternative‘s significance Qj by applying Equation 4. And finally, the Alternative´s degree of efficiency in 0-100 scale is achieved (Equation 5), being 0 in current state (E) and 100 in objective (O).

Equation 1: $$\bar{b}_{ij} = \frac{2b_{ij}}{(\sum_{j=1}^{n} b_{ij})} * W$$

Equation 2: $$R_j = \frac{1}{2}\sum_{i-k+1}^{m}(\bar{b}_{ij})$$

Equation 3: $$P_j = \frac{1}{2}\sum_{i=1}^{k}(\bar{b}_{ij})$$

Equation 4: $$Q_j = \frac{\sum_{j=1}^{n} Rj}{R_j \sum_{j=1}^{n}\frac{1}{R_j}} + P_j$$

Equation 5: $$N_j = \frac{Q_j - Q_{min}}{Q_{max} - Q_{min}} 100\%$$

Table 2: final assesment

	Existing	**Objective**	**BERTIM**
Total sum of maximizing normalized indices Rj	0,00	0,21	0,13
Total sum of minimizing normalized indices Pj	0,37	0,13	0,17
Alternative‘s significance Qj	3,08	7,90	6,08
Alternative‘s degree of efficiency	**0,00**	**100,00**	**62,27**

We can see that the scenario BERTIM hasn´t surpassed the objective of the BERPM research objectives. and there is room for further amelioration. The objective of the research is to ameliorate the position of all cases during the next phases of the research project. For that purpose, all indicators must be taken into account.

4 Conclusion

This paper explains the method for evaluating developing technology. It takes into account the eleven main existing characteristics. Those are used for qualitative aspects using the Axiomatic Design. Besides, the eleven Indicators and their Functional Requirements are proposed to be used for a quantitative evaluation using the COPRAS method. It can be said that for the analyzed case study, this assessment will guide the ongoing research and clarify the approach for future solutions. In the case of BERTIM, it has been pointed out the major needs for achieving the so called BERPM. It has to be noted that this method can be also used for evaluating research proposals within a certain context. In this paper, the BERPM has defined the characteristics and the criteria. But the method can be valid for being applied in some other contexts. This approach can be useful for both drafting research proposals and for evaluating research proposals. As future desirable works, it could be interesting to use this assessment with other projects.

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