Decision Making in Near Zero Energy Building Refurbishment: A Technology Alternatives Ranking Tool

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Decision Making in Near Zero Energy Building Refurbishment: A Technology Alternatives Ranking Tool

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Abstract: Decision making in the context of Near Zero Energy Building refurbishment is subjected to heterogeneous stakeholders, tools and objectives. This paper presents a methodology to facilitate stakeholders collaboration in the refurbishment processes and identifies decision support approaches to help on the main decision milestones. This methodology is supported by a prototype (user interface and algorithm) of a decision support system (DSS) that allows ranking different refurbishment technologies. The proposed DSS uses a multi criteria decision method that combines weighting and fuzzy dominances approach. The approach is illustrated with a real data set to rank insulation materials.

Keywords: Decision Support System, Sustainable Decisions, Near Zero Energy Building Refurbishment, multi criteria decision making, alternatives ranking

1. INTRODUCTION

Refurbishment of existing residential buildings has been identified as a top priority in the economic context of Europe. It is expected that, by 2050, about half of the existing building stock in 2012 would still be operational (European Parliament, 2008). Therefore, the European Union (EU) aims to increase the current 1% annual renovations rates to 2,5%. Considering also that the construction sector is a huge energy consumer (Ma et al., 2012), the EU aims to encourage Near Zero Energy Building (NZEB) renovation initiatives.

The challenges are multidisciplinary, and demands innovative developments focused on several targets including technical, economic, social, environmental and legal to enhance a high-technologized building sector.

The work presented here is part of REZBUILD H2020 project (Refurbishment decision making platform through advanced technologies for NZEB renovation). Within the numerous challenges, one of the project objectives is developing novel collaborative refurbishment methodologies.

NZEB refurbishment projects start with the need from a customer (e.g. building owners, occupants) to improve the characteristics (aesthetics, structure, insulation properties…) of an existing building. Three main operational processes are then to be fulfilled to achieve these improvements: the NZEB design process, the refurbishment implementation and finally the monitoring of the renovated building. These processes involve the participation of different stakeholders, starting with the customers, followed by the architects and designers, refurbishment managers, technology providers, constructors and simulation experts. Within the NZEB design process (Figure 1), three main decision milestones have been identified as critical in the REZBUILD project: (i) the preliminary assessment step (i.e. setting sustainability goals, building diagnosis) (ii) the selection of refurbishment technological solutions and (iii) the final refurbishment plan decision.

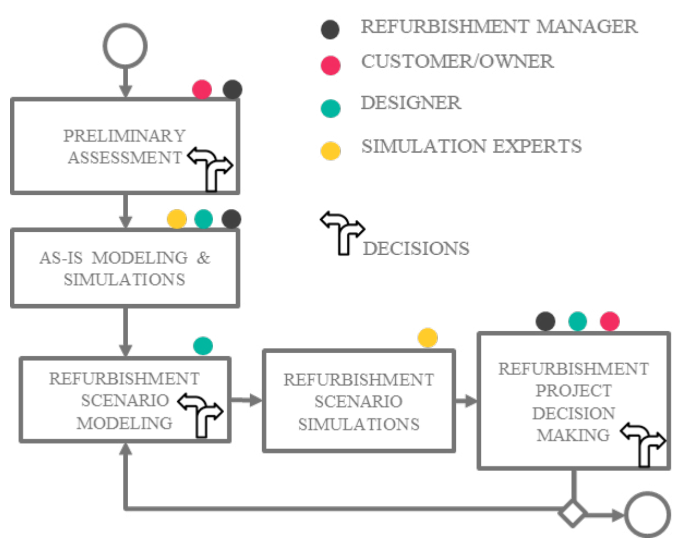

Fig 1. NZEB design process milestones

To enhance NZEB building performances and to align with EU time and cost reduction targets, decision makers (DM) must consider a huge amount of information. Therefore, like in the production industry in the 90's, the building sector is being more and more confronted with the necessity for capitalization and exploitation of knowledge generated through all its value chain. The three decision milestones of the process involve an important amount of very diverse data that must be collected from multiple stakeholders from diverse fields, and from multiple heterogenous information systems. Therefore, the use of this data in the decision process is complex and difficult to

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be performed without support tools, and only based on experience or a single expertise.

The building sector started addressing the challenge of data structuring through the development of Building Information Modelling (BIM) which is a digital representation of physical and functional characteristics of a facility. The recent effort to create interoperable BIM file format for this model may allow the gathering and contextualization of any data related to the future building, and the building process, in a centralized repository. This provides an opportunity to address decision stakes with the development of Decision Support Systems (DSS) which allow the building industry to exploit all available data and to help DM(s) on their choices.

The diversity of stakeholders and performance objectives creates three challenges to be addressed by decision making approaches (Section 2) that lead us to introduce a general methodology to support the refurbishment decision process (Section 3). Part of this strategy is then implemented as an interactive selection of refurbishment technologies tool dedicated to designers (Section 4).

2. DECISION IN NZEB REFURBISHMENT PROCESS

Decisions are related to the renovated building and the refurbishment process. (Ma et al., 2012) produced an extensive review which covers all the refurbishment process and points out the -- still -- long way for academics and professionals to go to make existing building stock sustainable. From our point of view, the complexity of decision making in the context of sustainable building retrofitting comes mostly due to both the performance objectives diversity (renovated building) and the stakeholder collaboration (refurbishment process) on the different decision milestones.

2.1 Decision milestones

From Figure 1, we identify three main decision milestones where DSS can assist stakeholders:

- Pre-assessment step (1st step in Figure 1): the purpose of this assessment is to provide the scope of the work by setting project general targets (e.g. 15% of energy savings) and by identifying priorities about the technological solutions to be implemented (e.g. changing of windows).
- Selection of refurbishment technologies (3rd step in Figure 1): during the design of the future building, designers must choose within alternative technologies the ones to be implemented in each building part (e.g. windows, insulation, heating system…). There is a plethora of alternatives that exists for each family of refurbishment technologies and multiple criteria decision tools must be considered to fit end-user's requirements and designers' preferences.
- Final design decision (5th step in Figure 1): after designers have made several refurbished building proposals and simulation's experts have computed indicators related to end-user's requirements (e.g. energy consumption, return on investment, air quality…), there is a need to select the final design that will be built.

2.2 Renovated building: A multi-criteria problem

NZEB is defined as "a building with very high energy performance where the nearly zero or very low amount of energy required should be extensively covered by renewable sources produced on-site or nearby" (European Parliament, 2008). In the literature, proposed indicators to measure NZEB performance are close related to the sustainability Triple Bottom Line (TBL), which considers economic, environmental and social dimensions (Elkington, 1998).

Decisions in sustainable refurbishment are multi-objective problems subject to conflicting objectives, many constraints and limitations such as the building, the environment, or still the legislation (Ferreira et al., 2013; Jafari and Valentin, 2018; Ma et al., 2012; Mjörnell et al., 2014; Nielsen et al., 2016). Even if many indicators measures exist in the literature, Mjörnell et al. (2014) pointed out the difficulties of gathering the necessary data to compute them. Thus, many simplifications and assumptions are often made in multi-criteria decision tools. However, the approaches that includes exhaustive evaluation such as a group decision framework incorporating outranking preference model and characteristic class (Kadziński et al., 2018) or decision support based on neural networks proposed by (Zavadskas et al., 2004) are highly time consuming.

On their literature review, Ferreira et al. (2013) identified two main research challenges for refurbishment decision making: develop fast and effective methods which take advantage of existing algorithms and consider uncertainty to avoid poor decisions. Ma et al. (2012) also stress that a critical challenge encountered is that there are many uncertainties, such as climate change, services change, human behavior change, government policy change, … Considering uncertainty is essential to help finding the best retrofit options in terms of energy efficiency, but also costs and other indicators, during building whole life.

2.3 Stakeholders Collaboration

Unlike many industrial sectors, the building industry is characterized by fragmented decision-making processes in which actors participate according to their own set of rules, tools, skills and interests to collectively achieve the final goal of satisfying customer needs (van Bueren and Priemus, 2002). Furthermore, customers are important stakeholders in the decision process of the overall refurbishment project but are usually not part of the building industry. Decentralized decision-making presents the risk to miss opportunities in terms of sustainable decisions if there is not a collaborative approach.

2.4 Stakes for research

From the discussion above, we point out three challenges to improve refurbishment decision process:

- **Heterogeneity of objectives / goals**: Balancing between algorithms complexity (number of criteria, exhaustivity) and decision time.

  Opportunities: Simplify algorithms (and tools) so that are flexible enough to meet the changing demands of sustainable building industry objectives.
- **Heterogeneity of stakeholders:** Understanding and integrating stakeholder's view point in the different decision milestones.

  Opportunities: '*A priori*' and 'interactive' multi-criteria decision-making (MCDM) methods allows integrating DM preferences in the decision-process (Wang et al., 2009). Special attention must be put to the user interface ergonomics to ensure dynamic stakeholders elicitation (Ambrosino et al., 2016).
- **Heterogeneity of tools:** Facilitating information exchange within incompatible tools and files formats in heterogeneous context to Accelerate and improve the integration of stakeholder's contributions.

  Opportunities: BIM data files have been pointed out to gather and exchange building related information, including performance indicators (Gerrish et al., 2017; Habibi, 2017).

3. METHODOLOGY

To address the challenges discussed on the previous section, we don't expect stakeholders changing specific business tools or decision processes but being able to exchange and exploit useful information.

Thus, the REZBUILD project innovates by developing a methodology based on an "ecosystem" (Figure 2) of stakeholders, tools and technologies that facilitates the NZEB refurbishment decision making. This "ecosystem" is organized around a Collaborative Refurbishment Platform (CRP) with a BIM centered data management.

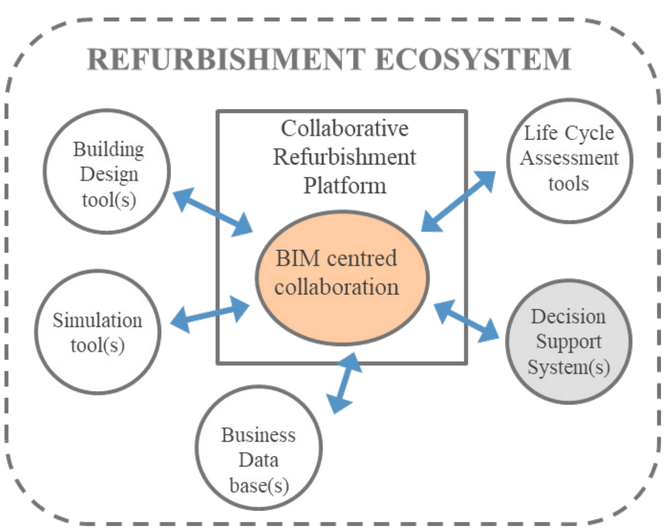

Fig 2. Refurbishment ecosystem

3.1 The Collaborative Refurbishment Platform

The CRP is intended to gather and manage data coming from different and sometimes incompatible sources. BIM has been identified as a crucial technology to implement this hub due to the huge potential expectations regarding interoperability and decision making. It allows to ensure that any information related to a refurbishment project is traceable from the project BIM (Figure 3).

This approach will enable stakeholders to visualize almost any kind of information, integrate their contributions and export data generated previously, always associated to the BIM. Among the data stored in the project BIM, end-user requirements, building pre-assessment results, computed indicators from simulations and designer's propositions (alternative designs) are particularly relevant for decision-making (Habibi, 2017).

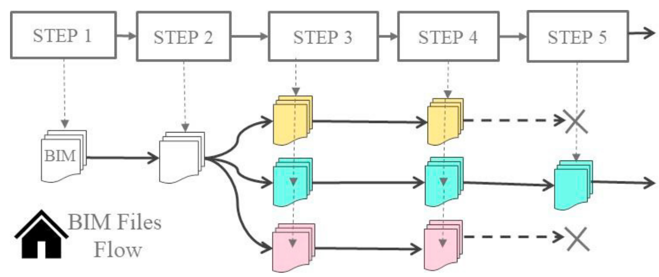

Fig 3. BIM files flow in the CRP

In association with the BIM files, the refurbishment process needs the use of external data sources to provide useful information for the decision process. Among them, databases containing descriptions of all the usable refurbishment technologies, expert knowledge (business rules…) or external indicators (financial, environmental…) are relevant to help designer's decision-making. However, the huge amount of available data may become an issue because it renders the comprehension and control of the decision by human operators very complex. That is why DSS are required to collect, synthesize and pre-analyse all available data, to make them intelligible to designers and to help them in their choices.

In this article, we develop a DSS for the 'selection of refurbishment technologies' milestone. This decision milestone has the particularity to be performed by a single stakeholder (designer) but with the inputs from end-user expectations and the information from technology alternatives database. The decision process needs a dynamic interaction between the DM and the DSS to find a suited technologies order.

3.2 Ordering alternative technologies

As discussed in previous works (Laguna Salvadó et al., 2018), (i) considering human knowledge (end-user and/or experts) while implementing decision making algorithms in multi-objectives problems, and (i) using ordering fuzzy approaches (instead of only considering technological indicators and finding "optimality"), enables to find suitable solutions aligned with the DM priorities. Moreover, hybridization of human knowledge and technological data (statistics) can also improve decision processes (Villeneuve et al., 2017).

In the context of refurbishment, MCDM methods have been widely implemented to rank alternatives. The most used approaches for weighting criteria in building literature is the AHP (analytical hierarchy process) method, in which criteria are compared pair-wise, subjectively determining their relative importance. Other such as elementary weighted sum, or outranking methods (PROMETHEE, ELECTRE) also can be relevant for technology ranking. As discussed in (Arroyo et al., 2015) research to find alternative approaches is encouraged. Being aware that criteria contain perhaps imprecision or vagueness inherent in the information. MCDM "a priori" methods combined with fuzzy methodologies can be applied to take care of the data imprecision (Wang et al., 2009).

4. PROPOSAL

Two main contributions are presented in this section:

(i) a dynamic user interface, and

(ii) a ranking algorithm to gather user preferences and provide the ordered refurbishment technologies list.

The proposal is illustrated with a scenario based on data from (Kadziński et al., 2018). A prototype is available at: https://rezbuild-sorter.herokuapp.com/

4.1 Alternative technologies decision problem

The objective of the DSS is to dynamically combine the user preferences and indicators to provide a ranking of suitable refurbishment technologies.

Thus, designers must be able to define the most important indicators (preferences) to give more weight to some indicators in the final ranking. Moreover, to avoid discriminating too closely near-indicators technologies, it is relevant to be able to add some uncertainty to the indicators values so that rankings of two similar, but not identical, technologies are not too different.

In consequence, we defined two decision parameters to reflect these features in the decision support algorithm. The **importance** parameter characterizes the judgment of the DM about the weight of an indicator compared to others in the ranking of technologies. As discussed previously (section 2.2), considering uncertainty is essential in a DSS, that is why we defined the **fuzziness** parameter characterizes the uncertainty level defined by DM on an indicator allowing more flexibility in the ranking.

4.2 Dynamic user Interface

The interface gathers the indicators selection, importance and fuzziness and provides the refurbishment technologies ranking (Figure 4).

On the center of the screen (A), the list of refurbishment technologies is displayed. On the left (B), the list of indicators that characterize the refurbishment technologies is shown. A drag and drop system towards the "show" box (C) allows showing the indicators in the center.

To trigger the **ordering algorithm**, indicators must be drag and drop towards the "preferences" box (D). The **selected** indicators are placed there depending on the **importance (↔)** and the **fuzziness (↕)** that the user grants to them.

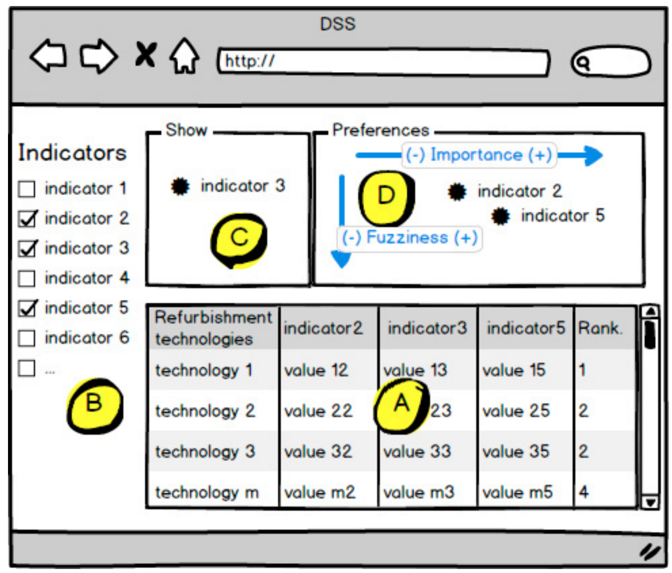

Fig. 4. User interface mock-up

Once there is at least one indicator placed in (D), the ordering algorithm is triggered, and the center of the screen (A) shows an ordered list (ranking) of refurbishment technologies. The computing time is insignificant, so the user can adjust the position of the indicators and obtain the ranking on a dynamic way.

4.3 Ranking Algorithm

From the user interface the algorithm gets the indicators to be considered, the fuzziness, and the importance (Table 1 & 2) of the chosen indicators. Importance can take any value between 1 and 100% of weight. Fuzziness is limited between 0 and 20% of the indicator value range to avoid from becoming the only information and ordering from being irrelevant.

Table 1. Data from the refurbishment technologies database

	indicator1	indicator 2	indicator'n'
Techno1	Value '11'	Value '12'	Value '1n'
Techno2	Value '21'	Value '22'	Value '2n'
Techno'm'	Value 'm1'	Value 'm2'	Value 'mn'

Table 2. Data from the user interface

	indicator 1	indicator 2	indicator'n'
Importance	Importance(1)	Importance(2)	Importance(n)
Fuzziness	Fuzziness(1)	Fuzziness(2)	Fuzziness(n)

The ordering algorithm is based on four steps:

1. *Fuzzy Indicators*: an interval [min max] for each techno-indicator couple centered on the *Value* and proportional to the indicator range and fuzziness.
2. *Fuzzy Dominances:* is the number of technologies dominated by *Fuzzy Indicator* (among the same indicator).
3. *Total dominance*: Importance weighted sum of *Fuzzy Dominances*.
4. Refurbishment Technologies *ranking* by *Total dominance.*

4.4 Use case: Selecting an isolation material

To illustrate the proposal, we present here a scenario. Let's consider a Designer that must choose among a list of 13 isolation materials (refurbishment technologies). Each material has been evaluated from the socio-economic and environmental viewpoints: (g1) comfort, (g2) CO2 emissions reduction, (g3) profitability, (g4) human health, (g5) ecosystem quality and (g6) resources consumption. The data (Table X) comes from a real case. For more information on the indicators, materials and data gathering please refer to (Kadziński et al., 2018). For the illustration purpose, all the indicators have been normalized in a 0 to 5 scale, where the more is the better.

Table 3. Scenario dataset (Kadziński et al., 2018)

	SOCIAL	ECONOMIC		ENVIRONMENTAL		
Insulating material	**g1**	**g2**	**g3**	**g4**	**g5**	**g6**
Autoclave aerated complete	3,21	3,33	3,86	4,61	4,99	4,52
Corkslab	4,28	4,26	3,83	3,94	4,55	3,59
Expanded perlite	4,37	4,29	4,64	4,78	4,99	3,49
Fibreboard hard	4,65	4,58	3,13	3,03	4,64	0,00
Glass wool	4,62	4,68	4,47	4,56	4,97	3,86
Gypsum fibreboard	0,68	0,73	1,18	2,60	4,91	2,47
Hemp fibres	4,34	4,46	4,78	5,00	4,93	4,81
Kenaf fibres	4,62	4,65	4,92	4,87	4,63	5,00
Mineralized wood	3,79	3,75	3,17	2,83	4,89	2,00
Plywood	0,00	0,00	0,00	0,00	0,00	0,38
Polystyrene foam	4,54	4,67	4,56	4,98	5,00	4,50
Polyurethane	5,00	5,00	4,71	4,42	4,99	3,49
Rock wool	4,65	4,73	5,00	4,10	4,98	4,75

To place the preferences, the assumptions are (Table 4): the designer gives more importance to g2 and g6 than to g1 to express the customer preferences. Moreover, she/he knows that most of the alternatives have a good comfort indicator and is quite confident, so a little fuzziness is given. Then for g2 and g3, he/she has some mistruth, so the fuzziness is more important.

Table 4. Data from the user interface

	comfort	CO2	Resources consumption
Importance	50%	100%	100%
Fuzziness	5%	10%	15%

The algorithm will treat the information as follows:

1) Fuzzy indicators are computed for all the technology-indicator couple based on the Fuzziness (Table 5). A fuzziness of 10%, over an indicator range of 5, rest and adds a 0.5 to all the comfort values.

Table 5. Scenario fuzzy indicators

Insulating material	g1	g2	g6
Fuzziness	***5%***	***10%***	***15%***
Autoclave aerated complete	[2,96 3,46]	[2,83 3,83]	[3,77 5,27]
Corkslab	[4,03 4,53]	[3,76 4,76]	[2,84 4,34]
Expanded perlite	[4,12 4,62]	[3,79 4,79]	[2,74 4,24]
Fibreboard hard	[4,40 4,90]	[4,05 5,08]	[-0,75 0,75]
Glass wool	[4,37 4,87]	[4,18 5,18]	[3,11 4,61]
Gypsum fibreboard	[0,43 0,93]	[0,23 1,23]	[1,72 3,22]
Hemp fibres	[4,09 4,59]	[3,96 4,96]	[4,06 5,56]
Kenaf fibres	[4,37 4,87]	[4,15 5,15]	[4,25 5,75]
Mineralized wood	[3,54 4,04]	[3,25 4,25	[1,25 2,75]
Plywood	[-0,25 0,25]	[-0,50 0,50]	[-0,37 1,13]
Polystyrene foam	[4,29 4,79]	[4,17 5,17]	[3,75 5,25]
Polyurethane	[4,75 5,25]	[4,50 5,50]	[2,74 4,24]
Rock wool	[4,40 4,90]	[4,23 5,23]	[4,00 5,50]

2) The dominances are computed (Table 6). Each interval is compared with the rest of intervals within the same indicator. If the upper bounds are smaller than the reference lower bound, there is a dominance.

3) The total dominance is computed with the importance weighted sum (Table 6).

Table 6. Technologies ranking by Total dominance

Insulating material	g1	g2	g6	Total dominances	Ranking
Importance	***50%***	***100%***	***100%***		
Polyurethane	7	4	2	3,8	1
Hemp fibres	4	3	3	3,2	2
Kenaf fibres	4	3	3	3,2	2
Rock wool	4	3	3	3,2	2
Glass wool	4	3	2	2,8	5
Polystyrene foam	4	3	2	2,8	5
Autoclave aerated complete	2	3	2	2,4	7
Expanded perlite	4	2	2	2,4	7
Corkslab	3	2	2	2,2	9
Mineralized wood	3	2	2	2,2	9
Fibreboard hard	4	3	0	2,0	11
Gypsum fibreboard	1	0	2	1,0	12
Plywood	0	0	0	0,0	13

4) The materials are ranked then considering the Total dominance (Table 6).

4.5 Results discussion

The algorithm permits to order the refurbishment technologies with both technological indicators and user preferences. Thanks to the fuzziness and dominances, the indicators with lightly different values are blurred and not crucial for the final ranking. In the use case, if the weighted sum is computed directly to the indicators value (no fuzziness and dominances) the Polystyrene foam (rank 5) takes the first position instead of the Polyurethane (rank 1). Also, if all fuzziness is diminished up to 1%, the polystyrene foam remains on the 5th position but Kenaf fibers takes the 1st one.

The fuzziness levels have a direct impact on the number of technologies with the same 'Total dominance' score (i.e. rock wool, kenaf fibers, hemp fibers). With the approach presented, there is no relative order between them, so they have equivalent rankings. Further research must depict the impact of this issue on the DM's choices, and potential criteria selection to obtain an absolute order.

Kadzinski et al. (2018) implemented a three-stage multi criteria approach. Instead of ordering insulation material alternatives, they propose to sort them within 3 pre-defined categories. The alternatives assigned to the best class (most sustainable) are the same that we find on our top 6 ranking.

To go further and objectively evaluate the proposed methodology, we plan to compare it with all the alternative methods identified in (Wang et al., 2009). Moreover, as discussed previously, we are going to test the benefits of the proposed user interface by conducting user tests with REZBUILD project partners.

5. CONCLUSIONS

This paper presents (i) a methodology for the refurbishment NZEB buildings process that facilitates stakeholder's collaboration, tools interoperability, data gathering, decision making, and (ii) a dynamic approach to rank alternatives based on criteria and user preference in the context of building refurbishment. A prototype is available at: https://rezbuild-sorter.herokuapp.com/

Several perspectives emerge from this initial works. On one side, the user-interface must be tested with potential users in the context of REZBUILD H2020 project. The objective is to address the human-machine interactions challenges (i.e. interface ergonomics, data visualization). On the other side, the algorithm must be tested and adjusted with larger data set volumes coming from the Consortium to validate the fuzzy dominance approach and the relevance for end-users with a full set of real and contextualized data.

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