Reno-DM: A Knowledge model to support the decision-making process in the context of residential building renovation projects

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Abstract. The decision-making process to select solutions in residential building renovation projects is a complex task. These projects encounter rigid governance and ownership structures, participation of multiple stakeholders, diverse requirements, and a lack of consensus regarding methodologies and tools used within the decision-making process. Addressing some of these challenges requires a shared understanding of this domain. Therefore, this paper presents the Renovation-Decision-making (Reno-DM) model mapping key knowledge from the decision-making in renovation projects. It considers project characteristics, context information, building features, and their relation to aspects of the decision-making itself. The development of the Reno-DM model relies on an existing decision-making representation and the extraction of new concepts from interviews with stakeholders taking part in renovation projects and related literature. The interviews are analysed following an inductive content analysis approach. The Reno-DM model is developed in the form of an ontology. It provides a basis from which future knowledge management and reuse applications can be developed and deployed to support improvements in the decision-making process in the renovation field.

Keywords: Decision-making, building renovation, knowledge representation, ontology

1. Introduction

While new developments are built with high energy efficiency standards, renovation projects are often considered complex because they encounter challenges such as shared governance structures, ownership models, interests and incentives alignment complexity between different actors, and strict rules on decision-making procedures [1]. These projects face complex scenarios such as multi-family buildings with multiple owners, some of them living in the building and other units occupied by tenants [2]. Due to the complexity of different factors and diversity of stakeholders involved, barriers arise at multiple levels of the decision-making process, threatening to stop the renovation initiative [3].

Almeida & Ferreira [4] suggested that acceptance, motivation, and other aspects from stakeholders and decision-makers need to be characterized and understood to overcome some of the barriers in renovation projects. Elements such as regulation, legal aspects, and projects characteristics need also to be mapped to understand how they influence the decision-making process. The lack of shared understanding can often lead to difficulties in identifying requirements for tasks from a certain domain [5]. This can be the case of the decision-making process in renovation projects. Multiple possible scenarios, stakeholders’ interests, and renovation solutions requirements bring particularities to each
project that may reduce the possibility to replicate decision-making practices in new renovation projects. According to Kamari et al. [6], there is a lack of consensus regarding criteria, methodologies, and tools to support the decision-making process in renovation projects.

A shared understanding of decision-making aspects can contribute to building a more uniform approach to address some of the challenges of renovation projects [7]. Knowledge representations have been developed to support the decision-making process in the context of environmental problems [8], selection of domestic hot water systems [9], collaborative product design [10], among others. However, to the best of our knowledge, the decision-making process in residential building renovation projects seems to be a neglected area of study in this field. A knowledge representation covering the decision-making process in residential renovation projects can formalize abstract objects influencing the decision-making, the relation between them, and the knowledge of stakeholders and practitioners taking part in the process. Moreover, developing this knowledge representation in a machine-readable format can contribute to developing and implementing tools to support the acquisition, management, reuse, and retrieval of key information throughout the decision-making process of renovation projects.

Therefore, this paper presents the Renovation-Decision-making (Reno-DM) model, a knowledge representation in the form of an ontology, mapping relevant aspects of the decision-making process to select renovation solutions in the context of residential building renovation projects. The proposed model reuses an existing decision-making knowledge representation and extend it to match the particularities of the renovation domain. The Reno-DM model gathers key elements such as project characteristics, context information, building features and their relation to aspects of the decision-making itself such as alternatives, criteria, stakeholders, etc. The development of the model relies on the extraction of new concepts from interviews with stakeholders playing different roles in renovation projects and related literature. Transcripts of the interviews were coded and analyzed following an inductive approach to identify key concepts and build a knowledge network including different classes, properties, and relationships between them. The remainder of the paper is structured as follows: Section 2 presents the background and research motivation. Section 3 summarizes the methodology to develop the Reno-DM model. Section 4 presents the Reno-DM knowledge model. Finally, the discussion and conclusions are synthesized in Sections 5 and 6, respectively.

2. Background and research motivation

Common barriers and drivers of decision-makers in renovation projects are related to the building context, regulatory and financial aspects, external factors and information, knowledge and socio-economic issues [4]. Some of these aspects can impact the decision-making process. Authors such as Mangold et al. [11] classified the decision-making process according to the ownership structures and stakeholders involved in renovation projects. The EU Heating and Cooling strategy [12] also highlighted that different ownership forms require different approaches to drive building renovations. Decisions on renovation are also dependent on stakeholders’ motivations, demographic characteristics, among other elements [13]. For instance, owners often do not have the expertise required to select renovation alternatives [14] and they require professional assistance [15]. Interactions with an external expert can provide explanations, generating more trust in the alternatives [16], which can influence the decision-making process itself. These and other interactions between stakeholders play an important role. A common barrier in European countries is the collective decision problem, in countries such as Germany and France stakeholders should reach >75% and >50% of consensus on decisions on renovation [2]. Another important constraint is the aesthetics and cultural heritage of buildings or neighborhoods, which makes it difficult to reach a consensus about the best solution to implement [4].

Furthermore, other elements such as legal frameworks, construction regulation, and policies can also influence the decision-making process. For instance, the Energy Efficiency Directive (Directive 2012/27/EU) in Europe required member states to address the split of incentives between stakeholders, regulating decision-making processes in cases such as multi-owner properties [1]. Regulation may also impose time frames and alternatives for the renovation. In Luxembourg, an energy certificate obtained for an existing building includes renovation measures, which should be performed within 4 years after
the certificate was issued [3]. Having a shared understanding of aspects related to stakeholders, building features and its context, ownership, regulations, among other relevant concepts can facilitate the communication between stakeholders, acquisition and management of key data, and identification of requirements to perform the decision-making process efficiently. Friege & Chappin [13] suggested that a model mapping decision-making processes may result in refining existing instruments or developing new innovative mechanisms to tackle the decision task.

A formalized knowledge representation can enable a shared understanding for a certain domain [5]. A knowledge model in the form of an ontology includes a set of concepts/classes, relations/properties, instances/individuals, and axioms representing a domain. Some of the existing ontologies covering the decision-making domain include the decision provenance ontology [17], the decision ontology [18], and the core ontology proposed by Guizzardi et al. [19]. These existing models approached the decision-making from a general perspective, which may not reflect the view and requirements of renovation projects. For instance, the model proposed in [17] focused on decisions already made, and the models proposed in [18,19] included abstract concepts such as QuestionForConfirming/Indicating, IntrinsicMoment, ValueAscription, among others, which may be not familiar for renovation projects stakeholders. When considering decisions in renovation projects, it is important to recognize that such decisions are not separate from other decisions concerning the building and its users [2]. An ontology covering this domain should map not only the information requirements to select a renovation solution but the particularities and elements that can influence or have an impact on the decision-making components such as criteria, alternatives, stakeholders, etc. Overseeing or not anticipating these elements may bring difficulties to the decision-making process within the project.

Therefore, the objective underlying this study is to develop a knowledge representation in the form of an ontology to map and formalize the knowledge from the decision-making domain in renovation projects. Figure 1 shows how the proposed Reno-DM model could support stakeholders involved in the decision-making process. A knowledge base relying on the Reno-DM model can add transparency to the decision-making process since the key information can be documented in it and stakeholders can access and review criteria, renovation alternatives’ characteristics, applicable regulations, etc.

![Figure 1. Potential use of a knowledge representation of decision-making in renovation projects.](image_url)

Since ontologies support humans and computers to understand and fully utilize domain knowledge [20], the Reno-DM model can be the starting point to develop knowledge management applications to acquire, process, retrieve, and reuse key information. Strategies such as the pattern recognition applied in [21] and similarity measures presented in [22] can be combined with the Reno-DM model to study how capturing, storing, and re-utilizing knowledge from previous projects can support and enhance the decision-making process in new renovation projects. Moreover, literature suggests that the success of policies depends on how stakeholders’ decision-making is taken into account [13]. Capturing and reusing this knowledge can support policymakers. They can access information from experiences in previous renovation projects, allowing them to align the policies to real practices and promote policies...
to encourage new methods or enhance the existing ones that hinder the decision-making process. The research approach to develop the proposed Reno-DM model is presented in the following section.

3. Research approach and methods

Figure 2 presents the procedure to develop the Reno-DM knowledge model in the form of an ontology. It relies partially on the guidelines proposed in [23]. The review of the state of the art identified the motivation to develop the model. The specification of the ontology defined its purpose, scope and uses. Meanwhile, the acquisition and conceptualization step identified the relevant knowledge to be included in the model. These steps are discussed in the following subsections. The validation of the model is proposed as a future research step in Section 5. Discussion.

![Figure 2. Methodology to develop the Reno-DM model.](image)

3.1. Knowledge model specification

The specification stage established a general description of the ontology using natural language to define minimum information regarding its purpose, domain, users, and use.

**What is the purpose?** Reno-DM is developed to: a) model concepts related to the decision-making process to select renovation solutions in residential renovation projects, using graphical descriptions understandable and accessible to users and practitioners involved in this domain; b) create a shared understanding of the decision-making process to enable better communication between stakeholders; c) develop a starting point to collect heterogeneous data in a structured approach to enable the acquisition, management, retrieval, and reuse of knowledge in renovation projects.

**What is the scope?** The model covers concepts, relations, and attributes concerning the building under renovation, the project (e.g. local regulation, property governance, stakeholders, etc.), and the decision-making process (potential alternatives, criteria, consensus mechanism, etc.). Competency questions such as *Who is the final decision-maker that selects the renovation solution? What are the alternatives defined for the renovation project? What are the risks that could appear throughout the decision-making process?* guided the identification of relevant concepts from the studied domain.

**Who are the intended end-users?** The final intended users are project managers, housing companies, owners, tenants’ associations, and other stakeholders involved in the decision-making process to select a renovation solution in the context of residential renovation projects.

**What is the intended use?** The intended use of the ontology is to support the characterization of residential renovation projects regarding the decision-making process and encourage the structured acquisition and recording of key data to support this task. A knowledge base relying on the Reno-DM model can facilitate retrieval and reasoning over relevant information throughout the decision-making process. A user may list the information related to alternatives, the preferences of the different stakeholders, the requirements imposed by regulations, among others. Stakeholders involved in future renovation projects can also reuse the accumulated knowledge and experiences from previous projects.

3.2. Knowledge capture and conceptualization

Since the reuse of existing knowledge resources is important in the development of ontological models, we searched for existing resources in repositories such as the Linked open vocabularies [24]. Using *Decision* and *Renovation* as individual search terms, we identified the decision provenance
ontology [17] and the decision ontology [18]. Nevertheless, since the former focused only on decisions already made and the latter included abstract concepts that may not be clear for renovation projects stakeholders, we did not reuse these models. From the related literature, we identified the model proposed by Kornyshova and Deneckère [25]. Since it was developed to clarify decision-making concepts for formalizing decision-making situations and specifying their requirements using a clearer structure, we reused this model as part of the proposed Reno-DM representation.

At this stage we also aimed at identifying additional key concepts from the decision-making in renovation. A common knowledge elicitation strategy to do this relies on social science methods [20]. Hence, we conducted six semi-structured interviews with diverse stakeholders as summarized in Table 1. Sample questions include: Could you describe the process to select the renovation solution that was implemented? Once you define alternatives, what was the next step?. The total set of questions was developed based on a grand tour approach and the queries presented in [26,27]. The interviews were conducted between January 2020 and April 2021, each one lasted around one hour. We coded the transcripts and implemented an inductive content analysis following some of the steps for a manifest study [28]. The process was assisted by the qualitative analysis tool ATLAS.ti. We grouped the codes into categories such as Renovation project, Decision-making, Stakeholders, Interactions, among others. These groups allowed identifying key concepts and building a knowledge network including classes and relationships between them. The resulting model is presented in the following section.

### Table 1. Interviews summary

| Interviewees | Role in the decision-making process                                                                 |
|--------------|------------------------------------------------------------------------------------------------------|
| 1            | Architect specialized in renovations working in a public housing association                         |
| 2            | Two owners of dwelling units of a multi-family building under renovation                           |
| 3            | Civil engineer, R&D director of a construction company focused on renovation                       |
| 4            | Installation engineer, PhD in Civil engineering, Senior team leader in a large construction company  |
| 5            | Two civil engineers working in a research institute and private company focused on building construction, renovation, operation, and maintenance |
| 6            | Architect leading a construction company focused on building renovation                            |

#### 4. Proposed decision-making knowledge model for renovation

Figure 3 presents the overview of the Reno-DM knowledge representation. The model comprises a decision-making module, which is based mainly on the model proposed in [25]. It models the decision-making from a general perspective. On the other hand, the renovation project module comprises specific knowledge from the renovation domain identified through the approach presented in Section 3.2. These concepts are presented with a thicker outline. The two modules, their relations, and motivations supporting their conceptualization are discussed in the following subsections.

![Figure 3. Overview of the Reno-DM knowledge model.](image)
4.1. Decision-making modelling

Figure 4 depicts the decision-making module. In the renovation domain, the DMSituation derives from the RenovationProject and the need to select a renovation solution for a Building. The DMSituation contains a DMProblem (a choice, ranking, etc.). The description of the DMSituation defines whether the solution is selected evaluating individual renovation products or packages of measures. This leads to defining the DMObjekt as a single product or a package of measures, which is associated with the concept Alternative. The DMSituation contains an AlternativeSet. It can also contain a CriteriaSet, which is not mandatory as a decision could be made without evaluating criteria. A criterion represents any kind of information that enables the evaluation of alternatives and their comparison [25].

The DecisionMaker (individual or collective) defines the DMProblem, has Goals and Preferences, evaluates Alternatives, and validates Decision. Weights, preference rules, and thresholds represent the decision-makers preferences, i.e. the relative importance of a criterion or its wishful or acceptable value according to a given requirement. The Decision that responds to the DMSituation can be made intuitively or based on a method. For decisions relying on a method, the AlternativeValue represents the evaluation of an alternative according to a Criterion. More details regarding modelling a certain decision-making method can be found in [25,29]. Certain concepts and relations were removed from the original model proposed in [25] to simplify the representation and align it to the renovation domain. In the original model, consequences or stakeholders could be considered as criteria. In the Reno-DM model, we considered that Criterion includes any type of criteria, which can be classified according to the three categories of sustainability environmental, social, and economic. This facilitates understanding and encourage stakeholders to define a comprehensive criteria set to characterize the renovation alternatives. The hasCalculationMethod data property captures the procedure to quantify a certain criterion. In countries such as Poland and Spain, the current regulation establishes methods and tools to calculate the building energy consumption. The Stakeholder class was modified to represent a more general notion. This class and its relations with other concepts from the renovation domain are discussed in the following section.
4.2. Renovation projects and other concepts

Figure 5 presents the renovation project knowledge module. The decision-making module was simplified in Figure 5 to facilitate the reading process. A RenovationProject involves diverse stakeholders such as owners, tenants, investors, advisors, contractors, certification bodies, etc. Each Stakeholder can have the rights to vote, to be informed, among others.

![Figure 5. Renovation project module.](image)

Action represents activities such as communicating, designing, advising, representing, managing, etc. performed by stakeholders. For instance, Interviewee 3 mentioned: “This company is planning all the interventions, all the renovation activities yes, is also gathering money for the renovation fund, is also selecting the moment to make the intervention works and fixed all the papers”. Interviewee 2a mentioned: “she was collaborating a lot with us to contact the institutions or the associations... To be honest we have also felt very supported for the people from the BE (pseudonym) company that all the time has been giving us their advice, consulting, and counselling, that gives much tranquility when trying to transmit trust to the neighbours”. Representativeness was also mentioned in multiple interviews, Interviewee 6 stated: “... it was a small group of tenants as a representative of the tenants, to ask what they prefer...”. These and other actions play a key role in the decision-making, their representation in the model is relevant to capture the different stakeholders’ roles. The object property interactsWith, with sub properties communicatesTo, representsTo, etc. complements this purpose.

Each RenovationProject is executed on a Building, which is described by general data properties. BuildingCurrentStateData represents data concerning the current state of the building that can promote goals and influence the renovation alternatives. Multiple interviewees highlighted the role of PreliminaryInspections. Interviewee 4 stated: “the municipality is obliged by the law to make those energy performance analyses (of the current situation), the assessor usually gives some solutions... you need at least 10 or 15 cm of insulation for this building, for the walls, you will need 20 or 25 cm for the roof...”. CompatibilityRequirements are important to define renovation alternatives for historical buildings, where façade and windows usually cannot be modified. Interviewee 5a recalled: “we identified several alternatives due to the compatibility of these alternatives with a historical building... you cannot apply insulation material, in this case, we identified different solutions that take into account the compatibility with the historical building first of all”. Compatibility requirements between the existing building systems and new components are also relevant. Information related to PreviousRenovation activities can delimit the alternatives of the new renovation project.

The DMRelatedData represents the data from the RenovationProject that can influence the decision-making process. It includes two main subclasses, ProjectData and ContextData. The former
gathers characteristics such as Funding sources, Contract, among others. The type of Funding can have a large impact on alternatives and the decision-making process itself. For instance, public funding institutions impose often minimum requirements. Interviewee 1 mentioned: “To get the main grant, they have to fulfil the two conditions, insulate the building and connect to the new district heating”. While talking about projects funded by the municipality, Interviewee 4 stated: “usually it depends on the person you are talking to from the municipality, you can propose some alternative energy solutions... I know photovoltaic panels to cover the lighting inside ... or use sensor lighting or something like that”. In the case of a housing company making a private investment, Interviewee 6 stated: “they were really ambitious with the project and wanted to renovate almost to zero energy... they could have done less but they thought ok this is a project we want to test a more ambitious approach”.

The subclass ContextData captures the elements from the context that can influence the decision-making process. PhysicalContextData represents aspects such as natural hazards that should be considered while designing the renovation alternatives (e.g. seismic risk level, wind storms, floods, etc.) and characteristics of the neighbourhood and surroundings (e.g. availability of district heating system, external noise level, air quality in the surroundings, etc.). LegalContext gathers legal elements that can regulate the renovation project and the decision-making. For instance, GovernanceAndOwnershipRegulation represents rules and guidelines that impact the way the decision-making process is conducted, what kind of decisions on the renovation can be made, how to make them, and who participates. The ConsensusMecanism should be defined explicitly. Furthermore, ConstructionRegulationRequirements can impose exigences on thermal transmittance and airtightness values, acceptable energy performance [30], among other requirements that influence the alternatives that can be considered, criteria thresholds, and other elements of the decision-making.

The Risk concept associated with the DMProblem represents elements that can affect the decision-making process negatively. For instance, conflicts between stakeholders are a social risk. Interviewee 1 mentioned: “we are going to insulate the slab between the first floor of the apartments and the ground floor, but not in all the slab ... they have a previous fight before with the owner, between the community of apartments and the owner of the commercial local, he did not want to do anything in this project”. Differences between the owners investment capacities are an economic risk. Interviewee 4 mentioned: “As I said, all the participants need to be part of this project because the cost of the project will be split equally, so you can imagine that not every owner will have the money in a certain period of time like the others do”. Difficulties can appear due to other situations such as the need for the inhabitants to move out during the renovation because of the complexity of the renovation alternative selected, etc. These kinds of situations represent a limitation in the alternatives that can be considered, they can even stop the renovation project including the decision-making process itself. After asking about experiences where consensus was not reached, Interviewee 3 recalled: “Yes, they did not make the renovation, it was blocked, or it was like after 5 years finally”. Other interviewees also mentioned situations where conflicts, demographic characteristics, and lack of consensus were barriers to moving forward with the decision-making process to select the final renovation solution.

5. Discussion
This paper introduces the Reno-DM model representing knowledge from the decision-making process in the residential renovation domain. The model comprises aspects related to the general idea of decision-making and specific concepts from renovation projects that frame and influence key elements such as stakeholders, characteristics of renovation alternatives, criteria to evaluate different alternatives, and risks that could affect the decision-making process. Mapping the knowledge from this domain can create a shared understanding of the decision-making process between the stakeholders involved and support the developments of new data and knowledge management applications.

One of the limitations of the model can be associated with the interviewees and the renovation projects where they were involved. In four of the interviews, the stakeholders took part in public funding or research projects. This might have influenced the way the decision-making process was performed in those cases and the knowledge shared by the interviewees. However, it is important to
notice that the stakeholders involved in the other two interviews offered a more general perspective from their multiple experiences in diverse renovation projects. Furthermore, the conceptualization decisions were also supported by the related literature and results from previous studies.

Future research activities include the verification and validation of the proposed Reno-DM model. A workshop with experts and stakeholders from the renovation field will be conducted. The aim is to evaluate the content of the model to verify that it covers the relevant concepts, relations, and attributes and it represents the terms and concepts structure from the real world. The model will be implemented in Web Ontology Language (OWL) using Protégé tool [31]. This language enables a machine-readable representation, making information collection, processing, reuse, and retrieval easier. Additionally, knowledge reusing strategies will be combined with the proposed model to study how capturing, storing, and re-utilizing knowledge from previous projects can support and enhance the decision-making process in new renovation projects. Application to a real case study using a specific decision-making method can also be studied to illustrate how the model can support these situations.

6. Conclusion
This paper presents the Reno-DM knowledge representation in the form of an ontology mapping the knowledge from the decision-making domain in the context of renovation projects. The model covered not only the knowledge related to the decision-making process itself but also key elements that have a direct influence on it such as legal frameworks and regulations, stakeholders involved, the current state of the building, type of funding, etc. The Reno-DM model can be a starting point to collect heterogeneous data available in renovation projects in a structured approach to enable the acquisition, management, retrieval, and reuse of knowledge. The implementation of the knowledge model in OWL and different verification and validation activities will be performed as future research activities to illustrate how the proposed model can support different stakeholders during the decision-making process and can enable the reuse of knowledge and lessons learned for future renovation projects.

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