Extending the Flexibility of Case-Based Design Support Tools: A Use Case in the Architectural Domain

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Abstract. This paper presents results of a user study into extending the functionality of an existing case-based search engine for similar architectural designs to a flexible process-oriented case-based support tool for the architectural conceptualization phase. Based on a research examining the target group's (architects) thinking and working processes during the early conceptualization phase (especially during the search for similar architectural references), we identified common features for defining retrieval strategies for a more flexible case-based search for similar building designs within our system. Furthermore, we were also able to infer a definition for implementing these strategies into the early conceptualization process in architecture, that is, to outline a definition for this process as a wrapping structure for a user model. The study was conducted among the target group representatives (architects, architecture students and teaching personnel) by means of applying the paper prototyping method and Business Processing Model and Notation (BPMN). The results of this work are intended as a foundation for our upcoming research, but we also think it could be of wider interest for the case-based design research area.

Keywords: CBR and creativity · Process-oriented CBR · Knowledge modeling · Business process modeling · Case-based design

1 Introduction

In this paper, we address the early conceptual design phase in architecture, where searching for helpful, inspirational, and similar previous designs and solutions

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can support the design and development process by offering insights and conclusions from existing solutions. The ability to compare and evaluate relevant reference examples of already built or designed buildings helps designers assess their own design explorations and informs the design process. Most computational search methods available today rely on textual rather than graphical approaches to representing information. However, textual descriptions are not sufficient to adequately describe spatial configurations such as floor plans. To address these shortcomings, a novel approach was introduced by Langenhan et al. [13] which facilitates the automatic lookup of reference solutions from a repository using graphical search keys. In the basic research project, Metis[1], these issues were examined further using methods of case-based reasoning (CBR), multi-agent systems (MAS), and computer-aided architectural design (CAAD).

As part of the project activities, a distributed case-based retrieval engine *MetisCBR* [2] was developed that retrieves similar building designs using case-based agents that apply search methods implemented in the CBR framework myCBR. In its general mode of operation, MetisCBR's core functionality seeks the most suitable *strategy* for each query from a set of such strategies. Currently, these strategies *do not have a structural definition according to architectural requirements*, that is, MetisCBR has only basic similarity assessment strategies that were designed using an adapted bottom-up method based on the basic elements of the domain model described in Ayzenshtadt et al. [1]. However, as we are planning to extend MetisCBR to a *process-oriented* case-based design support tool for the architectural conceptualization phase, such structural definitions are needed to provide a common interface for implementating different high- and low-level processes. To address this issue, we conducted a *process modeling* study among the target group representatives to examine their similarity assessment processes (low-level) and the inclusion of the similarity assessment in the whole conceptualization process (high-level). Our main aims for this research were:

- Determine common features in a multitude of architects' own strategies and infer a methodology for defining such strategies in our system.
- Find a common structure for the conceptualization process (that we call a *user model*) with inclusion of similarity assessment strategies for the further design of user models for the system.

This paper is structured as follows: in Sect. 2, we describe our previous work in the Metis project and other related research in this area. In Sect. 3, we show which suggestions from previous research in this field led us to work on the strategic and process-related aspects for the system. In Sect. 4, we describe in detail the modeling study we conducted, presenting the background and short descriptions of the main elements we used (POCBR, BPMN, paper prototyping) and then describing the study's main phases and summarized results. In Sect. 5,

[1] *Metis – Knowledge-based search and query methods for the development of semantic information models for use in early design phases.* Funded by DFG (German Research Foundation).

we provide definitions of the foundations (strategy and process) for user models for our system. Finally, in the last section we conclude with a review of this paper and an outlook on future work.

2 Related Work

The research area of case-based design (CBD) has a long history in the communities of both CBR and knowledge-based design research fields. As an important part of early CBR research, CBD (and its application in architecture especially) has gained much interest from the beginning of the advanced domain-bounded CBR research. Many projects have been initiated since then and several approaches and applications have been developed for both basics as well as advanced methodologies in this research domain. In this section, we review research conducted our Metis project began and the work accomplished since over the course of the project activities.

Research conducted prior to our project includes a number of essential approaches and fundamental work, now well-known in the research community. An example of such fundamental work is [14] and an overview of the prior approaches can be found, for example, in [18]. FABEL [22], CaseBook [8], or DIM [10] are examples of approaches that apply CBR to design problems. One of the most comprehensive work in studies of the application of CBR to the architectural design process is Richter's work [17], and [19] contains a summary of this research including an overview of suggestions for improving such applications.

In the Metis project, which was initiated to enhance architectural design by providing knowledge-based retrieval methods to support the early conceptualization phase, a number of different approaches to searching for similar architectural design solutions were developed. MetisCBR, mentioned above, is one such approach, while others include an adapted VF2 approach (described in [5]) for (sub)graph matching, index-based retrieval with the *Cypher* language queries of the graph database Neo4j, and the enhancement [23] of the original Messmer-Bunke algorithm [15]. Comparative evaluations of MetisCBR and other retrieval methods were undertaken, for example, in [3,20]. Retrieval support tools, such as a web-based floor plan editor *(Metis WebUI)* [4] and a content management system *mediaTUM*, were also developed.

The theoretical foundation underlying our systems is the paradigm of *Semantic Fingerprint* [12] and *AGraphML* [11] (a representation format for graph-based floor plans). For example, a case in MetisCBR is a semantic fingerprint of a floor plan that is imported as an AGraphML from mediaTUM and represented in the myCBR internal case format according to the domain model described in [1].

3 Problem Definition in the CBD Domain

Richter [19] presents the results of research conducted in the field of case-based reasoning in architecture and makes a number of recommendations for further research in this area. One of the main recommendations is that *query strategies* *should be optimized* in case-based design support systems. In our work, we tried to find an initial solution to this problem. First, we try to obtain knowledge for constructing such strategies from the actual knowledge carriers by means of a modeling study. From an analysis of this study, we then infer and propose a structural definition for query strategies and, more general, superstructural definition of processes (user models) which we can then use for MetisCBR, but this can also potentially serve as a foundation for other approaches.

Another suggestion made in [19] is that an unaddressed issue of quality assessment in case-based design (especially in architecture) should be investigated. We also address this in our study, but in addition to similarity assessment. Although, the question of quality should be investigated in a separate context, our work may provide a starting point or serve as inspiration for more detailed research in this direction.

The last suggestion from [19] we deal with is the variability of the CBD approaches. This is also a question that needs to be fully examined in a separate context, for example to identify which degrees of variability are required in which context of the conceptualization phase. We also address this suggestion in our study, and initially investigate how this feature can be included (e.g., in strategies).

4 The Process Modeling Study

4.1 Background and Main Aspects

As mentioned in Sects. 1 and 3, our process modeling study was conducted to define the foundations for developing user models for enhancing our system from a search engine to a design support tool. While developing ideas for solutions to the questions mentioned in Sect. 3, i.e., how best to strategically improve the system to provide the most suitable design recommendations at the right point in time in the conceptualization process, the most logical and valuable source of potential answers seemed to be expert knowledge from the target group (representatives of the architectural design domain). Likewise, we expected that there would be many commonalities in strategies among different representatives of the target group. To gain this knowledge, to confirm or disprove our assumptions, and to conduct the study we developed a small methodology that consists of a questionnaire, modeling, and cross-evaluation (see more in Sect. 4.2). During the development of this methodology, we tried to consider how components of thinking (such as *categorization, comparison*, and *condition* that are explained, e.g., in [7]) could be combined to extract the most valuable aspects of knowledge for our aims. In the next sections, we describe the main aspects and components of our study and how we use (and/or are going to use) them in our research and development.

Process-Oriented CBR. POCBR is an approach for applying case-based reasoning to process-oriented information systems (POIS). Today, the applications of POCBR extend beyond classical POIS domains, such as workflow management, to include other domains, such as medical healthcare, e-science, or cooking [16] and in recent years, POCBR has been the subject of research for major CBR problem fields: retrieval is covered, for example, in [9], and adaptation in [16].

To enhance MetisCBR from a CBR-based retrieval system to a CBR-based design support tool, we decided to extend it into a POIS with a number of implemented processes (user models), where the most suitable user model is activated when certain user behavior is detected (i.e., the user behavior will be a case with actions as attributes that, when sufficiently matched, activate the model).

BPMN. *Business Process Model and Notation* (BPMN) is a graph-oriented process modeling language for the visualization of business workflows with predefined elements and notations. It has become a very widely-used standard form of notation for the analysis of processes on the corresponding domain's high level system design [6]. The current Version of BPMN is *2.0*. BPMN consists of a number of element groups, the most important of which are *Flow Objects* for denoting tasks and events, and *Connection Objects* for denoting the connections between the elements. A multitude of software tools is available for BPMN-based process modeling.

For our post-study analysis, i.e., the transformation of processes modeled by our participants into a digital form, we used *Camunda Modeler*[2]. In a comparative evaluation of open source tools for building research prototypes, it was determined that Camunda Modeler is a cross-platform application that provides full BPMN 2.0 support [21].

Paper Prototyping. *Paper Prototyping* (or *Rapid Paper Prototyping*) is a method for evaluating user interfaces in early stages of the software development process. It is commonly-used by usability engineers for implementing user-centered design and to test the functions of future software products among the potential user group. The principle relies on the concept of a printed or sketched version of the software's user interface that prototypically represents its functions. The user interacts with these to detect usability problems in early phases of implementation of the software.

For our study, we adapted and modified the paper prototyping method to allow our participants to model their similarity assessment and conceptualization processes with several sketched elements of the BPMN. In contrast to a usability study for a software prototype, our participants did not have a concrete prototype to test, but were instead asked to *model a prototype of their processes using the sketched BPMN elements.*

4.2 Study Process and Results

Five representatives of different areas of the architecture domain agreed to take part in the study, including architects, architecture PhD students, and

[2] https://camunda.org/features/modeler/.

architecture teaching staff. On average, we spent approximately 2 hours per interview for each of the participants. In the next sections, we describe the methodology we developed and used, the questions and tasks we used when working with the participants, as well as the corresponding results.

Methodology. Our methodology for conducting the study consisted of four main phases described below (see also Fig. 1. Detailed descriptions of phases and corresponding results are provided in the following sections):

1. *Criteria Survey:* the participants were asked to name the criteria for rating the quality and similarity of architectural designs.
2. *Similarity Assessment Modeling:* the participants were asked to manually select the most similar design(s) from a collection of designs for a given predefined query. After the selection they were asked to model their process, i.e., to reconstruct their cognitive similarity assessment process using the sketched BPMN element prototypes. This phase consisted of three sub-phases that correspond to three complexity levels of a floor plan.
3. *Conceptualization Process Modeling:* the participants were asked to model their entire (early) conceptualization process, including how they incorporate similarity assessment.
4. *Cross-Evaluation:* the current participant was asked to evaluate the similarity assessment process of one of the previous participants.

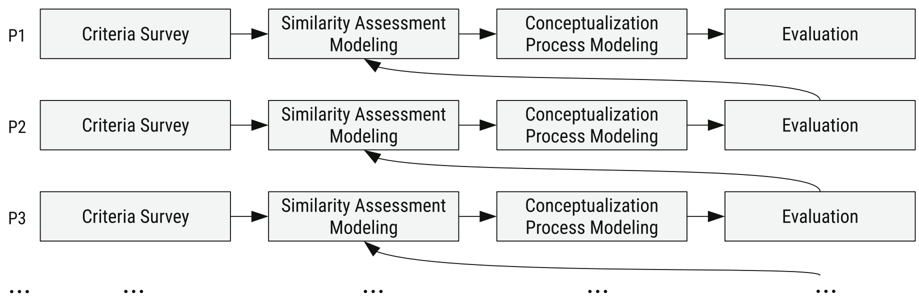

Fig. 1. The main steps of the methodology we applied during the process modeling study. P[n] denotes a participant.

Preliminary Questionnaire. Before the main phases, we conducted a preliminary questionnaire phase to ascertain the participants' familiarity with CBR or at least the term *case-based reasoning*, and also if they have applied or worked with CBR applications during their job-related activities. This was essential for the subsequent interview, especially with respect to the terms used in the interview (e.g., CBR technical terms for participants who are familiar with CBR).

In general, most of our participants were familiar with the main concepts of the CBR paradigm, but only 40% of the participants were aware of using CBR applications in their professional work. The non-academia participants were not aware of CBR at all and told that architectural practices rarely apply CBR-based or similar reasoning and/or retrieval applications in practice, confirming results of Richter's research in [19].

Phase 1 – Building Design (Floor Plan) as a Case: Criteria Survey. The criteria survey was the first phase of the interview with a participant. In this phase, we asked participants about the criteria they use to rate quality and similarity of architectural designs. The theoretical background of this phase is that *a case in our CBR-based retrieval engine is a fingerprint of an architectural building design (floor plan)* as defined in [1]. The following questions were asked in this phase (referred below as Q[n], e.g., Q1):

1. Which criteria do you use to assess the *quality* of an architectural design?
2. Consider this floor plan. *(The participant is given a printed floor plan for analysis.)* How would you rate its quality using your quality criteria?
3. Which of the quality criteria do you consider to be the key criteria?
4. For more complex floor plans, would you change the priority distribution of your criteria? Are there criteria that you would consider important only for abstract floor plans? *(The participant is shown an abstract and a more complex floor plan for comparison. In Sect.* 4.2 *we show the difference between abstract and complex floor plans.)*
5. Which criteria do you use to assess the *similarity* of an architectural design?
6. Which terms would you use to/how would you describe the similarity between two designs to another person? *(Assuming this person has some basic familiarity with architecture and its terms.)*

The results of the quality assessment questions Q1–Q4 show that there are many commonalities, but also some differences in the criteria used to determine the quality of a building design. For example, all participants mentioned the relationship between rooms and general structure/layout as a criterion, but location criteria were named only once. A criterion that was also named only once, but was considered one of the key criteria by the corresponding participant in Q3 is client requirements. In Q4, most participants mentioned that they would accord different criteria a greater priority for floor plans of other complexity. For example, the form/shape of the rooms on the abstract level could become more important.

In Q5, most participants said they would use virtually the same criteria as in Q1–Q4 to assess the similarity of two floor plans. However, some participants did introduce some new terms for similarity assessment only. For example, the criterion of cost-economy (which surprisingly did not feature in the quality assessment questions). In Q6, participants said they would additionally use examples and situations to explain the difference between two designs to another person (the results of Q6 have been also preserved for our upcoming research into explanation-aware systems in architecture).

For our analysis of the results of Q1–Q6, we categorized the criteria named by the participants, as shown in Fig. 2.

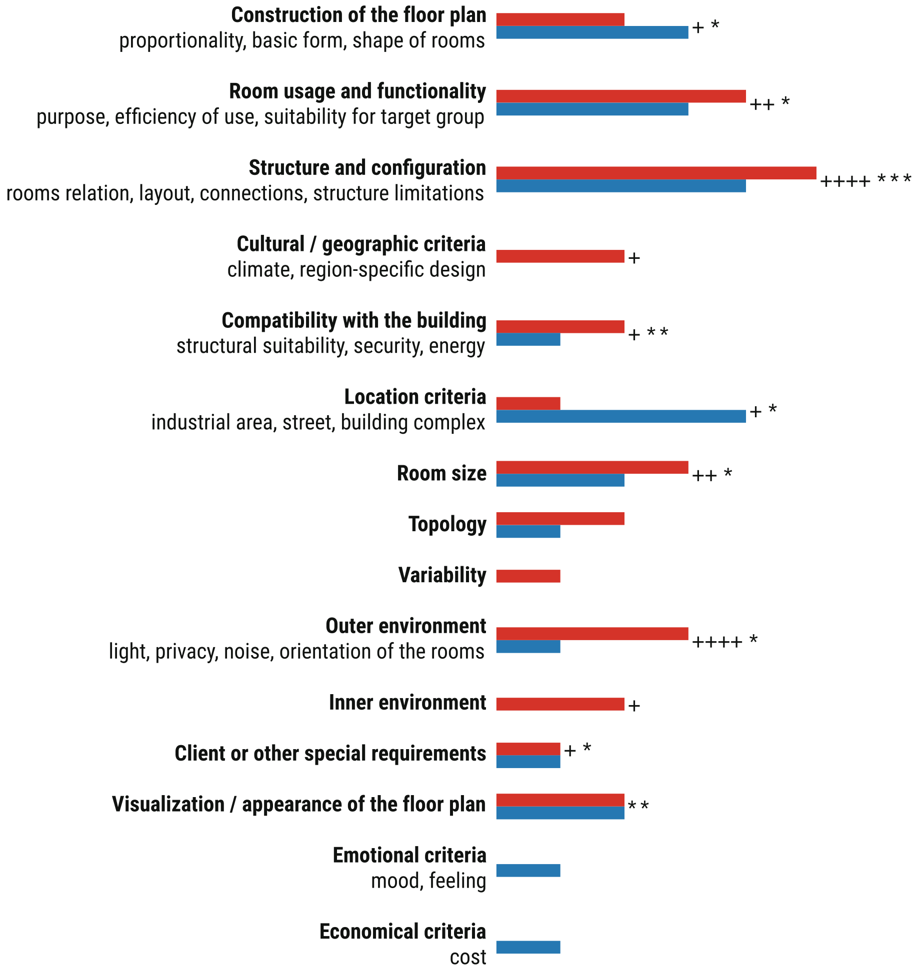

Fig. 2. Results of the categorization of Q1–Q6. The length of the lines indicates how often they were mentioned as quality criteria (red) and as similarity criteria (blue). [+] indicates the frequency of mention as the *key criterion* (Q3). [∗] indicates the frequency of mention as criteria that changes its priority when it comes to the change of complexity level of a floor plan (Q4). (Color figure online)

Phase 2 – Similarity Assessment Modeling. In the next step of our study, our intention was to reconstruct and understand how our target user group (architects) would *manually select the most similar design* from a collection of architectural designs for a given predefined query. To accomplish this, we asked the participants to assume the role of our CBR-based retrieval system, that is, to imagine him- or herself as the system assigned with task of selecting the most similar floor plan to the query drawn by a user.We undertook this phase in three sub-phases, each corresponding to a different level of complexity (referred to as CL[n], e.g., CL1, the queries and examples of cases are shown in Fig. 3):[3]

1. *Abstract* – Connected bubbles or abstract rectangles as rooms
2. *Simple* – Complete floor plans with a simple structure and smaller size
3. *Complex* – Complete floor plans with a complex structure and bigger size.

Fig. 3. The queries and cases for manual similarity assessment. Each column consists of the query (built with the Metis WebUI [4]) in the corresponding CL and a selection of some cases from the corresponding CL case base. The case base of CL1 consisted of 10 cases (also built with the Metis WebUI), the case base of CL2 of 11 cases, and the case base of CL3 of 10 cases.

After each manual selection process, we asked the participants to apply paper prototyping and model their cognitive process of selection using the sketched elements of the BPMN. Because the number of BPMN elements is quite large and it can be time-consuming to explain all of them to a participant, we decided

[3] The designs for CL2 and CL3 were taken from Flickr. In Fig. 3: *1391 Second Floor Plan* https://www.flickr.com/photos/philmanker/3516873511/ by Phil Manker, CC-BY 2.0; *Architecture and Building, 1922* https://www.flickr.com/photos/revivaling/5549896664/ by Learn From. Build More., CC-BY-SA 2.0; *A104: Level 2 Dimensioned Floor Plan* https://www.flickr.com/photos/therichardlife/5574176101/ by Stefanie Richard, CC-BY-SA 2.0; *216 Brookwood floor plan - Main Floor* https://www.flickr.com/photos/homesbycharlotte/26899442344/ and *216 Brookwood floor plan - 2nd Floor* https://www.flickr.com/photos/homesbycharlotte/27409880812/ by Charlotte Turner, Public Domain/all scaled from original. All visited on 23.04.17.

not to use all the BPMN elements, but to restrict the selection of elements to the basic ones. Figure 4 shows the BPMN elements used for modeling, and Fig. 5 a result of the process modeling by one of the participants. During the selection and modeling process, we also asked the participants to *think aloud* to give us more insights into their thinking process while selecting and modeling. After each modeling process, we asked the participants if they applied their own criteria (named in Q1–Q6) determining the similarity and quality of results. To analyze this phase after the experiment, we reconstructed the paper-prototyped processes with the Camunda Modeler software, mentioned in Sect. 4.1.

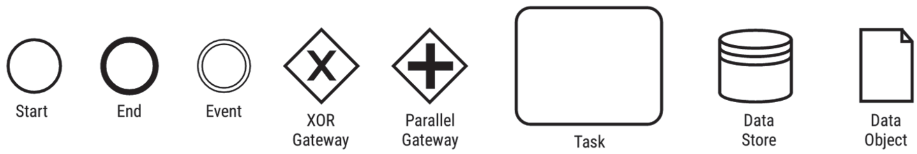

Fig. 4. The BPMN elements used for paper prototyping of the processes.

Fig. 5. Similarity assessment process by one of the participants modeled using the sketched BPMN elements.

During the manual selection of the most similar floor plan, in 14 of the 15 comparison processes the criteria named in Q1–Q6 were applied. An analysis of the results of the modeling phase shows that several tasks in all of the processes have at least similar intentions. For example, a criteria-based comparison takes place in each of the processes, but for some of the participants (minority) the set of criteria is immutable, whereas others tend not to restrict this set of criteria.

The main difference was mostly the method of application: *sequential* as well as *parallel* comparison took place, mostly in a mix where some criteria were used initially for pre-selection (e.g., topology and functionality, or room count and functionality) followed by a parallel process of comparison with other criteria. However, purely sequential processes were also modeled for each complexity level. The flexibility of criteria played a role for participants who did not want to restrict their comparison to a set of pre-defined criteria. It is also notable, that some of the participants excluded some criteria when dealing with a greater complexity level. Also, expert knowledge and meta information about the floor plans were also drawn on for the comparison processes.

Phase 3 – Conceptualization Process Modeling. The aim of the next step of our study was to examine how the similarity assessment process can be integrated into the overall (early) conceptualization process. This step was initially planned as part of the previous task, but was separated out to allow the participants more freedom during modeling, that is, not to restrict them to think of it as an additional question. In the modeling, the only requirement was to reflect on how the similarity assessment process fits into the conceptualization process. Participants were free to choose whether to model this process using paper prototyping or simply drawing on paper with or without the BMPN elements. The majority of the participants chose to draw on paper, but most of them used the BPMN notation to visualize their processes (these were also transferred to digital form for later analysis).

An analysis of the models of (early) conceptualization processes reveals that, generally speaking, the iterative nature of the process is obviously natural to all the participants. We identified two general structural setups of the processes:

– The process is sequential with a number of subsequent sub-processes, where some sub-processes are of iterative type.
– The process is an enclosing iteration that consists of sub-tasks, which can also be iterative.

The similarity assessment was placed at different positions in the overall conceptualization processes. For example, one of the participants positioned it in the beginning of the conceptualization phase, applying it only once for abstract floor plans with bubble-shaped (i.e., undefined shape) rooms. Another bias case is the dynamic positioning of similarity assessment, that is conducted either during the analysis of requirements or during the synthesis of possible solutions. The normal case however, was to place the similarity assessment either in the middle or in the final phases of the process after the determining client requirements and identifying the key issues, and before the evaluation by the client (other phases being, for example, cost calculation or 3D conceptualization).

Phase 4 – Cross-Evaluation. The final step of our study was to cross-evaluate the participants' similarity assessment processes. To accomplish this, we asked the participants to compare their process against a random process from one of the previous participants. The current participant was asked to identify differences, commonalities, pros and cons, advantages and disadvantages, as well as anything else that came to mind during the comparison. Using this evaluation method, we tried to obtain a competent opinion on the similarity process models, to see how to improve if one process becomes an inspiration or a template for a strategy in a user model in our system.

The participants mostly criticized the lack of different types of knowledge that could help in the comparison process: for example, one of the processes lacked the expert knowledge component (i.e., comprehensive professional knowledge in the architectural domain), which the evaluating participant viewed as being an essential part of such processes. Similarly, the lack of control of criteria (e.g., when have enough criteria been compared to achieve a sufficient degree of similarity) and the non-dynamic nature of criteria in some of the processes was criticized. On the positive side, the flexibility of some of the processes was emphasized, for example, a flexible threshold for criteria match evaluation. Another positive aspect was the application of a more systematic approach, than the evaluating participant's own process.

5 Definitions Inferred from the Results

To achieve our actual goal – the *definitions of the foundations for user models* – we generalized the results of the questions and modeling phase to infer structures for the foundations, as defined in the following sections.

5.1 Strategy

Strategy is a basic element of the user model. Strategy will be used as a controlling structure for the actual algorithm for searching for similar floor plans. That is, the algorithm should satisfy all the requirements of the definition to become a strategy in our system. We define strategy as follows:

Definition 1. *Strategy is a quadruple $S = (C, K, \mu, F)$, where C is criteria, K is knowledge, μ is similarity measure, and F is flexibility. $C = C_s \cup C_d$ (criteria can be of dynamic and static type), where $C_s \vee C_d \neq \varnothing$. $K = K_m \cup K_e$ (meta knowledge about the cases in the case base and expert knowledge in the domain, e.g., in architecture), where $K_m \vee K_e \neq \varnothing$. $\mu = \mu_s \cup \mu_p$ (similarity measures can be of parallel or sequential type), where $\mu_s \vee \mu_p \neq \varnothing$. $F = (f_c, f_\mu)$, where f_c is the value of the strategy's flexibility that corresponds to the criteria and f_μ is the value for the conditional variability of μ, i.e., the variability of the similarity value's conditional values (such as weight or degree[4]) under certain constraints (e.g., different complexity levels of the floor plan).*

To explain the application of this definition, we defined an exemplary strategy that satisfies all the requirements of the definition (see Fig. 6).

[4] In our research, we use the following classification of degrees of similarity since [1]: *very similar, similar, sufficiently similar,* and *unsimilar.*

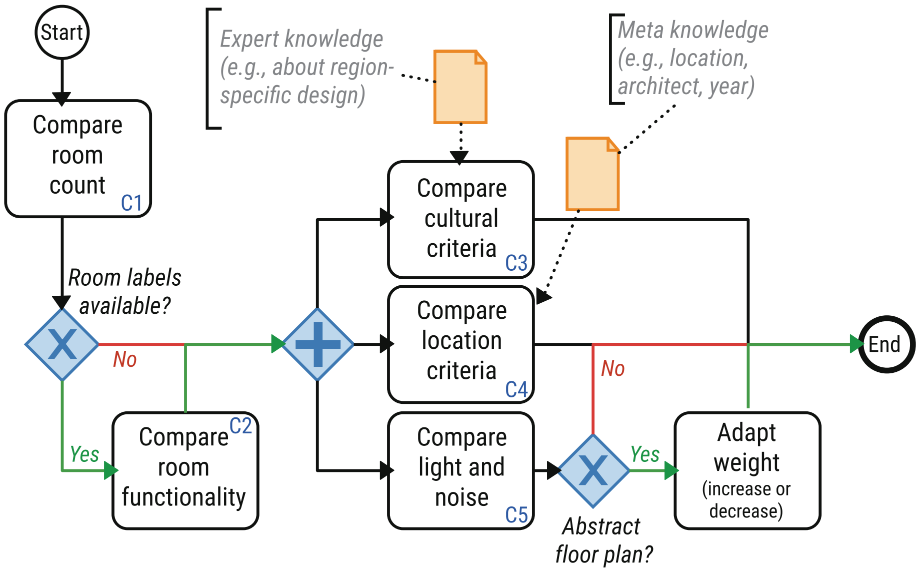

Fig. 6. An exemplary strategy that satisfies all of the requirements named in Definition 1. Here, C1 and C3–C5 are the static criteria that are always applied as comparison criteria. C2, however, is a dynamic criteria that depends on the availability of room labels, i.e., functions. Expert and meta knowledge help to resolve the comparison of C3 and C4. C1 and C2 are resolved with sequential similarity measures, i.e., C2 follows C1. In contrast, C3–C5 are resolved with a parallel type of similarity measure (e.g., with agents that work concurrently and then apply weights and calculate an amalgamated similarity value out of these three). Assuming, we have applied $f_c = 0.6$, we get a flexibility that 3 of 5 criteria should be at least sufficiently similar for a floor plan to be considered for inclusion in retrieval results, where the weight of similarity value of C5 depends on the complexity of the floor plan (alternatively, C5 can be defined as a dynamic criterion with complexity of floor plan as its condition).

5.2 Process

Process is a wrapper for the user model and is intended to represent the (early) conceptualization phase as a template that will be activated when user's actions and behavior indicate a sufficiently similar match in the set of processes implemented in the system (what we will consider an action and a behavior, is one of the subjects of our upcoming research, see also Sect. 6).

Definition 2. *Process is a triple $P = (S, t, A)$, where S is a set of strategies as defined in Definition 1, t is the type of the process (e.g., sequential, semi-sequential, enclosing iteration), and A is the set of actions. $A = A_s \cup A_i \cup A_e$ (actions can be of starting, ending, and intermediate type), where $A_s \wedge A_e \neq \varnothing$. Strategies are linked to actions with a surjective mapping $S \twoheadrightarrow A$, i.e., $\forall a \in A \exists s \in S$ (for each of the strategies at least one action exists that this strategy is mapped to).*

6 Conclusion and Future Work

In this paper, we presented a study that investigates the search for similar architectural references during the early conceptualization process in architecture, and from this inferred definitions for strategic foundations for structures for user models in our system MetisCBR. We conducted this study with various representatives of the architectural domain. The study surveyed quality and similarity criteria, similarity assessment modeling and conceptualization phase modeling (both with BPMN elements), and then undertook a cross-evaluation. The results have shown that it is possible to infer definitions of *strategy* and *process*, and therefore to provide structures for query strategies (which is recommended in [19]). The study and the definitions also address the problems of quality criteria and variability discussed in [19].

Our future work will include the investigation of what an action (e.g., step, intermediate step, or iteration) and behavior can be in the specific context of architectural design (as mentioned in Sect. 5). We will also work on developing an explanation module for the target group-specific explanation of retrieval results with special explanation patterns – for this research we will use some results of the experiment presented in this paper (see Sect. 4.2). Our next step in the context of this paper is the implementation of the strategies according to the results and definitions derived in this paper, and then to undertake a performance comparison with the system's former strategies.

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