EVOLVING DESIGN LAYOUT CASES TO SATISFY FENG SHUI CONSTRAINTS

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Abstract. We present a computational process model for design that combines the functionalities of case-based reasoning (CBR) and genetic algorithms (GA's). CBR provides a precedent-based framework in which prior design cases are retrieved and adapted in order to meet the requirements of a new design problem. GA's provide a general-purpose mechanism for randomly combining and modifying potential solutions to a new problem repeatedly until an adequate solution is found. In our model we use a GA to perform the case-adaptation subtask of CBR. In this manner, a gradual improvement in the overall quality of the proposed solutions is obtained as more and more adaptations of the design cases originally retrieved from memory are evolved. We describe how these ideas can be used to perform layout design of residences such that the final designs satisfy the requirements imposed by *feng shui*, the Chinese art of placement.

1. Introduction

We have developed a process model that combines the precedent-centered reasoning capabilities of case-based reasoning (CBR) (see for example (Kolodner, 1993)) with the incremental evolution of multiple potential solutions, an idea taken from the paradigm of genetic algorithms (GA's) (see for example (Goldberg, 1989)). The process model involves the use of CBR as the overall reasoning strategy and the use of a GA to perform the case-adaptation subtask. Because a general-purpose knowledge-independent GA is used, case adaptation is knowledge-lean. It is only in the evaluation module of the GA that domain knowledge is required so that proper decisions are made about which potential solutions generated by the GA are useful to keep in future GA cycles.

Our process model is shown in Figure 1. In this model we assume the existence of a case memory in which descriptions of previously-existing designs are stored. The cases that are retrieved from memory given a new design problem are adapted by repeatedly combining and modifying their features. After each cycle of combination and modification, solutions are evaluated and the best are kept, to be adapted in the next cycle. Through this incremental, evolutionary process, eventually the case adaptation process converges to an acceptable solution to the new problem. The solution will contain features and/or modifications of features from several of the cases that were initially retrieved from memory. Thus, our process model adapts past designs by evolving different combinations of their features in parallel and continuously, until an acceptable combination is found.

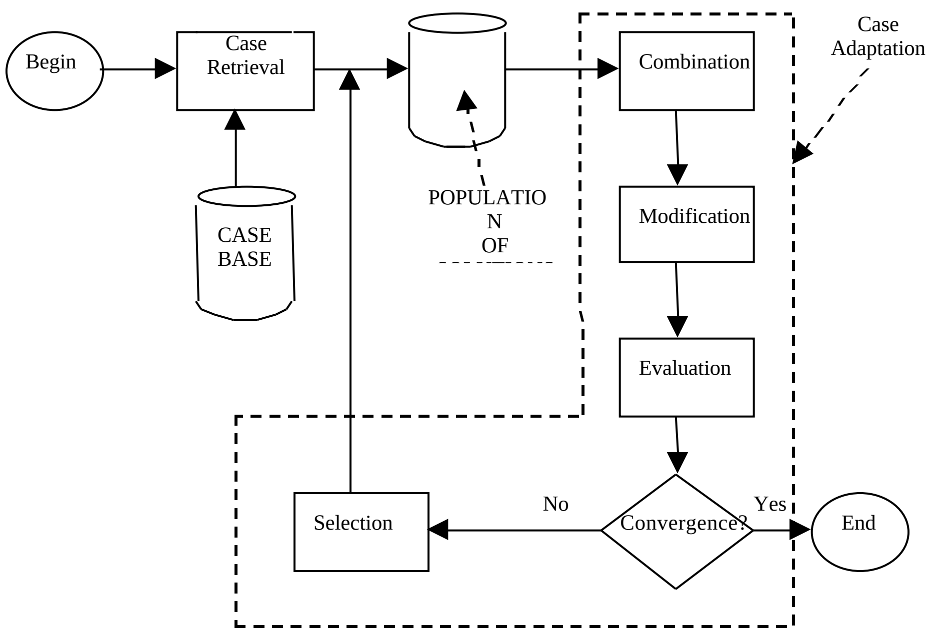

Figure 1. Process model.

The main emphasis of the process model is on proposing new designs based on the knowledge contained in previously-known designs, i.e., it is a precedent-based approach. But a major component is the evolutionary approach to adapting the known designs in order to generate solutions to new problems. The two strategies of CBR and GA's complement each other. The cases retrieved from memory serve as the initial population to a genetic algorithm, while the genetic algorithm adapts the cases until it finds an acceptable solution.

We have applied this process model to performing layout design of residences such that the final layouts proposed satisfy the constraints imposed by *feng shui*, also known as Chinese geomancy. The cases initially in memory do not necessarily have to comform to the principles of *feng shui*, but our process model, by combining different features from different cases (and intermediate potential solutions), can produce results that *are* acceptable according to *feng shui*. To apply our process model to the *feng shui* domain, knowledge about this domain has been included in the evaluation function of the case adaptation GA. Our process model has also been applied to the domain of structural engineering design of high-rise buildings (Gómez de Silva Garza and Maher, 1998).

2. *Feng Shui* Domain and Knowledge Representation Issues

We now give a brief overview of *feng shui*, discuss some knowledge representation requirements imposed by this domain, and present some knowledge representation requirements imposed by the use of CBR and GA's as the main reasoning strategies in our process model.

2.1. *FENG SHUI*

Feng shui, also known as Chinese geomancy, is an ancient Chinese technique that, among other things, determines the quality of proposed or existing layouts of residences according to several rules of thumb. Some of these heuristics seem to have a basis in common sense, or in a psychological or sociological appreciation of the human beings that inhabit (or intend to inhabit) the residence. Other heuristics seem to be of a more superstitious nature.

There are several different *feng shui* sects that contradict each other or place different priorities on different aspects of residential layouts. Despite this variety, of prime importance to performing any *feng shui* analysis is information on the relative positions of objects. In addition, other attributes of objects are usually also taken into account, such as their orientations, shapes, and relative sizes. In our work on GENCAD we have used the knowledge of *feng shui* presented in (Rossbach, 1987), which corresponds to the Tibetan black-hat sect of *feng shui*.

Feng shui analyses different aspects of a residential layout to determine its auspiciousness or lack thereof. Some classes of inauspicious layouts can be "cured" by the proper placement of an acceptable curing object. Thus, *feng shui* knowledge is complex, in that some potentially bad layouts can actually be acceptable if the proper cure is present. It is not just a matter of determining whether a layout is "good" or "bad," but even if it would normally be considered bad, one has to determine whether it has been cured or not before rejecting it outright.

2.2. KNOWLEDGE REPRESENTATION REQUIREMENTS RELATED TO *FENG SHUI*

The *feng shui* knowledge contained in (Rossbach, 1987) applies to three different levels of description of a residence:

- The landscape level (which describes the location of a residence with respect to other objects in its environment such as mountains, rivers, roads, etc.),
- The house level (which describes the relative placement of the rooms and functional spaces within a residence, such as bedrooms and bathrooms, as well as the connections between them, such as doors and windows), and
- The room level (which describes the location of furniture, decorations, and other objects within each room or functional space in a residence).

Our knowledge representation scheme thus keeps this separation into three possible levels of description for each residence.

As mentioned earlier, of prime importance to a *feng shui* analysis of a residence is the relative positions of objects. Absolute locations and exact measures of distances and other geometric quantities are not as important. Because of this, a qualitative spatial representation has been chosen to describe the locations of objects within each of the three levels.

The qualitative scheme we employ consists of separating each level into a 3x3 spatial grid, with each sector within the grid assigned a unique number between 1 and 9 to identify it. The grid is shown as follows, with north assumed to be at the top of the page:

```
1  2  3
4  5  6
7  8  9
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Objects can occupy more than one grid sector, and grid sectors can contain more than one object, making the representation flexible. The resolution of this representation is not high, but considering the qualitative nature of a typical *feng shui* analysis and the number of objects that typically need to be represented at each of the three levels, it is adequate in most cases.

2.3. KNOWLEDGE REPRESENTATION REQUIREMENTS RELATED TO THE USE OF CBR AND GA's

The fact that we have chosen to use CBR as the main reasoning strategy in our process models implies the need to develop a knowledge representation scheme for cases. Using a GA as the reasoning strategy with which case adaptation is performed raises the need to address the representation of phenotypes, genotypes, and evaluation knowledge (for the GA's fitness function). In the following subsections we describe the knowledge representations we have chosen for these concepts.

2.3.1. Case and Phenotype Representation

Cases are represented symbolically by describing each residence at all three levels (or as many levels as we have knowledge about). Within each level, objects that exist at that level are listed, together with any attributes (and the values of those attributes) that might be necessary in order to fully describe the objects for the purposes of *feng shui*. Some attributes such as locations and types of objects are required in order to be able to adequately use the cases, whereas others such as shapes and steepness are optional, and don't even make sense for some objects. A diagrammatic example of a residence is shown in Figure 2. This is followed by an abbreviated version of the symbolic case representation of the same residence.

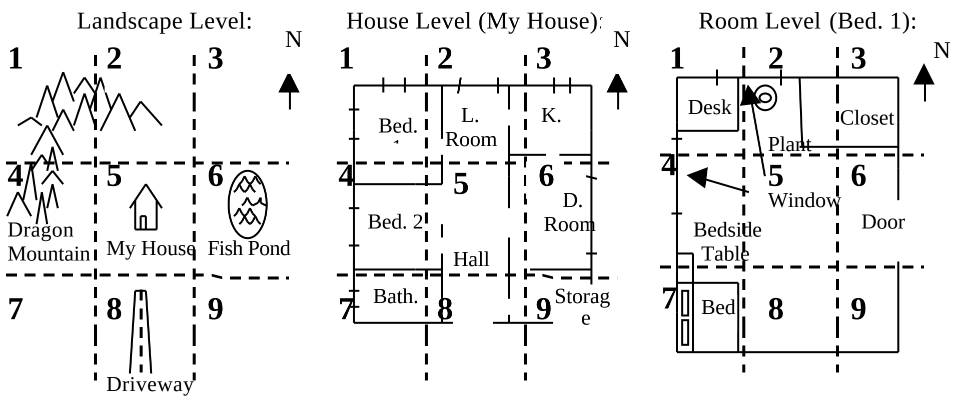

Figure 2. Three levels of description of a residence.

```
(((level landscape)
  (elements (((type hill) (name dragon-mountain)
              (location (1 2 4)) (steepness high) ...)
             ((type pond) (name fish-pond) (location (6))
              (clarity murky) ...)
             ((type house) (name my-house) (location (5)))
             ...)))
 ((level house)
  (elements (((type bedroom) (name bedroom-1) (location (1))
              (shape square))
             ((type bedroom) (name bedroom-2) (location (4)))
             ((type hallway) (name hall-1) (location (5 8)))
             ...))
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```
  (connectors (((type door) (name b2-hall) (location (5))
                (side-a bedroom-2) (side-b hall-1)
                (direction ew))
               ((type window) (name b1-window-1) (location (1))
                (side-a bedroom-1) (side-b outside)
                (direction ew))
               ((type window) (name b1-window-2) (location (1))
                (side-a bedroom-1) (side-b outside)
                (direction ns))
               ...)))
 ((level room)
  (name bed-1)
  (elements (((type bed) (name b-1) (location (7)))
             ((type desk) (name d-1) (location (1)))
             ((type window) (name w-1) (location (1 2)))
             ...))))
```

Retrieved cases are used in our process model to seed the population of our case adaptation GA, i.e., as the initial “proposed solutions” in the GA’s population. Therefore, the representation of a phenotype (the physical manifestation of the potential solutions being generated and evolved) in the GA is the same as the case representation described and shown above. The only difference is that the GA operates on each hierarchical level independently, so from the perspective of the GA, at any given moment a phenotype only contains the fragment of a case-like representation that corresponds to one particular level.

2.3.2. Genotype Representation

The GA evaluates phenotypes to determine how good they are as potential solutions to a new problem. However, GA’s usually don’t operate directly on phenotypes; instead, they operate on encoded representations of the phenotypes known as genotypes.

In the *feng shui* domain, at the landscape and room levels, the combination and modification of past solutions in order to evolve them can be performed on genotypes which look exactly like their corresponding phenotypes. This is because the information on each object present within the level is independent of the information describing any other object. However, at the house level it is not only important to know which objects exist (and what their locations are), but also the connections that exist between them. Thus, there are dependencies between the descriptions of different objects, and combining and modifying objects becomes non-trivial.

A complex implementation of the combination and modification operators of the GA in our process model has been developed which requires the re-representation of house-level phenotypes into equivalent genotypes in order to operate. The genotype representation used is based on the concept of adjacency matrices which describe what connections, if any, exist between each pair of objects in a graph. House-level phenotypes must be encoded into their genotype form before the GA can operate them, and the resulting offspring genotypes must be decoded back into phenotype form before their quality can be evaluated by the GA's evaluation function.

2.3.3. Representation of Feng Shui *Analysis Knowledge*

The *feng shui* knowledge which is used as the evaluation function of the GA is represented procedurally. It is implemented as a series of procedures that determine whether different constraints imposed by the domain are violated or not by a given phenotype. Within the procedures, checking for potential cures to the corresponding "bad omen situation" is also done before making a final decision on the "auspiciousness" of a phenotype according to the corresponding constraint. There are several constraints at each level of description of a phenotype.
An example of a *feng shui* constraint at the house level (quoted directly from (Rossbach, 1987)) is:

```
Traditionally, the Chinese avoid three or more doors or
windows in a row...this...funnels ch'i [positive energy] too
quickly...[CURE:]...to stop ch'i from flowing too quickly,
hang a wind chime or crystal ball...
```

This constraint is implemented by first finding the description of all the connectors at the house level, particularly their locations and directions. If at least three connectors are aligned such that their locations are in consecutive (or the same) sectors *and* they are all have the same direction (e.g., north-south), then the constraint has been violated. However, before jumping to this conclusion, we must check whether or not there are any crystal balls or wind chimes in the house that are positioned in line with the violating doors/windows. The pseudocode that performs this analysis, i.e., the procedural representation of the constraint, given a phenotype P, is shown as follows:

```
Get the list C of all connectors in P;
Get the list Q of all potential cures for this constr. in P;
For each connector c in C or until a bad omen has been found:
   Get the location l of c;
   Get the direction d of c;
   Set the list of connectors LU lined up with c to the empty
      list;
   Get the list Reduced of all elements in C except c;
   For each connector r in Reduced:
      If the direction of r is d And
         the location of r lines up with l along direction d,
         Then add r to LU;
      End-If;
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      End-For;
      If there are two or more connectors in LU And
         no potential cure in lines up with r,
         Then signal a bad omen situation;
      End-If;
   End-For;
```

At the house level, additional constraints have been implemented that are not imposed directly by the *feng shui* domain, but rather by common sense. For instance, after the GA operates on its population some of the proposed solutions might have "pathological" features such as a house ending up with no door connecting it to the outside. These non-viable designs are also detected, as are those that violate the principles of *feng shui*, by the GA's evaluation function.

3. Implementation of Process Model

The process model presented in this paper has been implemented in a system called GENCAD. Some of the characteristics of the knowledge represented in GENCAD have been discussed above. The GA used in GENCAD operates on only one of the three levels of description of a residence at a time. This is because there are very few *feng shui* constraints that relate objects belonging to different levels of description; the constraints involve relations between objects within the same level. Thus, potential solutions to the new problem at the landscape level can be evolved (and evaluated) independently from potential solutions to the same new problem at the house level, etc.

This leads in general to faster convergence than if solutions were evolved that included in their descriptions all three levels at once. In the second case the solutions would simultaneously have to satisfy all *feng shui* constraints at all levels, so even if they already satisfy the constraints at one level, the algorithm would continue evolving them. It would be counter-productive to continue evolving the part of the solution that has already converged, which is why the implementation separates out each level and evolves the portion of the solution corresponding to each level independently. In the following sections we describe in more detail the crossover, mutation, and evaluation operators of the GA used in GENCAD, as applied to the *feng shui* domain.

3.1. CROSSOVER

Crossover is an operator that combines features of two potential solutions by "cutting" the descriptions of the two solutions and "pasting" together pieces from the two old solutions to create two new potential solutions. At the landscape and room levels of description of a residence, crossover simply consists of randomly choosing a crossover point in the descriptions of the two parent landscapes (or rooms), performing the “cut” operation at that point, and performing the “paste” operation of the resulting pieces such that each resulting offspring combines features of each of the parents.

At the house level, crossover is more complicated, as a simple cut-and-paste operation is not viable when there are multiple cross-dependencies between the descriptions of the items in the parents. This occurs at the house level due to the importance not just of the rooms in the house, but also of the connections between them. As mentioned earlier, at the house level phenotypes are first converted into genotypes which are based on the concept of adjacency matrices, and crossover is performed on these genotypes before re-converting the resulting genotypes into equivalent phenotypes. Figure 3 shows a schematic of this matrix-based crossover operation (where the vectors that label the adjacency matrices with the names of rooms are also crossed over); the parent genotypes are of different sizes because they have different numbers of rooms.

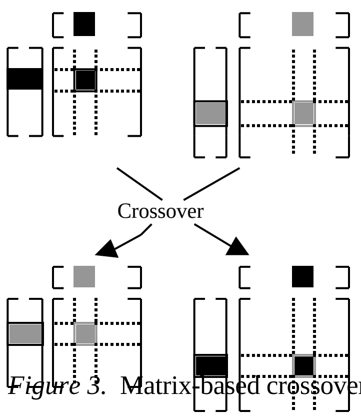

Figure 3. Matrix-based crossover.

The matrix-based operation that implements crossover at the house level is based on extracting (and interchanging) submatrices from each of the parent genotypes, resulting in offspring genotypes that combine both elements (e.g., bedrooms, kitchens, etc.) and connectors (e.g., doors, windows, etc.) of both parent genotypes, and at the same time are internally consistent (i.e., meaningful semantics can be ascribed to them). After the operation, the equivalent offspring phenotypes together contain the same types of elements and connectors that the parent phenotypes had. Each of the offspring has the same total number of elements that one of the parents had (though each will have some elements inherited from both parents). The total number of connectors in each offspring might be different from that in each of the parents, but the total number of connectors in both offspring will be the same as the total in both parents together.

3.2. MUTATION

While the crossover operator maintains in the offspring it produces the information present in the parents, the mutation operator serves to make modifications that might help the GA find an acceptable solution faster (or find it at all, as without mutation convergence might not occur in some situations). The modifications performed by mutation are random, so the "right" type of mutation (in order to achieve convergence, or to achieve it faster) might not occur quickly, and many useless mutations might have to be explored before a "good" one occurs. But the mutation operator can be very useful in achieving convergence in situations where crossover would not be able to search enough parts of the solution space.

Mutation is implemented by randomly choosing an attribute whose value will be modified, and then randomly choosing a new value for it, from amongst a list of values known to be valid (meaningful) for the given attribute. The system's memory contains knowledge of which values are acceptable for each known attribute in the *feng shui* domain.

3.3. EVALUATION AND SELECTION

As mentioned previously, the evaluation function of the GA embodies the *feng shui* knowledge in GENCAD. This knowledge is implemented procedurally, looking for potential "bad omen situations" (i.e., constraint violations), and if found, looking for the existence of potential "cures" for these. The total fitness F of a given phenotype, given N constraints (C_1 through C_N) and M problem requirements (R_1 through R_M), is calculated with the following equation:

$$F = \sum_{i=1}^{N} C_i + \sum_{j=1}^{M} R_j$$

where $C_i = 0$ if constraint C_i is not violated by the phenotype or
$C_i = 1$ if constraint C_i is violated by the phenotype, and
$R_j = 0$ if requirement R_j is met by the phenotype or
$R_j = 1$ if requirement R_j is not met by the phenotype.

At the end of each GA cycle, the total fitness of each newly-generated proposed solution in the population is calculated. Convergence to an acceptable solution occurs if an individual in the population has a total fitness of 0, meaning that none of the constraints has been violated and all of the problem requirements have been met.

The best solutions (those with lower fitness value) found by combining the new ones with the ones from the previous GA generation are kept to participate in the GA's next generation, assuming that convergence has not been achieved. This process is known as selection. The percentage of solutions from the population that are selected is chosen so as to keep the total size of the population constant. This percentage depends on how many new solutions were generated in the previous generation (usually this will be a constant amount, but because of potentially meaningless solutions that are filtered out during crossover and/or mutation, it may vary).

4. Summary

We have presented a process model for design that combines the use of precedents, an idea taken from case-based reasoning research, with the incremental evolution of potential solutions, an idea stemming from genetic algorithms. This process model adapts design cases by evolving combinations and modifications of them until they achieve the user's problem requirements and they meet the constraints of the domain to which the process model is being applied. In this paper we have described the process model as it would be applied to the domain of layout design of residences that conform to the principles of *feng shui*.

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