ANALYSIS OF ARCHITECTURAL SPACE COMPOSITION USING INDUCTIVE LOGIC PROGRAMMING

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Abstract. In this paper, we summarized an application of the ILP technique to the analysis of the human design process in architectural design. We focused particularly on discovering the patterns in the spatial composition process in the framework of design analysis called Architectural Space Montage Technique. Spatial composition data used in this paper are complexly structured data, which are collections of architectural objects with geometric relationships. The objects and relationships are constrained within a given set of attributes (such as object type, object angle, time stamp, relation type) together with background knowledge on the class hierarchies of object types and relation types. We modeled these spatial composition process data in first-order logic and applied the ILP system Progol to discover design patterns that characterized the given data.

1. Introduction

In this study, the process of architectural design was analyzed by Inductive Logic Programming (ILP) (Muggleton, 1994; Lavrac and Dzeroski et al., 1999). ILP is a machine learning technique based on first-order logic that executes Inductive Reasoning, which is the generalizing of results from examples to generate new concepts.

In various contexts, it has been reported in the domain of phenomenology or developmental psychology that humans have unconscious spatial schemata that enables them to recognize space (Merleau-Ponty, 1945; Piaget, 1963). In support of this theory, it has been proposed that the human design process is affected by the schemata, and these appear as compositional patterns of such architectural elements as walls, furniture, buildings and so on (Schulz, 1973; Bollnow, 1963). In order to create an architectural space suitable for human recognition, it is important to find the latent patterns of spatial composition affected by the spatial schemata from a psychological point of view. This is currently a key issue in the architectural field.

From the above, this study investigates the patterns in the initial process of architectural design, which is the process of visualizing one's own mental images. We focused particularly on discovering patterns that indicate the differences between groups of architecturally trained and untrained individuals.

Several studies on architectural design patterns have been done. For example, the Shape-Grammar for F. L. Wright, who was a famous architect, was defined. It was a set of production rules, which could generate floor plans in Wright's architectural style (Koning et al., 1981). The Shape-Grammar, however, does not reflect the actual design process. In this paper, actual design processes using Architectural Space Montage Technique (ASMT) were analyzed.

The ASMT was developed by one of the authors to elucidate the fundamental patterns of spatial composition that exist in human beings. In an experiment using ASMT, a subject composes architectural space by placing various miniatures such as walls, furniture, and so on, at a scale of 1:50 on a white board. Figure 1 illustrates two examples of architectural models developed using this method. In this study, we regard a spatial composition process using this method as an architectural design process.

In single ASMT experiment, it is possible to have dozens to hundreds of miniatures placed. Moreover, a miniature newly placed has plural relationships to the previously placed miniatures. It is difficult to discover patterns by only relying on human inspection in complexly structured data such as those in the spatial composition process. Therefore, in this study, we applied Progol, one of the ILP systems, to find latent patterns of the spatial composition process in ASMT.

Recently, machine learning systems (see C4.5 (Quinlan, 1993)) that generate decision trees based on propositional logic have been used as data mining engines in practical domains such as the medical field (Tsumoto and Tanaka, 1997) and the distribution industry (Numao and Shimizu, 1997). However, in order to learn the chain of relationships between miniatures, ILP, based on expressive first-order logic, is more appropriate for ASMT than systems of learning based on propositional logic.

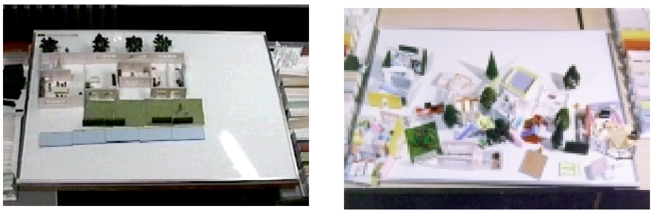


Figure 1. Examples of models constructed using ASMT by an undergraduate student (left) and a kindergarten child (right)

We modeled the spatial composition process with the Entity-Relationship (ER) model and designed a module to convert the spatial composition process data recreated with a CAD system to Prolog clauses, which constitute input data to Progol. The integration of the CAD system with Progol is applied to discover patterns of the spatial composition process.

Brief overviews of ASMT and Progol are given in Sections 2 and 3, respectively. In Section 4, the spatial composition process is modeled in first-order logic. We show the procedure for analysis in Section 5. In Section 6, we show an example of discovering characteristic patterns of architecturally trained subjects and untrained subjects from their spatial composition process data. The results of ASMT experiments and pattern discovery are shown. Our conclusions and future work are stated in Section 7.

2. ASMT

ASMT was originally developed in the context of psychotherapy. Clinical psychological analysis has been undertaken on the characteristic patterns of the spatial compositions formed by schizophrenic patients, school children, mentally handicapped children, and kindergarten children (Okazaki et al., 1992a, 1992b, 1997, 1999, respectively). In ASMT, architectural space is composed by simply placing three-dimensional miniatures. Therefore, the subject is not limited by his or her drawing ability. Various subjects can readily express a 3-D architectural space. Moreover, we can observe the steps in the design process clearly.

The types of miniatures used in ASMT differ slightly depending on the experimental groups. In this study, we prepared the following 44 kinds of miniatures: six kinds of walls made of styrene board of different lengths (1800 mm, 2700 mm, 3600 mm, and 5400 mm) and in various colors (blue, red, yellow, green, white, gray, pink, ivory, cream, mint, and grain) with various openings, mirror walls and glass walls in lengths of 3600 mm and 5400 mm with the glass walls in various colors (blue, orange, and clear), columns, twelve kinds of furniture (e.g. table, sofa, carpet, shelf), six different sanitary fixtures (e.g. sink, toilet, bathtub), four different figures (i.e. man, woman, boy and girl), two types of animals (i.e. dog and cat), six types of vegetation (e.g. lawn, conifer, broadleaf, hedge), and five different architectural elements (e.g. balcony, stairs). Figure 2 shows examples of these miniatures.

The experimental setting and procedure are stated as follows. A white board (60 cm by 90 cm) was placed horizontally on a desk in the experimental room. Two smaller white boards (45 cm by 30 cm) were placed on both sides of the larger board, with miniature walls arranged on top of the boards. The other

Figure 2. Miniatures used in ASMT experiment (From left: walls, furniture, sanitary fixtures, figures, vegetations, and architectural elements)

miniatures were displayed on a shelf.

Each subject constructed the model of his ideal house on the large white board. The experiment ends whenever the subject tells the experimenter that he is finished with the model. The state of the model in the experiment was constantly recorded by a video camera.

3. Progol

Progol is one of ILP systems by Mugletton (1995). Progol combines Inverse Entailment with general-to-specific search through a refinement graph. It allows arbitrary Prolog programs as the background knowledge and arbitrary definite clauses as examples. Input data to Progol consist of a set of positive example $E+$, a set of negative example $E-$, a set of background knowledge BK, and mode declarations used by Progol to guide the process of constructing a generalization from its example. From these data, a hypotheses in the form of a Horn clause are constructed.

Hypothesis H is complete if $\forall e \in E+ : BK \cup H \models e$, where "$\models$" means logical entailment. Hypothesis H is consistent if $\forall e \in E- : BK \cup H \not\models e$.

In this paper, one of the versions of Progol, P-Progol 2.7.5, was used. P-Progol was implemented by Srinivasan and Rui in Prolog based on the Progol algorithm (1999).

4. Modeling of the Spatial Composition Process

In order to describe the design process logically, we defined a unit of the spatial composition process as a miniature placement with relations to the miniatures previously placed. The spatial composition process is a set of miniature placements.

4.1. DATA MODEL

In this study, we modeled the spatial composition process with the ER model, which is a well-known semantic data model. An ER model is built with three elements: entity, relationship, and attribute. Shimazu and Hurukawa expressed relational data of plane figures with the RER (Refined Entity-Relationship)

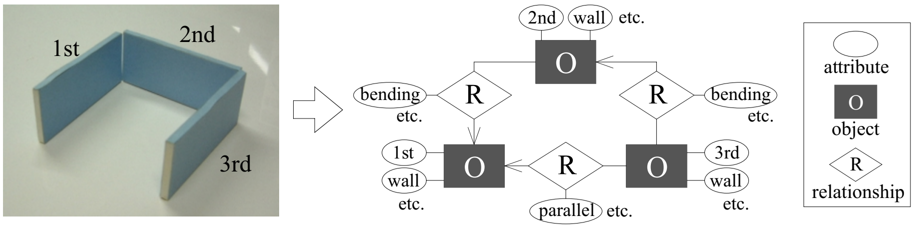


Figure 3. Example of representation of spatial composition process using ER data model

model, which has two types of attributes called "primitive" and "derived" (2000). On the other hand, we refined the ER model in order to express not only a static relational data of figure elements but also the process of generating a figure (See Figure 3). In our data model, the relationship has a direction. A placed miniature corresponds to an entity. After this, we universally called the miniature the "object." A geometric relationship occurs between newly placed objects and the existing objects. Each object has attributes such as an object type and an ordinal number of placement occurrence. Each relationship has attributes such as a relation type. In addition, IS-A hierarchies of the attributes based on the inclusion relation among concepts are known in advance. Details of attributes are described in the following section.

4.2. FIRST-ORDER REPRESENTATION

In this subsection, we show how to describe the above ER model in the form of clauses on first-order logic. The first-order description of a spatial composition process has a finite domain $D = (O \cup R)$, where O is a set of all objects placed and R is a set of all relationships occurred between objects.

4.2.1. Description of the object

Each object o has three attributes: ID number *ObjID*, type *ObjType*, and absolute angle *ObjAngle*, where $o \in O$. The ID number is in four digits, with the first digit representing the experimental case, and the remaining three representing the ordinal number of placement occurrence attached to the object. For example, *ObjID* attached to the object placed in the third placement of experimental case 1 is 1003. Two predicates, `type`/2 and `angle`/2, were defined for each object o, and these represent the type of the object and the absolute angle of the object, respectively. The number described after " / " means arity.

The type of object is represented as follows:

`type(ObjID, ObjType)`,

where `ObjType` $\in$ *OT*. *OT* is a set of 44 vocabularies that represent the minia-

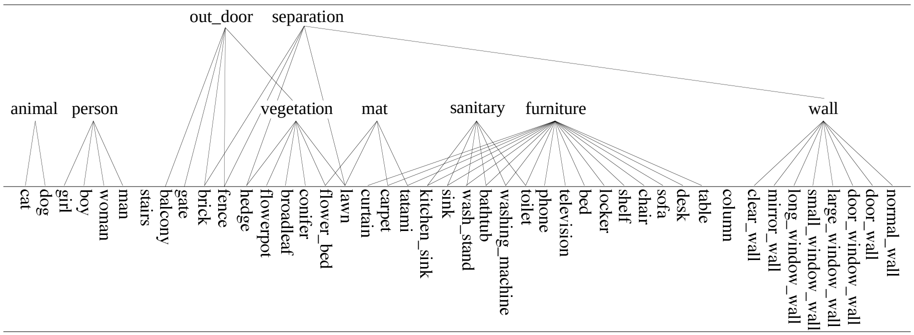


Figure 4. Object type hierarchy

ture types prepared for the ASMT experiment. The object types constitute a hierarchy based on the IS-A relationship. The hierarchies are shown in Figure 4.

The absolute angle is an angle between the miniature and the long side of the white board. The angles are measured in degrees.

The absolute angle of the object is represented as follows:

`angle(ObjID, ObjAngle)`,

where ObjAngle $\in$ {0, 45, 90, ambiguous}. "Ambiguous" means angles other than the 0, 45, or 90 degrees.

4.2.2. description of the relationship

Each relationship *r* between objects has three attributes: type of relation *RelType*, connecting point *C_Point*, and difference *Diff* between the ordinal numbers attached to the objects, where $r \in R$.

A predicate `relation`/5 was defined on each relationship *r*. The relationship between objects is represented as follows:

`relation(N-ObjID,RelType,C_Point,Diff,E-ObjID)`,

where `N-ObjID` and `E-ObjID` are the ID numbers of the newly placed object and the previously placed object related to the newly placed object, respectively. *RelType* and *C_Point* are defined as follows.

The relation type has the following seven sub-attributes.

(1) Contact between objects: This attribute takes a value *Cont* $\in$ {attach, detach, isolate}, where each element represents the condition that objects are in contact, objects are out of contact but close to each other, and objects are isolated from each other, respectively.

(2) Relative angle between objects: This attribute takes a value *Ang* $\in$ {0, 45, 90, ambiguous}.

(3) Arrangement type of objects: This attribute is available in the case where *Cont* is "attach" or "detach", and takes a value *Arr* $\in$ {on, paral-

lel, T_type, bending, I_type, close}, where "close" represents arrangements other than the formers.

(4) Alignment of the edges of objects: This attribute is available where *Arr* is "parallel", and takes a value $Align \in$ {reg, semi_reg, irreg}, where each element represents the edges of both sides of the objects in alignment, the edges of one side of the objects in alignment, and the edges of both sides of the objects out of alignment, respectively.

(5) Distance between objects: This attribute is available where *Arr* is "parallel", and takes a value $Dist \in$ {attach, near, right, far}, where "right" means the distance between the objects and the length of the newly placed object are the same.

(6) Direction of bending: This attribute is available where *Arr* is "bending", and takes a value $Direc \in$ {-r,-l}, where "-r" and "-l" represent right-handed and left-handed, respectively.

(7) Combination of object shapes: The shapes of the objects are classified into three classes: line, point, and mat. The relationship depends on a combination of the classes. Table 1 shows the object types that correspond to these classes. The combination is represented in a row of two letters. Each letter corresponds to the first letter of the object shape. For example, the combination of line and point is described as "lp." This attribute takes a value $Comb \in$ {ll, lp, lm, pp, pm, mm}.

TABLE 1. Shape classification of object types

Class of shape	Type of object corresponding to class of shape					
Line	normal_wall door_wall door_window_wall large_window_wall small_window_wall	long_window_wall mirror_wall clear_wall washing_machine table	desk sofa rack locker bed	television phone toilet curtain bathtub	wash_stand sink kitchen_sink hedge fence	brick gate balcony stairs
Point	column, conifer, broadleaf, flowerpot, man, woman, boy, girl, dog, cat, chair					
mat	tatami, carpet, lawn, flower_bed					

Theoretically, $RelType \subseteq (D_{cont} \times D_{ang} \times D_{arr} \times D_{align} \times D_{dist} \times D_{direc} \times D_{comb})$, where "$D_{\sim}$" means the domain of the sub-attribute of *RelType* given above. In this paper, 65 combinations of the sub-attributes that occurred frequently in the ASMT experiment were selected. Each combination was assigned a vocabulary which represent the relation type. The relation types constitute a IS-A hierarchy based on the inclusion relation. The hierarchy is shown in Figure 5.

The attribute of connecting point indicates where the newly placed object is connected to the previously existing object. This attribute takes a value $C\_Point \in \{(\text{bottom, top, left, right}) \cup (\text{center, corner, edge, ambiguous})\}$, where "bottom" and "top" denote the left and right ends of the previously placed object,

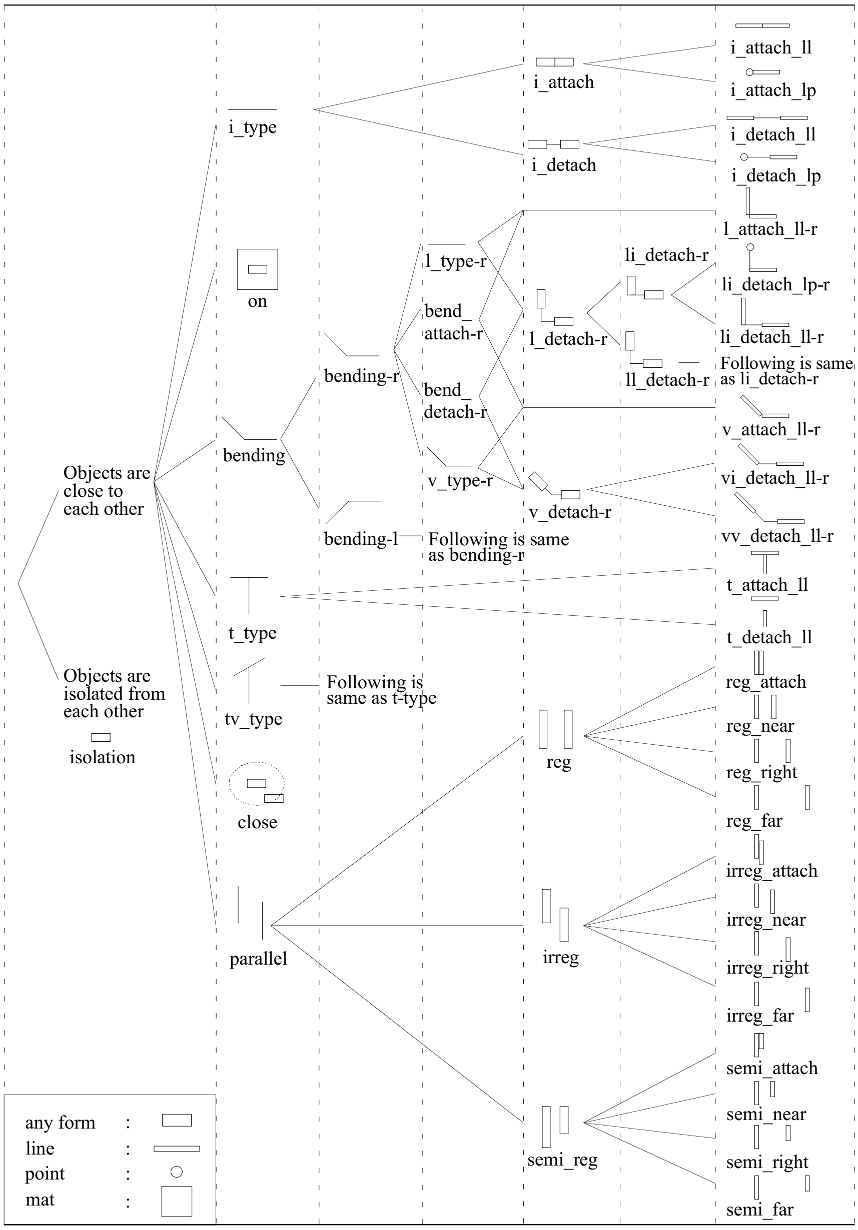


Figure 5. Hierarchy of relation types

respectively. “Left” and “right” mean left and right side of the existing object, viewing from bottom to top, respectively (see Figure 6(a)). The former four elements are available where *Arr*, which is an attribute value of the arrangement type, is “parallel,” ”T_type,” “bending,” or “I_type.” The latter four elements are available where *Arr* is “on” (see Figure 6(b)).

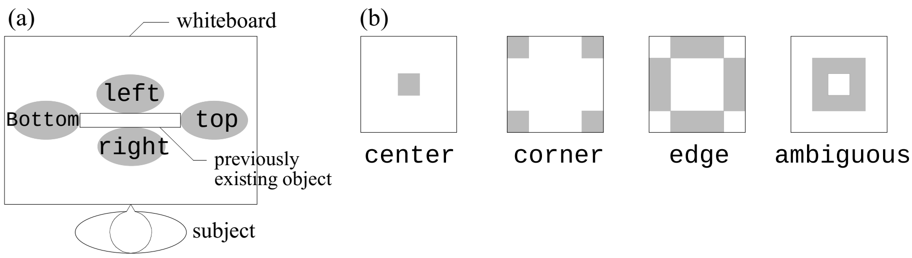


Figure 6. Spheres indicating the connecting points: (a) in the case of "parallel," "T_type," "bending," "I_type," and (b) in the case of "on"

5. Procedure of Analysis

The analysis procedure consists of the following three steps (Figure 7).

- Step 1: The ASMT experiments are conducted.
- Step 2: The actual model is recreated with a CAD system where the order of placements is consciously taken into consideration.
- Step 3: The CAD data are converted automatically into Prolog clauses readable by Progol. These data constitute the input data to Progol.

Steps 2 and 3 are repeated in every experimental case.

- Step 4: The descriptions of the positive examples, the negative examples, and the IS-A relationships of the object type and the relation type are added to descriptions generated in step 3. Every placement is set as the example. These data are inputted to Progol.
- Step 5: Progol acquires rules from the input data.
- Step 6: The rules found are interpreted by a person.

Steps 2, 3, and 4 are detailed in the following subsections.

5.1. RECREATION OF THE MODEL

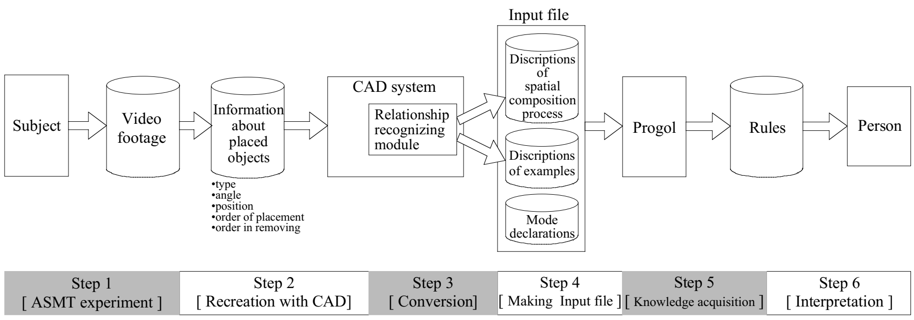


Figure 7. Analysis procedure of the spatial composition process

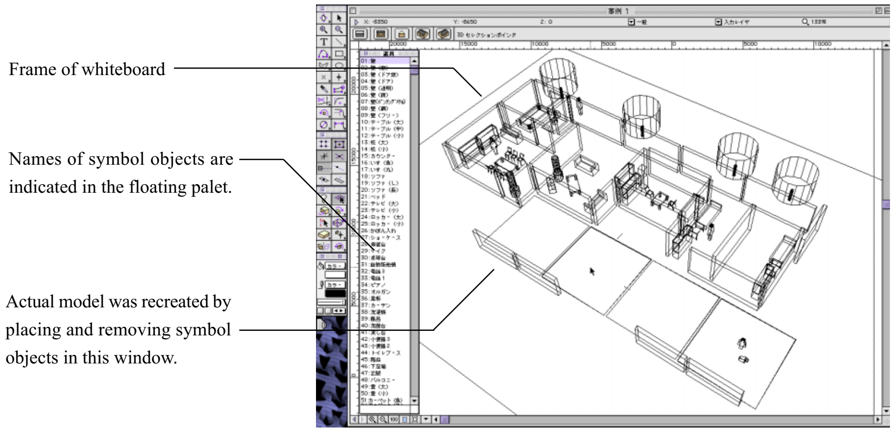


Figure 8. Example of model recreated with CAD system

First, the following information about the placed object was extracted from the video footage of the ASMT experiment:

- type of object
- angle between the object and the long side of the white board
- position on the white board
- order of the object placement
- order in removing the object

Next, the actual model was recreated with one of the CAD systems *MiniCAD7* by placing and removing symbol objects according to the above information. Symbol objects are three-dimensional models of the miniatures prepared for the ASMT experiment. An example of a model recreated with the CAD system is shown in Figure 8.

An ordinal number *PlaceID* indicating the occurrence of the placement is assigned automatically to the object placed. Moving an object is regarded as removing it and placing a new one. To remove an object in the CAD system, the object is simply changed to be invisible by changing its color. An ordinal number *RemoveID* is assigned to it, which indicates the occurrence of the removal.

5.2. CONVERSION TO PROLOG CLAUSES

The Relationship-Recognizing (RR) module was designed to recognize the attributes of the objects and relationships among them, such as *ObjID*, *ObjType*, *ObjAng*, and *RelType*, and so on from the CAD data. These are automatically converted by the module to the first-order representation. The RR module was integrated with the CAD system described in subsection 5.1. The basic infor-

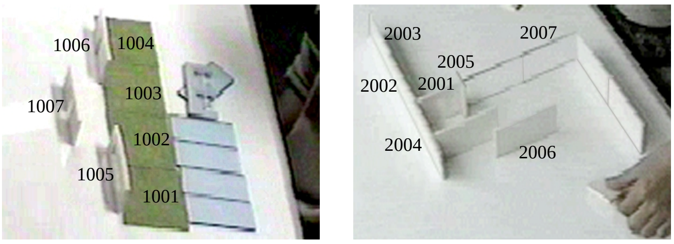


Figure 9. (a) Disposition in experimental case 1, (b) Disposition in experimental case 2 (Numbers in the figure indicate the object ID numbers *ObjID*)

(a) Positive examples

```
placement(1001).
placement(1002).
placement(1003).
placement(1004).
⋮
```

(b) Negative examples

```
placement(2001).
placement(2002).
placement(2003).
placement(2004).
⋮
```

(c) First-order representation of every placement

```
type(1001,lawn).
angle(1001,0).
relation(1001,isolation,none,no_dif,no_obj).
type(1002,lawn).
angle(1002,0).
relation(1002,close,none,1,1001).
⋮
type(2001,door_window_wall).
angle(2001,90).
relation(2001,isolation,none,no_dif,no_obj).
type(2002,normal_wall).
angle(2002,0).
relation(2002,l_touch_ll-l,bottm,1,2001).
⋮
```

(d) IS-A relationships

```
type(A,wall):-type(A,normal_wall).
type(A,wall):-type(A,door_wall).
type(A,wall):-type(A,clear_wall).
type(A,separation):-type(A,normal_wall).
type(A,separation):-type(A,door_wall).
type(A,separation):-type(A,clear_wall).
⋮
relation(A,i_attach,B,C,D):-
        relation(A,i_attach_ll,B,C,D).
relation(A,i_attach,B,C,D):-
        relation(A,i_attach_lp,B,C,D).
relation(A,i_detach,B,C,D):-
        relation(A,i_attach_ll,B,C,D).
⋮
```

(e) Mode declarations

```
:-mode(1,placement(+miniature_id)).
:-mode(1,type(+obj_id)).
:-mode(1,angle(+obj_id)).
:-mode(1,relation(+obj_id,#rel_type,#c_point,#diff,-obj_id)).
:-mode(1,relation(+obj_id,#rel_type,-c_point,#diff,-obj_id)).
:-mode(1,relation(+obj_id,#rel_type,#c_point,-diff,-obj_id)).
:-mode(1,relation(+obj_id,#rel_type,-c_point,-diff,-obj_id)).
```

(f) Determinations

```
:-determination(placement/1,type/2).
:-determination(placement/1,angle/2).
:-determination(placement/1,relation/5).
```

(g) Induced rules

```
placement(A):-relation(A,irreg,B,C,D),relation(D,bend_attach-l,E,F,G),relation(G,irreg,H,I,J).
placement(A):-relation(A,bend_attach-l,B,C,D),type(D,wall),relation(D,irreg,E,F,G),type(G,wall).
⋮
```

Figure 10. Examples of input and output data in the case that targets are characteristic patterns in case 1: (a) Positive examples, (b) Negative examples, (c) First-order representation of each placement, (d) IS-A relationships of object type and relation type, (e) Mode declarations, (f) Determinations, (g) Induced rules

mation used by the RR module includes (1) vertex coordinates of the objects, (2) *PlaceID*, (3) *RemoveID*, and (4) ID number indicating the object type.

Descriptions of the object types and the relationships in the form of a ground unit clause are outputted. The object type and the relation type recognized correspond to the leaves of the tree illustrated in Figures 4 and 5, respectively. In the case of object disposition shown in Figure 9, the descriptions generated by this module are illustrated in Figure 10(c).

5.3. INPUT FILE TO PROGOL

In this study, the input file to Progol was designed as follows:

• **Positive and Negative Examples.** The target concept in this study is the spatial composition process by a specific group *P*. All placements by subjects belonging to group *P* were set as positive examples, and all placements by subjects belonging to another group were set as negative examples.

Examples can be represented as `placement(ObjID)`. Typical descriptions of positive examples and negative examples are shown in Figure 10(a) and (b), respectively. These descriptions are generated by the RR module together with the description of the attributes of the objects and the relationships.

• **Background Knowledge.** The background knowledge *BK* consists of two kinds of data. One is the knowledge of attributes of the objects and the relationships, and the other is knowledge of the IS-A relationships between the attribute values. The IS-A relationships between the object types (see Figure 4) and the relation types (see Figure 5) are set as *BK*. IS-A relationships are represented in the form of Horn clause. Examples of descriptions of IS-A relationships are shown in Figure 10(d).

• **Mode Declarations and Determinations.** In P-Progol, the user indicates the language in which hypotheses are to be constructed by invoking mode declaration and determination. For example, mode declaration can be represented as follows:

```
:- mode(recall,p(+a,-b,#c)). ,
```

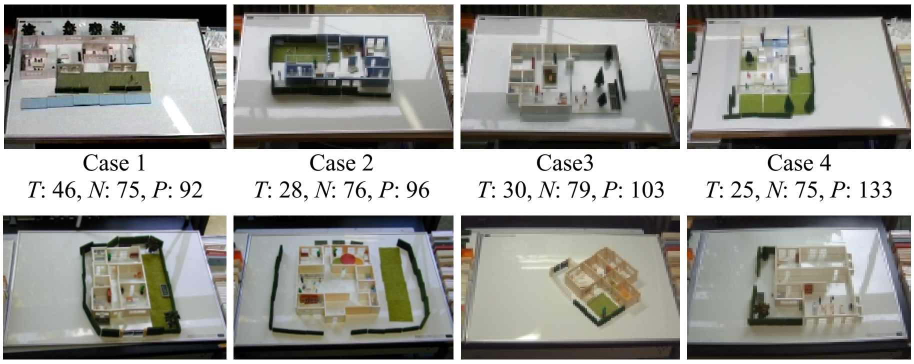
where recall is the number of successful calls to the predicate and "+" indicates that the argument is an input. For all calls to this predicate, the argument will be bound to a value. The symbol "-" indicates that the argument is an output. For all calls to this predicate, the argument will output a term. The symbol "#" indicates that a constant should appear in this argument.

Determination takes the following form:

```
determination(TargetName/Arity, BackgroundName/Arity ).,
```

where the first argument is the name and arity of the target predicate, that is, the predicate will appear in the head of hypothesized clauses. The second argument is the name and arity of a predicate that appears in the body of such clauses.

Mode declaration and determination in this study are shown in Figure 10(e) and (f), respectively. According to these instructions, the head of a hypothesis is the predicate `placement`, and the body of a hypothesis is a combination of attributes represented with the predicates `type`, `angle`, and `relation`. In



Case 1 T: 46, N: 75, P: 92
Case 2 T: 28, N: 76, P: 96
Case3 T: 30, N: 79, P: 103
Case 4 T: 25, N: 75, P: 133
Case 5 T: 60, N: 80, P: 149
Case 6 T: 29, N: 90, P: 110
Case 7 T: 25, N: 52, P: 70
Case 8 T: 47, N: 57, P: 71

Figure 11. Results of ASMT experiments on architecturally trained students (upper) and untrained students (lower) (working time T (min.) of the experiment, the number of miniatures on the white board at the end of the experiment N, the number of placements P)

other words, the body of the hypothesis represents the transitive closure based on the relationships in the ER model. Examples of rules are shown in Figure 10(g).

6. Analysis

ASMT experiments were conducted, and the experimental cases were analyzed by a system integrated from the CAD system, the Relationship-Recognizing module, and Progol.

6.1. RESULTS OF ASMT EXPERIMENTS AND LEARNING METHOD

One ASMT trial was conducted on each of the four university students trained in architectural design and the four untrained university students. Results are shown in Figure 11. Progol induced rules from the following two kinds of input data.

(1) Input data in which the placements by the trained students were set as positive and the placements by the untrained students were set as negative.

(2) Input data in which the placements by the untrained students were set as positive and the placements by the trained students were set as negative.

Rules induced from input data (1) and (2) indicate the characteristic patterns of the trained students and those of the untrained students, respectively.

6.2. RESULTS OF PROGOL LEARNING

As a result, 147 and 149 rules were extracted from data (1) and (2), respectively. In this paper, the rules that cover the placements by more than half of the members of each group were regarded as characteristics common to the group. The numbers of the common rules were 28 and 32, respectively. Rules of the trained students and the untrained students are shown in Tables 2 and 3, respectively. The coverage shown in the tables is defined as the ratio of positive examples covered by the rules to the total number of positive examples. The rule with the largest coverage is regarded as most general. The variables shown in the "diagram" column in these Tables denote the ID numbers of objects that were generalized. Reverse alphabetical order indicates the order of placement is reversed, where *"A"* would represent the last placement.

6.3. DISCUSSION

6.3.1. Validation of rules

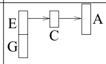
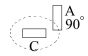
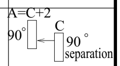
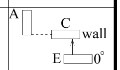
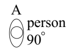
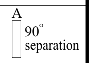
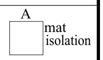
We measured predictive accuracy for unseen cases by using four-fold cross-validations. The eight experimental cases shown in Figure 11 were split into four folds. Each fold contains two cases by the trained student and the untrained student. The examples containing three folds were set as training examples. Rules were induced from the training examples by progol. The examples contained in a remaining fold were classified into negative or positive by using the induced rules. The above procedures were repeated four times while changing the combination of the folds. Predictive accuracy is calculated by $PA = (P^{+}+P^{-})/E$, where P^{+} and P^{-} are the number of correctly predicted positive examples and negative examples, respectively, and E is the total number of the training examples. In the case where the placements by the trained students were set as positive examples, the average of *PA* was 0.511. In the case where the placements by the untrained students were set as positive examples, the average of *PA* was 0.572.

6.3.2. Interpretation

• Patterns found for the architecturally trained students. Rules of the trained students were interpreted as follows.

(1) Rules *T1*, *T2*, *T3*, *T4*, *T9*, *T10*, *T11*, *T16*, *T17*, *T18*, *T20*, *T23*, *T27*, and *T28* refer to only relationships, indicating that the objects are separated from each other, e.g. "irreg," "close," "li_detach-r." It can be inferred from these rules that one of the characteristics of the trained students is placement with each object separated from the others.

TABLE 2-1. Rules found for trained students (ID of rule *RID*, Coverage of rule *Cov*(%), Number of members whose placements are covered by the rule *CM*, Description of rule, and Diagram of rule)

RID	*Cov* (%)	*CM*	Description of common rule	Diagram
T1	3.78	3	placement(A):-relation(A,irreg,right,B,C), relation(C,semi_reg,right,D,E),relation(E,i_attach,top,F,G).	
T2	3.54	4	placement(A):-angle(A,90),relation(A,close,none,B,C).	
T3	2.12	4	placement(A):-angle(A,90),relation(A,irreg,left,B,C), angle(C,90),relation(A,irreg,left,2,C),type(C,separation).	
T4	1.89	3	placement(A):-relation(A,li_detach-r,bottom,B,C), type(C,wall),relation(C,irreg,left,D,E),angle(E,0).	
T5	1.89	4	placement(A):-type(A,person),angle(A,90).	
T6	1.42	4	placement(A):-type(A,separation),angle(A,90), relation(A,isolation,none,B,C).	
T7	1.18	3	placement(A):-type(A,mat),relation(A,isolation,none,B,C).	

(2) Rules *T1* and *T23* state that three objects were frequently placed with "semi_irreg" or "irreg" relationships, which indicate that objects are parallel to each other. It can be inferred from these rules that the trained students constructed stratiform compositions.

(3) Rules *T2*, *T3*, *T5*, *T6*, *T14*, *T18*, *T24*, *T25*, *T26*, and *T27* refer to an object angle of "90." It can be inferred from these rules that the trained students placed objects in the vertical direction.

(4) Rules *T9*, *T13*, *T16*, *T18*, and *T20* state that objects with the "i_detach" relationship were frequently placed. It can be inferred from these rules that one of the characteristics of the trained students is the placement in a straight line with the object's ends detached.

(5) Rules *T6*, *T7*, *T13*, *T14*, *T15*, and *T25* state that objects were frequently placed in "isolation." It can be inferred from these rules that trained students constructed elements in isolation, and integrated them at the end.

• **Patterns found for the untrained students.** Rules of the untrained students were interpreted as follows.

(1) Rules *U2*, *U3*, *U4*, *U6*, *U8*, *U13*, *U16*, *U19*, *U22*, *U23*, *U24*, *U26*, *U27*, *U28*, *U29*, *U31*, and *U32* only refer to relationships indicating that the objects are in contact with the others at their ends, e.g. "bend_attach-l," and "i_attach." It can be inferred from these rules that one of the characteristics of the untrained students is placement with each object in contact with the others.

TABLE 2-2. Rules found for trained students (continuation of Table 2-1)

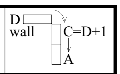
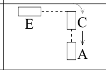
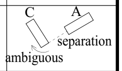
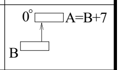
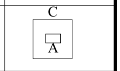
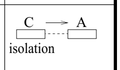
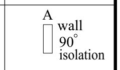
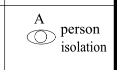
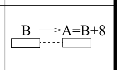
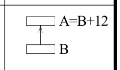
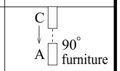
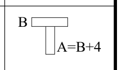
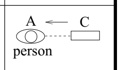
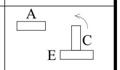
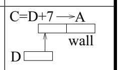
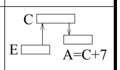
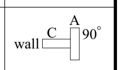
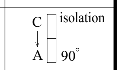
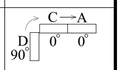
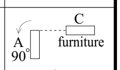
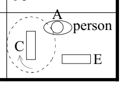
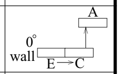
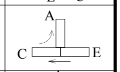
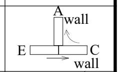
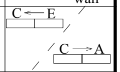
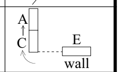
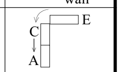
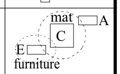
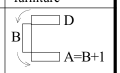
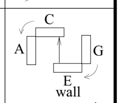
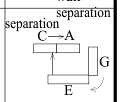
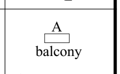
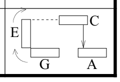
T8	1.18	3	placement(A):-relation(A,i_attach,bottom,B,C), relation(C,bend_attach-r,top,1,D),type(D,wall).	
T9	1.18	4	placement(A):-relation(A,i_detach,bottom,B,C), relation(C,li_detach-r,top,D,E).	
T10	1.18	3	placement(A):-angle(A,fuzzy), relation(A,li_detach-r,bottom,B,C),type(C,separation).	
T11	1.18	3	placement(A):-angle(A,0),relation(A,irreg,left,7,B).	
T12	1.18	4	placement(A):-relation(A,on,center,B,C).	
T13	0.94	3	placement(A):-relation(A,i_detach,top,B,C), relation(C,isolation,none,D,E).	
T14	0.94	3	placement(A):-type(A,wall),angle(A,90), relation(A,isolation,none,B,C).	
T15	0.94	3	placement(A):-type(A,person),relation(A,isolation,none,B,C).	
T16	0.94	3	placement(A):-relation(A,i_detach,top,8,B).	
T17	0.94	3	placement(A):-relation(A,reg,left,12,B).	
T18	0.94	3	placement(A):-type(A,furniture),angle(A,90), relation(A,i_detach,bottom,B,C).	
T19	0.94	3	placement(A):-relation(A,t_attach,right,4,B).	
T20	0.94	3	placement(A):-type(A,person), relation(A,i_detach,bottom,B,C).	
T21	0.94	3	placement(A):-relation(A,li_detach-l,top,B,C), relation(C,t_attach,left,D,E).	
T22	0.94	3	placement(A):-type(A,wall),relation(A,i_attach,top,B,C), relation(C,irreg,left,7,D).	
T23	0.94	3	placement(A):-relation(A,irreg,right,7,C), relation(C,irreg,left,D,E).	
T24	0.94	3	placement(A):-angle(A,90),relation(A,t_attach,top,B,C), type(C,wall).	
T25	0.71	3	placement(A):-angle(A,90),relation(A,i_attach,bottom,B,C), relation(C,isolation,none,D,E).	
T26	0.71	3	placement(A):-angle(A,0),relation(A,i_attach,top,B,C), angle(C,0),relation(C,bend_attach-r,top,B,D),angle(D,90).	
T27	0.71	3	placement(A):-type(A,furniture),angle(A,90), relation(A,li_detach-l,bottom,B,C),type(C,furniture).	
T28	0.71	3	placement(A):-type(A,person),relation(A,close,none,B,C), relation(C,li_detach-r,bottom,D,E).	

TABLE 3-1. Rules found for untrained students (ID of rule *RID*, Coverage of rule *Cov*(%), Number of members whose placements are covered by the rule *CM*, Description of rule, and Diagram of rule)

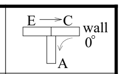
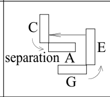
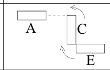
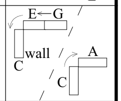
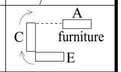
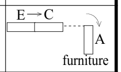
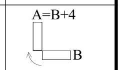
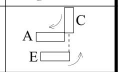
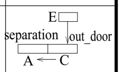
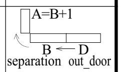
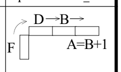
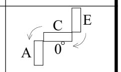
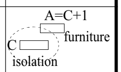
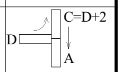
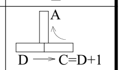
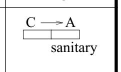
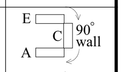
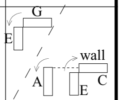
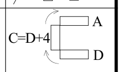
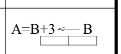
RID	*Cov (%)*	*CM*	Description of common rule	Diagram
U1	3.72	3	placement(A):-relation(A,irreg,left,B,C), relation(C,i_attach,top,1,E),type(E,wall),angle(E,0).	
U2	2.98	3	placement(A):-relation(A,bend_attach-l,top,B,C), relation(C,i_attach,bottom,D,E).	
U3	2.98	4	placement(A):-type(A,wall),relation(A,bend_attach-r, bottom,B,C),type(C,wall),relation(C,i_attach,top,D,E).	
U4	2.73	3	placement(A):-relation(A,i_attach,top,B,C),type(C,wall), relation(C,i_attach,bottom,D,E),type(E,wall).	
U5	2.73	4	placement(A):-relation(A,i_attach,top,B,C), relation(C,li_detach-r,bottom,D,E),type(E,wall).	
U6	2.73	3	placement(A):-relation(A,i_attach,bottom,B,C), relation(C,bend_attach-l,bottom,D,E).	
U7	2.48	3	placement(A):-relation(A,close,none,B,C),type(C,mat), relation(C,close,none,D,E),type(E,furniture).	
U8	2.23	4	placement(A):-relation(A,bend_attach-l,bottom,1,B), relation(B,bend_attach-l,bottom,C,D).	
U9	2.23	3	placement(A):-relation(A,bend_attach-l,bottom,B,C), relation(C,irreg,left,D,E),type(E,wall), relation(E,bend_attach-r,bottom,F,G).	
U10	1.99	3	placement(A):-type(A,separation),relation(A,i_attach, top,B,C),type(C,separation),relation(C,irreg,left,D,E), relation(E,bend_attach-r,bottom,F,G).	
U11	1.74	3	placement(A):-type(A,balcony).	
U12	1.74	3	placement(A):-relation(A,irreg,right,B,C),relation(C, li_detach-r,bottom,D,E),relation(E,bend_attach-r,bottom,F,G).	

(2) Rules *U2*, *U3*, *U13*, and *U27* state that objects with the “i_attach” relationship were placed first, and another object with a relationship such as “bend_attach-l” or “bend_attach-r” was placed after that with its end in contact at the joint of the former objects. It can be inferred from these rules that compositions by the untrained students are more spread out in branches.

(3) Rules *U8*, *U12*, *U17*, *U29*, and *U31* state that three objects with “bending” relationships in the same direction were placed. It can be inferred from these rules that the untrained students constructed U-shaped enclosures.

(4) Rule *U1* states that object *C* is related to object *E* ,of an angle “0,” with the “i_attach” relationship, and object *A* is related to object *C* with the “irreg” relationship. This condition means that all of the objects have “0” angle. It can be inferred from these rules that the untrained students constructed in a

TABLE 3-2. Rules found for untrained students (continuation of Table 3-1)

U13	1.74	3	placement(A):-relation(A,bend_attach-l,bottom,B,C), type(C,wall),angle(C,0),relation(C,i_attach,top,D,E).	
U14	1.74	3	placement(A):-type(A,separation),relation(A,bend_attach-l, bottom,B,C),relation(C,irreg,left,D,E), relation(E,bend_attach-l,top,F,G).	
U15	1.74	4	placement(A):-relation(A,li_detach-l,bottom,B,C), relation(C,bend_attach-r,bottom,D,E).	
U16	1.74	4	placement(A):-relation(A,bend_attach-r,top,B,C), type(C,wall),relation(C,bend_attach-l,bottom,D,E), relation(E,i_attach,bottom,F,G).	
U17	1.49	3	placement(A):-type(A,furniture),relation(A,li_detach-r, top,B,C),relation(C,bend_attach-r,bottom,D,E).	
U18	1.49	4	placement(A):-type(A,furniture), relation(A,li_detach-r,top,B,C),relation(C,i_attach,top,D,E).	
U19	1.24	4	placement(A):-relation(A,bend_attach-r,bottom,4,B).	
U20	1.24	3	placement(A):-relation(A,bend_attach-r,bottom,B,C), relation(C,li_detach-l,top,D,E).	
U21	1.24	3	placement(A):-type(A,separation),relation(A,i_attach,bottom, B,C),type(C,out_door),relation(C,semi_regular,right,D,E).	
U22	1.24	3	placement(A):-relation(A,bend_attach-r,bottom,1,B),type(B, separation),relation(B,i_attach,bottom,C,D),type(D,out_door).	
U23	1.24	4	placement(A):-relation(A,i_attach,top,1,B),relation(B, i_attach,top,C,D),relation(D,bend_attach-l,top,E,F).	
U24	1.24	3	placement(A):-relation(A,bend_attach-l,bottom,B,C), angle(C,0),relation(C,bend_attach-r,bottom,D,E).	
U25	1.24	3	placement(A):-type(A,furniture),relation(A,close,none,B,C), relation(A,close,none,1,C),relation(C,isolation,none,D,E).	
U26	0.99	3	placement(A):-relation(A,i_attach,bottom,B,C), relation(C,bend_attach-l,top,2,D).	
U27	0.99	3	placement(A):-relation(A,bend_attach-r,bottom,B,C), relation(C,i_attach,top,1,D).	
U28	0.99	3	placement(A):-type(A,sanitary),relation(A,i_attach,top,B,C).	
U29	0.99	3	placement(A):-relation(A,bend_attach-r,bottom,B,C), type(C,wall),angle(C,90),relation(C,bend_attach-r,top,D,E).	
U30	0.99	3	placement(A):-relation(A,li_detach-l,bottom,B,C), type(C,wall),relation(C,bend_attach-r,top,D,E), relation(E,bend_attach-l,bottom,F,G).	
U31	0.74	3	placement(A):-relation(A,bend_attach-r,top,B,C), relation(C,bend_attach-r,bottom,4,D).	
U32	0.74	3	placement(A):-relation(A,i_attach,bottom,3,B),type(B,wall).	

horizontally parallel manner.

6.3.3. Comparison between the two groups

By comparing the rules of the trained and the untrained students, the contrasts between the two groups shown in Table 4 were surmised.

TABLE 4. Contrasts between architecturally trained individuals and untrained individuals

Feature \ Group	Trained individuals	Untrained individuals
Angle	vertical direction	horizontal direction
Condition of contact	not in contact	in contact
Characteristic composition	stratiform composition	U-shaped enclosure

7. Conclusions

ILP was applied to the analysis of spatial composition processes using ASMT. Complexly structured data of spatial composition processes that consist of many objects, relationships between them, and their attributes were modeled in first-order logic. A RR (Relationship-Recognizing) module was designed to convert the spatial composition process into first-order representations automatically, after the actual model was recreated using a CAD system.

One ASMT experiment was conducted on each of the four architecturally trained students and on the four untrained students. These experimental cases were analyzed by a system integrated from Progol, which is one of the ILP systems, and the RR module. As a result, 28 rules for the trained students and 32 rules for the untrained students were found. These rules stated characteristic patterns of miniature arrangement of trained students (i.e. (1) placing objects with each object separated from the others, (2) stratiform composition, (3) placing objects in the vertical direction, (4) placing objects in a straight line with their ends detached, and (5) constructing elements in isolation) as well as the characteristic patterns of miniature arrangement of untrained students (i.e. (1) placing each object in contact with the others, (2) spread out elements in branches, (3) U-shaped enclosure, and (4) parallel composition in the horizontal direction).

In the future, we will need to analyze a greater number of experimental cases in order to find more universal patterns. We also need to refine the RR module in order to recognize more geometric relationships among objects.

References

Bollnow, O. F.: 1963, *MENSCH UND RAUM*, W, Kohlnammer GmbH, stuttgart.

Merleau-Ponty, M.: 1945, *Phénoménologie de la Perception*, Gallimard.

Koning H., and Eizenberg J.: 1981, The Language of the Prairie: Frank Lloyd Wright's Prairie Houses, *Environment and Planning B 8*, pp. 295-323

Muggleton, S. and De Raedt, L.: 1994, Inductive logic programming: Theory and methods, Journal of Logic Programming, 19-20, pp. 629-678.

Muggleton, S.: 1995, Inverse Entailment and PROGOL, *New Generation Computing*, 13, pp. 245-286.

Lavrac, N., Dzeroski, S., and Numao, M.: 1999, Inductive Logic Programming for Relational Knowledge Discovery, *New Generation Computing*, 17, pp. 2-23.

Numao, M., and Shimizu, S.: 1997, Data Mining for Distribution Industry, *Journal of Japanese Society for Artificial Intelligence*, Vol.12, No.4, pp.528-535 (In Japanese).

Okazaki, S., and Ito, T.: 1992a, Architectural Space Montage Technique and Schizophrenic Patient, *Journal of Archit. Plann. Environ. Engng. AIJ*, No.436, pp. 127-137 (In Japanese).

Okazaki, S.: 1992b, Architectural Space Montage Technique and School Children, *Journal of Archit. Plann. Environ. Engng. AIJ*, No.438, pp. 109-118 (In Japanese).

Okazaki, S., Ooi, F., et al.: 1997, Architectural Space Montage Technique and Mentally handicapped children, *Journal of Archit. Plann. Environ. Engng. AIJ*, No.496, pp. 237-245 (In Japanese).

Okazaki, S., Yanagisawa, K., et al.: 1999, Architectural Space Montage Technique and kindergarten children, *Journal of Archit. Plann. Environ. Engng. AIJ*, No.518, pp. 313-320 (In Japanese).

Quinlan, J. R.: 1993, C4.5: Programs for Machine Learning, Morgan Kaufmann, San Mateo, CA.

Piaget, J.,and Inhelder,B.: 1963, Image. Fraisse, P., and Piaget, J. (Eds.) *Traité de psychologie expérimentale: 7 L'intelligence*. Paris: Presses Universitaires de France.

Schulz, C. N.: 1971, *EXISTENCE, SPACE AND ARCHITECTURE*, Studio Vista Limired, Great Britain.

Shimazu, K., and Hurukawa K.: 2000, KDD System, DB-Amp -Design, Implementation and Its Application to an Expert System-, *Journal of Japanese Society for Artificial Intelligence*, Vol.15, No.4, pp. 629-637 (In Japanese).

Srinivasan, A., and Camacho, R.: 1999, P-Progol User Manual http://oldwww.comlab.ox.ac.uk/oucl/groups/machlearn/PProgol/ppman.html. Hosted at the Oxford University, Machine Learning at the Computing Laboratory.

Sugiura, N., and Okazaki, S.: 2001, Analysis of Spatial Composition process by Inductive Logic Programming - Extracting Peculiar Rules in Process of Spatial Composition on Space Montage Technique -, *Journal of Archit. Plann. Environ. Engng. AIJ*, No.546, pp. 141-148 (In Japanese).

Tsumoto, S., and Hiroshi T.: 1997, Medical Application of Data Mining, *Journal of Japanese Society for Artificial Intelligence*, Vol.12, No.4, pp.536-543 (In Japanese).