A Framework for Concept Formation in CAD Systems: a Case Study of Japanese Rock Garden Design

Yuval Kahlon[1], Haruyuki Fujii[2]

[1]Tokyo Institute of Technology, kahlon.y.aa@m.titech.ac.jp
[2] Tokyo Institute of Technology, fujii.h.aa@m.titech.ac.jp

Corresponding author: Yuval Kahlon, kahlon.y.aa@m.titech.ac.jp

Abstract. Designers often identify desirable design typologies and utilize them as building blocks of high-level conceptual frameworks for designing spatial configurations. Each building block can be seen a concept connoting with lower level meanings, which are in turn grounded in sets of spatial relations associated with those meanings. Formalizing this practice will enable to further inform CAD systems regarding the potential meanings of certain spatial configurations for their user. In this research we propose an implementable framework for assigning spatial configurations with meanings in CAD systems, by integrating a CAD environment with an inference engine. The framework is constructed and tested in the context of Japanese rock garden design. Automatic matchings of spatial configurations with conceptual abstractions are presented and interpreted, and generalization as well as future research directions are discussed.

Keywords: Concept Formation, Spatial Design, Logical-Inference Systems, Japanese Rock Garden
DOI: https://doi.org/10.14733/cadaps.2020.419-428

1 INTRODUCTION

Computer-Aided Design (CAD) systems enable designers to create digital representations of their designs by storing, manipulating and visualizing information regarding the designed artifact's configuration [4]. Utilizing object-oriented approaches, CAD systems continuously strive to minimize the gap between the designer's conceptual understanding of the artifact being designed, and its digital representation [8]. As a result, advanced CAD systems are highly informed with respect to the representation's denotative meaning in the designer's conceptual world. This is evident in Building Information Modelling systems for architecture, where a set of elements is often associated with a higher-level entity; for example, a set of window part is encapsulated in a single object of a window, informing the system of this high-level denotation.

Contrary to this, most systems are less informed regarding the representation's connotative meaning in the designer's mind. This paper proposes an implementable framework for concept formation in CAD environments, to enable designers inform the system regarding possible connotative meanings of spatial configurations, in a given context. This is conducted by representing and storing spatial configurations as high-level descriptions, enabling designers to encapsulate desirable design typologies in concise verbal expressions. The proposed framework was implemented and tested in the context of Japanese rock garden design (JRGD), by storing popular rock configuration typologies as short verbal descriptions, and retrieving them from memory.

1.1 Background

Tying desired sets of spatial relations under a single verbal description is an old-time design practice, evident as early as in the classical Greek orders of architecture (Figure 1), where certain proportions and parts are explicitly named as a single entity (i.e. Doric etc.). These names form a conceptual framework for the design of artifacts, by serving as high-level abstractions of multiple spatial relations. Such abstractions denote a range of desired design solutions, while connoting with additional possible meanings that may be attributed to the artifact by the designer. In the above example, the description "Doric" denotes a certain set of column parts and their relative proportions, while connoting the design with the concepts of masculinity and dignity often attributed to such columns [13].

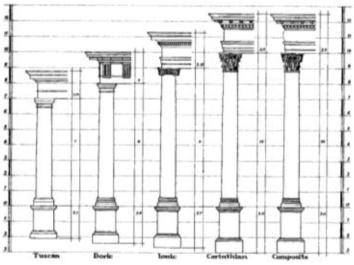

Figure 1: The Greek orders; an early form of formalizing spatial relations (source: Chitham R., The Classical Orders of Architecture).

Facilitating the above practice in current CAD systems will not only enable designers to construct digital conceptual frameworks, but will inform the system with respect to high-level semantic attributes which the designer associates with a given spatial configuration. How may we formalize this practice, to enable its support by current CAD systems? Various disciplines such as structural and mechanical design have long recognized the potential and advantages of informing systems of high-level abstractions, referred to as "features" of the design [1] [14][15]. These refer mainly to structural [19] and functional [3] properties of a given configuration of the designed artifact. We propose to approach the conceptual descriptions used by designers as a type of visual feature of the spatial configuration.

This paper examines the practice of assigning spatial configurations with high-level conceptual descriptions it in the context of JRGD; this has served as suitable grounds for an initial investigation of this practice, owing to two main considerations 1) its frugal nature consisting on a relatively small number of well-defined elements 2) its flexibility with respect to concept formation (as compared with the rigid nature of concepts in Greek architecture, for example, which allows minimal freedom for designers when applying the concepts in their designs).

As an abstract form of art, JRGD makes extensive use of conceptual descriptions denoting a specific design typology, to the extent of offering a composition catalog for designers, as a reference for selecting and positioning rocks in the garden space [16]. These descriptions are not arbitrary names, but rather connote with high-level meanings that are attributed to the design. In (Figure 2c) we present an example of a configuration attributed with the concept "Dry Waterfall". This attribution implies on certain spatial relations (for example, verticality, downward flowing texture etc.), while tying the configuration with connotative meanings external to the designed artifact (the concept of water, natural scenery etc.). By analyzing the relation between the spatial configuration and its description in existing compositions, we may progress towards formalizing this practice of concept formation, to implement it in CAD systems.

Figure 2: Examples for common typologies serving as high-level conceptual abstractions in JRGD, in varying levels of complexity: (a) "Buddhist Triad" (Tofukuji temple, Kyoto), (b) "Crane Island" (Tofukiji temple, Kyoto), and (c) "Dry Waterfall" (Senshukaku garden, Tokushima; source: japanesegardening.org).

1.2 Aim

The aim of this research is to enable users to inform CAD systems regarding possible connotative meanings of spatial configurations, by allowing designers to externalize conceptual structures of signification and representation as formal descriptions.

1.3 Significance and Contribution

The main contribution of this research is the proposed computational framework, which enables users to assign meaning to the digital representations of their designs, by adding a layer of high-level semantic descriptions. This framework expands the notion of meaning in CAD systems, enabling designers to embed conceptual information into their digital models. Among the potential implications are 1) enabling to store and share conceptual frameworks and desirable design typologies among designers 2) contributing to development of co-creative design systems, capable of understanding high-level conceptual abstractions 3) supporting automatic semantic enrichment processes in CAD systems.

2 METHOD

This research follows the Constructive Methodology which relies on pragmatist views in its attempt to bridge between existing theories and practical problems, via the creation of artifacts [2]. As explained by Lehtiranta et al. in [11], a constructive process can concisely be outlined as 1) problem definition 2) pre-analysis 3) construct-design 4) feasibility demonstration 5) clarification of relation to theory 6) examination of generalizability. Accordingly, in our attempt to address the problem of relating high-level concepts with spatial configurations, we follow a similar process, as outlined below.

In order to establish the proposed framework for tying concepts with spatial configurations we have 1) studied this practice in the context of JRGD design, by conducting a literature review of the traditional manuals [16][17] and documenting rock configurations in classical JRG 2) devised a standardized syntax to express common concepts as sets of lower-level entities 3) digitized a collection of small rocks using a desktop 3D scanner and stored them as mesh geometries, as a preparatory step for the implementation 4) implemented the framework by integrating the 3D CAD environment Rhinoceros with the logical inference system SWI-Prolog 5) constructed a set of formal concepts and attempted to automatically match them with spatial configurations using our system.

2.1 Scope

This paper focuses solely on the spatial configuration aspect of rock compositions in JRGD, excluding other JRGD elements from consideration (such as the moss, gravel etc.); while the other elements greatly contribute to the design and affect its interpretation by users, the traditional manuals of JRGD teach us that the rocks serve as the foundation for the design activity, and are strongly viewed as the backbone of the design [18]. Evidently, the classical manual for general Japanese garden design opens with the words "The art of setting stones", reflecting their centrality in this art form [17]. Accordingly, we have chosen to begin developing the framework by focusing on the rocks, while keeping in mind the need for extending it to include additional elements in the future. Similarly, the aesthetic dimension of the composition is beyond the scope of this paper, considering that it may be integrated later as an additional layer of filtering and searching the solution space spanned by our framework, according to the visual desirability of potential spatial configurations.

3 THE PROPOSED FRAMEWORK

The proposed framework is used to construct high-level concepts by combining multiple lower-level entities (Figure 3). This framework is inspired by Gero's FBS framework [6] and Gardenfors's Conceptual Spaces framework [5]. We define four main entities: behaviors, relations, meanings and concepts. Each entity is assigned with a formal syntactic representation, following the syntax of the logical programming language Prolog, as given in Table 1. The formal syntax enables to harness logical inference systems for matching spatial configurations with high-level descriptions. A valid matching of a concept with a spatial configuration is inferred by logically deriving the existence of the associated lower-level entities in the system.

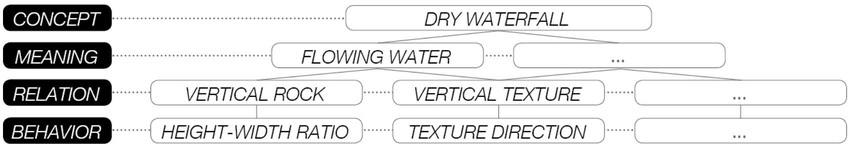

Figure 3: A possible partial formalization of the concept "Dry Waterfall" (presented in Figure 2c) using our proposed framework.

Entity	*Syntax*	*Example*
behavior	rock(A,has_behavior(type,value))	rock(A,has_behavior(width,1))
Relation	rock(A,has_relation(type,name,B))	rock(A,has_relation(size,taller_than,B))
meaning	rock(A,has_meaning(name,B))	rock(A,has_meaning(listening,B))
concept	concept(concept_name,A,B,C)	concept(teacher_and_students,A,B,C)

Table 1: Syntax and representation of our basic entities.

4 IMPLEMENTATION AND SYSTEM BEAHVIOR

In order to implement the framework, we have created a live connection between a 3D environment (Rhinoceros 3d) and an inference system (SWI-Prolog). This implementation enables users to 1) create concepts based on pre-defined relations and meanings 2) generate random spatial configurations from a digital rock collection 3) automatically match given spatial configurations with existing concepts. The manner of creating concepts and matching them with spatial configurations, as well as the structure of the system, are explained below.

4.1 Concept creation

Concepts are represented by rules written in Prolog syntax; a concept is created by combining several lower-level entities, using the syntax presented previously in Table 1. Users can create meanings and concepts by selecting and combining relations from a pre-defined relation pool stored in a knowledge base, via a simple graphical user-interface (GUI), referred to as "concept editor" (Figure 4). In general, all semantic descriptions as well as the newly created concepts, are stored in the knowledge base. Relations are divided into three categories (size, proportion and position) and are either dual or triad (between two or three objects, accordingly). Table 2 presents the different sub-types for each type of relation, while Table 3 further presents three different relations that are associated with a single sub-type.

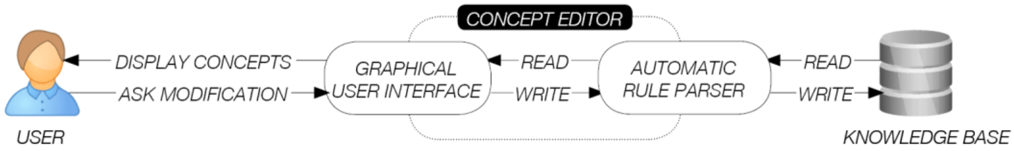

Figure 4: Creating and managing a concepts knowledge base by utilizing an automatic parser.

Relation Type	*Relation Sub-Types*		
Size	height	width	depth
Proportion	self-proportions	proportion similarity	proportion difference
Position	side	proximity	overlap

Table 2: Object features and their corresponding predefined relations.

Relation Sub-Type	*Relation*	*Condition*
Height	"taller"	H1>H2
	"significantly taller"	H1/3>H2
	"tallest"	H1>H2 and H1>H3

Table 3: Let H1,H2,H3 represent the heights of three rocks. We then define the three specified relations in order to express important height-associated relations in the configuration.

4.2 Matching Concepts with Spatial Configurations

The implemented system enables to automatically match a given spatial configuration of rocks with a high-level concept, according to the concepts currently defined in the knowledge base. The process of using the system consist of four main steps, as shown below (Figure 5).

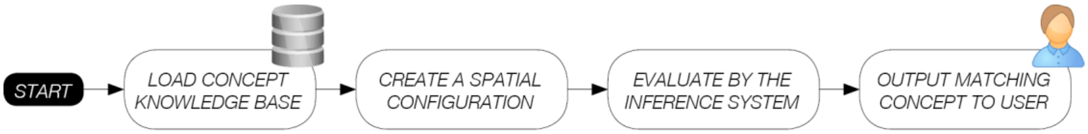

Figure 5: Matching concepts with spatial configurations using the system.

In order to enables this matching process we 1) read the geometric data from the CAD environment 2) parse it as facts in Prolog syntax; these describe the current state of the spatial configuration, and are stored in the knowledge base 3) convert the information stored in the knowledge base into a *.pl (Prolog) file 4) run this file to be evaluated by SWI-prolog, returning the result of the inference process to the user. An overview of the complete system is presented below in Figure 6, and an example of the system's behavior using a concrete example is provided in Figure 7.

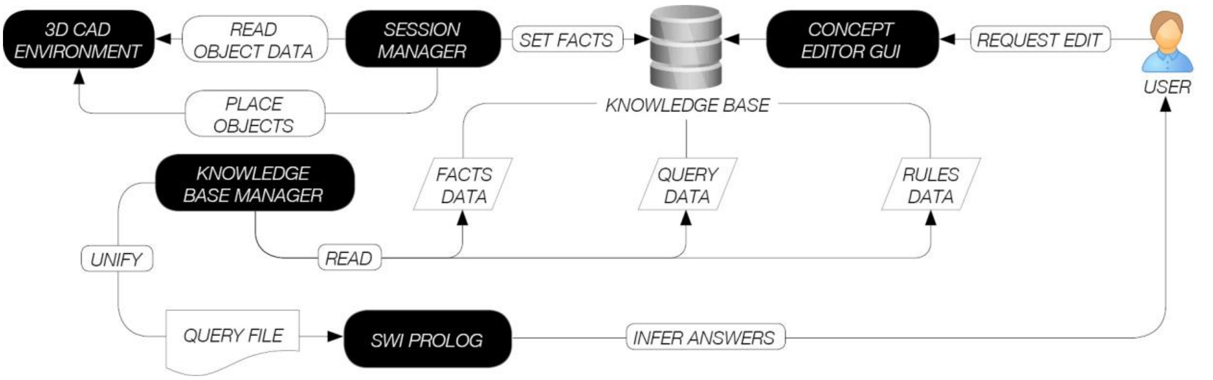

Figure 6: Overview of the implemented system.

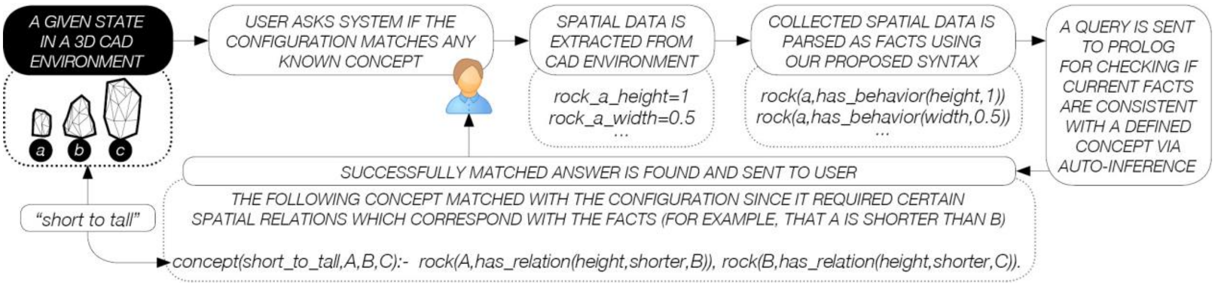

Figure 7: Basic concept-matching for a given configuration via our computational system.

5 RESULTS AND DISCUSSION

5.1 Results

The ability of the system to tie spatial relations with verbal descriptions was demonstrated by 1) defining a set of basic dual and triad spatial relations and meanings 2) utilizing the above relations to define a set of eight concepts (listed in Table 4) 3) randomly generating spatial configurations consisting on three rocks 3) auto-evaluating these configurations using the inference system and recording the matching concepts given as output. Below are four examples for automatic matchings between configurations and concepts produced by the system, as well as a concise breakdown of each concept into lower-level entities (Figure 8).

Number	*Concept*
1	concept(parent_watching_brothers,A,B,C)
2	concept(mother_protecting_children,A,B,C)
3	concept(a_man_with_his_pets,A,B,C)
4	concept(parents_and_child,A,B,C)

5	concept(teacher_and_students,A,B,C)
6	concept(couple_with_pet,A,B,C)
7	concept(a_mountain_range,A,B,C)
8	concept(mountains_in_the_sea,A,B,C)

Table 4: The eight concepts defined for testing our implementation.

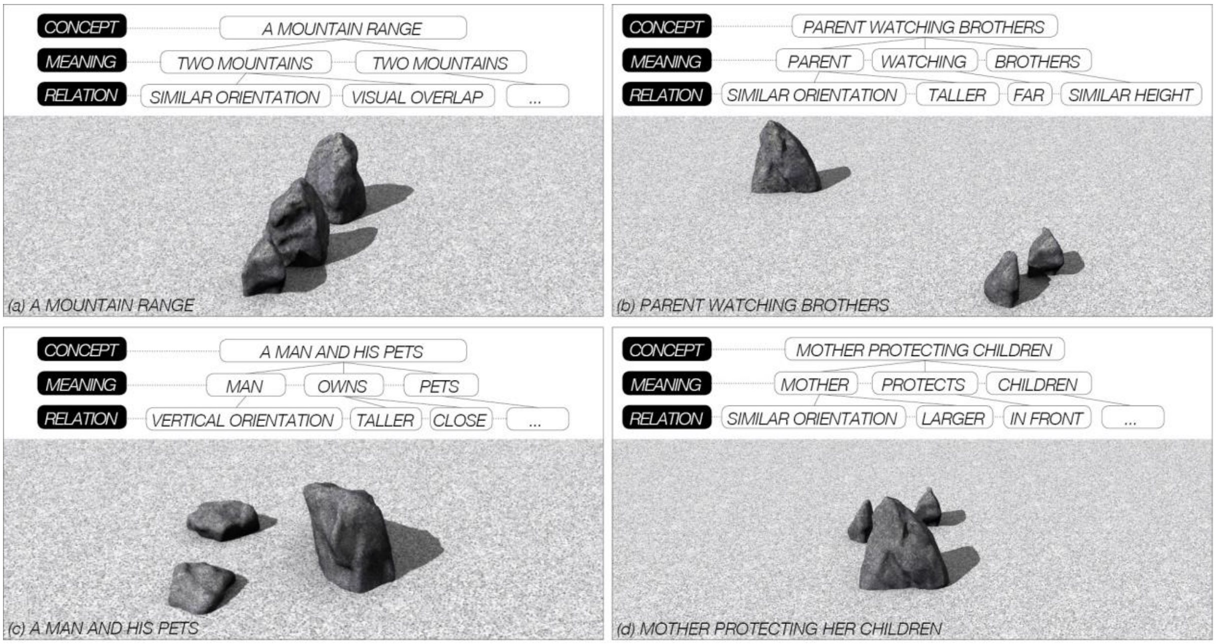

Figure 8: Examples of automatic matchings between a concept and a spatial configuration: (a) "a mountain range" (b) "parent watching brothers" (c) "a man and his pets" (d) "mother protecting her children".

5.2 Evaluation

When evaluating our system, we 1) explain how to interpret the results by referring to two matchings presented above in Figure 8 as representative examples 2) compare it with several related systems which take a different computational approach.

First, in order to explain how to interpret the results, we focus on the configuration presented in Figure 8a. This arrangement was matched with the concept "a mountain range", via identifying consecutive overlapping between elements, as well as similarity in orientation and differences in height. Visual overlap is the spatial expression associated with the meaning "two mountains", which served as the basis for defining the corresponding concept, along with the demand for a height difference. Therefore, when the system tried to match the configuration with the concepts of "a mountain range", it identified two couples of "two mountains", resulting in a successful match with the presented configuration.

For further clarification, we now focus on the composition presented in Figure 8b. This spatial arrangement was matched with the concept "parent watching brothers", by successfully matching its rocks with the three meanings of "parent", "watching" and "brothers". Each of these demanded different set of spatial relations: the meaning "parent" is associated with having a similar vertical orientation, as well as with the demand for being taller, as fulfilled by the large rock in relation to the smaller ones. Further, the meaning "watching" is expressed by the large rock being positioned relatively far from these, and the meaning "brothers" is expressed by the height similarity between the two small rocks. All of these are then combined to generally match with the concept of "parent watching brothers".

Finally, while this research has taken a traditional AI approach, relying on logical inference as a means for relating meaning with spatial configurations, other researches have approached similar tasks from machine and deep-learning perspectives; this was done both via supervised processes (for example, Karimi et al. [9] have used the well-known VGG-16 to detect the potential meaning of sketches) and unsupervised processes (in [10] outlier detection was used to identify the core geometric characteristics of elements such as walls etc.). We believe that the key difference between the two approaches lies in the fact that while machine learning-based practices can be seen as a means for feature extraction in this context, our approach is better seen as a form of "feature construction"; this is due to the fact that meaning is not merely detected in the configuration, but is also embedded in it by the designer via the creation of concepts. Each of the approaches above, however, is subject to natural limitations: logical inference demands a rigorous elaboration of each concept, supervised-learning requires many samples as a basis for training and unsupervised learning generally ignores important semantic attributes which enable the intelligibility of a categorization to a human designer. Consequently, we see them as rather complementary in attempting to derive meaning from spatial configurations. Accordingly, we aim to gradually integrate the other approaches into our work, as further discussed in 5.4.

5.3 Possibility for Generalization

With respect to the generalizability of the proposed framework - since the framework does not make any assumptions regarding the nature of the elements in discussion, it is generalizable, to a large extent, for a wide range of artistic or design domains consisting of spatial configurations (architecture, sculpture etc.), including those of a lower dimensionality (graphic design etc.). Yet, utilizing this framework in-practice in a different context would require a preliminary three-step process of 1) determining which design elements are to be represented in the framework 2) defining the behaviors of these elements, which are domain-specific 3) defining the relations between these elements which are domain-specific, given these behaviors. In implementing the framework for assigning meanings to spatial configurations in JRGD, we had followed a similar process of 1) identifying the rocks as our elements of focus 2) defining their behaviors (dimensions, location etc.) and 3) defining the relevant relations between them (size relations, distance relations etc.). Once this preliminary phase has been completed, we began assigning meanings to spatial configurations by combining several relations with our syntax into a single meaning, which could then be used to structure higher level concepts, as presented.

5.4 Future Work

When discussing our future work we would like to 1) mention a possible future direction for further developing the proposed framework from the perspective of JRGD 2) propose an additional future direction from a broader view which may therefore be applicable for any other field in which the framework is implemented 3) conclude with a potential method for testing and verification of computational systems implemented based on our proposed framework.

First, in the context of JRGD, we have chosen to focus on rock elements, and have restricted our scope to a limited number of variables, i.e. mainly size and proportion. Considering the boundless variety of rocks in nature, incorporating additional rock features such as shape, texture and color, may enable us to dramatically expand the range of expression in our system. We aim to address this in our future research, possibly by integrating a feature-extraction module consisting of a convolutional neural network component, to auto-identify visual features effectively and phrase them as formal entities using our syntax. Moreover, while this research has focused on the selection and placement of rocks, it is both possible and desirable to further represent additional garden elements (gravel, moss etc.), in order to enable a more comprehensive description of the relation between spatial configuration and meaning in the garden. Indeed, while rocks undoubtedly serve as key elements (see 2.1), many compositions in JRGD receive their meanings from additional elements that are incorporated into the design.

When examining the framework and the implementation as a whole, another important aspect which calls for further research is the possibility of auto-formulation of concepts. Although manual formulation using a GUI is possible, it is a time-costly task which demands designers to reflect upon their conceptualizations, analyze them and then re-construct them using the proposed syntax. These burdens can be gradually removed from the process by further developing classification modules to automatically derive formal concepts from existing design representations, guided by an input from the designer. This may be seen as a type of auto-feature extraction, as already conducted in CAD/CAM processes [7][12].

Finally, an effective method of evaluating systems constructed using our framework would potentially consist of a human-in-the-loop-based practice. Since the framework aims to enable designers to communicate conceptual structures in a formal manner, it is important that new concepts will be verified either by their creator or by a fellow designer from a closely-related discipline, to confirm that the formal description and its spatial expression indeed match in a human-intelligible manner. Such verification processes may generally consist of 1) selecting a concept to be examined 2) auto-generating a large number of random spatial configurations 3) matching the selected concept with these, filtering out irrelevant configurations 4) presenting the subject the remaining configurations which matched the concept for evaluating the adequateness of each, potentially by grading 5) using these grades to revise the original concept by adding further restrictions and demands onto the spatial configuration, to correspond with the configurations ranked highly by the testing subject.

6 CONCLUSION

The proposed framework enables a structured approach for creating high-level abstractions of spatial configurations, encapsulating them in concise verbal descriptions named concepts. These concepts can metaphorically be seen as words forming the vocabulary of the designer's internal world, or the building blocks of an artistic style. Thus, further developing the framework to express different relations between a set of concepts in a given context may serve in constructing the syntax and grammar which constitute distinct stylistic forms of expression. Moreover, although the concepts are formed here manually by the designer via interacting with our interface, the process can be greatly simplified by further research targeted at auto-generation of concepts. This can be done via supervised-learning-based processes, by matching concepts with their corresponding relations (while being guided by the designer) and phrasing them as formal entities in the system.

Yuval Kahlon, https://orcid.org/0000-0002-3914-7945
Haruyuki Fujii, https://orcid.org/0000-0002-8984-8512

REFERENCES

[1] Catania, G.: Form-features for mechanical design and manufacturing, Journal of Engineering Design, 2(1), 2007, 21–43. https://doi.org/10.1080/09544829108901668
[2] Dodig-Crnkovic, G.: Constructive research and info-computational knowledge generation, Studies in Computational Intelligence, 314, 2010, 359–380. https://doi.org/10.1007/978-3-642-15223-8_20
[3] Feng, C.-X.; Huang C.-C.; Kusiak, A.; Li, P.-G.: Representation of functions and features in detail design, Computer-Aided Design, 28(12), 1996, 961–971. https://doi.org/10.1016/0010-4485(96)00027-9
[4] Fujii, H.; Yoshitsugu, A.: Dual deep-structure to associate a shape with its linguistic description: a hypothetical framework and an experimental implementation, Journal of Asian

Architecture and Building Engineering, 2(1), 2003, 115–121. https://www.tandfonline.com/doi/abs/10.3130/jaabe.2.115
[5] Gärdenfors, P.: Conceptual Spaces: The Geometry of Thought, MIT press, Cambridge, 2000. https://doi.org/10.1016/S0001-6918(00)00067-6
[6] Gero, J. S.: Design prototypes: a knowledge representation schema for design, AI Magazine, 11(4), 1990, 26–36. https://doi.org/10.1609/aimag.v11i4.854
[7] Henderson, M.R.; Anderson, D.-C.: Computer recognition and extraction of form features: a CAD/CAM link, Computers in Industry, 5(4), 1984, 329–339. https://doi.org/10.1016/0166-3615(84)90056-3
[8] Kalay, Y. E.: Architecture's New Media: Principles, Theories, and Methods of Computer-Aided Design, MIT Press, Cambridge, 2004. https://doi.org/10.1080/17533015.2011.584886
[9] Karimi, P.; Grace, K.; David, N.; Maher, M.L.: Creative sketching apprentice: supporting conceptual shifts in sketch ideation, Design Computing and Cognition, 2018, 721-738. https://doi.org/10.1007/978-3-030-05363-5_39
[10] Krijnen, T.; Tamke, M.: Assessing implicit knowledge in BIM models with machine learning, Modelling Behavior, 2015, 397-406. https://doi.org/10.1007/978-3-319-24208-8_33
[11] Lehtiranta, L.; Junnonen, J.-M.; Kärnä, S.; Pekuri, L.: The constructive research approach: problem solving for complex projects. Designs, methods and practices for research of project management, 2015, 95–106.
[12] Liu, C.-H.; Chen, Z.: CAD-based automated machinable feature extraction, Proceedings of 27th Asilomar Conference on Signals, Systems and Computers, IEEE, 1, 2002, 558-562. https://doi.org/10.1109/ACSSC.1993.342578
[13] Onians, J.: Bearers of Meaning, Princeton University Press, New Jersey, 1988.
[14] Salomons, O. W.; van Houten, F. J. A. M.; Kals, H.J.J.: Review of research in feature-based design, Journal of Manufacturing Systems, 12(2), 1993, 113–132. https://doi.org/10.1016/0278-6125(93)90012-I
[15] Shah, J.J.: Assessment of features technology, Computer-Aided Design, 23(5), 1991, 331–343. https://doi.org/10.1016/0010-4485(91)90027-T
[16] Slawson, D.: Secret Teachings in the Art of Japanese Gardens: Design Principles, Aesthetic Values, Kodansha International, Tokyo, 1991.
[17] Takei, J.; Keane, M.P.: Sakuteiki, Visions of the Japanese Garden: A Modern Translation of Japan's Gardening Classic, Tuttle Publishing, North Clarendon, 2001.
[18] Van Tonder, G. J.; Lyons, M.J.: Visual perception in Japanese rock garden design, Axiomathes, 15(3), 2005, 353–371.https://doi.org/10.1007/s10516-004-5448-8
[19] Zamanian, K.; Fenves, S.; Thewalt, C.R.; Finger, S.: A feature-based approach to structural design, Engineering with Computers, 7(1), 1991, 1–9. https://doi.org/10.1007/BF01208341