20. Refinement and Adaptation: Two Paradigms of Form Generation in CAAD

Rivka E. Oxman, Robert M. Oxman

Faculty of Architecture and Town Planning
Technion, Israel Institute of Technology
Haifa, 32000, Israel

Within a transformational paradigm of form generation, refinement and adaptation are presented as two distinct concepts which can provide formalisms for encoding design knowledge. Refinement and adaptation are treated as syntactical models of form generation. Computational formal analysis is proposed as a method for the study and modelling of refinement and adaptation in design. Employing the analytical method we demonstrate that formal transformations are dependent upon their membership in classes of architectural designs. Computational issues in form generation through refinement and adaptation are identified.

Introduction: Modelling Design Generation

The generation of form in architectural design is one of the significant research areas in design computing. Prominent among models of design generation, which provide a basis for the computational generation of form, are transformational models which are founded upon symbolic processing. Shape grammars are a well-known application in which symbols of shapes are represented and transformed (Stiny 1980a). The formalism has proven to be useful in the modelling of form generation in art, design and architecture (Mitchell 1990). The work described in this paper, is part of the research tradition which investigates formal representations and transformational models in encoding design knowledge and in the computation of design generation.

Within a transformational approach to form generation, refinement and adaptation are proposed as two models which may provide computational formalisms for generation. Refinement and adaptation are relevant to form generation in design, since they are considered as two distinct ways in which formal knowledge in architectural composition is employed by designers through *typological* and *precedent-based* design. In refinement processes a generalized schema is transformed into a specific design; in adaptation, a specific precedent is transformed into a new design. The current research has focused upon these two models of form generation, their formalization, and their potential role in the computation of generation in design.

Computational formal analysis is proposed as a method for the study of refinement and adaptation operations. Employing this analytical method we demonstrate that formal transformations, which have been previously exploited to model refinement, can potentially be used to model adaptive operations in design. The analytical method is employed to formalize

syntactical steps in architectural composition. It provides a basis for categorizing and formalizing various strategies of refinement and adaptation in design. Both refinement and adaptation operations appear to be influenced by membership informal classes of *architectural designs*. Such formal classes have been previously defined according to *architectural syntax (Flemming 1990; Oxman and Oxman 1989, 1990).*
The objectives of this research were:

- development of a formal analysis method in the study of refinement and adaptation

- modelling form generation in refinement and adaptation as transformational operations

- identification of computational issues in form generation within the two models

In addition to these primary goals, we have undertaken a preliminary explanation of formal classes *in* architectural *syntax*. In this paper we demonstrate two classes through the use of case studies.

Form Generation in Architectural Composition through Refinement and Adaptation

Form generative processes in architectural composition have been modelled as transformations of syntactic representations of designs. In such models of generation, design knowledge is encoded as transformation rules. The application of rule-based formalisms to encode syntactical knowledge of architectural designs is well founded in CAAD. Architectural designs have been represented through hierarchical rule sets in the Palladian Grammar (S tiny and Mitchell 1978); multiple rule sets in the Queen Anne Grammar (Flemming 1986), and replacement rules (Weissman Knight 1981). These models are based upon a refinement process of a generic representation of the design. However within the syntactic paradigm, adaptive processes which are based upon the modification of specific architectural precedents, have so far received little attention.

Several distinct approaches to form generation can be identified and can be divided into two main groups. The first, including construction and refinement, is based upon a generic representation of a design which has been generalized from past experiences of many designs. The second, including adaptation, is based upon the modification of specific precedents from past design experience. These approaches are elaborated below.

Construction: Transformation as Assemblage

Construction is the sequential generation of a design in a bottom-up fashion in which a general constructive principle is applied to a vocabulary of elements. The transformational rules for construction are defined as operations without reference to an underlying schema. That is, the rules define element to element relations without specifying underlying organizational concepts. This bottom-up application is exemplified in the Kindergarten Grammar (Stiny 1980b). In distinction to such grammars, building designs are complex formal constructs which may require multiple rule sets for their representation. In the case of multiple rule sets, the existence of an underlying schema may be required to establish the relationships among the rule sets.

Refinement: Transformations upon a Generalized Schema

Refinement is generation through transformation in a top-down fashion. The generic representation of a design schema underlies the refinement process. Refinement is form generation through sequential particularization of designs. Refinement steps specify the transformation from a schematic state to a specific state.

In accomplishing this, refinement instantiates sub-types from a given generic representation of a design. The representation is generic in the sense that it captures the salient attributes of the class of designs. These may include an underlying reference system, such as a grid or axial system, which constitutes the referential system for particularization. These concepts are illustrated in the well-known sequence of drawings, plate 21, of Durands Leçons in which the initial representation of a spatial order of plan composition is refined. In the accompanying plate 20, Durand provides a range of sub-types for the class of squarebased, concentric, dual axis plan compositions. Substitution may be regarded as a method for transforming the generic to the specific representation. This is, in fact, the approach exemplified by Durand. The skeletal syntax of the plan provides the framework for the substitution of detailed column arrangements, partition arrangements, porches, courts, stairs and building masses. Through substitution the schema is elaborated in a top-down fashion. The Palladian Grammar (Stiny and Mitchell 1978) and the Top-Down System (Mitchell, Liggett and Tan 1988) exemplify approaches to generation through refinement in architectural computing.

Adaptation: Transformations upon Design Precedents

Adaptation is a process for modifying an existing design to generate another design. A precedent represents an existing design selected from a precedent repertoire of past experience. In comparison to generic design, a precedent may be regarded as a specific design. Adaptation is defined as modification through transformations upon particularized design descriptions. The use of precedents in design was well established methodologically within the Classical tradition and Beaux Arts theory (Szambien 1982). Among the functions of the analytique' in the Beaux Arts method was the selection and study of past precedents which were relevant to a current design situation (Crowe and Hunt 1986). In these historical examples, precedents as complete designs are adapted in order to create a new design.

Modelling Form Generation in Refinement and Adaptation

Historically, adaptation has been considered to be a significant model for design. Building a repertoire of designs is one potential basis for encoding design knowledge which may be employed in generation. However, until now adaptation has been little explored in architectural design computation. Reasoning in adaptation is a current research subject in artificial intelligence. Case-based reasoning addresses research questions which are relevant to generation through the adaptation of a precedent repertoire. Work in case-based reasoning

(Kolodner 1988) in indexing, selection and repair of the case-base may provide concepts and methods which are relevant to generation through adaptation in design.

In the current research, we have employed formal analysis as a basis for modelling transformation operations in refinement and adaptation. The concept of syntactical classes of designs has been found to be relevant in these models, since types of operations in refinement and adaptation appear to be characteristic of these classes. The method of study has been to analyze a cycle of designs in the work of selected architects, which constitute a sequence of designs within a distinct syntactical class. In the following sections operations in refinement and adaptation and their relationship to syntactic classes will be illustrated.

In this section we propose an approach to modelling refinement and adaptation as transformational operations within the context of architectural syntactical classes. What is a syntactical class? A design world has been defined as a world that is characterized by it's shape vocabulary and operators (Mitchell 1990). According to this view, a syntactical class is a *generalized design world.* Architectural syntax is the formalization of knowledge of general classes of designs (Oxman and Oxman 1990). The concept of grammars has been employed to formalize general syntactical classes in architecture (Flemming 1990). Classes may be based upon morphological principles of two and three-dimensional design which characterize compositional styles. Centralistic-concentric layered designs, and grid-based designs exemplify such general classes.

In our analyses, it appears that in generation, formal operations function in a way characteristic of the syntactic class. Five basic formal operations - instantiation, deletion, transformation, combination and replacement - have been identified (Mitchell 1990). Composition is, therefore, a characteristic set of operations within a specific class of designs.

Refinement of Formal Classes in Design

In design the term schema is often used to indicate the properties of a formal structure which specify the general properties and omit specifications irrelevant to the class of designs. The concept of the schema may be employed to represent generative knowledge which supports an hierarchically structured top-down refinement process. This includes an initial abstracted representation of a design (the schematic, or generic state), which contains the salient elements and relationships of the type. Refinement particularizes this initial state of the schema. The generative refinement process of a syntactical class is a specific set of refinement operations which transform representations from higher-level to instantiated representations. This establishes a state-action tree of specified descriptions of the class.

Design refinement is considered as the sequence of formal transformations upon the initial schema representation. Within formal classes of designs characteristic sets of refinement operations may be defined. These can be represented as part of a design schema. A *generative schema* (Oxman 1990) contains a form design description generator which derives the properties of each level of the refinement tree according to design principles and characteristic operations of the class.

Figure 1 illustrates the basic concept of design generation as transformation operations upon formal representations.

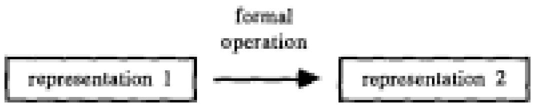

Figure 1. Design generation as a transformation upon a design representation.

Figure 2 illustrates refinement as a process of transforming a schematic description into a specified design. This is a mapping process between a high-level, abstracted representation and its successive specified descriptions. In the computational refinement of the class of designs, inheritance can be employed as a technique to maintain class characteristics. Operations may contain specifications of elements, their attributes, variables and parameters. Representations illustrated in figure 2 are numbered according to their level of refinement.

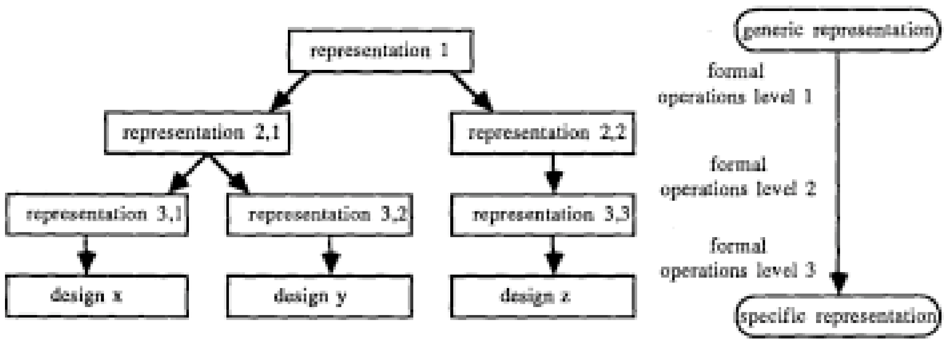

Figure 2. The refinement of a schema as formal transformations of representations through characteristic sets of formal operations.

A rule-based formalism provides computational means to achieve refinement. This is illustrated in figure 3 which is a rule-based representation of the refinement tree. The rule sets of the refinement steps provide alternatives within levels.

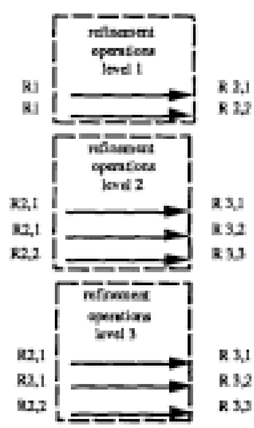

Figure 3. Sets of transformational rules within a formal class.

A simple example of refinement operations within a class of centralistic designs is illustrated in figure 4. In this example a particularization of the core is specified through substitution rules. Thin lines indicate the generic representation, heavy lines indicate a particularization.

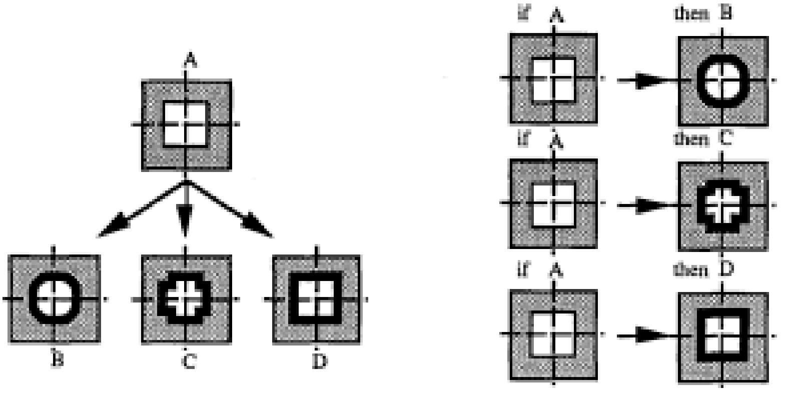

Figure 4. Tree representation and a comparable substitution rule representation for sub-type generation.

In design computation various formalisms support the encoding of refinement. Grammars are the most well-known formalism which can be employed in transformational models of refinement. Grammars are powerful in encoding syntactic descriptions for generation through refinement (Stiny and Mitchell 1978). The formalism of the design prototype (Gero 1987) supplements this syntactical knowledge through the representation of other kinds of knowledge. The design prototype is a conceptual schema for representing a class of generalized design knowledge. It represents and integrates three kinds of descriptions: functional, structural and behavioral descriptions as well as the relations between them. The use of such a formalism provides mapping between structure, (which can be considered the syntactical description of a design) and behavior and function, (which can be considered the semantics of a design).

Adaptation of Formal Classes in Design

Refinement is a model of design generation which is established in the literature and has a substantial body of research in design computation. However, refinement does not explain another significant cognitive style in design, designing with precedents. In contrast to refinement which employs a generic representation as an initial state, adaptation can be regarded as a manipulation process of a specific precedent, or prior design. Adaptation may be defined as the process of transforming a precedent, or precedents, into a new design. The existing design provides an entire solution which is represented and transformed.

Adaptation appears relevant to the modelling of form generation in architectural design. There are various strategies of adaptation in design. We suggest that among these, three classes of strategies can be identified: elemental adaptation, schema adaptation, and hybrid adaptation.

Elemental Adaptation

This is the basic strategy of design adaptation. It is achieved through transformational operations upon the elements of a prior design. The strategy maintains the topological integrity of the existing design schema. The form and geometry of the elements may be modified while the integrity of the scheme is preserved. Figure 5 illustrates a replacement operation in this strategy. The basic operations of elemental adaptation can exist within each of the other strategies.

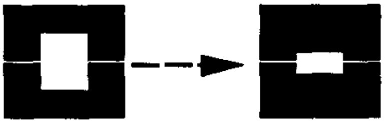

Figure 5. Elemental adaptation by a replacement operation.

Schema Adaptation

The precedent design suggests an entire schema. Schema adaptation modifies this schema. Certain of its topological characteristics are maintained. Figure 6 illustrates an example of a schema adaptation. In this example, the schema is extended by addition. The insertion of new elements within the existing design extend the number of elements of the schema while maintaining essential characteristics of the composition. Schema adaptation may be exemplified by the design method of the Ecole des Beaux Arts in which specific design precedents were frequently adapted to achieve new designs (Szambien 1982).

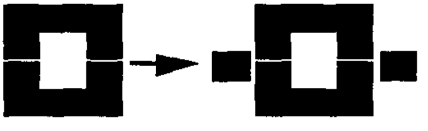

Figure 6. Schema adaptation by the addition of elements.

Addition of elements is the simplest form of schema adaptation. A more complex form of schema adaptation is the transformation of the high-level description which underlies the schema. For example, this may be a modification of the axial system underlying the design illustrated in figure 6.

Adaptation depends upon the interpretation of the precedent's schema. In this context it is interesting to mention the phenomenon of 'emergent form' which has been identified by Stiny (Stiny 1990). The significance of 'non-discrete' interpretations of existing representations is raised as a source of creativity. Ambiguity in interpretation of design representations may be a means of transcending the rigidity of the schema concept. A nondiscrete interpretation of the existing design may suggest an adaptation unrelated to the topology of the schema.

Hybrid Adaptation

In elemental adaptation, the element vocabulary is modified. In schema adaptation, the schema is modified. In hybrid adaptation more than one precedent is employed and multiple precedents are incorporated into a new design. Hybridization may maintain, or modify, the existing schema of each of the precedents resulting in an eclectic schema.

Refinement models utilize generic knowledge, which may be encoded by rules. Adaptation models in design computation raise the issue of how to represent and compute with specific cases. In order to develop computational formalisms for adaptation in design, we require a medium for representing design cases in a computer system and, potentially, for reasoning with the knowledge of these cases. Various research efforts have begun to address the relevance of cased-based reasoning for design generation using precedent knowledge. This research may contribute to the development of formalisms which integrate diverse knowledge in reasoning about generation through adaptive strategies with large precedent repertoires of designs. These issues are currently being addressed in the development of integrated CAD databases, general compiled knowledge and case-based knowledge (Rosenman, Gero and Oxman 1991).

Formal Analysis of Transformations in Refinement and Adaptation Analysis of Refinement through Formal Analysis of Case Studies

We have proposed the modelling of refinement as a successive particularization which begins with a generic representation of a design as an initial state. A *formal analysis of refinement* consists of defining a series of operations which transform a specified representation back to the schematic representation. The analysis reconstructs the refinement tree by working towards the generic representation. The objective is to identify and categorize the operations of particularization starting from specific designs and working to their source. Figure 7 illustrates the analysis process.

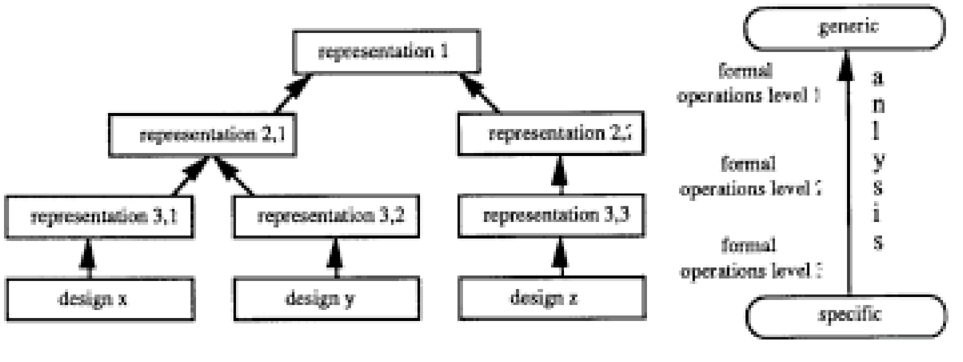

Figure 7. Method for analysis of refinement schema within a class of designs.

The Ring Cycle: Refinement in Kahn's Concentric Layered Designs

In the case studies we have selected designs of various architects which constitute a set of designs within a compositional class and have analyzed the transformations. We have found that transformational operations appear to be characteristic of the class of compositions. In the first series we have analyzed centralistic organizational schemes and have attempted to define the characteristic operations within this class of designs.

The refinement analyses employs the concept of a *general refinement schema in architectural design*. The model proposes an order of design particularization which starts from spatial-organizational representation and ends with a specified physical representation. The refinement model incorporates the following levels: schematic spatial organization, particularized spatial organization, partitioning, boundary conditions, thematic structural elements, non-thematic elements, detailed elements.

In the work of the architect Louis Kahn the recurrent examples of concentric layered designs provide an interesting class of designs which can be analyzed as refinements. Kahn is a fitting source for such an analysis. In his use of the concepts of *form,* as the generic representation which initiates design, and *design,* as specific particularized design, Kahn defined design as a refinement process (Scully 1962). In the series of designs which we have analyzed, Kahn appears to have developed a unique approach to the formal syntax of centralistic organization in ringed layers. It is interesting to observe the continuities in this class of compositions in a tradition including Durand and Ledoux. Kahn maintained certain salient characteristics of this compositional tradition, while extending others.

How might Kahn employ schema-driven refinement within a class of centralistic designs? We selected for study the Goldenberg House of 1959, the Unitarian Church of 1959-1967, and the Phillips Exeter Library, 1967-1972. An illustration of the refinement process as analyzed is given in figure 8 and figure 9. The steps of refinement include: establishing of the spatial scheme of rings, the syntactic subdivision of the ring zones by particularizing a sub-structure of axes and additional rings, the elaboration of the physical structure, etc. Characteristic of Kahn's refinement of this schema is the relationship between the central cross axes and the diagonal axes, which also occurs frequently in Durand. Unique to Kahn is the multiple, hierarchical subdivision of the major rings, sub-themes of asymmetry within the axially symmetrical scheme, and the high degree of formal particularization of the external ring.

The refinement model in the analysis of Kahn's concentric schemes includes the following levels:

- schematic spatial organization: the ring scheme
- elaborated spatial scheme: axial system
- particularized spatial organization: sub-axial scheme and syntactic elaboration
- partitioning and boundary elements: boundary and corner conditions
- thematic structural elements
- non-thematic elements and detailed elements

These categories of the model of refinement have been sub-divided into two groups. The first, illustrated in figure 8, consists of the definition of the spatial syntax of the ring scheme. The second grouping of refinement processes, illustrated in figure 9, includes the physical elaboration of the spatial scheme. Each of the steps within the levels of refinement can be further elaborated according to the formal operations which achieve the refinement.

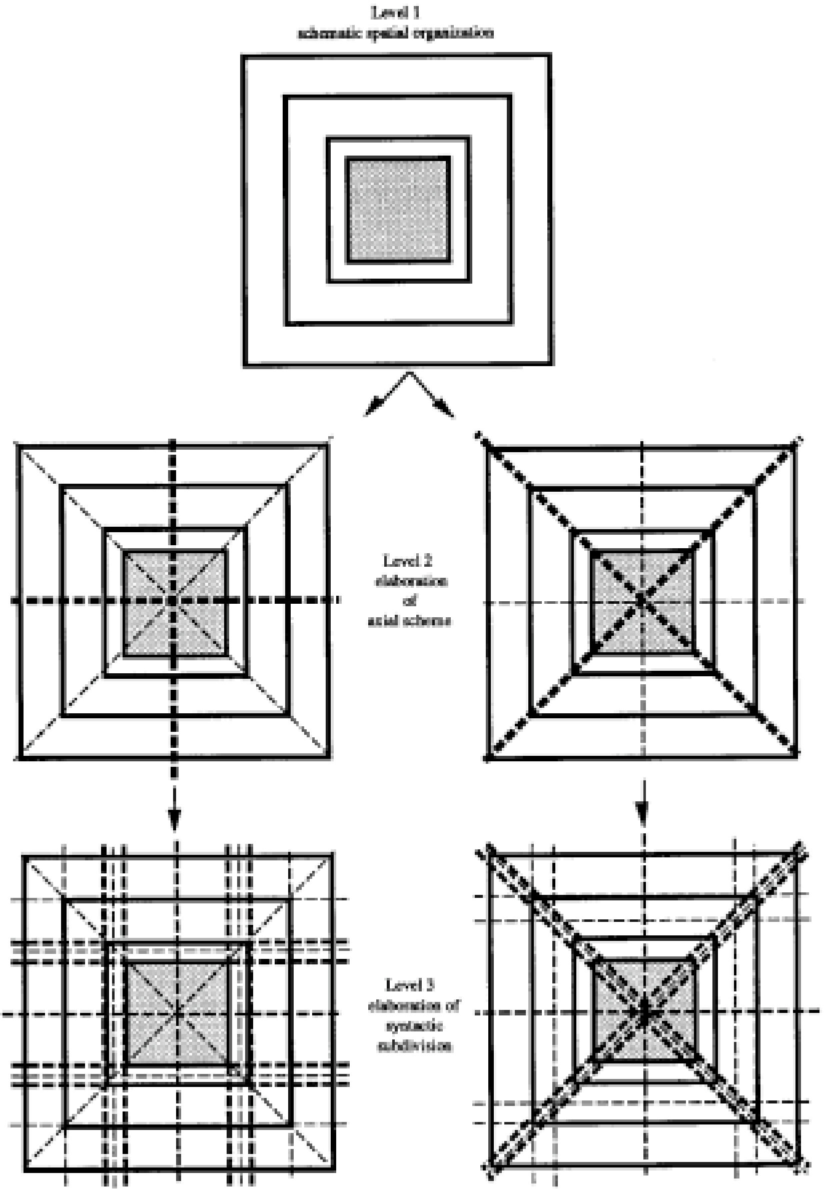

Figure 8. The Ring Cycle: refinement in a class of Kahn's design. I - spatial scheme.

The formal analysis of transformational operations in a class of designs may be applied to the study of facade designs. We have analyzed Kahn's refinement of the syntax of facades within a recurrent facade schema. Figure 10 illustrates the syntactic particularization of facade designs, all of which have a common tri-partite governing scheme. Operations in elevation display the high level of particularization which also characterized Kahn's refine-

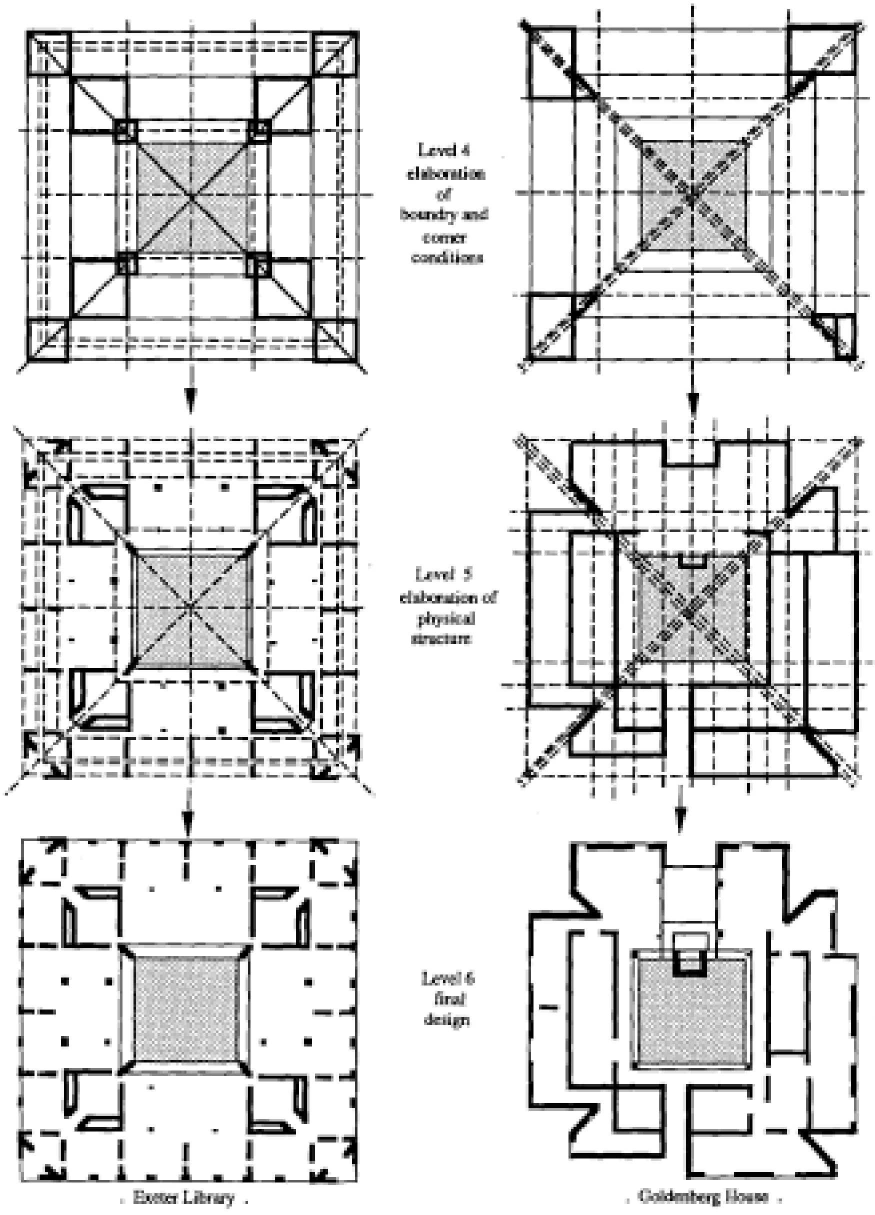

Figure 9. The Ring Cycle: refinement in a class of Kahn's designs. 11 - physical elaboration.

ment of plans. The highly syntactic nature of operations, the significance of ordering devices such as axial schemes, the tendency to hierarchical order within the scheme are among the high-level principles which underlie the refinement operations of this class of designs.

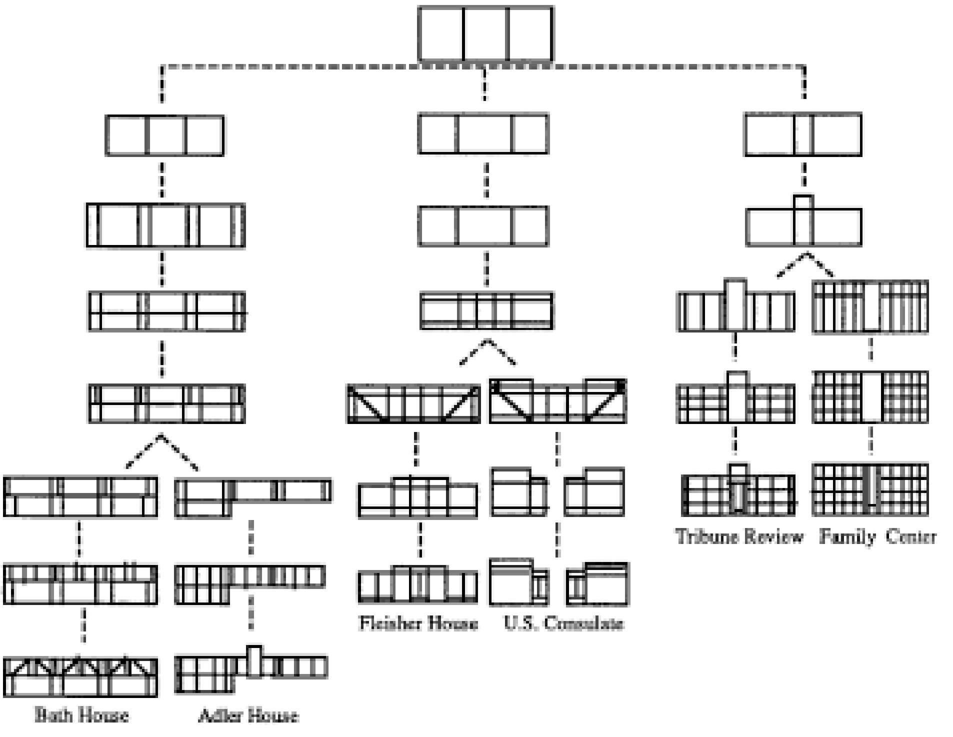

Figure 10. A refinement tree of six facade designs of Kahn.

Analysis of Adaptation through Formal Analysis of Case Studies

Generation through adaptation can be modelled as a series of transformations upon a specific design. Our approach to the analysis of adaptation is the mapping of one precedent into a related precedent in the same class of designs. This mapping is a reconstruction of the operations of adaptation which transform one specific design into another specific design. In the analysis, precedent is mapped into precedent as a sequence of transformation operations. Each step in the sequence identifies an operation of adaptation. These operations and sequences of operations of adaptation may be characteristic in classes of designs.

As in the case of refinement, we have employed sets of related designs as the basis for analysis. A case study of adaptation has been analyzed in the villa designs of Palladio. The mapping between the Villa Rotonda and the Malcontenta provides an example of schema adaptation in which a bi-lateral axial scheme (Rotonda) is mapped into a preference of one of the axes (Malcontenta). Figure 11 illustrates the mapping of adaptive operations. The two designs are superimposed. The dotted lines (Rotonda) are the state to be modified. The solid lines (Malcontenta) are the modified design.

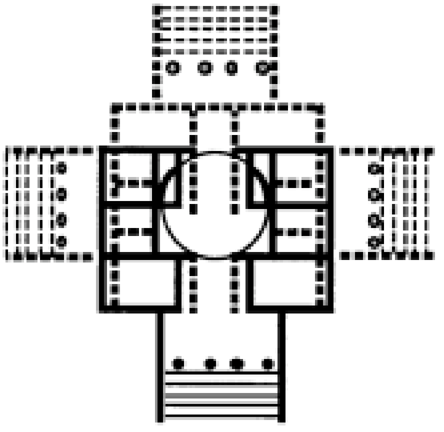

Figure 11. Mapping adaptation in two villas of Palladio.

The Ticino Cycle: Adaptation in Botta's Villa Designs

Botta's cycle of villa designs including Pregassona, 1979, Massagno, 1979, Viganello, 1980, Stabio, 1980, and Origlio, 1981 is a set of related designs with certain common formal characteristics. The source scheme at Pregassona is a bi-axial, nine-square spatial form. An exterior thematic space is incorporated in the spatial diagram within the ninesquare form and creates a major element on the main facade. The masses, element vocabulary, roof shapes, treatment of fenestration and the way of introducing natural light share common formal characteristics in all of the villas. They provide an interesting case study of the mapping of one design into another as a process of adaptation.

Figure 12 illustrates an adaptive mapping of Pregassona into Massagno. The adaptive process exemplifies two strategies of adaptation, elemental adaptation and schema adaptation. The increase in length of the diagonal elements (step 2) and the replacement of the stair type (step 3) are examples of elemental adaptation. In schema adaptation, the schema is modified while certain of its other characteristics are preserved. For example, the transverse niche has been transformed into an internal forecourt (step 4). The emergence of this interior-exterior space as the main focal space of the house is the major transformation of the schema. The bi-lateral symmetry of this court is then adapted (step 5). Despite the compression of the square plan base into a rectangle, the remaining schematic characteristics are similar in the two villas. Similar mappings between other pairs of Botta villas in this series were undertaken in the research. Adaptation, at least in this class of designs, appears to be strongly controlled by the discipline of the compositional class.

Adaptive mappings of precedent-based designs have also been studied in the work of architects of different historical periods. For example, the mapping of Schinkel's Altes Museum into Stirling's Staatsgalerie was analyzed, employing the technique of adaptive transformation represented as successive mappings.

Computational formal analysis has provided a means to analyze and model both refinement and adaptation. The computer programs employed (geometrical modelling and animation) have given us a *dynamic mapping of* one design representation into another. This has provided a unique medium for simulating refinement and adaptation as design processes. Furthermore, computational formal analysis has proved to be an effective method for knowledge acquisition in design research and as a medium for teaching concepts *of* design by means *of* computer modelling.

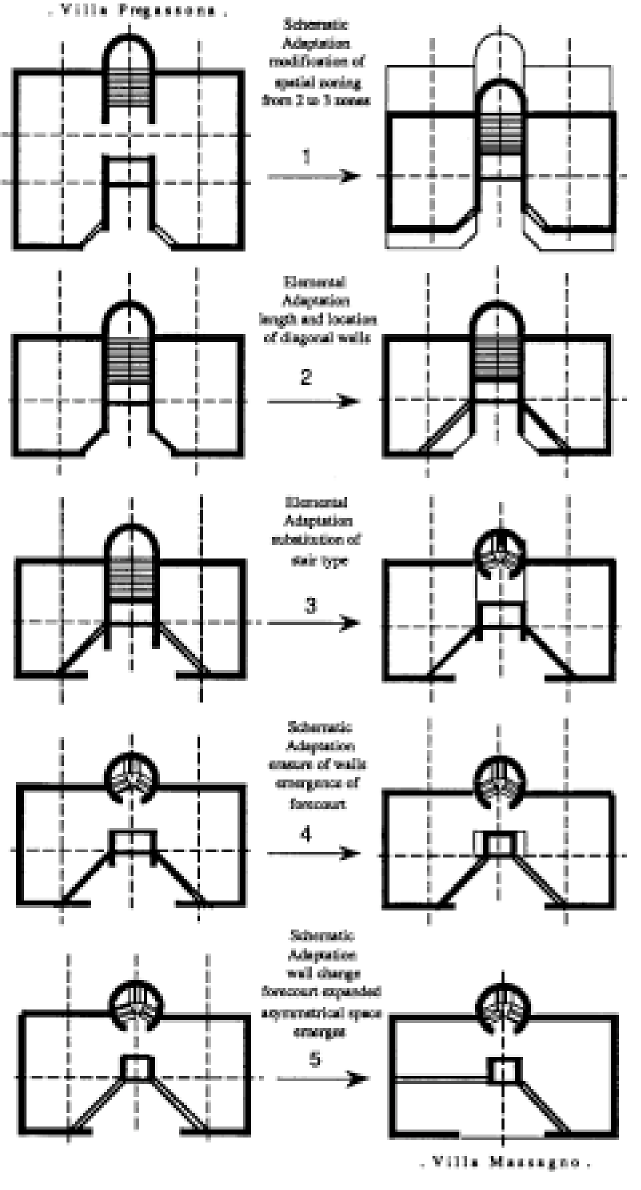

Figure 12. The Ticino Cycle: the adaptive mapping of precedents in a class of villas by Botta.

Conclusions

Refinement and adaptation have been proposed as two distinct approaches to design generation which have relevance for design computation. Representing and reasoning with generalized, typological knowledge, which we have referred to as generic design, and design with specific design precedents, which we have referred to as case-based design, are two paradigms which should be addressed in future research in knowledge-based CAAD.

The formal method which was utilized in the analysis of case studies has proved to be useful as a technique of design research in the study of refinement and adaptation. Additional research is currently being undertaken in the analysis of work of other architects in order to justify our conclusions regarding the general relevance of refinement and adaptation as models of design generation. The research has raised various issues with respect to the formalization of syntactical knowledge as a body of knowledge which we have referred to as architectural syntax. Much work in CAAD is dependent upon modelling this knowledge, and the formalization of syntactical knowledge for CA-AD appears to us to be a significant research priority.

Through formal analysis a general model of refinement was elaborated. Applying this general model, we have demonstrated that specific refinement operations are characteristic of architectural syntactic classes. It appears that refinement is related to the high level formal principles of the syntactical class. Exploiting this characteristic in design computing, these high level principles can be represented as a design schema. In knowledge-based CAAD, the representation of transformational operations of refinement may be encoded as part of the design schema. The formalization of schemata for knowledge-based design is dependent upon our understanding of the general compositional principles in architectural design.

Adaptation has so far received little attention in the architectural context. The utility of the transformational model to represent adaptation is one of the research questions addressed in the current work. In our analyses we have employed transformation to model adaptation. In the model we have distinguished between higher level adaptation strategies, termed schematic adaptation, and lower level, specific adaptation strategies, termed elemental adaptation. Adaptation operates directly on a representation of an existing design and results in the direct modification of specific designs. However, in order to achieve a non-trivial adaptation, design reasoning may transcend the detail of the specific design and access a generic level. There appears to us to be an integral relationship between generalized and specific knowledge in design thinking. In this view a design reasoner in knowledge-based CAAD systems should have a capacity to work with both pre-stored specific cases and the general schema.

The concept of a case base which provides access to a precedent repertoire appears to be a promising direction for research and development in CAD and knowledge-based design systems.

Acknowledgments

The research has been funded by the H. Kieval Research Fund through the V.P.R. Fund of the Technion. The authors gratefully acknowledge this assistance. The work illustrated is part of on-going research at the Technion into architectural syntax and the computation of

architectural knowledge. Student works were done in the framework of the course, *The Computation of Architectural Knowledge* taught by Rivka E. Oxman. The analysis of the Kahn facades was done by M. Shmuelovitch; the mapping of Palladian villas by U. Lehrman and M. Ben Dor. The concept of the Palladian analysis is based upon Lerup (Lerup, 1989). The analyses were done in Mac Architrion documented in Studio 8 and Gallery.

References

Crowe, N. A. and S. W. Hunt. 1986. "Visual notes and the acquisition of architectural knowledge." *Journal of Architectural Education, vol.* 39, no. 3: 6-16.

Flemming, Ulrich. 1986. "More than the sum of the parts: the grammar of Queen Anne houses." *Planning and Design* 14, no. 3: 323-50.

Flemming, Ulrich. 1990. "Syntactic structures in architecture." in Malcolm McCullough, William J. Mitchell and Patrick Purcell (eds.). *The Electronic Design Studio*. Cambridge, MA: MIT Press.

Gero, John S. 1987. "Prototypes: a new schema for knowledge-based design." *Working Paper, Architectural Computing Unit,* Department of Architectural Science, University of Sydney.

Kolodner, Janet, L. 1988. *Case-based Reasoning,* Proceedings of the Workshop on Case-Based Reasoning, Florida: DARPA.

Lerup, Lars. 1989. "On Eden, the geography of villas and Dolf Schnebli's Villa Meyer." *Architecture and Urbanism* 2.

Mitchell William J. 1990. *The Logic of Architecture*. Cambridge, MA: MIT Press.

Mitchell, William J., Robin S. Liggett, and Milton Tan. 1988. 'The Top Down System and its use in teaching: an exploration of structured knowledge-based design." In Pamela J. Bancroft (ed.). *Proceedings of ACADIA:* Ann Arbor.

Oxman, Rivka E. 1990. "Architectural knowledge structures as design shells.". In Malcolm McCullough, William

Oxman, Robert M., and Rivka E. Oxman. 1989. "The joy of syntax: the secrets of architectural composition as elucidated through computer graphics education." In *proceedings of ECAADE CAAD-Education Research and Practice*. Aarhus, Denmark.

Oxman, Robert M., and Rivka E. Oxman. 1990. "The computation of architectural knowledge." In Malcolm McCullough, William J. Mitchell and Patrick Purcell (eds.). *The Electronic Design Studio*. Cambridge, Mass.: MIT Press.

Rosenman, Michael, John S. Gero, and Rivka E. Oxman. 1991. "What's in a case." In Gerhard Schmitt (ed.). Proceedings of CAAD Futures '91. Zurich.

Scully, Vincent Jr. 1962. *Louis!. Kahn*. N.Y.: Braziller.

Stiny, George. 1980a. "Introduction to shape and shape grammars." *Environment and Planning B, vol.* 8: 343351.

Stiny, George. 1980b. "Kindergarten grammars: designing with Froebel's building gifts." *Environment and* Planning B, *vol.* 7: 409-462.

Stiny, George, and William J. Mitchell. 1978. "The Palladian grammar." *Environment and Planning B, vol. 5:* 5-18.

Stiny, George. 1990. "What designers do that computers should." In Malcolm McCullough, William J. Mitchell and Patrick Purcell (eds.). *The Electronic Design Studio*. Cambridge, MA: MIT Press.

Szambien, W. 1982. "Durand and the continuity of tradition." In R. Middleton (ed.). *The Beaux Arts,* Cambridge, MA: MIT Press.

Weissman Knight, T. 1981. "Languages of designs: from known to new." *Environment and Planning B, vol.* 8: 213-238.