Strategic use of representation in architectural massing

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Architectural massing is the primary sub-set of the early stages of built form creation. In this empirical study, we seek a better understanding of the specific cognitive processes contributing to massing. We found that these processes help the designer improve the management of the overall design process through strategies that facilitate a discourse between designer and her graphic representations. These strategies, which rely on the use of regulating elements, include management of part–whole relationships, design hierarchy, topology–geometry relationships, scaffolding the design process, structuring ill-structured problems, and the restructuring of problem parameters.
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Architectural massing is the act of composing and manipulating three-dimensional forms into a unified, coherent architectural configuration. During this process, the relations among massing elements are studied; this includes the relations of the building with its surrounding context and of the building with its sub-parts. Massing comprises all decisions affecting external architectural form. It is a crucial component of design because it is the phase where a designer defines her building's identity as well as the impact of her building upon its urban environment.

Le Corbusier defined architecture as "the masterly, correct, and magnificent play of masses brought together in light". In his statement, there is an emphasis on massing as if it were the very essence of architecture.[1]

Architectural massing is mostly described as a product in the architectural design literature, and has not been sufficiently analyzed as a process. Therefore, we set out to analyze the cognitive strategies that contribute to

1 **Le Corbusier** *Towards a new architecture* Preager Publishers Inc (1960)(p 31)

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architectural massing. Our primary motivation was the design of effective computational tools that would support massing. Although the study presented in this paper focuses on the cognitive aspects of massing, it is a part of a larger research effort dealing with the computational aspects required to support massing.

Our initial study consisted of observing six architects as they performed early design activities that led to three-dimensional massing models. We collected protocol data that revealed specific mechanisms that were repeatedly and consistently used as an integral part of several widely recognized cognitive strategies. These include management of part–whole relationships, design hierarchy, topology–geometry relationships, scaffolding the design process, structuring ill-structured problems, and the restructuring of problem parameters.

We begin our discussion with a description of our empirical study, followed by a review of regulating elements used as design strategies. We then discuss each strategy as described in the literature and manifested in our protocol episodes. We conclude by describing concepts for computational support for massing strategies and by discussing the implications of massing strategies for architectural education.

1 Empirical observation

Our initial investigation of the field revealed that the cognitive aspects of massing have not been adequately described in the architectural or design process literature. Consequently we set up an empirical study for the purpose of gaining a deeper understanding of the strategies that guide massing processes. Since massing does not occur in isolation, we designed a series of protocol sessions that capture massing as well as early design activities that, although peripheral, influence massing decisions; for instance, site design, layout planning, or elevation design.

1.1 Experimental set-up

Protocol analysis has been widely used for studying human cognitive behavior within problem-solving contexts.[2] Advantages and disadvantages of protocol analysis have been debated extensively[3] but are outside of the scope of this paper. We chose protocol analysis because it captures comprehensively and simultaneously the designer's graphical representation and her corresponding verbalization. These verbal expressions encapsulate the motivation and rationale that are not evident in graphical representations therefore, clarifying possible ambiguities that are often present in the latter.

2 **Kirwan, B and Ainsworth, L** *A guide to task analysis* Taylor and Francis, London (1993)
3 **Ericsson, K and Simon, H** *Protocol analysis: verbal reports as data* MIT Press, Cambridge, MA (1993)

Our protocol experiment consisted of observing six architects while they

designed a three-dimensional massing model. Each session lasted two hours on the average, but was not limited by time, in order to avoid putting participants under pressure. Each session was recorded on videotape and was followed by a brief post-experiment questionnaire.

We considered all participants as professional architects. Each had completed at least five years of architectural design education, and had variable work experience ranging between 2 and 25 years. Among the six participants, three were experienced CAD users with a minimum of three years experience.

The task consisted of designing the three-dimensional massing configuration of a dormitory building on the Carnegie Mellon campus. The program included various functions, both repetitive and specialized, with different privacy levels. The site was fairly complex: it comprised a steep slope and two axes of orientation. The required outcome was a 3D model; while plans, sections, and elevations were optional. Due to its level of complexity, the chosen task had potential to uncover interesting design strategies and a variety of solutions within a limited time frame.

Three sessions were completed in the sketch medium (pencil and paper) and three others in the computing medium (CAD system). This allowed us to capture strategies that transcend representational media. In the computing sessions, three different industry-standard CAD systems were used (AutoCAD, MicroStation, and FormZ) so that results would not be influenced by the limitations of a single system. The participants were also allowed to use paper whenever they needed in order to reveal the massing design activities that would be difficult to achieve on the computer. Furthermore, the switch between the media is considered to be significant data for analysis in other studies.[4]

1.2 *Analysis*

We refer to participants as P1 to P6 and the corresponding protocol sessions as S1 to S6. In the first three sessions (S1 to S3), participants used the pencil/paper medium, while for the remaining sessions they used one of three available CAD systems. Alternatives generated by each participant are referred to as Ai1 to Ain, where 'i' corresponds to the participant ID.

The protocol sessions were first transcribed into a series of moves, which included verbal expressions, drawing actions or their combination. Then these moves were categorized and color-coded according to the activity to which they contributed (massing, planning, site analysis, program review, and design structure) and their type (analysis, decision, and evaluation).

4 Moustapha, H *Architectural explorations: transforming configurations through interactive design structures* Carnegie Mellon University, Pittsburgh (2001)

Moves are referred to as Mi—n.n.n, where 'i' is the participant ID and n.n.n is the move number. The vocabulary of massing elements, precise massing manipulations, and massing strategies were identified in the transcriptions. Episodes illustrating substantial massing strategies were further analyzed.

1.3 Summary of results

The principal mechanism utilized in structuring massing activities was the use of regulating elements. These include tools such as axes of symmetry, centers of rotation, alignment axes, diagonal proportion lines, points of intersection, and bounding lines. All participants maintained geometric order in their designs using such mechanisms. Although they freely manipulated (added and removed) massing elements, through the use of regulating elements they were able to preserve their underlying structures and even accentuate them.

Analysis of the data showed that designers used these massing strategies, among other things, to regulate the overall design process. They used these strategies to help them manage part–whole relationships, design hierarchy, topology–geometry relationships, scaffolding the design process, structuring sub-problems, and the restructuring of problem parameters. In the following sections, we will consider each of these strategies as described in the literature and manifested in our massing episodes. We believe that these strategies illustrate that representation is used not as a passive mechanism merely to display the content of the mind onto external media, but to actively guide design.

2 Regulating elements

In each massing configuration, there is an underlying structure.[5] It is common practice in architecture to express the relational structure of massing elements through regulating lines. As a matter of fact, in the past, prominent architects have actively promoted the use of regulating lines. According to le Corbusier, "A regulating line is an inevitable… element of Architecture… It is an assurance against capriciousness… it confers on the work the quality of rhythm… The regulating line is a satisfaction of a spiritual order, which leads to the pursuit of ingenious and harmonious relations… The choice of regulating line fixes the fundamental geometry of the work".[6] In an effort to systemize the architectural design process, JNL Durand introduced a "method to follow in the composition of any project", which relies on establishing the structure through regulating lines as a primary design step.[7] Both Le Corbusier's and Durand's prescriptive approaches highlight the role that regulating lines have played in the development of architectural theory.

5 Chimacoff, A Figure, system and memory: the process of design in *Representation and architecture* Information Dynamics Inc, Silver Springs (1992)
6 Le Corbusier *Towards a new architecture* Preager Publishers Inc (1960)(p 71)
7 Madrazo, L 'Durant and the science of architecture' *Journal of Architectural Education* Vol 48/1 No May (1994) 17

We extend the concept of a regulating line to a regulating 'element' to include points, planes and volumes, which, in combination, express the entire structure of the architectural configurations in three dimensions. Regulating elements relate the massing configuration with surrounding buildings or other significant structures; they organize and structure the elements of massing configurations; they also form the spatial sub-division within masses; and they relate massing elements to their constituents.

Our concern in this study is not whether or not designers use or should use regulating lines, but rather 'how' they strategically use them in the creation of architectural form and the development of a design.

3 Regulating the design process

A designer's method, par excellence, is to 'divide and conquer'.[8] Design problems are too large and complex. Finding a design solution that satisfies all aspects of a problem invariably requires that the problem be decomposed into sub-problems. Once they are in hand, the solutions to each sub-problem needs to be re-assembled into a comprehensive solution. Specific strategies used by expert designers to synthesize partial solutions have been codified by Akin, attesting to the important role that decomposition–recomposition strategies play.[9]

During the design sessions we studied here, participants were observed using regulating elements of massing to organize their work. A popular regulating element is the symmetry or alignment line that aligns individual design elements (whether they are rooms, windows, columns or stairs) with respect to it. Aside from the compositional order that results from such use, symmetry or alignment axes represent meta-elements that control the spatial organization of other, lower level elements. The relationship between the latter to the former is one of part-to-whole. For example, a room arranged with respect to an axis is a mere component of a larger composition defined by the axis and the colony of rooms.

3.1 Management of part–whole relationships

In our protocol study, we frequently observed the use of regulating axes. Aside from the formal role that they serve, these axes provide the key element for relating the parts to the wholes.

Most cognitive design process literature considers external representation as a means for making records of mental concepts.[10] Often the focus is to identify, enumerate, and relate design moves in an attempt to model cognitive design processes. However, some sources such as Suwa and Tversky believe that drawings not only reveal designer's thinking, but also facilitate

8 Akin, O *How architects design. Artificial intelligence and pattern recognition in design* North Holland Publishing Company, Amsterdam (1978)

9 Akin, O 'Psychology of early design', Technical Report, Carnegie Mellon University, Pittsburgh, 1994.

10 Larkin, J and Simon, H 'Why a diagram is worth ten thousand words' *Cognitive Science Journal* Vol 11 (1987)

constraint inference problem-solving and understanding.[11] Van Summers explains that drawing can be a production system that helps people generate concepts.[12] Goldschmidt describes visual thinking through interactive imagery as the two-way interaction between the mental concepts and sketch representations. Her evidence illustrates that designers sketch to help generate new images and ideas in their mind, in addition to externalizing ideas and images.[13]

In our protocol sessions, the participants used external representations, whether verbalizations, sketches, or computational records, with the apparent purpose of carrying on a design dialogue with themselves. We focus our attention on specific representation mechanisms that they strategically choose not only to generate ideas, but also to guide further design decisions and structure upcoming design developments. They used regulating elements to express their design organization, either explicitly or implicitly. The explicit expression took either a graphic or verbal form. In the implicit expression, the relation was defined by the position of elements, but no lines were drawn nor discussed. Below we provide examples to support each of these forms of using axes to organize design elements.

3.1.1 Explicit

An explicit use of a regulating axis is illustrated in S3, where the participant repeatedly draws the main axis of the configuration on every trace over the design sketch. This is substantiated at several points in the design protocol, one of which is illustrated in Episode 1, below. The axis is clearly the organizing element for the courtyard, the two room-wings of the building, and the restaurant. These parts are used to create the whole (the entire building) by virtue of the axis, without which the parts would remain a set of unrelated elements.

Episode 1: Explicit expression of regulating axes (M3—5.1.1)

5.1.1   P3 places the three axes lines on the site perpendicular to the MMCH building.

5.1.2   She places a fourth axis perpendicular to the site's 45° angle.

5.2   She places function in relations to east-most axis.

5.2.1   '*In this axis, I can get my main courtyard.*'

5.3   P3 places the rest of the functions in relations to the other axes.

5.3.1   '*We have to change our direction for the study area.*'

5.3.2   She adjusts the size and alignment of
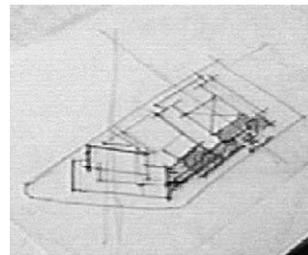
11 **Suwa, M and Tversky, B** 'What architects and students see in architectural design sketches' in *Descriptive Models of Design, Istanbul* (1996)
12 **Van Sommers, P** *Drawings and cognition: descriptive and experimental studies of graphics production processes* Cambridge University Press, Cambridge (1984)
13 **Goldschmidt, G** 'On visual design thinking: the wiz kids of architecture' *Design Studies* Vol 15 No 2 (1990)

the study areas and moves it in along
its 45° axis.

Participants also made verbal references to regulating axes as in the case of P4, who defines the geometric structure verbally prior to any drawing activity. Even though the axis is not explicitly depicted, its verbal presence serves, just as successfully, the same function that the explicit axes serve in other protocol episodes. In Episode 2, below, we see the evidence that supports the contention that verbally stated axes are just as functional as the others.

Episode 2: Verbal representation of regulating axes (M4—1.9)

1.9.1 '*One possibility is to make it a continuing line from Margaret Morrison and then design at the corner a transition into the new coordinate system.*'

1.9.4 '*The same way in which the dormitories use the octagon to transition between the Carnegie Mellon grid and the dorms grid, which happens to be 45° such that an octagon can do it very nicely.*'

3.1.2 Implicit

The power of the axis as a design strategy is perhaps best expressed when it is used implicitly as a virtual line. This clearly suggests that the designer is not relying on the axis line as a compositional element in itself. Rather, its sole function seems to be one of regulating relationship between design elements and the meta-organizational concept of symmetry. Implicit axes, derived from other elements in the design, can also be considered as emergent structures.

Participant P2, for example, sets out to design an axially bilateral, symmetric building. However, she (see note [1]) neither draws, nor expresses this relationship explicitly with a line. The rooms of the dormitory complex align the centrally positioned space along the main axis almost in the form of a cloister. The major public functions are situated at the two ends of the axis. It is clear that this regulating element provides the scaffolding around which the individual parts of the program have been organized (Figure 1a).

This is not the only example of virtual axes elements used to define part–whole relations in the protocols. In S6, for example (Figure 1b), several axial plan alternatives were developed, each with a different geometric structure. Yet, this participant does not express any explicit axes in her drawings.
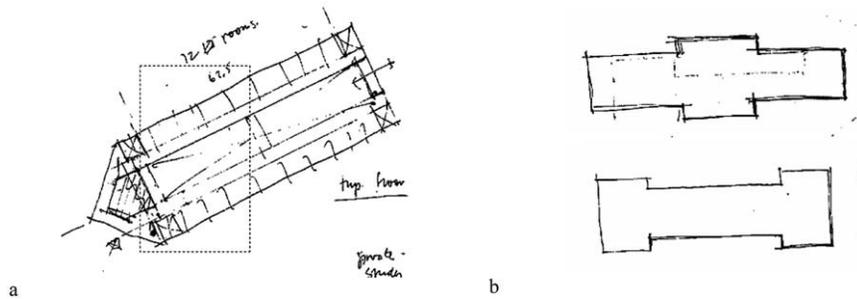
Figure 1 Implicit representation of axes of symmetry in S2 and S6, respectively

3.2 *Organizing hierarchies*

The part–whole relationship naturally leads to the notion of hierarchy. Parts are subsumed by higher entities, which in turn define other yet higher instances of design elements. It is not a surprise that architectural conventions include many examples of hierarchical decomposition: the building, its wings, their floors, suites found on floors, the individual rooms inside them, and so on. Both empirical evidence[14] and normative models of design rely heavily on such spatial hierarchies.[15] In a widely published study Akin[16] reports:

"t*o the untrained eye the complexity of the design problem appears as an endless maze…. While to the designer it merely constitutes a set of ingredients that are necessary for design. To both, the problem is overwhelming in its initial form. The general strategy (of the architect to overcome this complexity) is one of breaking the problem up into smaller sub-parts; initially, (using) a breadth-first approach to decomposition; later, (converting) this into a depth-first approach.*"

This peculiar combination of breadth-and-depth strategy is responsible for creating and navigating complex hierarchies in a design problem. First, there is the decomposition of the problem into sub-parts. Since design problems do not arrive with predetermined (or a priori) sub-parts, the essence of the decomposition problem is to figure out a strategy for doing just that. Experienced designers have clearly developed approaches to accomplish this decomposition.

The evidence we gathered here suggests that massing, in fact, relies on these universally accepted strategies. The massing strategies defined here, which use regulating elements to create geometric order, establish a two-tier hierarchy between the regulator (super-node) and the regulated (sub-node). Nested regulating elements of massing can then create indefinitely deep hierarchies.

In S4 (Episode 3), the participant uses fence-stretch to manipulate two

14 Eastman, C C 'Cognitive processes and ill-defined problems' in Proceedings of the International Joint Conference on Artificial Intelligence (1969)

15 Flemming, U and Woodbury, R 'Software environment to support early phases of building design: SEED overview' *Journal of Architectural Engineering* Vol 1 (1995) 4

16 Akin, O and Akin, C 'On the process of creativity in puzzles, inventions and designs' *Models of design (special issue), Automation in Construction* Vol 7 (1998)(Editorial)

adjacent elements. The bundling of the elements is clearly governed by the parameters of the fence-stretch command of the drafting system being used. Conceptually, we can view this as an action that traverses two tiers of a multi-tiered element hierarchy.

Episode 3: Changing two adjacent elements in a single step (M4—9.14)

9.14   P4 changes the proportion of the administration zone to make it narrower and the restaurant triangle to become deeper.

9.14.2   She uses fence-stretch to get both proportions changed in a single step.

In another instance in S4, the participant uses fence-stretch again to lower the top vertex of two separate, but symmetrical, roof elements. The participant wants to maintain the symmetry relation, yet she wants to adjust both roofs in a single step (Episode 4).
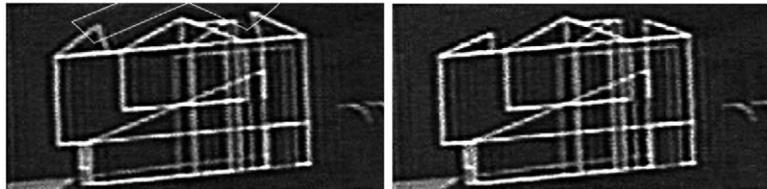
Episode 4: Simultaneously lowering two symmetric roof elements (M4—9.15.4)

9.15.4   P4 wants to lower the two symmetrical shed roofs without lowering the central gable.

9.15.5   She uses fence stretch and selects the shape fence.

9.15.6   She draws the fence around the top vertices of the two shed roofs.

9.15.7   P4 lowers the fence, which lowers simultaneously both shed roofs.

These examples also suggest a hierarchical relationship between elements, this time, however, between elements that are further down the ladder of hierarchy. These steps (9.14 and 9.15 in S4), seen together, suggest a hierarchy of elements that ascend from rooflines, to room clusters, to wings of buildings, and finally, to the entire building. The structure that govern such hierarchies have not been explained in design literature, other than to point to the part–whole relationship that exist between the immediate neighbors, that is, parent and child. When a regulating element is considered as part of the design hierarchy, it enables manipulations that preserve the configuration's structure.

Why are some elements (for instance the floor of a wing) broken down into individual rooms, expressed by windows on the facade, while other elements of the same wing are represented through roof alignments between them and other wings of the building. Such complex hierarchies
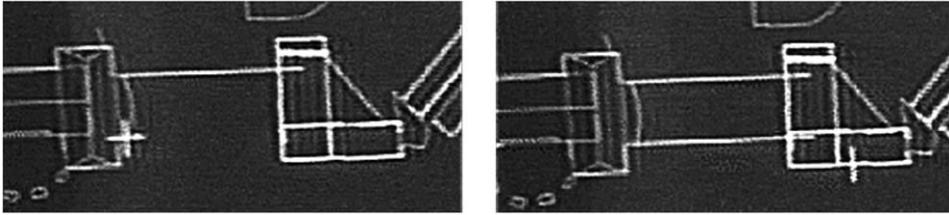
Figure 2 P4 extending a sub-division line (M4—2.4.5)

cannot be explained by simple spatial subsumption relationships like that of the spatial parents and children. However, they can be explained if regulating elements of massing are part of the hierarchy, each design element inheriting a property from a higher-level regulating element, such as an axis or alignment line.

3.3 Scaffolding the design process

Another view of our data relies on the scaffolding metaphor. Just as a scaffold provides a structure for accommodating construction activities, we observed that the relationship between the regulating elements and the spatial and physical massing of design elements rely on the framework created by the regulating elements. There appears to be a two-way interaction between the regulating and massing elements, particularly in the manner in which regulating elements are derived from masses and, inversely, masses are guided by regulating elements.

3.3.1 By extending lines from massing elements

Scaffold creation seems to be based on the extension of alignments in the current design. For instance, P4 extends a line from the boundary of an existing building on the given site, and using it to align massing elements in order to preserve a consistent setback. She says "*I definitely want to maintain the line with the Margaret Morrison building*". The existing alignment serves as a scaffold for additional massing elements in the composition.

We observe P4 accomplishing similar ends using slightly different strategies. One of these is extending two lines from an existing building's external protrusion and using them as guides to create a protrusion onto P4's proposed building. She then discovers a novel relation[17] between these lines and her own buildings sub-structure. She says "*Ahaaa… I found a very interesting relationship*". This causes an adjustment to the proposed massing configuration (Figure 2).

In another case of scaffolding new designs with existing elements, P1

17 Akin, O and Akin, C 'Expertise and creativity in architectural design' in *Descriptive Models of Design, Istanbul* (1996)

draws a massing element and then derives its central axis as the major axis of the configuration. Following the order specified by that axis, she draws the remaining massing elements. Rivka Oxman described semantic emergence as the emergence of the underlying structure or design organization.[18] In the following example, P1 has recognized the emergence of the central organizing axis, in the middle of the process of creating massing elements. This is significant because it shows that emergent features, such as implicit axes, are just as likely to become scaffolds as explicit ones (Episode 5).

Episode 5: Deriving an axis from a massing element (M1—5.1.1)

5.1.1   P1 draws the courtyard.

5.1.2   She draws the public (administration and restaurant) around the courtyard.

5.1.3   Then she draws the central axis line.

5.1   P1 develops the dorm zone.

5.2.1   She starts by drawing three blocks.

5.2.2   She then divides one of them along the central axis ending with four blocks.
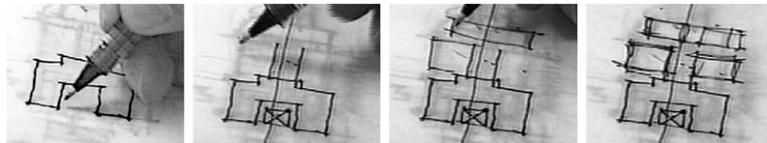
3.3.2 By extending plan and elevation lines

Finally, we observe P3 using a strategy that also falls in the category of scaffolding. She derives the geometric structure of the elevations by extending the axes of the plan, thus reusing the regulating elements of the plan in the elevation (Episode 6).

Episode 6: Extending plan lines to construct the elevation (M3—6.3)

6.3   P3 extends parallel lines from the plan to draw a projected elevation.

6.3.1   She extends the axis lines.

6.3.2   She draws the main lobby and entrance guided by the axes.

6.3.6   She draws the study areas and library.

3.4 Topology and geometry

Topology captures adjacency relationships within a configuration. March discussed topological relationships extensively. He illustrated the notion with three of Frank Lloyd Wright houses Life, Jester and Sundt, which share the same topological structure, exemplified by the same programmatic relations, while their individual geometries remain radically different.[19]

18 Oxman, R 'The thinking eye: visual recognition in design emergence' *Design Studies* (2002).

19 March, L and Steadman, P *The geometry of the environment* MIT Press, Cambridge, MA (1974)

Regulating elements of massing also appear to be one of the rare design tools that are suitable for representing the topology of a given geometric composition. For instance, axes can be used to represent associations and alignments of spaces independent of shape and size. Spaces can be strung along an axis creating a linear topological structure. Alternatively, multiple axes (either representing symmetry or alignment) can be used to create much more complex relationships, like grids and urban road patterns, in order to preserve the topological relationship between the elements whether they are rooms or city blocks.

3.4.1 From the context

The topological structure of a massing configuration can be defined in several ways. We found in our data that these styles are not mutually exclusive, they occur in hybrid combinations. A primary strategy is the creation of topological relationships from contextual information provided by axes. For instance, P2 starts her design by deriving the geometric structure from the site (Episode 7). She then picks up the axis of the streets and the setbacks from a neighboring building.

Episode 7: Deriving topology from the context (M2—1.2.5)

|	
1.2.5	P2 draws the central axis of the street.
1.2.6	'*Assume to build right up to the street*.'
1.2.7	'*We have an axis through Resnick Hall*.'
1.3.1	'*Buildings in vicinity: MMCH*.'
1.3.2	'*Assume that front line of building will not cross the reference line from MMCH*'.'
1.3.3	'*Assume that setback is maintained on other side*.'
1.3.4	She sketches the buildable area.
1.5	She then proceeds by developing her concept.
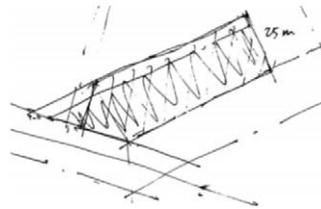
3.4.2 From program relations

We also observed that similar topological structures emerge from the building program. For example, P1 and P3 derive the initial geometric structure of their designs from the spatial relations included in the program. In moves illustrated in Episode 8, P1 expresses the topological structure of the program, even before creating graphic representations of the design.

Episode 8: P1 deriving working out his program relations (M1—1.2)

1.2 P1 identifies patterns in the program.

1.3 She divides the program into zones (entrance, administration zone, study

zone, dorm zone, etc.)

1.4   She analyses relationships between the zones by drawing arrows.
1.5   Adjacencies, accessibility (public, semipublic, private), exits.
1.6   Start developing concepts based on these relations.
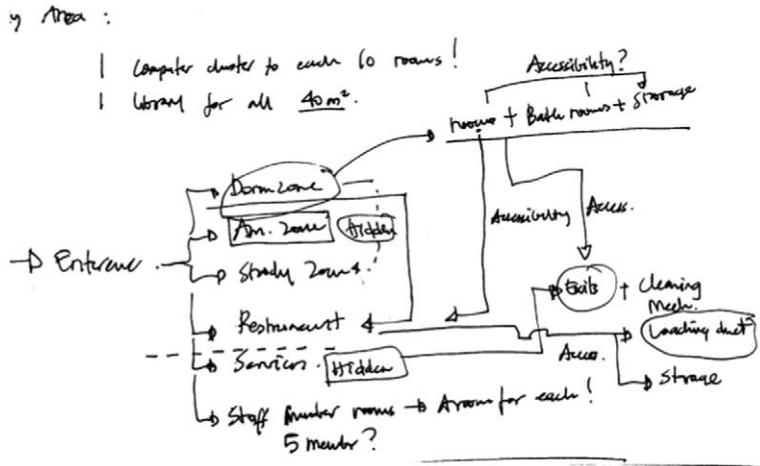
3.5 Structuring the Ill-structured design task

Simon's cognitive model describes the design process as problem-solving and categorizes design problems as ill-structured. Design is considered as a search for an adequate solution within a large space of alternatives.[20] Akin explains that problem structuring is a prerequisite to problem-solving; problem structuring consists of a series of transformations converting an ill-structured problem to a well-structured one.[21] This initial phase defines design the specifications and relations that need to be satisfied in the design solution. Failure to satisfy these would lead to restructuring the problem by modifying relations and redefining specifications, thus transforming the problem by altering its parameters. In other words, the solution is reconstructed according to the new problem parameters.

20 **Simon, H** *The science of the artificial* MIT Press, Cambridge, MA (1969)
21 **Akin, O** *Problem structuring in architectural design* Carnegie Mellon University, Pittsburgh (1987)
22 **Archea, J** 'Puzzle making: what architects do when no one is looking' in **Y Kalay** (ed.) *Computability of design*, John Wiley and Sons Inc, New York (1987)
23 **Maher, M** Modelling design exploration as co-evolution in *Microcomputers in civil engineering* (1996)

Another relevant paradigm, introduced by Archea, refers to design structuring as puzzle making.[22] Maher has introduced a different form of restructuring through the co-evolutionary model for design exploration.[23] This model, motivated by the fact that designers explore the problem spaces as well as the solution spaces, supports the simultaneous evolution of problems and solutions by means of genetic algorithms.

3.5.1 Structuring the problem

One of the most straightforward ways of structuring an ill-structured problem is to break it into more and more specialized parts. Massing with
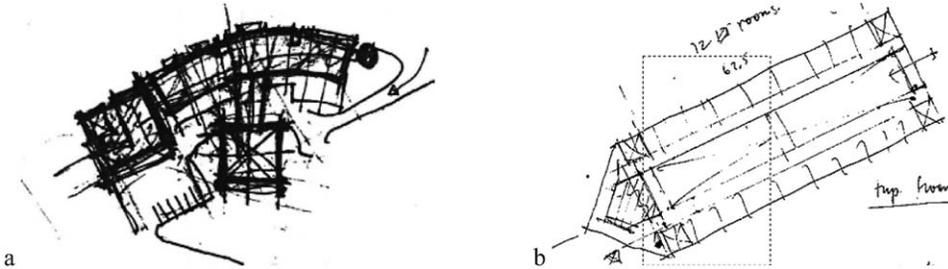
Figure 3 (a) P1 developing sub-structures; (b) P2 developing sub-structures

regulating elements seems to achieve this as well. In this case, the decomposition of the design problem is graphically driven.

Our participants appear to create local problem sub-structures by adding sub-division lines into the massing representation. For example, P1 uses modular sub-divisions lines to develop the sub-structure of the configuration (Figure 3a). She then uses these as guides in protruding and recessing parts of the mass.

Episode 9: Developing the structure by subdividing the mass (M3—8.1)

8.1   P3 revisits the storage in the basement and restaurant details.

8.1.1 '*here I have storage and here I have kitchen storage.*'

8.1.2 '*and restaurant is above that and it goes out and comes above the storage.*'

8.1.3 '*here I have main circulation for students.*'

8.1.4 '*to have the circulation for the students between the court and the restaurants*'

8.1.5 '*this can go to the main entrance to the study area to the vertical circulation of the library.*'

8.1.6 '*I have a path from here to there to reach the cluster.*'
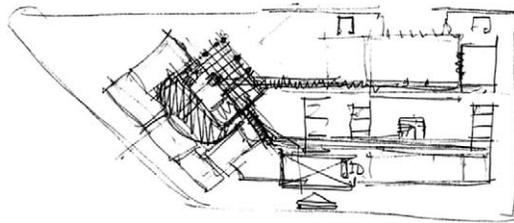
In another example, P2 uses sub-divisions to derive the internal geometric structure of the building (Figure 3b). In a slightly different case, P3 develops local structures and reuses the main geometric structure of the massing configuration (Episode 9) in an attempt to elaborate her configur-
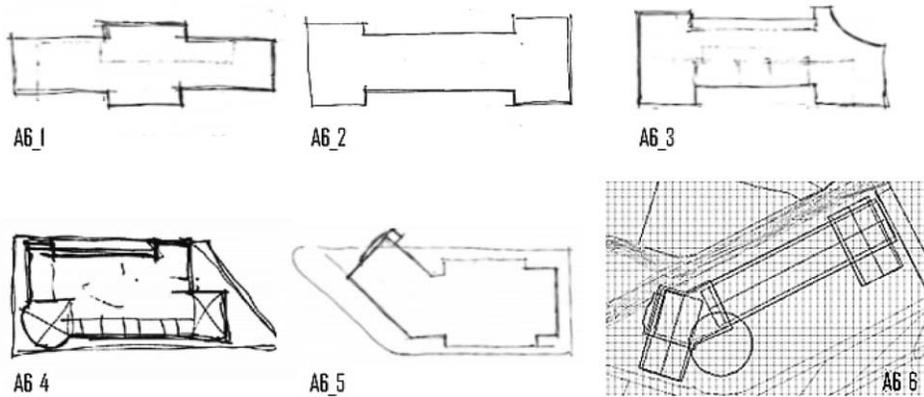
A6_1 has one main central axis and a secondary perpendicular axis in the middle.

A6_2 has one main axis and two secondary axes near the edges.

A6_3 is a variation of A6_2, but has a section subtracted to break the symmetry.

A6_4 a rectangular structure with no dominating axes.

A6_5 had an axis bent to 45 degrees.

A6_6 computer alternative combining axes of A6_2, bending concept of A6_5, and a circular element

Figure 4 P6's alternative illustrating a major change in structure

ation in greater detail. This is a clear example of the local feature inheriting structure of the overall configuration.

$3.5.2$ *Problem restructuring*

One of the behavioral characteristics of expert designers is a skill and propensity to restructure design problems.[24] In our data, we encountered several forms of restructuring, in the context of massing, through regulating elements.

A frequent form of restructuring is through the development of alternatives. For example, P6 developed six alternatives (five manual and one computer based) to visualize different geometric structures (Figure 4).

Moving from A6—1 to A6—2 is a shift in the central secondary axis and an addition of another axis. Moving from A6—1 to A6—5 is a bent in the longitudinal axis, and to A6—6 is a bend in the other direction.

Similarly, P1 develops three alternative configurations. Moving from A1—1 to A1—2 is a major change in ordering principle, the symmetry and well as the homogeneity is broken; new concepts emerge and new local grids are added (Figure 5). Moving from A1—2 to A1—3 however, is less dramatic, since the bridge concept is apparent in both configurations, as well as the curved path; and this change can be summarized as breaking the

24 **Akin, O** *Problem structuring in architectural design* Carnegie Mellon University, Pittsburgh (1987)
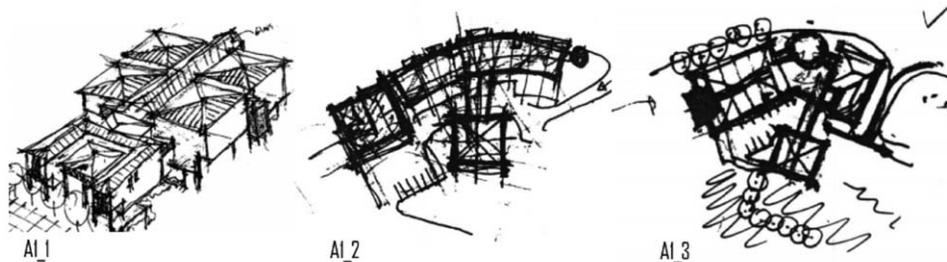
A1_1 has a clear bilateral axial symmetry consistent throughout the homogeneous configuration, and extending within the substructures.

A1_2 had a curvilinear axis and several massing elements linked by a bridge. Separate grids form the local structures of these massing elements.

A1_3 had several components joined by a bridge similar to A1_2, but without the curvilinear axes.

Figure 5 P1's alternatives illustrating major changes in structure

large curvilinear mass into separate components, with different forms and orientations.

Restructuring the problem does not always mean a wholesale redesign or the generation of an entirely new alternative. Occasionally, we observed our participants achieving the same effect by modifying key elements in the solution domain.

For example P4 restructures her left wing while designing her roof configuration. For this activity P4 leaves the computing medium to work on paper. She begins by drawing the right wing, and then she proceeds by drawing the left wing, while trying to create a similarity with the adjacent building's roof structure (Figure 6b). After completing the roof P4 gets another idea (at this point she asks for tracing paper) and then redraws over the left wing. She rotates the axis of the central gable roof by 90°, and adds two symmetrical shed roofs on both sides. One of these is continuing from the right wing, and both are parallel to the new axis. In this way P4 has partially restructured the roof configuration (Figure 6c).
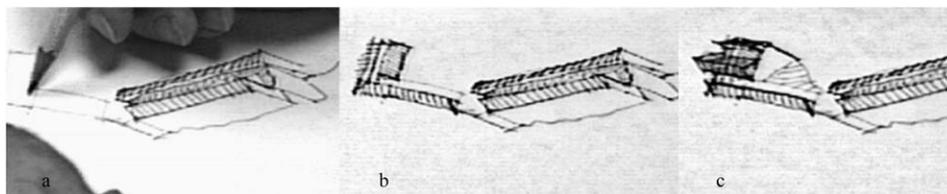

Figure 6 P4 changes the geometric structure of the roof configuration

P1 engages in restructuring as a means of developing a single alternative in two separate instances. P1 creates two variations of the third alternative, where she rotated the axes of the right wing, changed the proportions of the left wing and then shifted the bridge's axis (Figure 7). She also changes the curvature of her building from curvilinear to rectilinear, which illustrates a major restructuring within the second alternative (Episode 10 below).

Episode 10: Changing curvature of axes (M1—8.1)

8.1.1   P1 sketches the site boundary lines.

8.1.2   She draws reference lines along the site.

8.2   P1 follows these reference lines back and forth until she gets a new idea.

8.2.1   '*We could have a continuous building*.'

8.2.2   She adapts the form of the road.

8.2.3   P1 draws a curvilinear section for dorms.

8.2.4   She draws a block (for the restaurant) on the other side of the road.

8.2.5   She attaches theses two major zones with a bridge.

9.1   P1 redraws the plan on another paper.

9.1.5   She repeats the same reference lines along the site as the previous drawing.

9.1.6   She comes up with two linear building components coming together where the site bends.

9.1.7   P1 draws the administration zone.
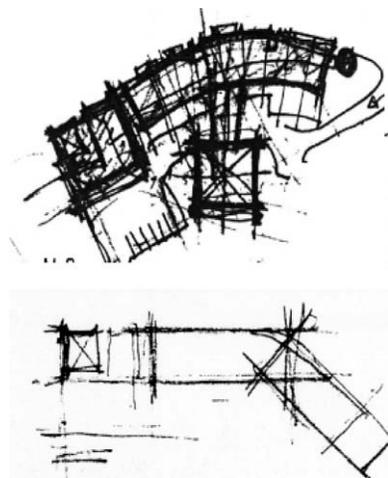
4 *Discussion*

The protocol results illustrated several situations where designers handled the geometric structure of a massing configuration in such a way that they seemed to be doing more than just composing forms. Repeatedly and consistently, we found behaviors that structure and manage the design development process.

Figure 7 P1 changing the direction of a major axis
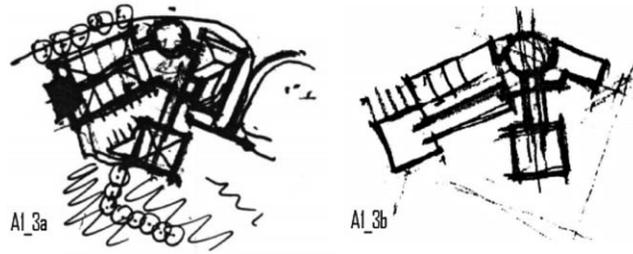
It is our contention that this is not merely a coincidence. We believe designers use the medium of representing massing elements, and in particular, elements of regulation to manage the design process itself. We illustrated this behavior in many guises related to design literature that deals with descriptive views of design. This includes management of part–whole relationships, design hierarchy, topology–geometry relationships, scaffolding the design process, structuring ill-structured problems, and the restructuring of problem parameters. Each of these is a separate facet of the same phenomenon of managing the design process through massing representations.

We would like to conclude our analysis by discussing two issues: computational support for these strategies and some of the possible ramifications of using these strategies in architectural design education.

4.1 Computational support for massing strategies

A major issue of concern is to capture the massing configuration's structure by means of regulating elements and their corresponding massing strategies. These strategies can be enhanced even further, if we assume that the regulating elements could be flexible. By interactively manipulating them, the designer could propagate changes onto the regulated elements. The choice of the regulating elements would define the strategies and would manage behavior of design development.

There have been very few attempts to utilize regulating lines as means for manipulating CAD representations. Branko Kolarevic addressed alignment and grid structures as regulating concepts. His approach has been based on the drafting metaphor, where pencil (or construction) lines regulated ink (or final design) lines.[25] In an earlier prototype, we addressed symmetry structures as a regulating concept. Centers of rotation and axes of mirror, translation, and glide, are treated as regulating elements that have control over other objects.[26] This system supports several of the protocol segments illustrated in this paper such as P4's strategy of simultaneously manipulat-

25 Kolarevic, B 'Lines and geometric relations as a framework for exploring shape, dimension and geometric organization in design' in *CAAD Futures 97*, Kluwer Academic Publishers, Munich (1997)
26 Moustapha, H and Krishnamurti, R 'Arabic calligraphy: a computational exploration' in Third International Conference, Geelong *Mathematics and Design 2001* (2001)

ing the symmetric roof structure, which can be done by using a reflection, regulating element.

We would like to extend these efforts by supporting additional operations such as sub-dividing, which is a key strategy for structuring the designer's configuration through decomposition. Regulating elements through decomposition contribute to hierarchic design strategies. Regulating elements could then become instrumental super-nodes that control massing element sub-nodes by propagating changes throughout the hierarchy.

Another major motivation is to support the two-way interaction among massing elements and regulating elements observed in the scaffolding category. Regulating elements can be automatically derived from massing elements by extension of axes, boundaries or sub-divisions. Additionally, we would like to support the two-way interaction between topology and geometry. A designer can manipulate the spaces specified by the program and compose layouts based on their relations and then derive masses. Alternatively, she can define masses then insert the spaces in these masses.

The ability to restructure massing configurations and instantaneously observe their complete effects, would perhaps be the most exciting and rewarding aspect of such a computational tool. Verstijnen et al. reported that the act of restructuring is difficult to conceive with mental imagery alone, and is significantly enhanced by sketching.[27] They also conducted studies illustrating that current computing tools do not support design-restructuring behavior. It is our intention to show that with the help of interactive regulating elements, the typically time-consuming, labor-intensive act of restructuring can be carried out quickly and accurately in a computational environment.

*4.*2 *Implications for design education*

While the strategies discussed above are common practices in architectural design, they do not play an active role in architectural education. Although regulating lines are most certainly used in constructing architectural drawings, using them as strategies to manage the design process is not a likely part of an architect's instruction. We assume, however, that our participants have acquired these skills not necessary in school but through their own experience as designers. Furthermore, we believe that using those strategies to manage their processes is not a conscious act.

We can only speculate on the impact of teaching design students the use of regulating lines as explicit mechanisms for managing their design process. We foresee the following advantages: (i) explicit instruction would

[27] Vertijnen et al. 'Sketching and creative discovery' *Design Studies* (2002).

takes trial and error out of the learning cycle and therefore reduces the amount of time required for design students to develop their own 'regulating' strategy; (ii) explicit use of these strategies may increase our understanding of how well or how poorly design students use them to their advantage.

We also foresee the following disadvantages: (i) the explicit instruction for these particular strategies might limit the natural flow of design, particularly in intuitively driven design episodes (often associated with creativity); (ii) the explicit instruction of those strategies would make the design student more self-conscious and therefore, it might slow down the design process, especially during early learning stages and might result in a steeper learning curve; and (iii) since its not a conscious act, we do not know whether making it explicit would result in disrupting the design process.

This notion of explicit instructions for these 'regulating' strategies raises questions about designing and implementing computing systems. Should we design the interaction such that the strategies are explicit? Or should the strategies remain implicit and just allow the regulating elements to be explicit? Alternatively developing the computational tool would contribute to teaching the students such strategies: the tool itself could be used as a pedagogical instrument for the explicit development of strategies that utilizes regulating lines to manage the design processes.

We consider that an exploration tool for supporting these strategies, whether in implicit or explicit form, which is currently underway, will greatly enhance massing design process and will be a significant step forward in CAD research and CAD-based instruction.

Notes
[1] For the purpose of anonymity, we consistently refer to second person singulars in the female gender. This is not for the purpose of signifying the gender of any individuals who may be referenced.