How Computers Design

- Generate alternatives – *systematic enumeration*
  - Define a problem space, which is
  - *Complete* ; generate all possible solutions
  - *Correct* ; indeed a solution
- Select alternative(s) – *evaluation*

Space Layout

- 2D
- Very important part of architectural design
- 5 levels in the environment [Habraken 1998]
  - Streets and blocks in a city
  - Buildings in a city block
  - Partitioning and rooms in a building
  - Furniture and equipment in a room
  - Objects

Levels in the built environment

- roads and city blocks
- buildings arranged inside city blocks
- rooms inside buildings
- furniture inside rooms
- objects

(Habraken, 1998)

Habraken, N. J. (1998). *The structure of the ordinary: form and control in the built environment*. Cambridge, Massachusetts: The MIT Press.

Space Layout Considerations

- Topological relations
  - adjacency
  - alignment
  - grouping
- Geometric properties & relations
  - shape
  - dimension
  - distance
- Other functions of spatial arrangement

Space Layout Systems

Liggett, “Automated facilities layout: past, present and future”, 2000.

- Graph-based
  - LOOS
- Constraint-based
  - WRIGHT
- Quadratic Assignment Problem [QAP]
  - Grid based
  - Optimization
- Shape grammars
  - Palladian Grammar
  - Queen Anne Grammar

Graph-based & Constraint-based Representations for Space Layout

Iconic

- plan
- convex map
- axial map
- isovist map

Symbolic

- graphs
- region connection calculus
- rectangle algebra
- equations

Space

- floor
- boundaries
- inside – outside

Space is discretized for analysis and synthesis

Different abstractions of space, using different representations in each space layout system

Plan

Starting point for analyses is the plan

Plan shows

- supporting plane that allows movement
- vertical boundaries that limit movement and visibility
- dimensions of the elements

Space Syntax

A method for describing and analyzing the relationships between spaces of urban areas and buildings.

Object of analysis

Configured space, voids between walls, fences, ...

- Building floorplans - rooms
- Plans of urban fabric – streets, squares, fields

Method

- Redescribed in an abstracted format - Graph
- Focuses on its topology
- Sociologically relevant aspects can be captured at the topological level

Creating a graph

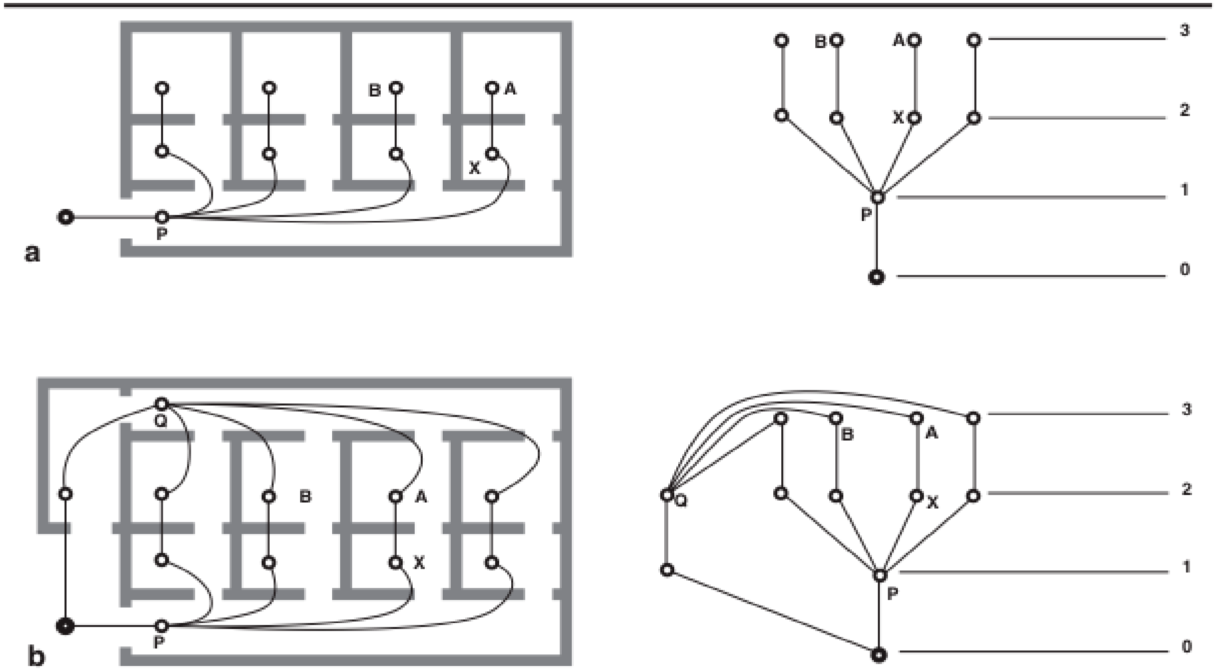


Figure 1: Mapping a Schematic Office Setting Onto a Graph

a. In this schematic plan of an office floor, A and X are asymmetrically located with respect to P, whereas A and B are symmetrical. The relationships between rooms can be represented as graphs in which nodes represent spaces (rooms) and edges represent the connections between them. The graph alongside is redrawn "justified" with respect to P, namely, with all spaces shown at their respective depth from the corridor P.

b. Opening up another corridor Q adds rings to the graph and effectively changes the sociological potential of the spatial structure.

Concepts

- Graph
  - Spaces are represented by dots *Nodes*
  - Relationships of premeability by lines *Links*
- Syntactic step – direct connection between spaces
- Depth between two spaces – least number of syntactic steps needed to reach one from the other
- Justified graph – restructured so that a specific space is placed at the bottom *The root space*

What is a space?

- **Convex space** is a space where no line between any two of its points crosses the perimeter. A concave space has to be divided into the least possible number of convex spaces.
- **Axial space** or an axial line is a straight line ("sight line"), possible to follow on foot.
- **Isovist space** is the total area that can be viewed from a point.

Convex space

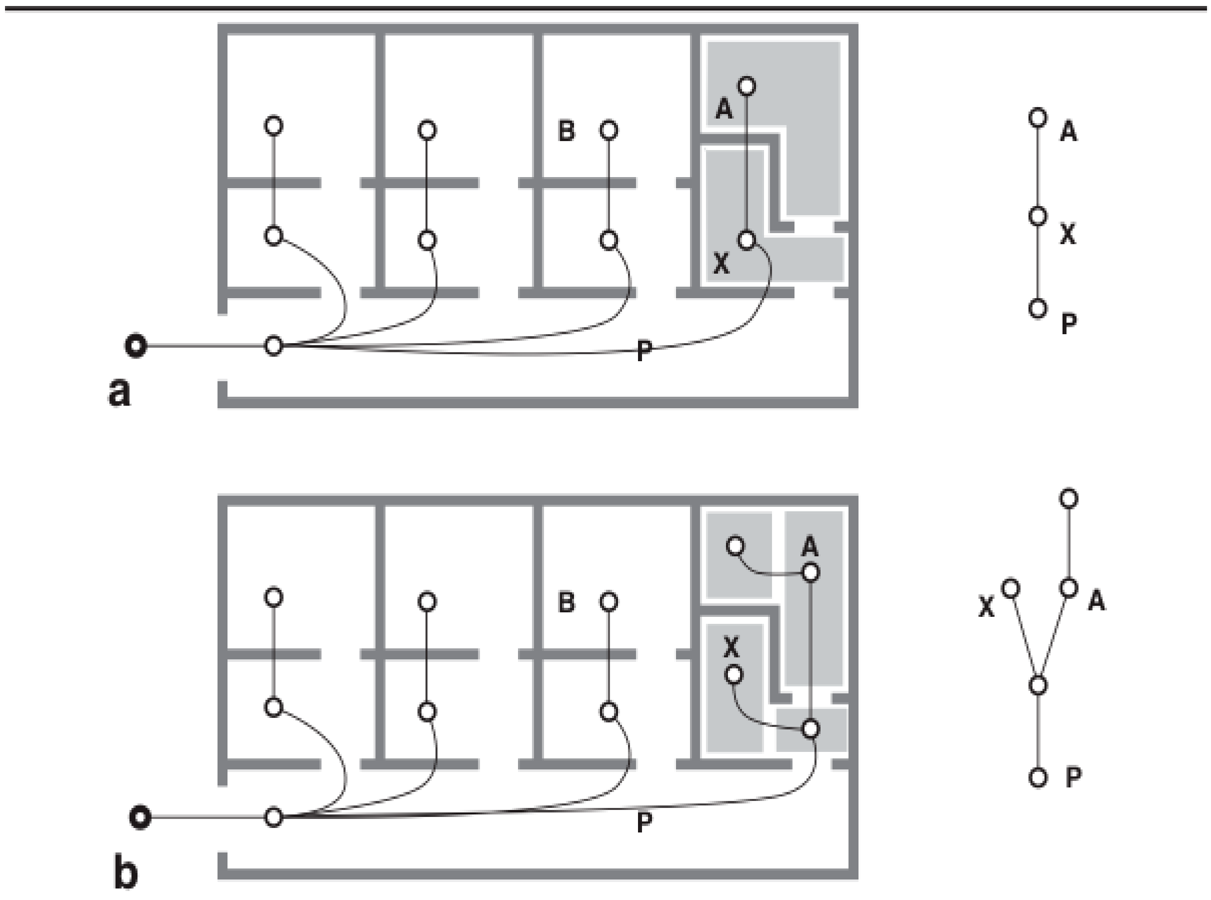
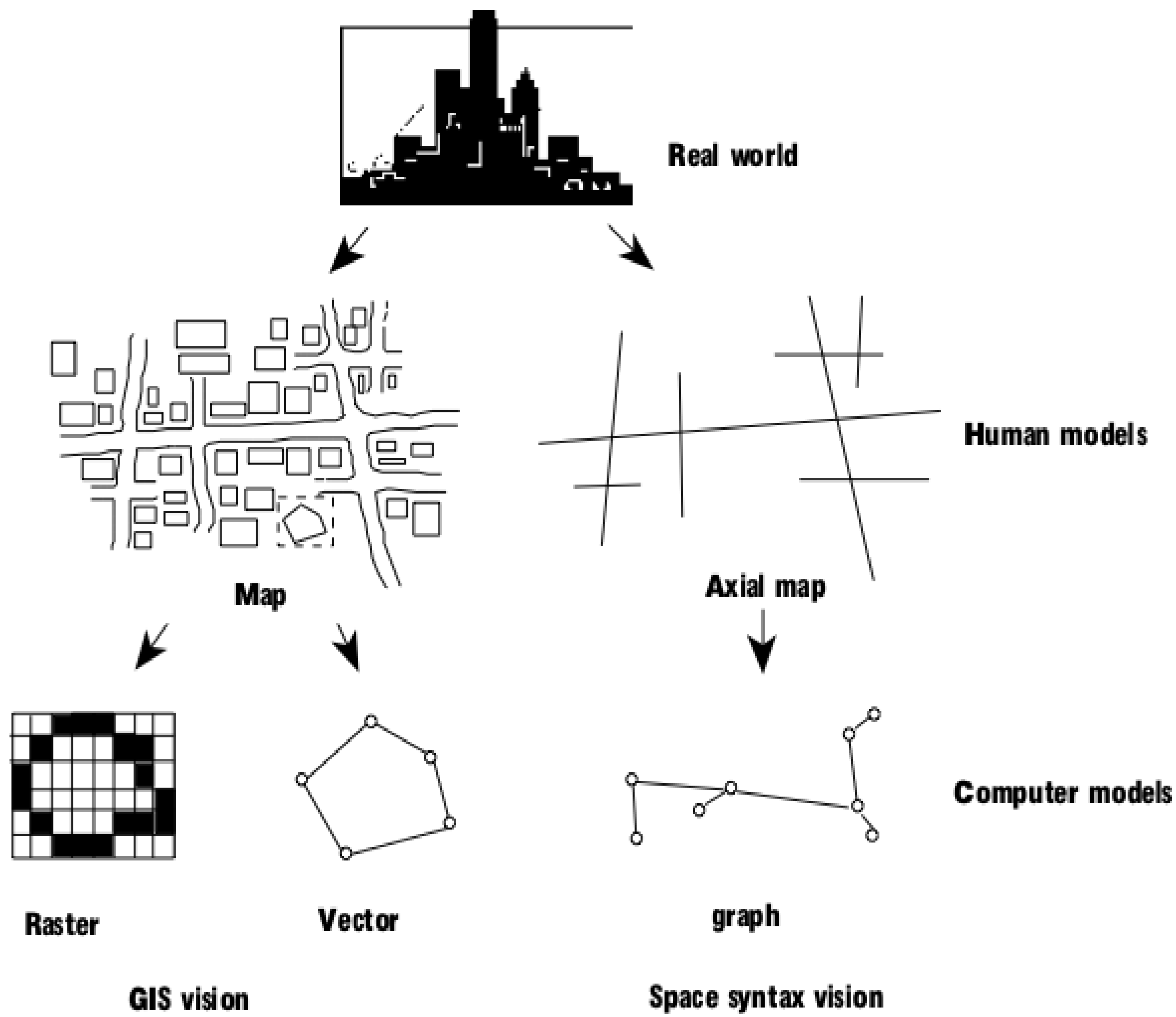


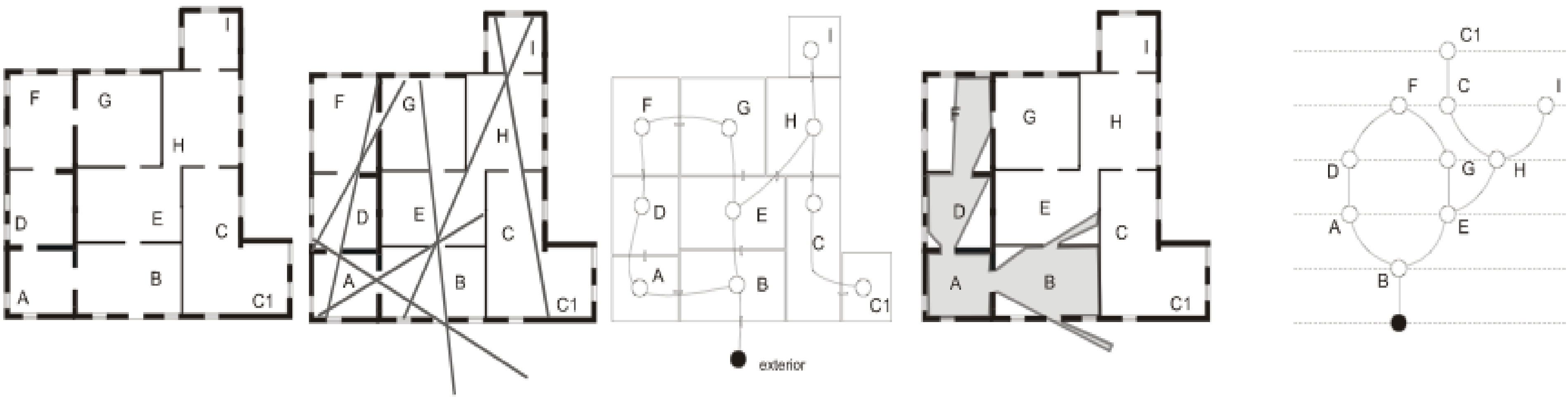
Figure 2: Mapping Nonconvex Spaces Directly as Nodes May Not Capture the Actual Sociological Potential of the Spatial Structure of a Setting

Axial Space



Real world
Human models
Map
Axial map
Computer models
Raster
Vector
graph
GIS vision
Space syntax vision

Isovist Space



original plan

axial representation of the plan

convex fragmentation of the plan with permeability graph

visual field (isovist) from space A

justified permeability graph

Syntactic Measures

Syntactic Measures that can be calculated from Space Syntax Graphs

- Connectivity
- Integration
- Control value
- Global choice

Connectivity

- Measures the number of immediate neighbors that are directly connected to a space.

Integration

- Measures the average depth of a space to all other spaces in the system.

Control Value

- The degree to which a space controls access to its immediate neighbors
- Takes into account the number of alternative connections that each of these neighbors has

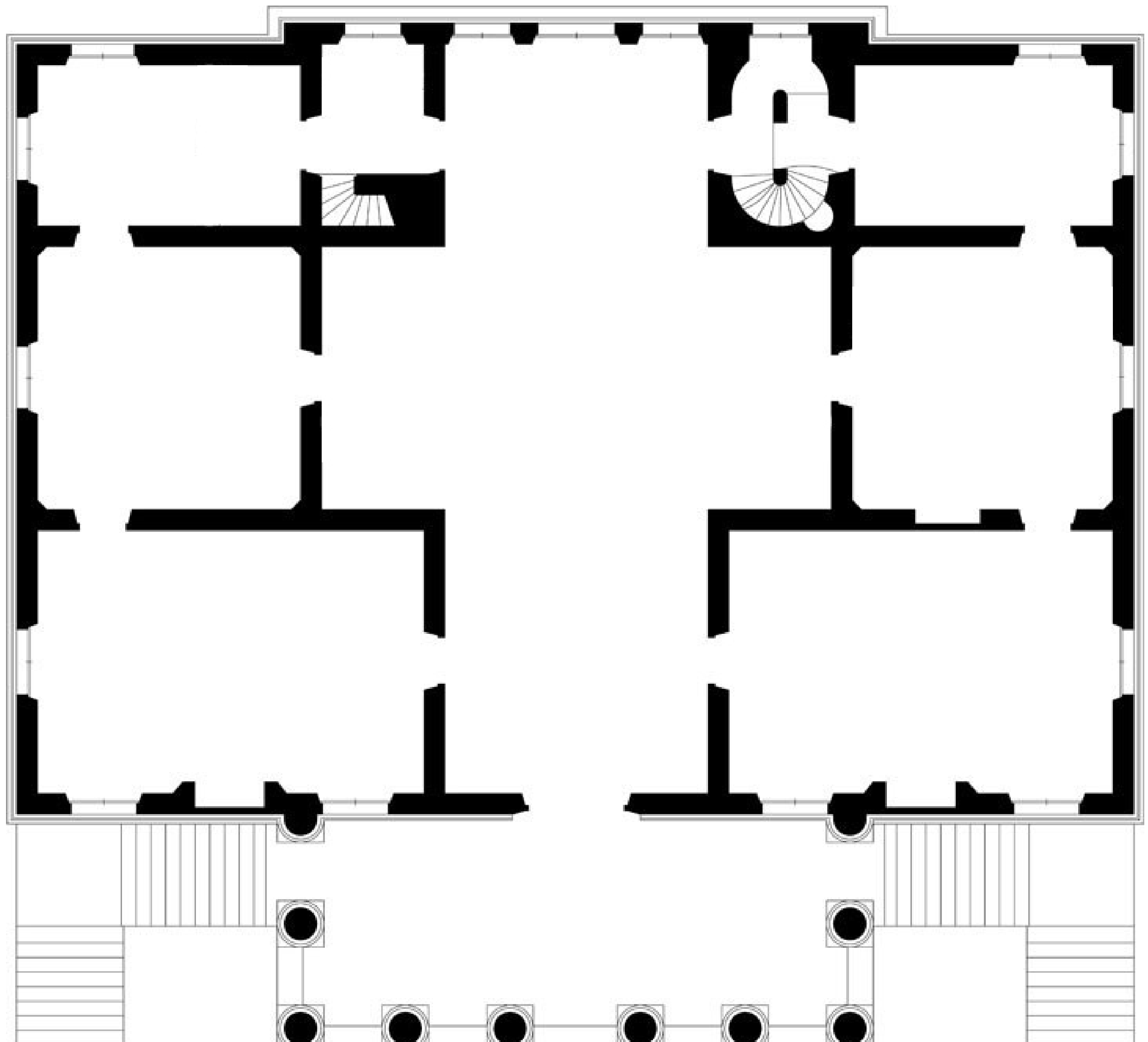
Global Choice

- Measure of flow through a space
- A space has a strong choice value when many of the shortest paths, connecting all spaces to all spaces of a system, pass through it

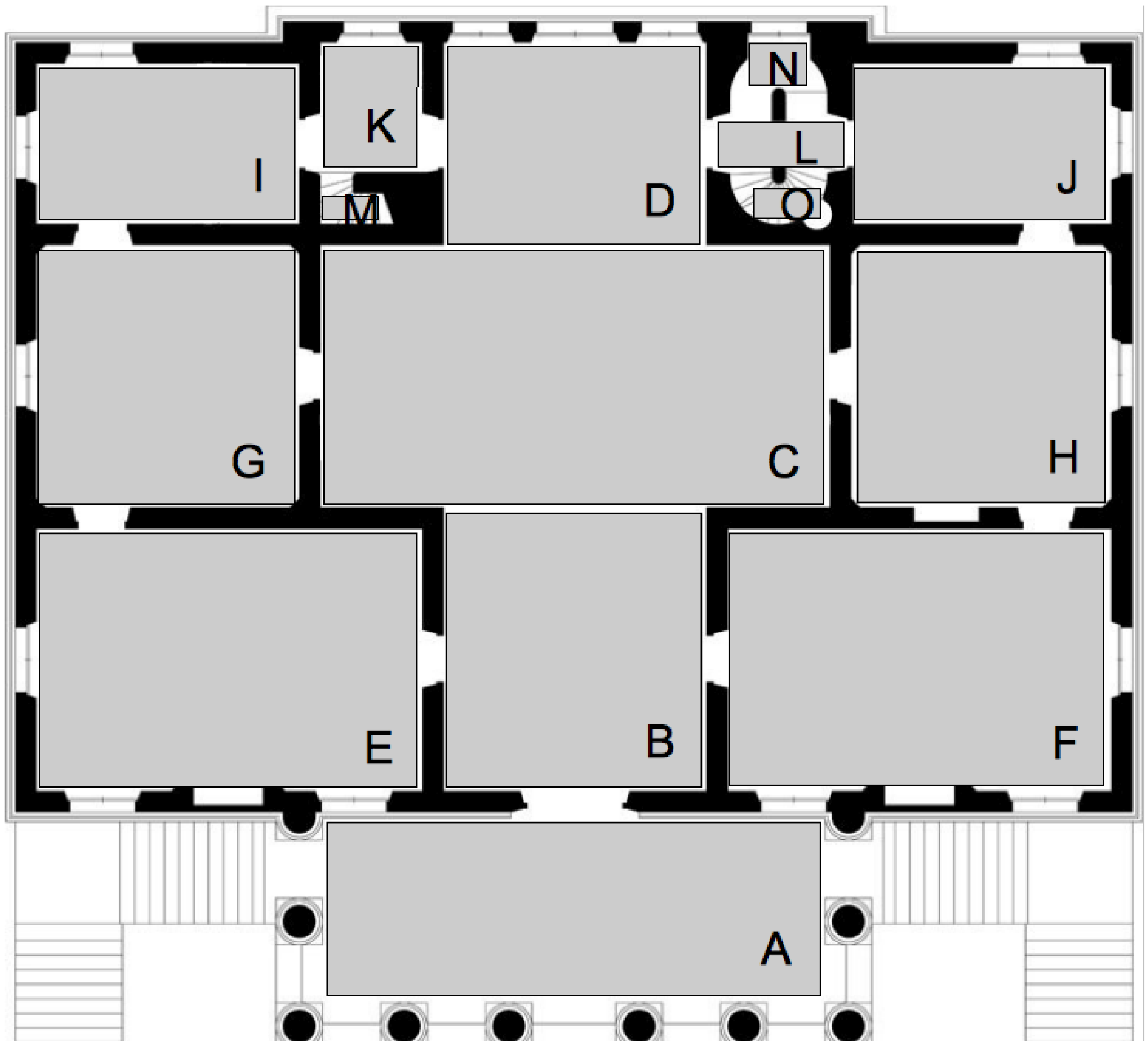
Using the measures

- The spaces of a layout can be ranked according to each of these measures .
- Mapping the rank order back onto the syntactic map gives a picture of syntactic structure.
- Core set is the most integrating or controlling spaces of a system. Integration core is the 10% most integrated spaces.
- Encounter rate is a measure of use density, i.e. pedestrian flow. Correlates to integration measure.

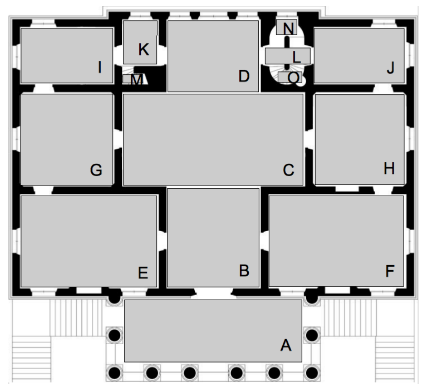
Plan of Villa Malcontenta



Convex map



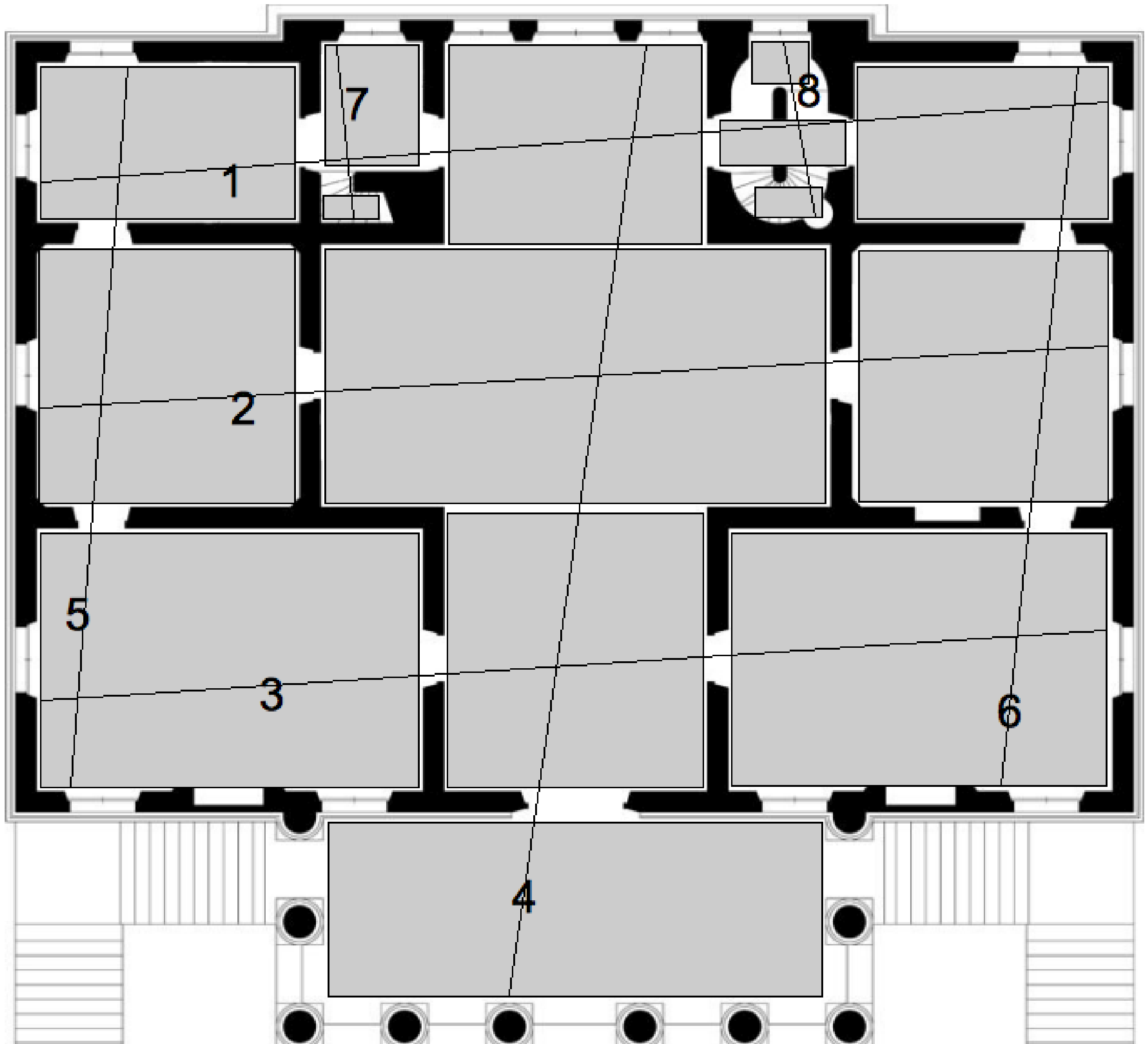
Convex map



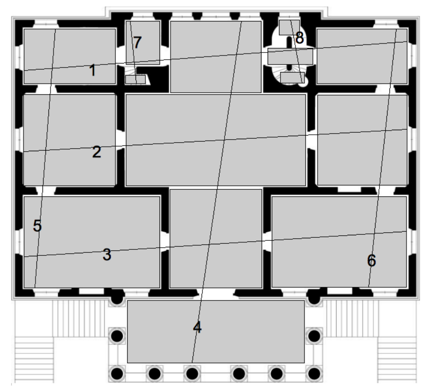
- convex space
- convex map
- start with fattest convex space
- continue until entire area is subdivided
- for analysis of building plans (Hillier and Hanson, 1984)

Hillier, B., Hanson, J. (1984). T*he social logic of space*. Cambridge, UK: Cambridge University Press.

Axial map



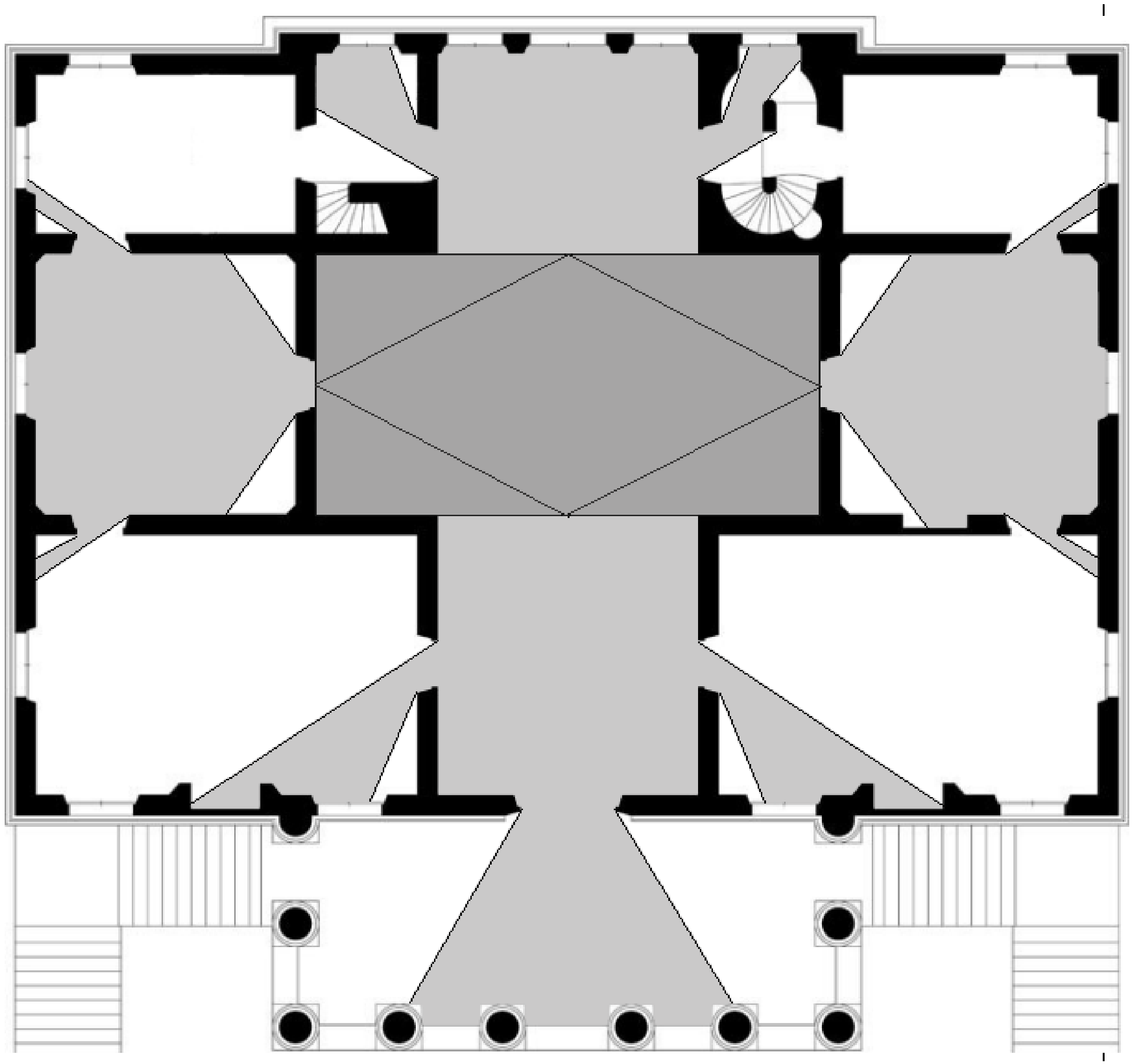
Axial map



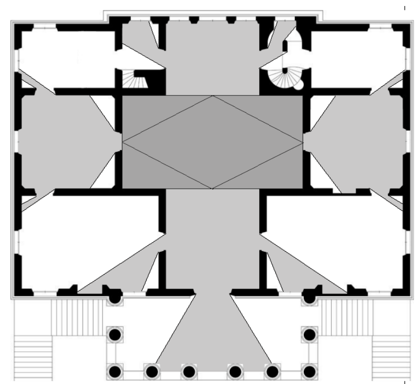
- axial space
- axial map
- longest line that passes through at least one threshold
- all points in space should be visible from line
- describe and analyze urban street network (Bafna, 2003)

Bafna, S. (2003). Space Syntax A Brief Introduction to Its Logic and Analytical Techniques, *Environment and Behavior, 35*, 17–29.

Isovist map

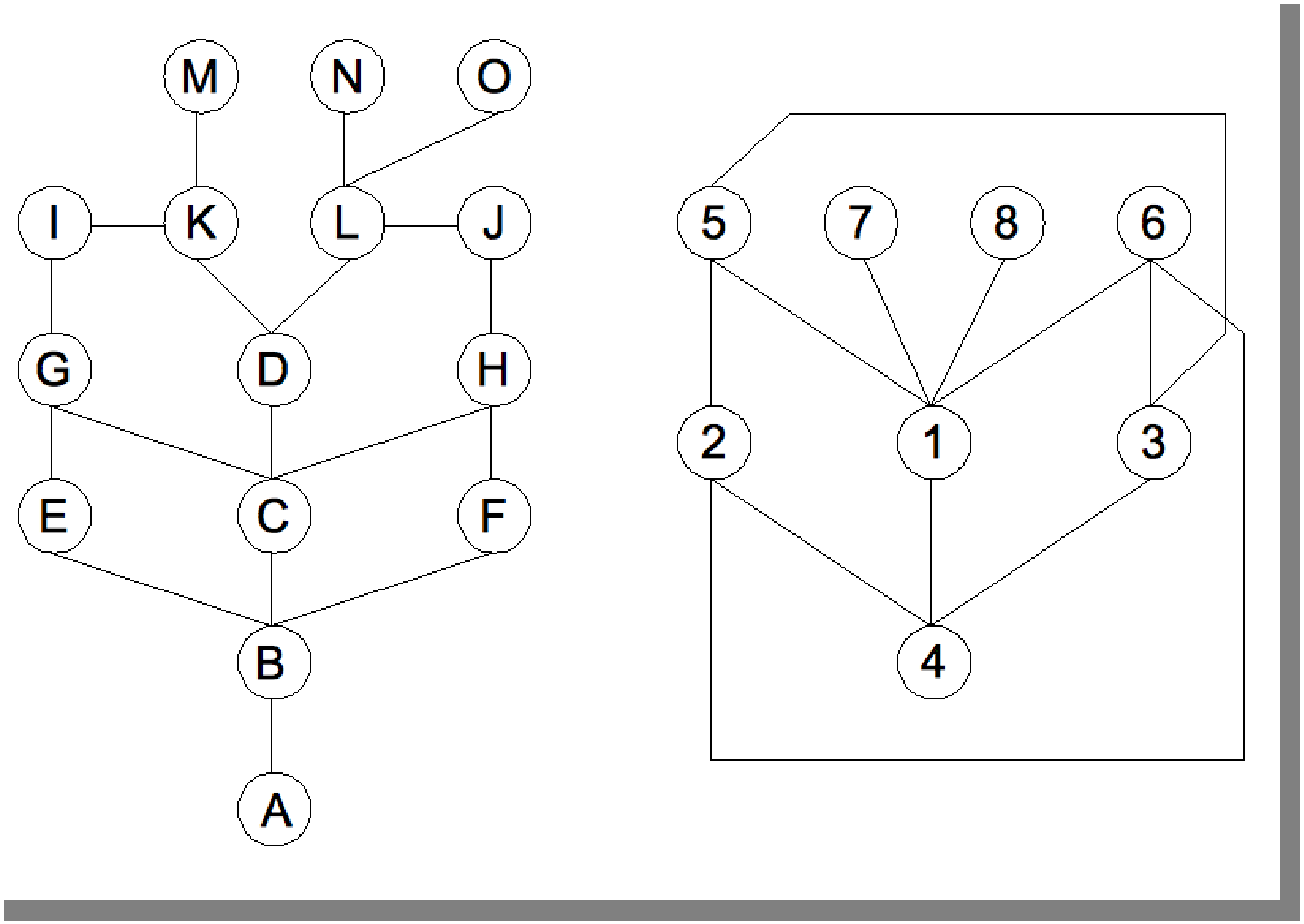


Isovist map

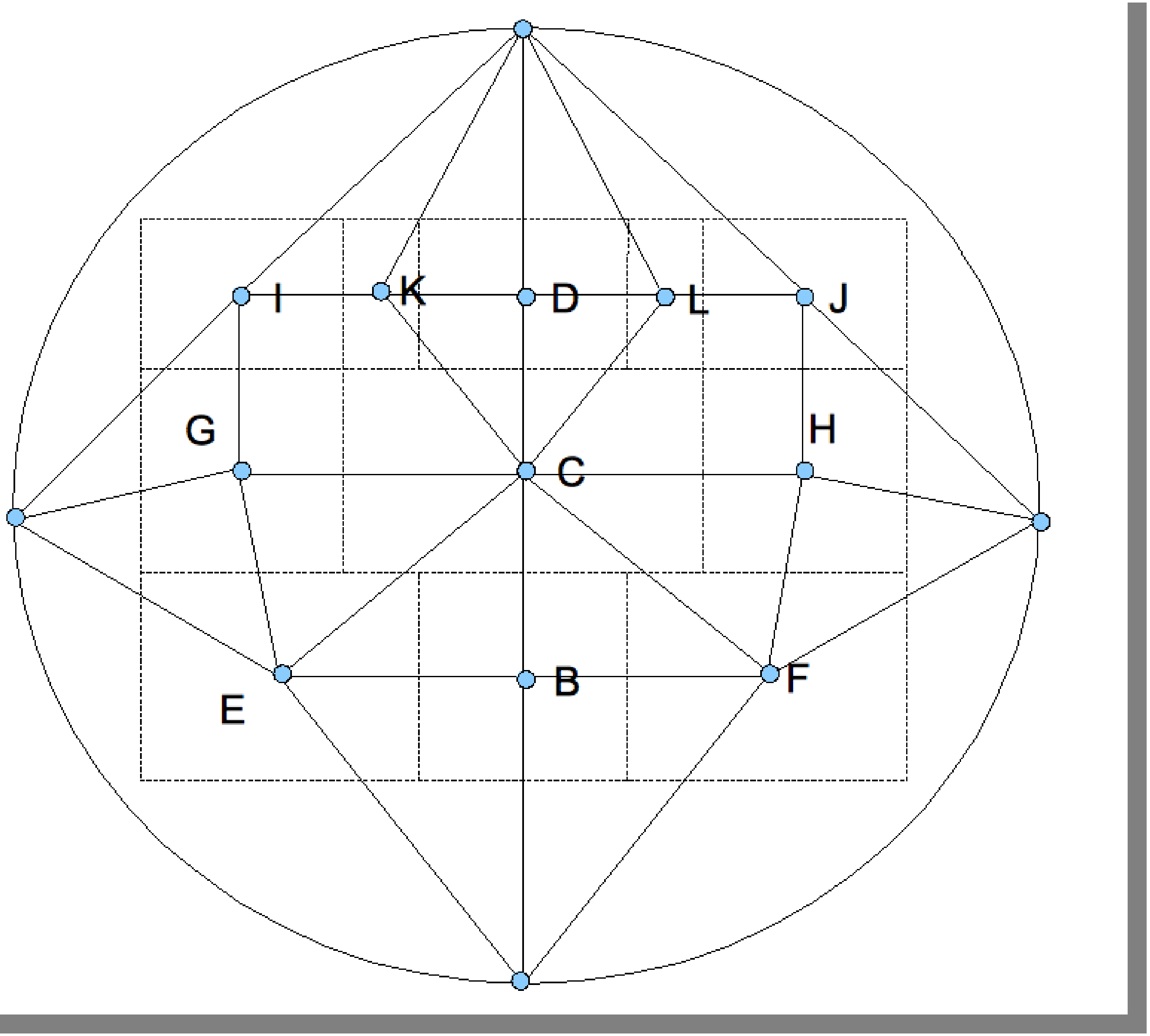


- isovist space
- isovist map
- visual or quantitative analyses of visibility differences

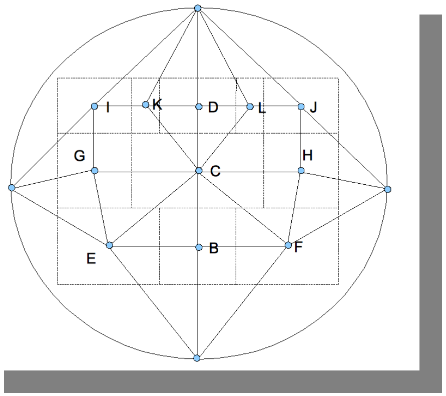
Convex & axial map graphs



Adjacency graph

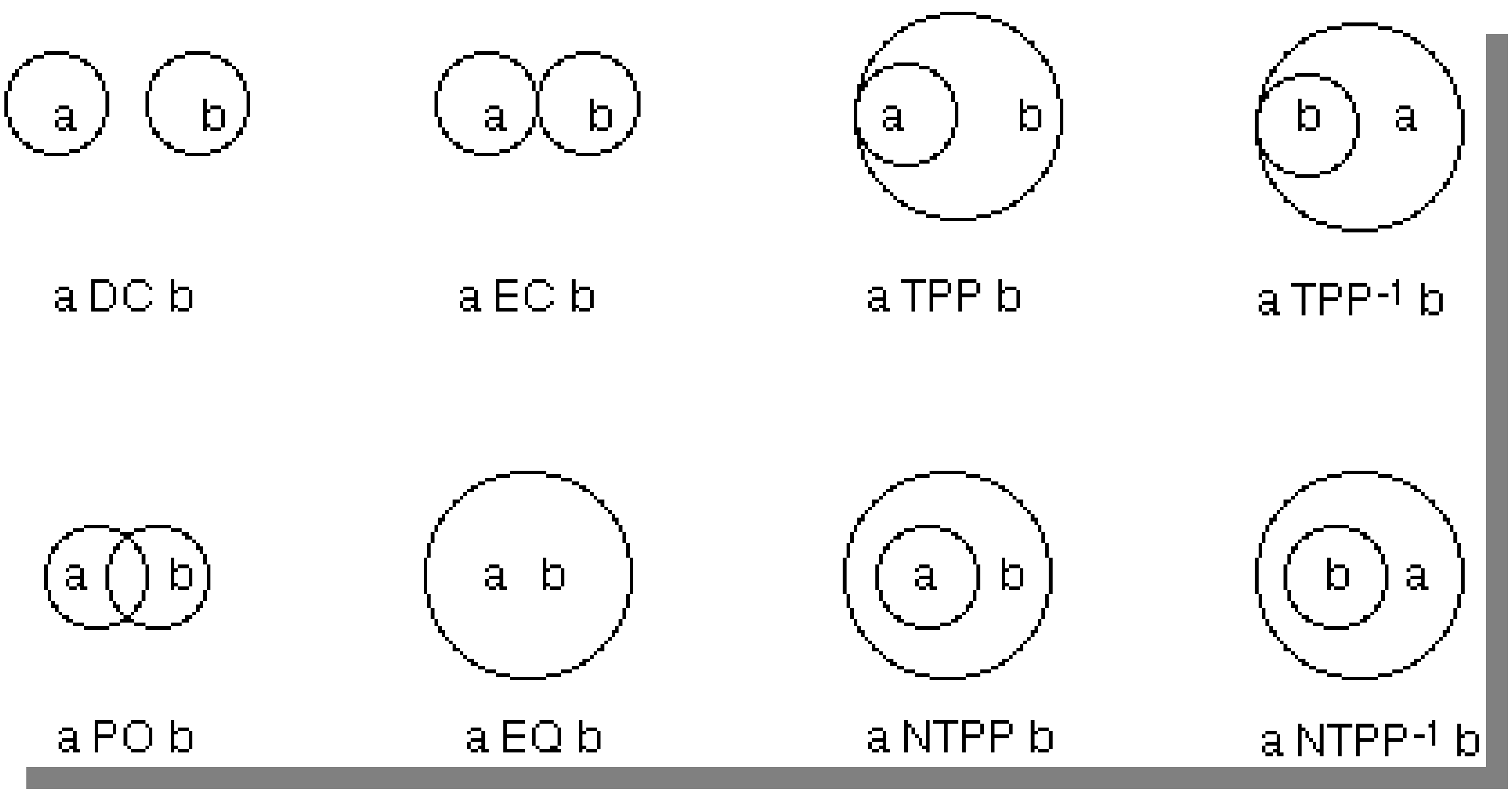


Adjacency graph

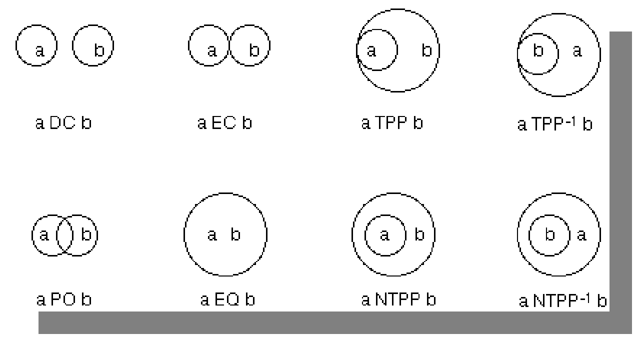


- node – space
- edge – common boundary
- adjacency graph – dual of the block plan

Region connection calculus – RCC8



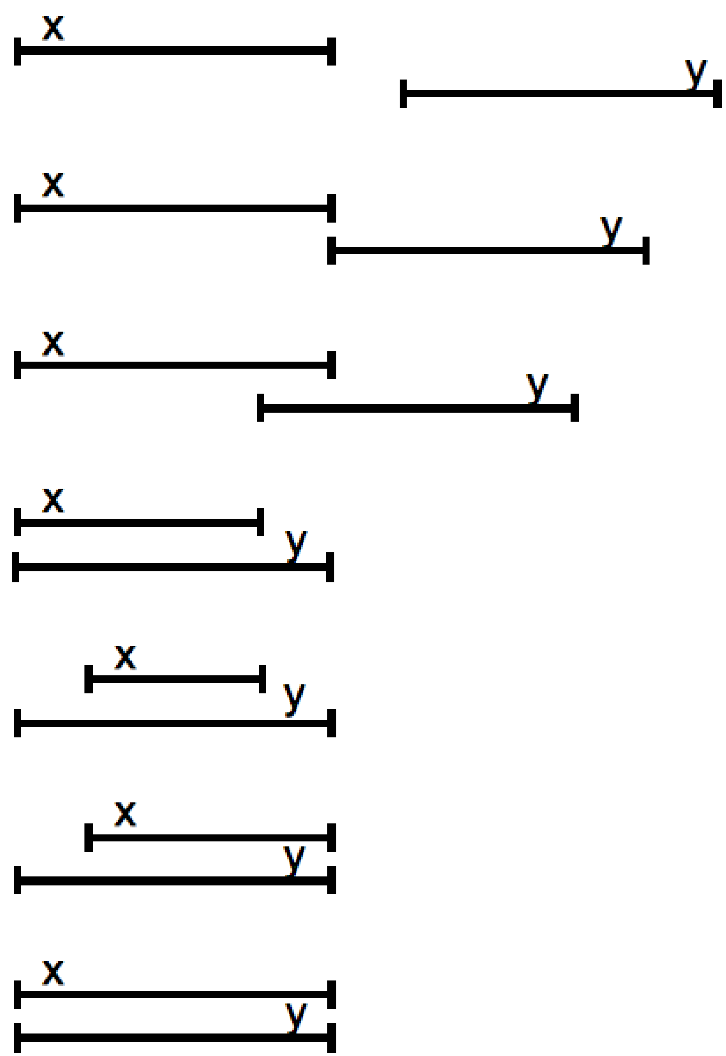
Region connection calculus – RCC8



- region – dimensionless, topological entity
- 8 exhaustive and mutually exclusive relations
- composition finds possible relations between regions A and C by composing the relations between A and B and B and C

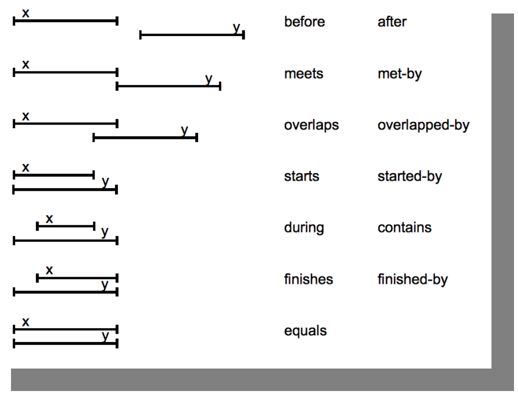
(A EC B)ґ (B NTPP C)→(A {PO TTP NTPP} C).

Allen's algebra for intervals



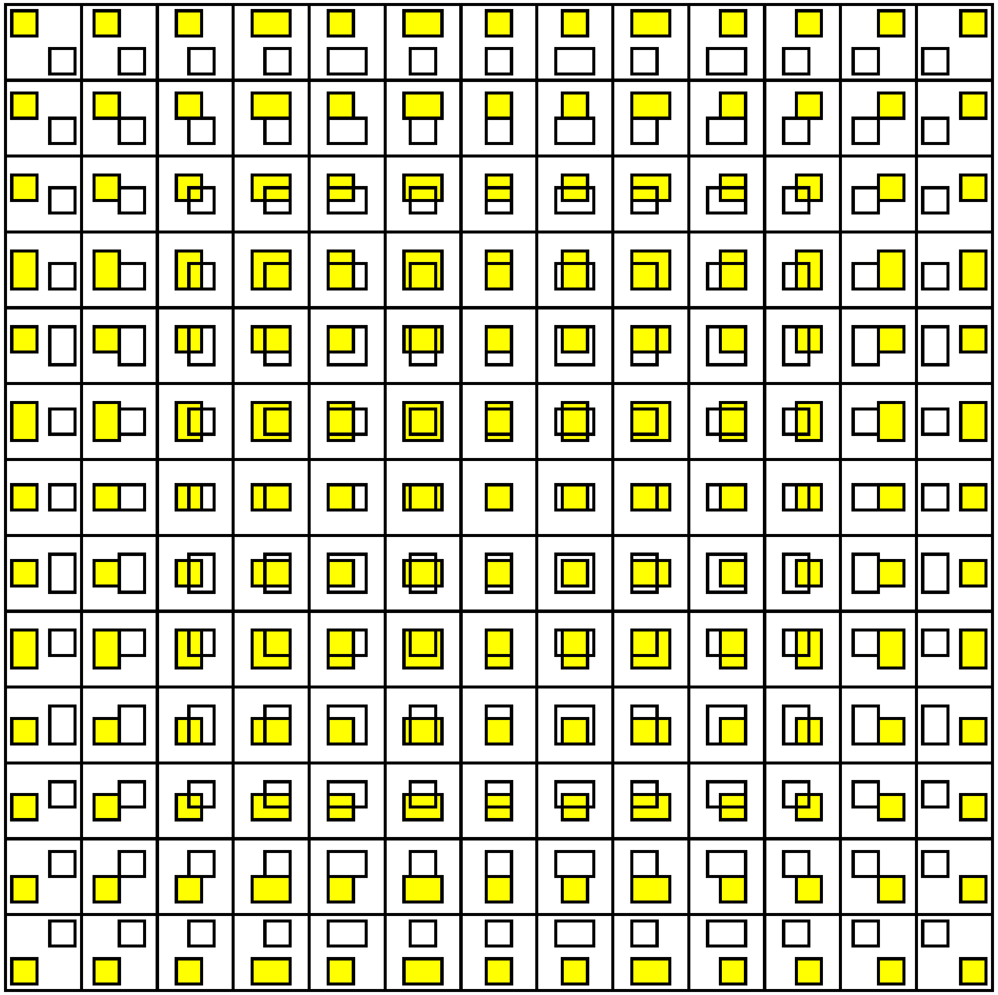
before	after
meets	met-by
overlaps	overlapped-by
starts	started-by
during	contains
finishes	finished-by
equals	

Allen's algebra for intervals

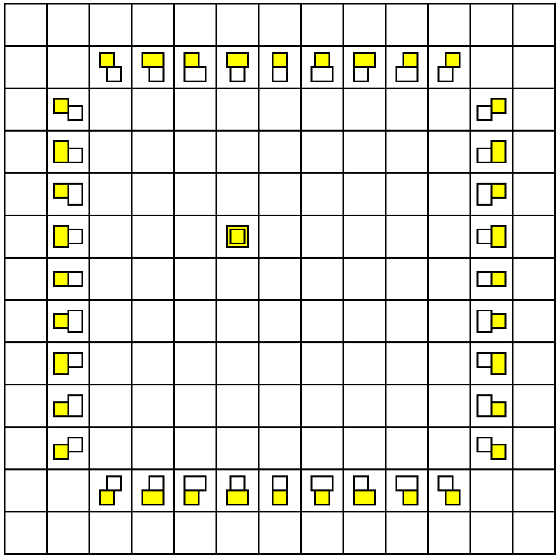


- interval – one-dimensional entity, i.e. time
- 13 exhaustive and mutually exclusive relations
- direction, such as before or after, is important; 6 relations have inverses
- reasoning by composition and constraint propagation

Rectangle algebra

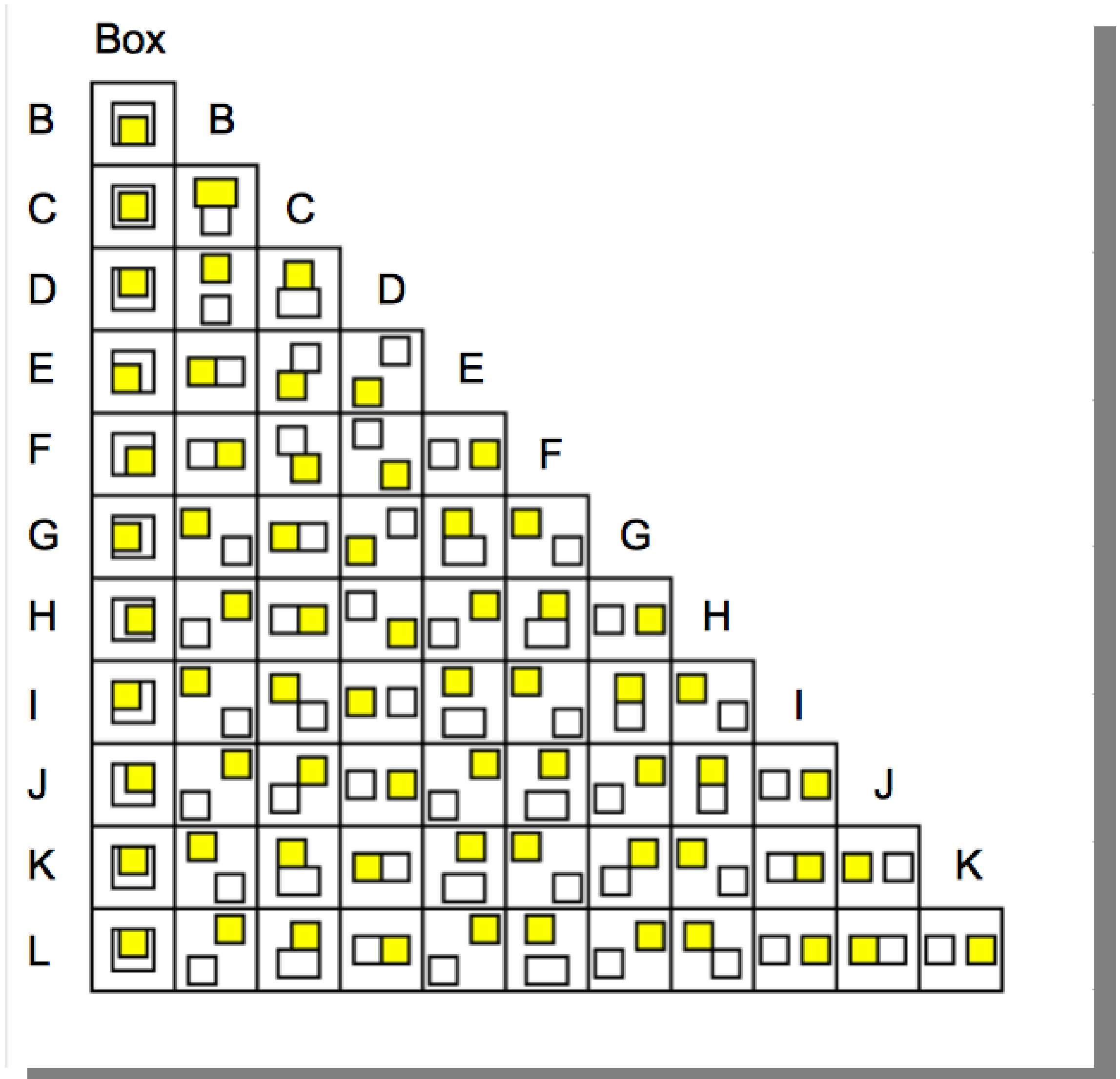


Rectangle algebra

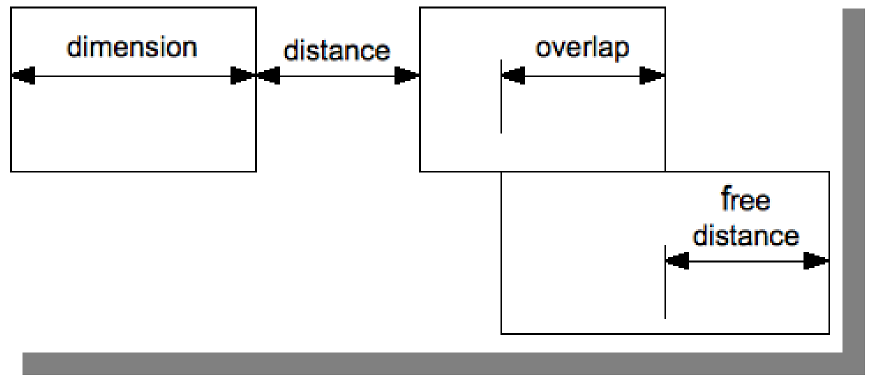


- rectangles parallel to Cartesian axes
- 13 x 13 = 169 relations
- EC and NTTP^{-1} relations

RA relations of Villa Malcontenta

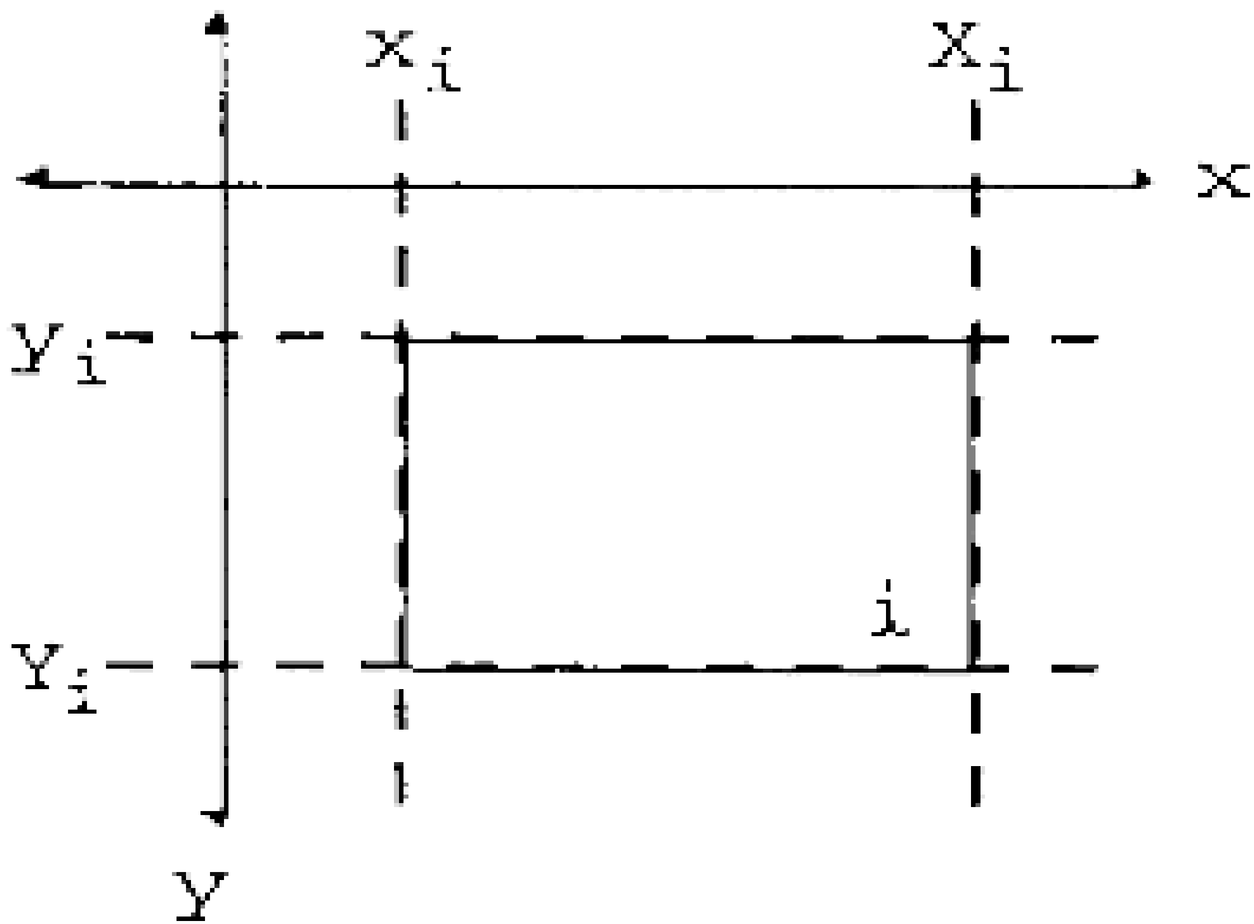


Bounded-difference equations

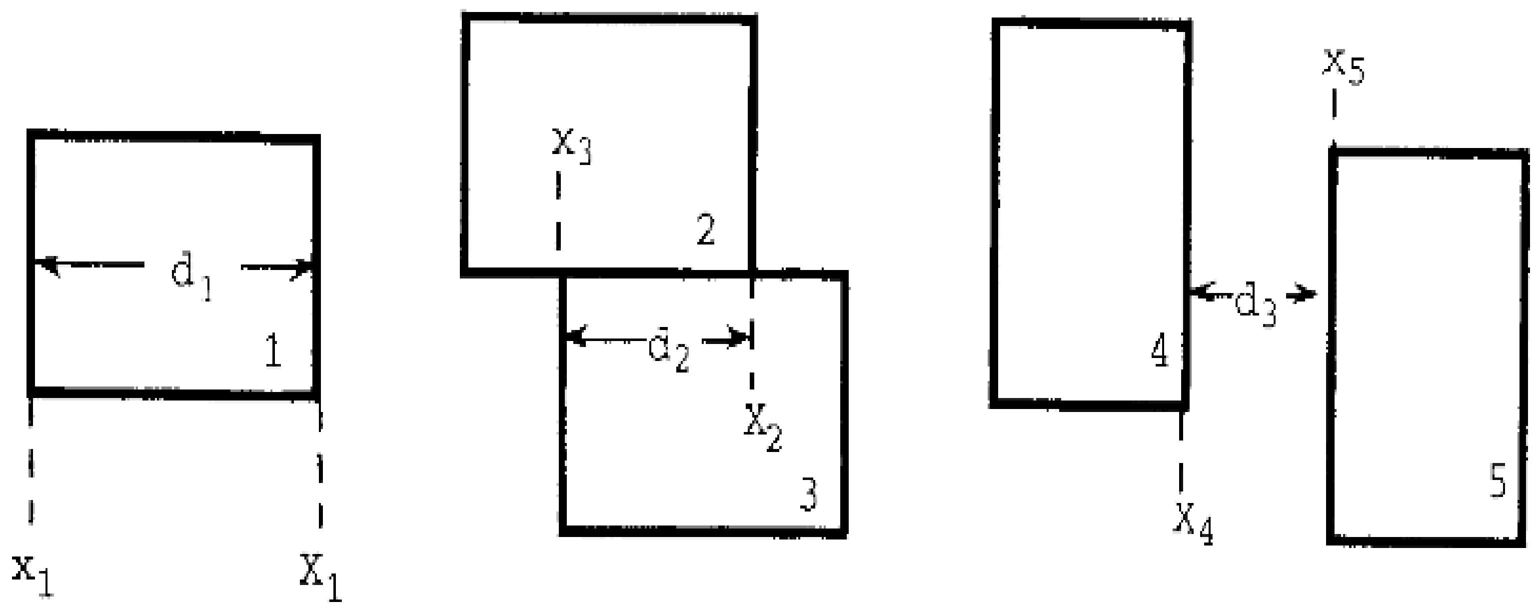


- difference between two lines
- shown by an equation of the form $x_i - x_j \leq d$
- can show qualitative and dimensional relations

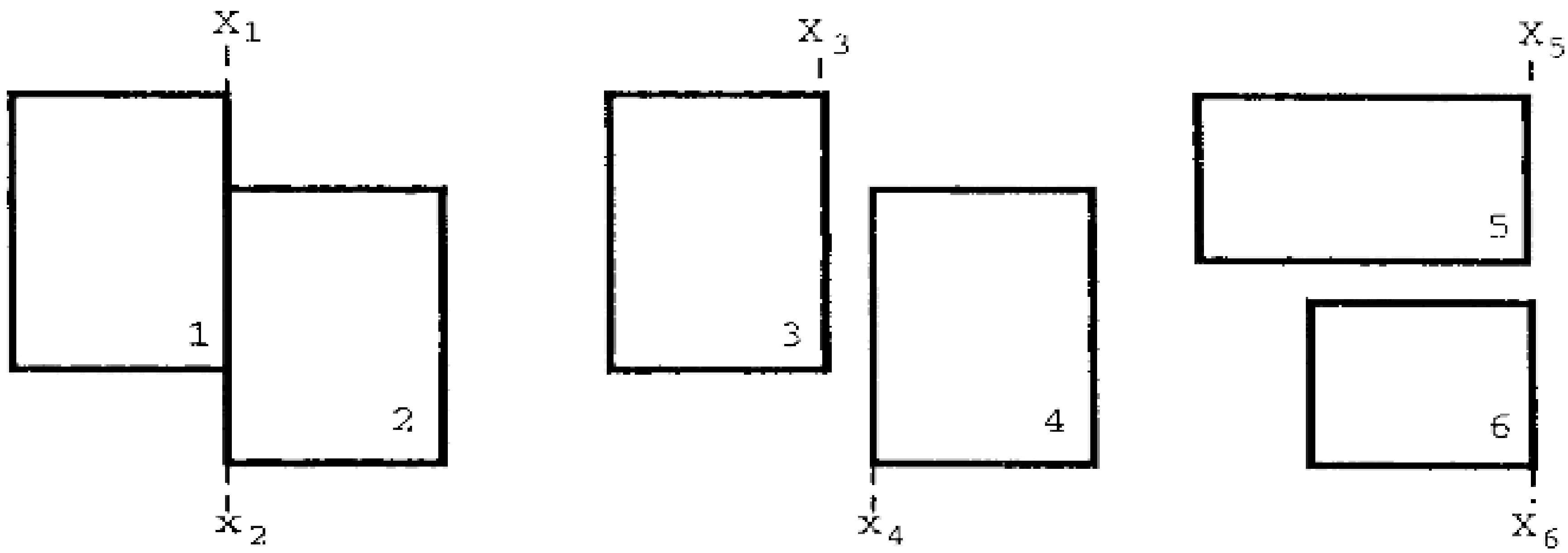
Bounded-difference equations



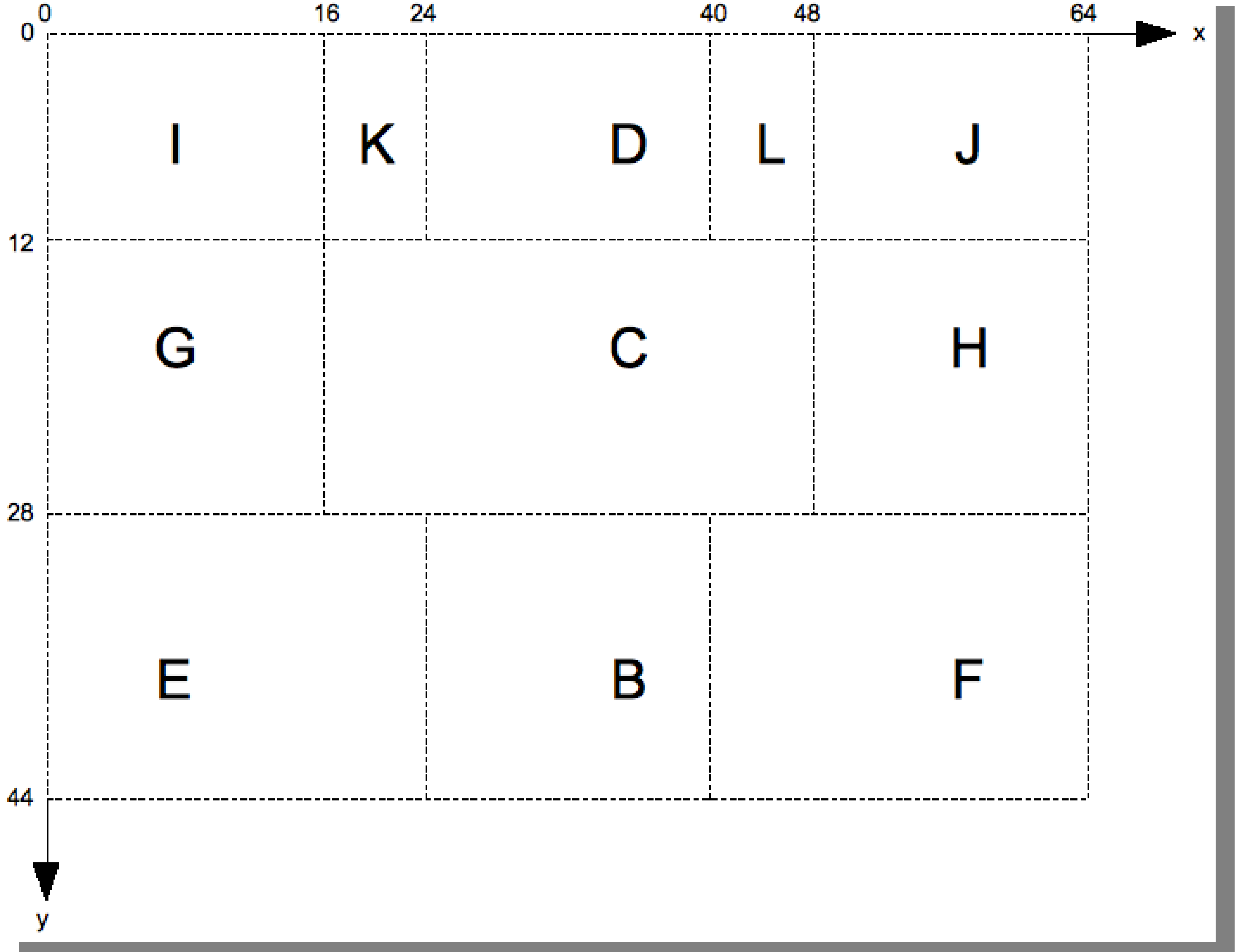
Bounded-difference equations



Bounded-difference equations



Block plan with dimensions



Bounded-difference equations

- interval $x_i - x_j \leq [d_{min}, d_{max}]$
- canonical form: $x_i - x_j \leq d_{max}$, $x_j - x_i \leq -d_{min}$
- shown on a matrix: *row – column ≤ -d*

X-coordinates of Villa Malcontenta

	A1	A2	B1	B2	C1	C2	D1	D2	E1	E2	F1	F2	G1	G2	H1	H2	I1	I2	J1	J2	K1	K2	L1	L2
A1	0	64	24	40	16	48	24	40	0	24	40	64	0	16	48	64	0	16	48	64	16	24	40	48
A2	-64	0	-40	-24	-48	-16	-40	-24	-64	-40	-24	0	-64	-48	-16	0	-64	-48	-16	0	-48	-40	-24	-16
B1	-24	40	0	16	-8	24	0	16	-24	0	16	40	-24	-8	24	40	-24	-8	24	40	-8	0	16	24
B2	-40	24	-16	0	-24	8	-16	0	-40	-16	0	24	-40	-24	8	24	-40	-24	8	24	-24	-16	0	8
C1	-16	48	8	24	0	32	8	24	-16	8	24	48	-16	0	32	48	-16	0	32	48	0	8	24	32
C2	-48	16	-24	-8	-32	0	-24	-8	-48	-24	-8	16	-48	-32	0	16	-48	-32	0	16	-32	-24	-8	0
D1	-24	40	0	16	-8	24	0	16	-24	0	16	40	-24	-8	24	40	-24	-8	24	40	-8	0	16	24
D2	-40	24	-16	0	-24	8	-16	0	-40	-16	0	24	-40	-24	8	24	-40	-24	8	24	-24	-16	0	8
E1	0	64	24	40	16	48	24	40	0	24	40	64	0	16	48	64	0	16	48	64	16	24	40	48
E2	-24	40	0	16	-8	24	0	16	-24	0	16	40	-24	-8	24	40	-24	-8	24	40	-8	0	16	24
F1	-40	24	-16	0	-24	8	-16	0	-40	-16	0	24	-40	-24	8	24	-40	-24	8	24	-24	-16	0	8
F2	-64	0	-40	-24	-48	-16	-40	-24	-64	-40	-24	0	-64	-48	-16	0	-64	-48	-16	0	-48	-40	-24	-16
G1	0	64	24	40	16	48	24	40	0	24	40	64	0	16	48	64	0	16	48	64	16	24	40	48
G2	-16	48	8	24	0	32	8	24	-16	8	24	48	-16	0	32	48	-16	0	32	48	0	8	24	32
H1	-48	16	-24	-8	-32	0	-24	-8	-48	-24	-8	16	-48	-32	0	16	-48	-32	0	16	-32	-24	-8	0
H2	-64	0	-40	-24	-48	-16	-40	-24	-64	-40	-24	0	-64	-48	-16	0	-64	-48	-16	0	-48	-40	-24	-16
I1	0	64	24	40	16	48	24	40	0	24	40	64	0	16	48	64	0	16	48	64	16	24	40	48
I2	-16	48	8	24	0	32	8	24	-16	8	24	48	-16	0	32	48	-16	0	32	48	0	8	24	32
J1	-48	16	-24	-8	-32	0	-24	-8	-48	-24	-8	16	-48	-32	0	16	-48	-32	0	16	-32	-24	-8	0
J2	-64	0	-40	-24	-48	-16	-40	-24	-64	-40	-24	0	-64	-48	-16	0	-64	-48	-16	0	-48	-40	-24	-16
K1	-16	48	8	24	0	32	8	24	-16	8	24	48	-16	0	32	48	-16	0	32	48	0	8	24	32
K2	-24	40	0	16	-8	24	0	16	-24	0	16	40	-24	-8	24	40	-24	-8	24	40	-8	0	16	24
L1	-40	24	-16	0	-24	8	-16	0	-40	-16	0	24	-40	-24	8	24	-40	-24	8	24	-24	-16	0	8
L2	-48	16	-24	-8	-32	0	-24	-8	-48	-24	-8	16	-48	-32	0	16	-48	-32	0	16	-32	-24	-8	0

Linear equations

Can show that

- 2 rectangles have equal length
- 2 rectangles are vertically centered

Non-linear equations

Can show

- aspect-ratios
- areas

Mixed-integer non-linear equations

- Integer variables which take 0 or 1 as values show topological alternatives
- A MINLP program can model both topological and dimensional aspects
- If it can be solved, a MINLP program finds one optimal solution
- It may not be possible to solve

References

Habraken, N. J. (1998). *The structure of the ordinary: form and control in the built environment*. Cambridge, Massachusetts: The MIT Press.

Bafna, S. (2003). Space Syntax A Brief Introduction to Its Logic and Analytical Techniques, *Environment and Behavior, 35*, 17–29.

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Stiny, G., Mitchell, W. J. (1978b). Counting Palladian plans, *Environment and Planning B, 5*, 189–198.

Quadratic Assignment Problem [QAP]

Consider the assignment of N activities to N or more sites, each of which can accommodate one and only one activity.

A(i) denotes the site to which activity *i* is assigned in a mapping A of activities to sites

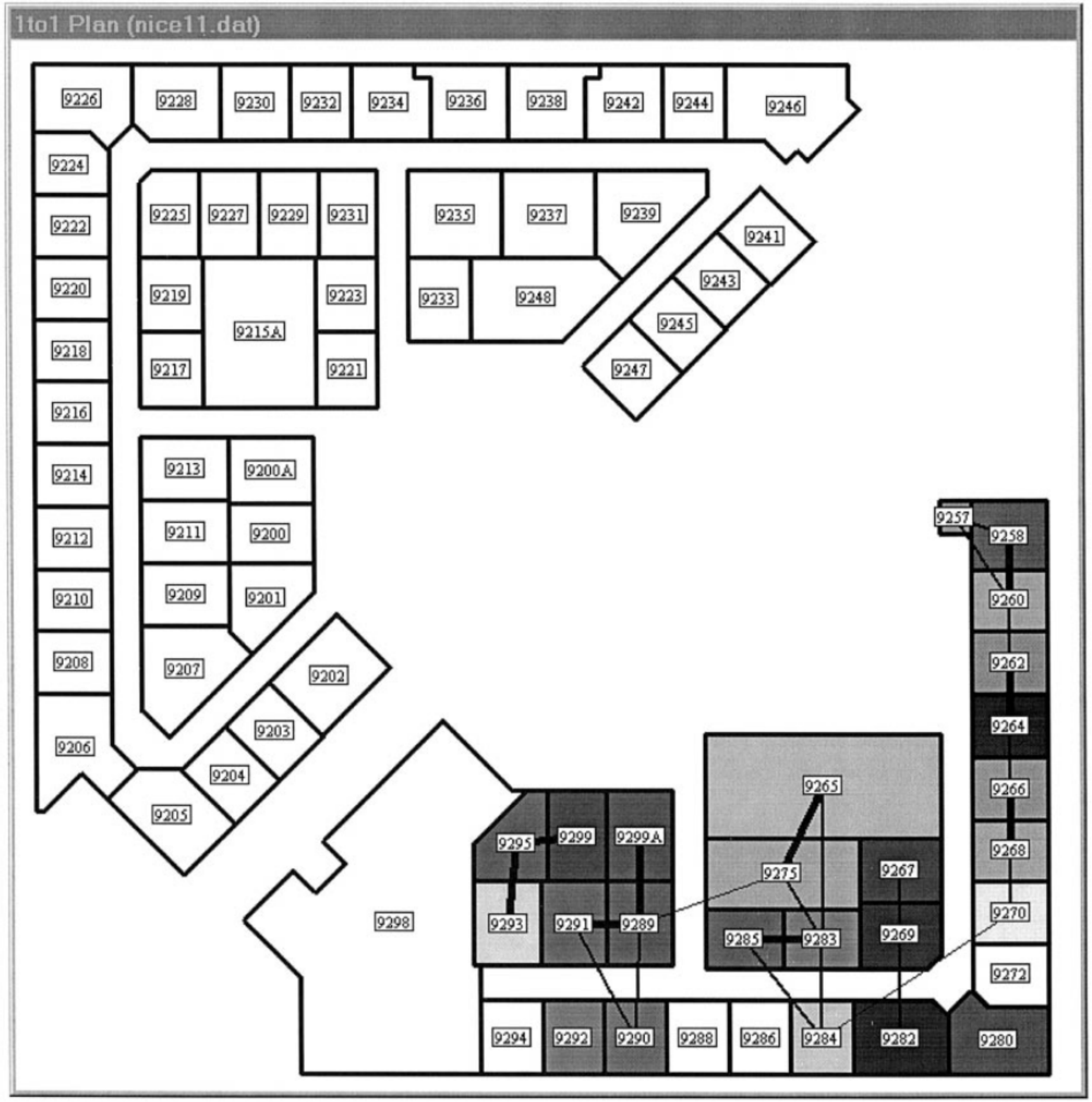


Fig. 3. One-to-one office layout.

Distance measure

Associated with each pair of sites *(k,l)* is a measure of spatial separation *C(k,l)* e.g., distance, travel time, etc...

- Manhattan distance
- Euclidean distance

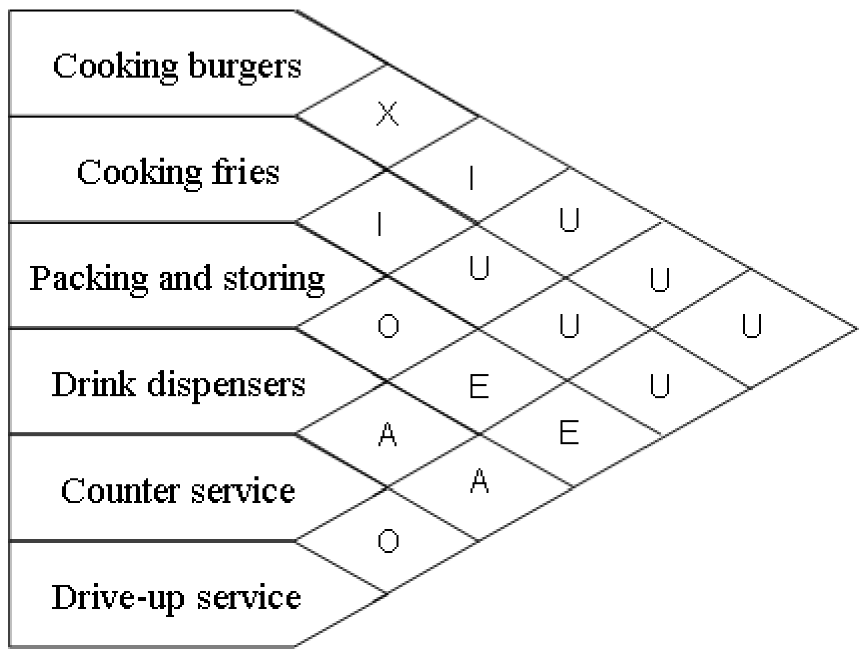
Interaction Measure

Associated with each pair of activities *(i,j)* is a measure of interaction *Q(i,j)* e.g., intensity of communication, level of traffic, etc...

Interaction Measure

- an actual measure of flow of goods
- number of trips by employees
- judgment about closeness requirements
  - A : absolutely necessary
  - E : especially important
  - I : important
  - O : ordinary importance
  - U : unimportant
  - X : undesirable

Interaction Measure Matrix



Space Layout Representations

Baykan, “Representations for the analysis and synthesis of space layouts”, 2010.

- Iconic
  - Plans
  - Grids
- Symbolic
  - Graph based
  - Constraint based
  - Shape grammars

Transportation Cost

- Interactive cost or transportation cost is *interaction measure* x *distance*

Fixed Costs

a fixed cost *F(i,k)* may be associated with the placement of activity *i* in site *k*

costs of assigning a particular activity to a particular location

some measure of preference for a particular site

- rent
- special facilities
- construction requirements

QAP Layout Evaluation Formula

$$\text{Cost}(A) = \sum_{\text{activity } i} F(i, A(i)) + \sum_{\text{activity } i} \sum_{\text{activity } j} [Q(i,j)C(A(i), A(j))].$$

QAP Minimizes Cost

The objective is to find a mapping A, such that this cost function is minimized.

- QAP is an optimization problem
- QAP is a combinatorial problem
- # of possible ways of assigning *N* activities to *N* sites is *N!*

Optimization

- Unconstrained optimization
  - there is an objective function
  - hill-climbing methods work
- Constrained optimization
  - there are constraints
  - there is an objective function
  - hill-climbing methods DO NOT work

QAP Solution Methods

- NP-complete problem
- There is no guaranteed way of finding the optimal solution to this problem other than trying all alternatives
- Not possible to look at all alternatives
- **Therefore use heuristics!**
- Similar to the traveling salesman problem
  - greedy heuristic

QAP Solution Heuristics

- Constructive initial placement strategies
- Improvement strategies

Constructive Procedures for QAP

Start with an empty layout

Make an activity – location selection

- select the activity which has the highest connectivity to any activity already placed
- select the activity which has the highest connectivity to all activities
- select a location w.r.t. activities already located
- select a location w.r.t. all activities

Improvement Procedures for QAP

Start with an initial solution and try to improve it

- hill-climbing
  - pairwise exchange
  - two, three, four, five way exchanges
- simulated annealing
  - accept exchange even if it lowers score p(T)
  - probability of acceptance depends on temperature

Improvement Procedures for QAP

- Genetic algorithms
  - An initial population of solutions
  - A mechanism for generating new solutions by combining features from the existing population : reproduction
  - A mechanism for generating a new solution by operating on a single solution : mutation
  - A mechanism for selecting the set of solutions with better objective function values : selection
  - A mechanism for removing solutions from the population : culling

Hybrid Approaches

Combine constructive and improvement strategies

- Use a constructive procedure to generate an initial solution
- Use an improvement procedure to refine the solution

- Combines global and local approaches

Shortcomings of QAP

- Does not allow for a multi-attribute/multi-objective approach
- Consideration of geometrical patterns, adjacency, alignment, shape, variable dimensions may not be possible
- The shape of a facility may be an irregular combination of grid cells
- Zoning requirements due to daylight, noise, hazardous materials, services or ceiling heights hard to consider

Express Requirements Indirectly

- Adjacency of the parts of a facility can be ensured by setting the interaction measure between them to high levels
- Assignment of a facility to a particular location can be prevented by setting the fixed cost of assignment relatively high
- A facility can be fixed at a location by a negative location cost

Use of QAP in Practice

- Used in block plan creation stage
- Determine flow of materials between facilities
- Run the system a few times
  - with different data
  - with different initial configurations
- Modify layout manually
- Have QAP program evaluate modified layout

Shape Grammars

- Grammars in natural language
  - English
  - Turkish
- Formal grammars, *ie*, programming languages
  - Fortran
  - Pascal
- Shape grammars
  - Stiny & Gips

Shape grammars are formal grammars

Formal Grammars

- Start symbol
  - sentence
- Terminal symbols
  - a, the, cat, dog, chased, bit
- Rules
  - sentence ::= noun phrase + verb phrase
  - noun phrase ::= article + noun
  - verb phrase ::= verb | verb + noun phrase
  - article ::= a | the
  - noun ::= cat | dog
  - verb ::= chased | bit

Palladian Style

- a corpus of existing villas designed by Palladio
- plans of unbuilt or since destroyed villas given by Palladio
- rules about villa design given in: Palladio, *The Four Books on Architecture*, The MIT Press, 1997.

Palladian Villa Design Rules

Palladio, *The Four Books on Architecture*, 1997.

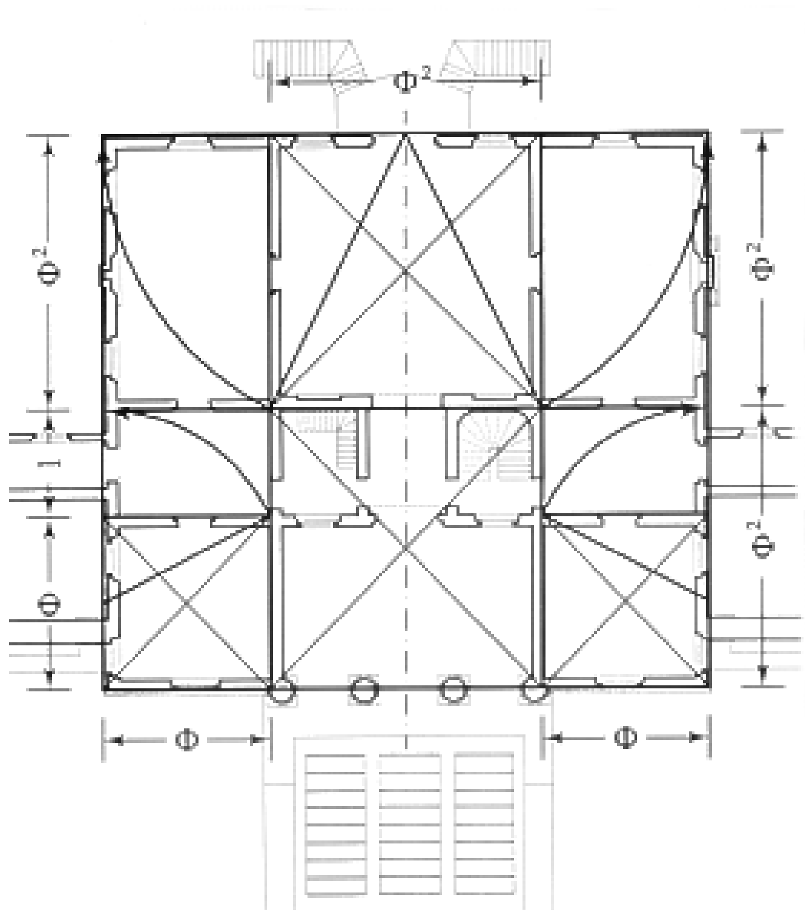
Rooms must be distributed at either side of the entrance and the hall, and one must ensure that those on the right are equal to those on the left.

There should be large, medium-sized and small rooms, one side by side with the next, so that they can be mutually useful.

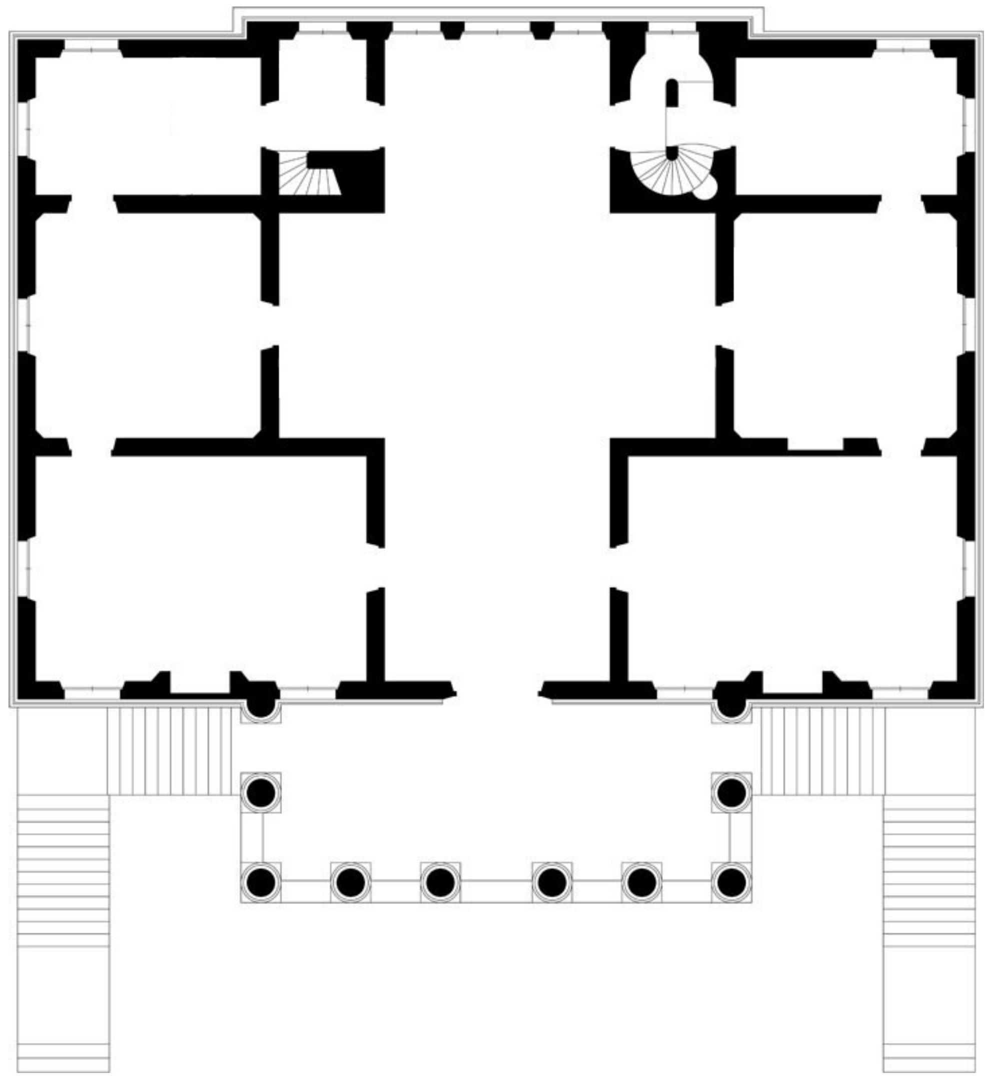
There are seven types of room that are the most beautiful and well proportioned: circular, 1:1, 4:3, √2:1, 3:2, 5:3, 2:1

Summer rooms should be spacious and oriented to the north and those for the winter small and oriented to the south.

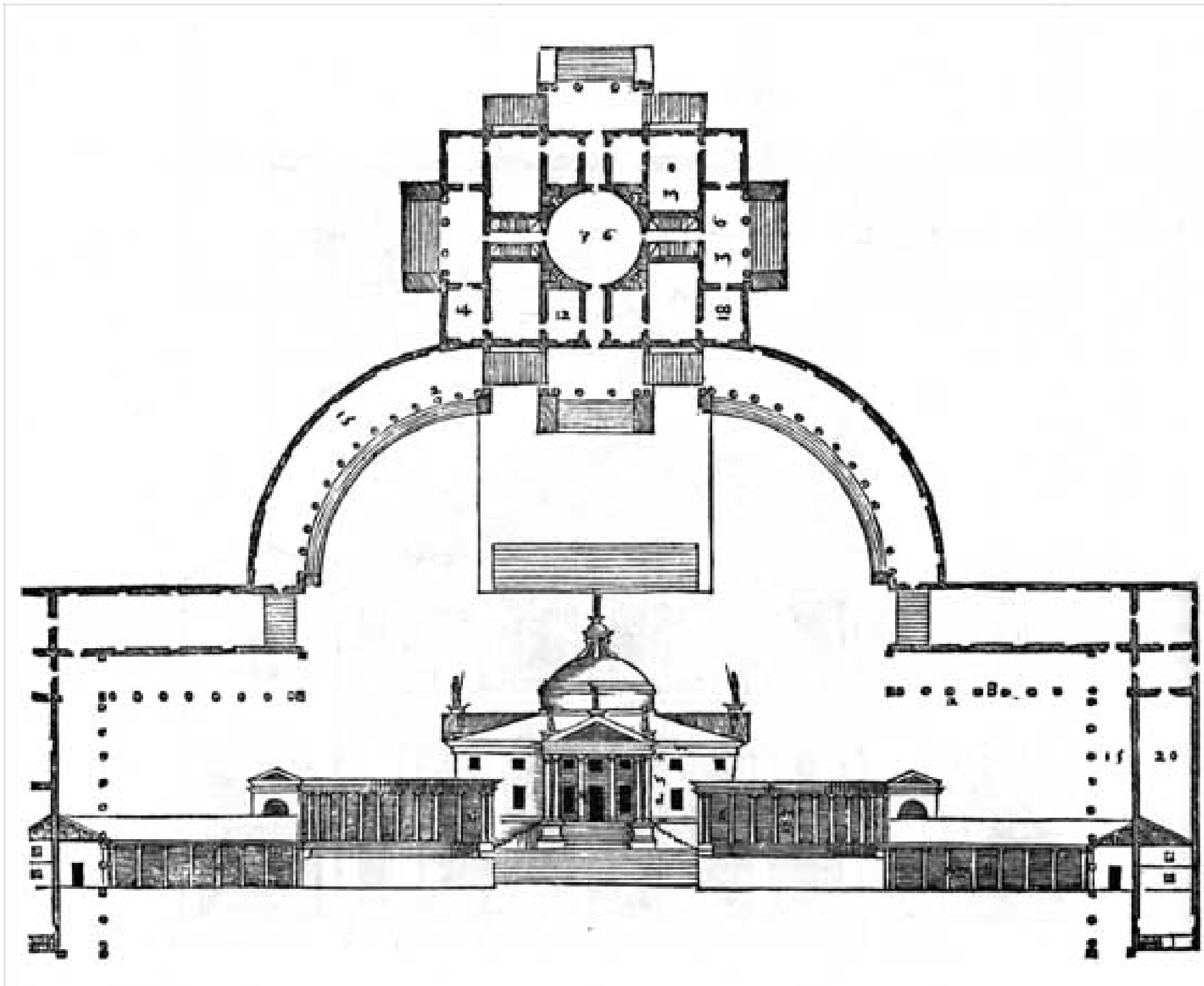
Palladian Villas
Villa Emo



Villa Malcontenta



Villa Trissino



The Palladian Grammar

Stiny, Mitchell. (1978a). The Palladian grammar, *E & P B*, v 5, n 1.

- The plans are generated in 8 stages
  - grid definition
  - exterior wall definition
  - room layout
  - interior-wall realignment
  - principal entrances – porticos, exterior-walls
  - exterior ornamentation – columns
  - windows and doors
  - termination

Grid Definition

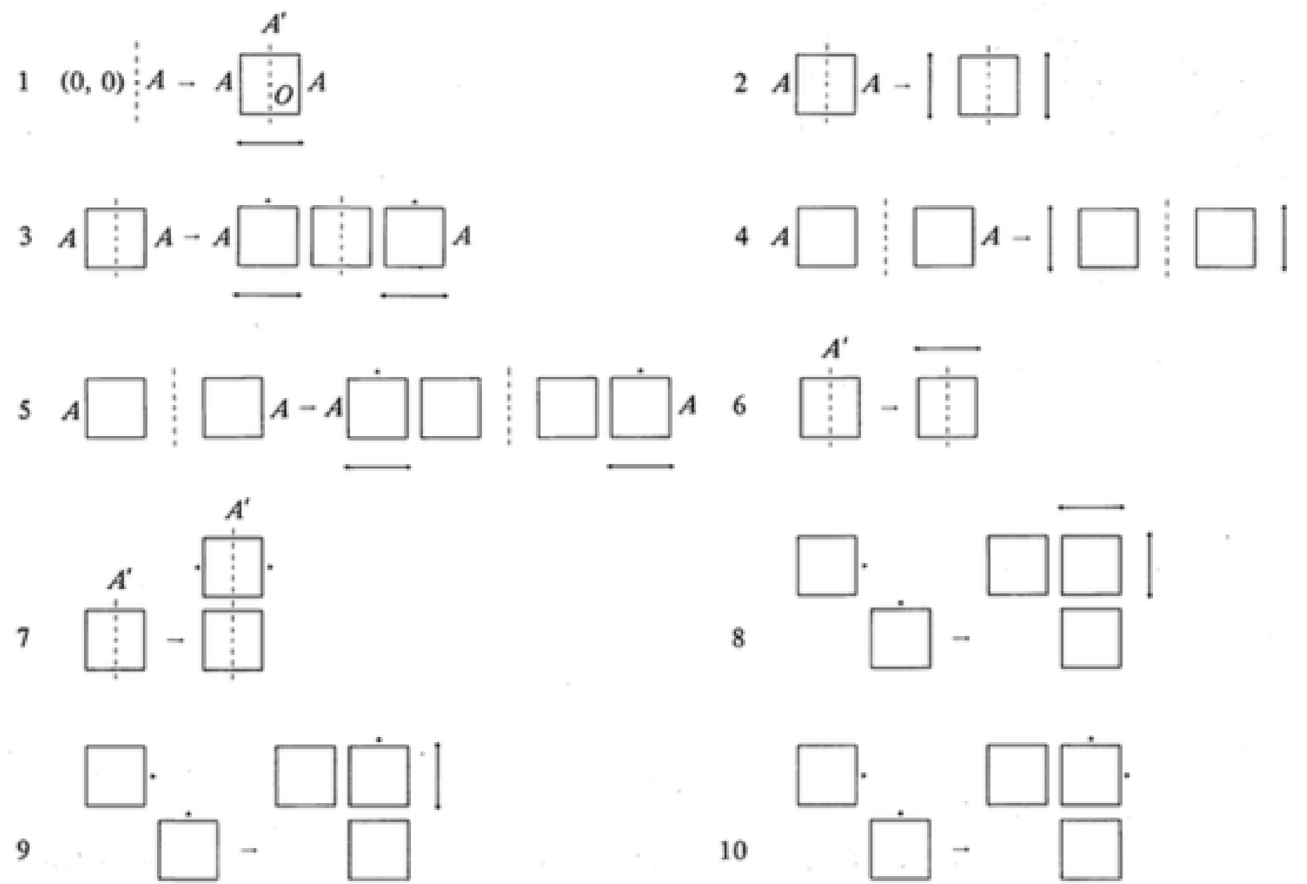


Figure 3. Rules for the generation of 'tartan' grids with bilateral symmetry. Grids generated by these rules are used to fix the underlying structure of villa plans.

Exterior Wall Definition

11

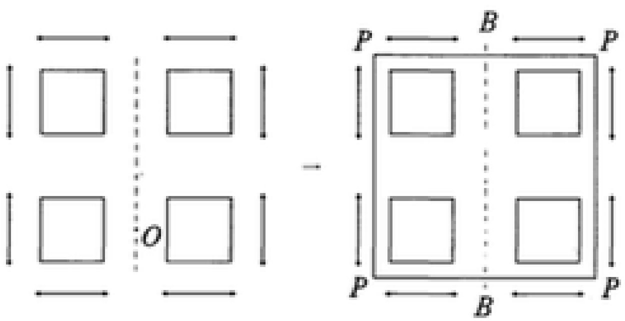


Figure 5. Rule for the generation of exterior walls.

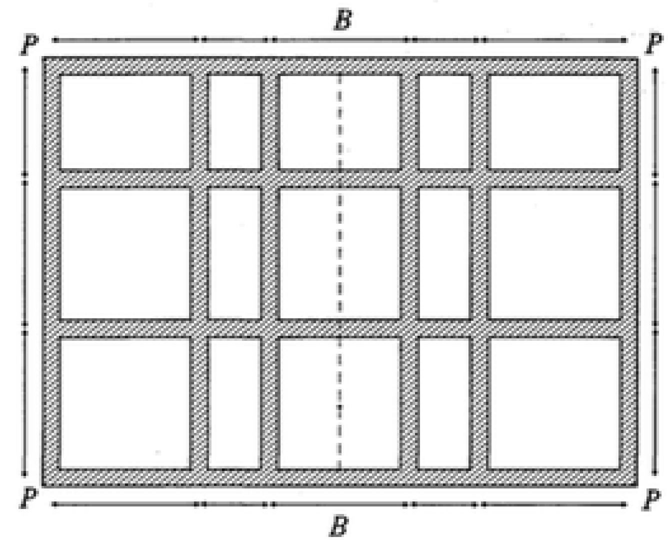


Figure 6. The underlying wall pattern for the Villa Malcontenta.

Room Layout

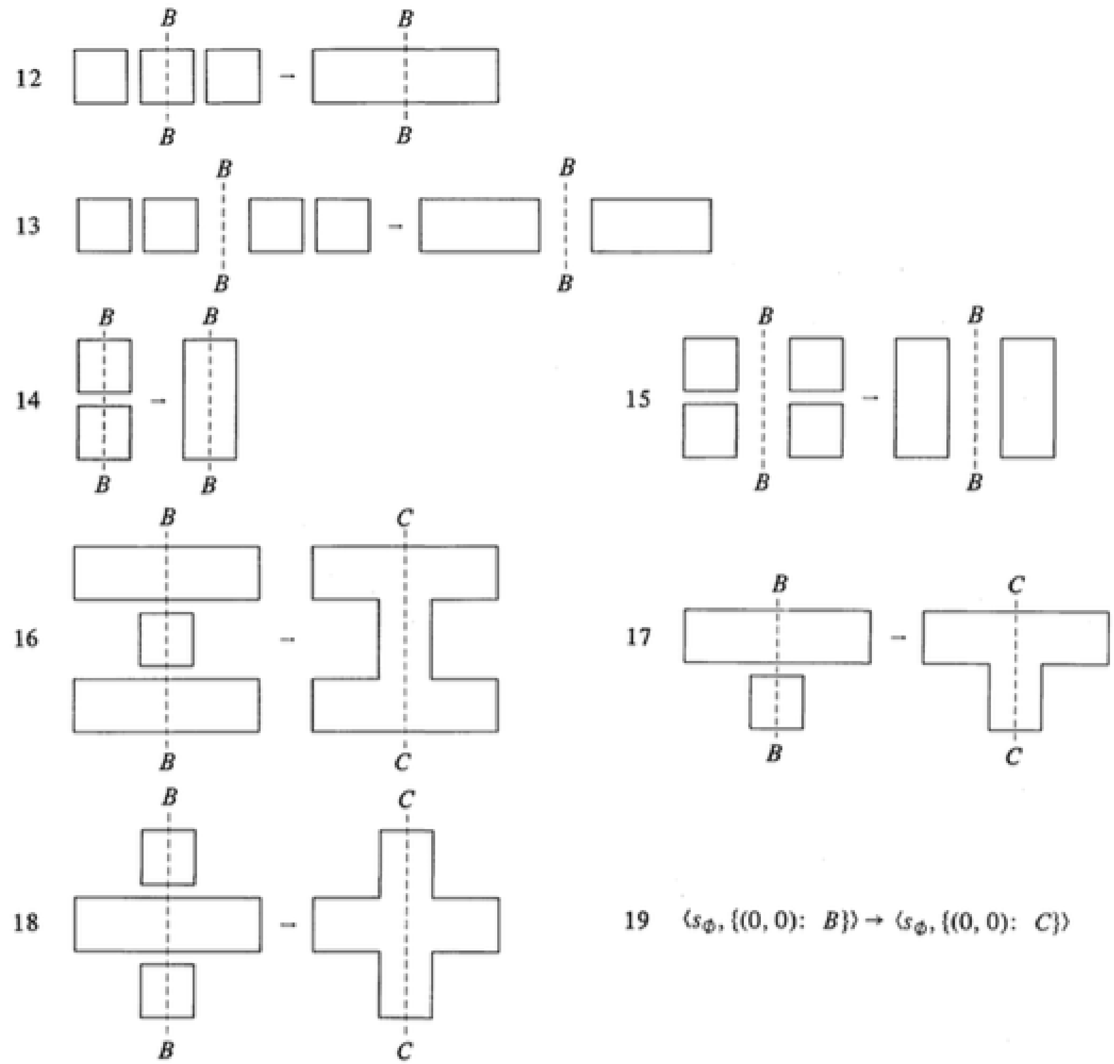


Figure 7. Rules for room layout.

Villa Malcontenta Room Generation

apply rule 13 to underlying wall pattern in figure 6, slide 15

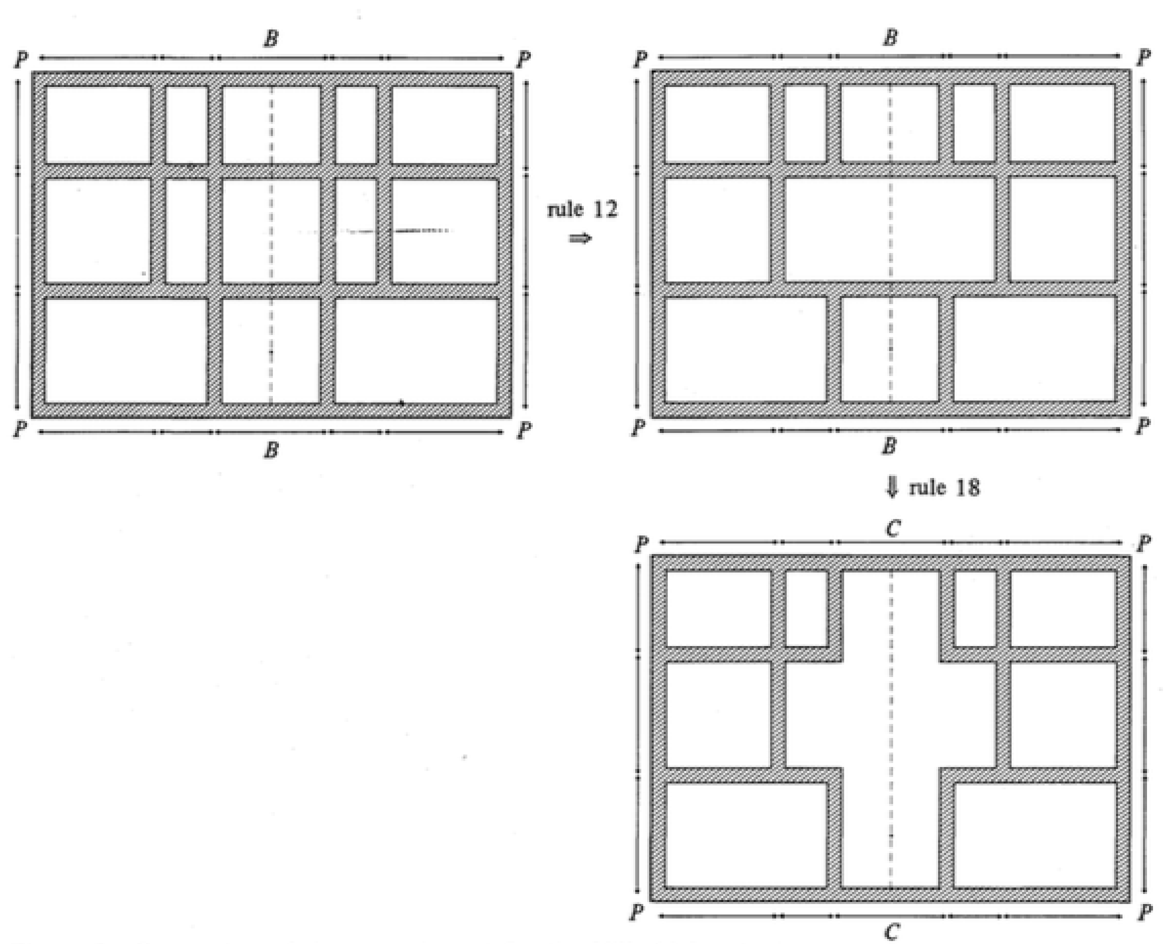


Figure 8. Generation of the room layout for the Villa Malcontenta.

Palladian Villas Generated

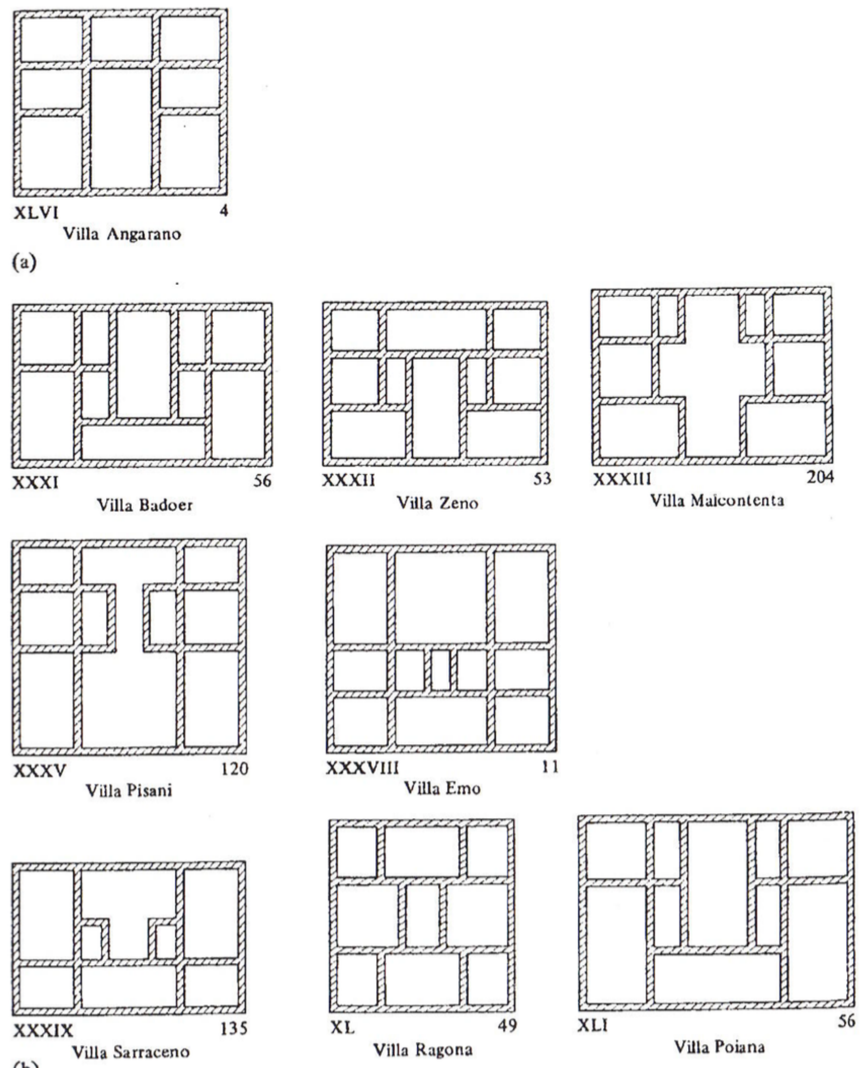


Figure 2. The room layouts of size (a) 3 x 3, and (b) 5 x 3 corresponding to Palladio's villa ground plans.

Number of Plans Generated

Table 1. The number of plans generated from initial plans of various sizes.

Plan size	Number of plans				
	containing rectangular rooms only	containing one central I-shaped room	containing one central T-shaped room	containing one central +-shaped room	total
3 x 3	12	1	6	1	20
5 x 3	119	5	78	8	210
5 x 4	1132	59	1039	136	2366
5 x 5	10192	704	12092	2029	25017
5 x 6	92664	7748	132120	25283	257815
5 x 7	836033	82869	1393116	292773	2604791
7 x 3	1114	31	780	65	1990
7 x 4	27916	1205	27110	3388	59619
7 x 5	644460	38307	791328	126222	1600317

Other Rules

- Eliminate symmetric plans
- Eliminate 5 x 3 grid plans that become 3 x 3
- Only rooms on the axis of symmetry can extend from one exterior wall to the other – Proviso 1
- Exterior rooms on the axis of symmetry must be as large as any other rooms in the plan – Proviso 2
- Any square grouping of 4 cells in the grid must not be in the same room – Proviso 3

Proviso 1

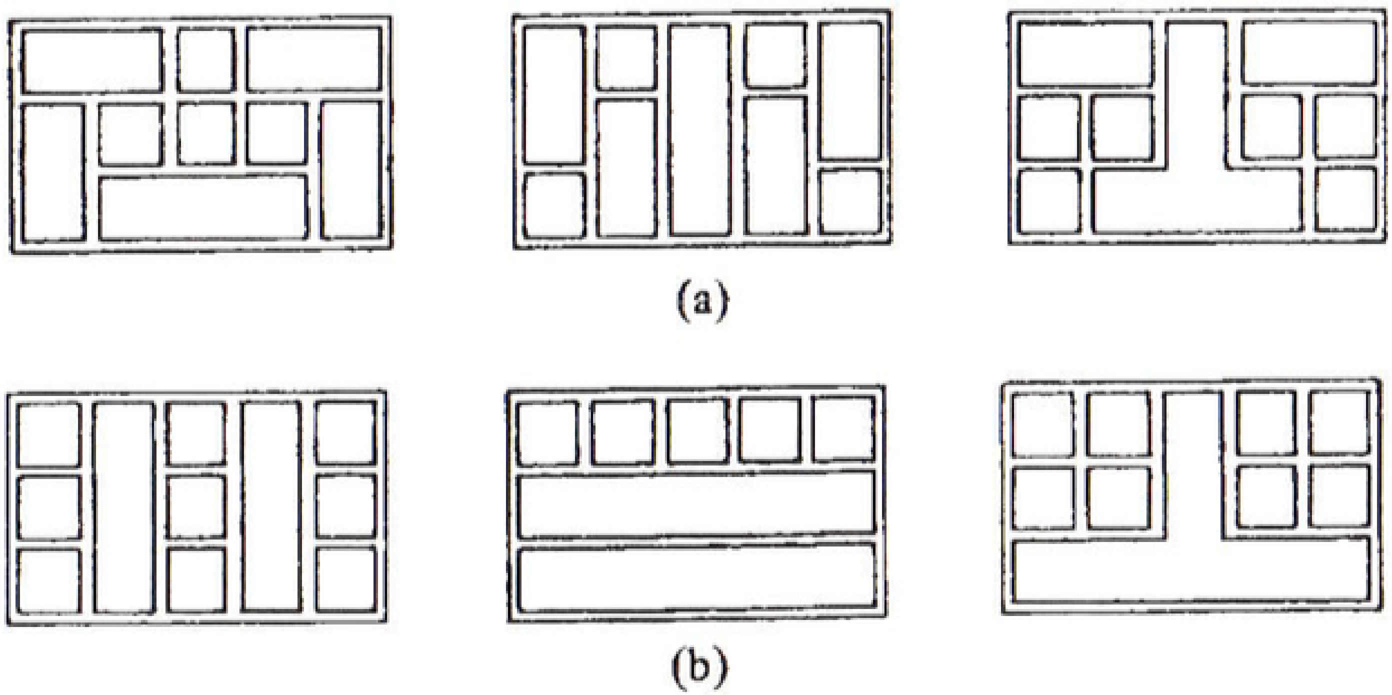


Figure 1. Plans shown in (a) satisfy proviso 1; plans in (b) fail to do so.

Proviso 2

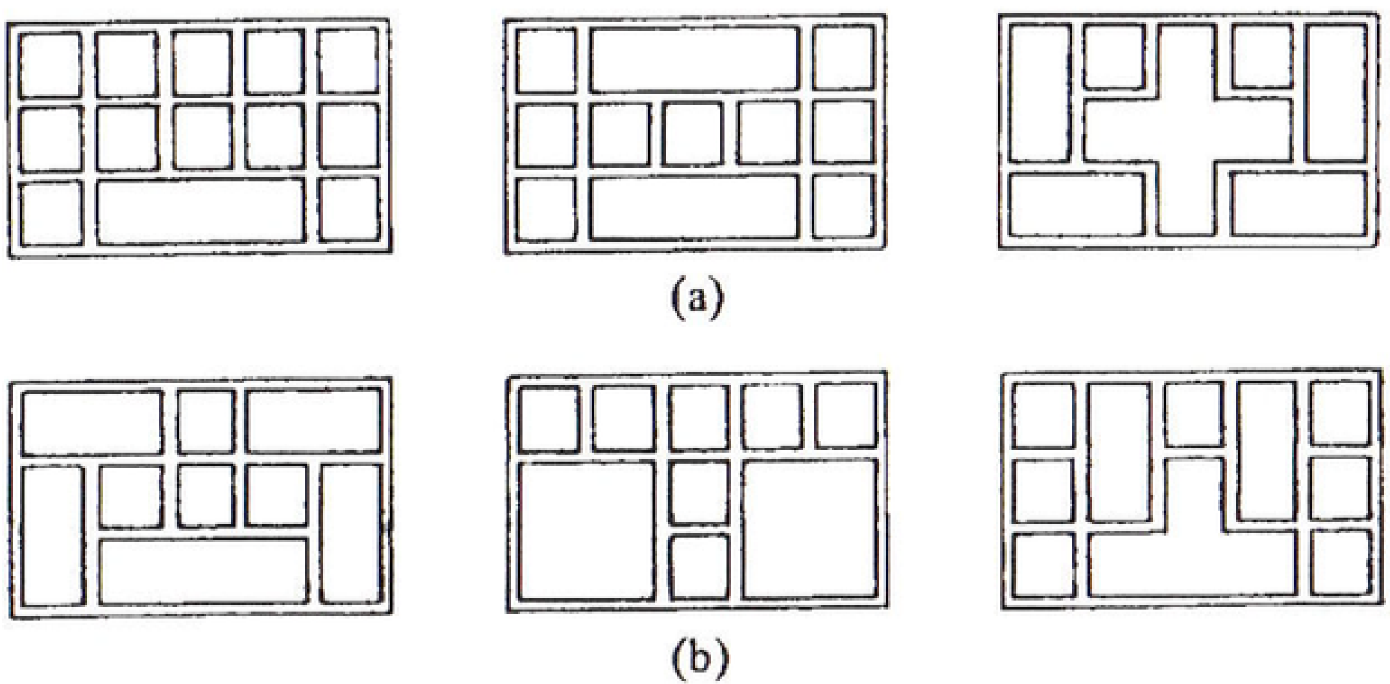


Figure 2. Plans shown in (a) satisfy proviso 2; plans in (b) fail to do so.

Proviso 3

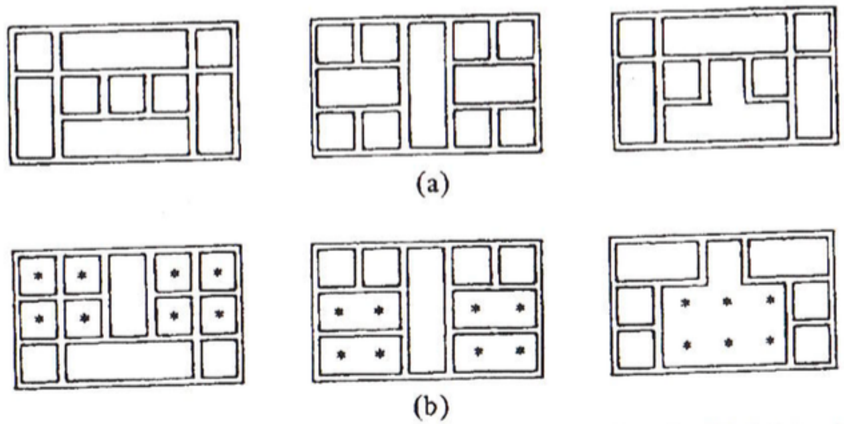


Figure 3. Plans shown in (a) satisfy proviso 3; plans in (b) fail to do so.

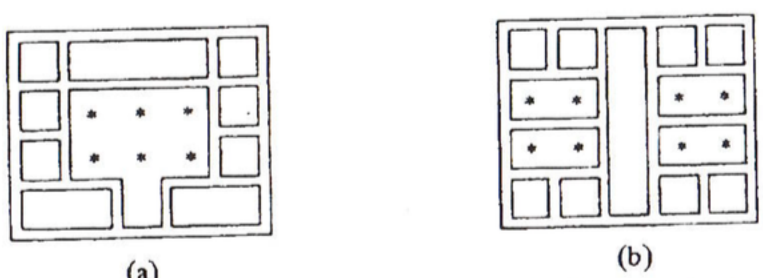


Figure 4. Two plans used by Palladio in his villa projects that fail to satisfy proviso 3. Plan (a) is used in the Villa Cornaro, and plan (b) in the Villa Moncenigo.

Palladian Grammar Representation

- A plan is represented by
  - A shape table which lists each distinct shape in the plan that contains more than one cell
  - An occurrence table which indicates the location of each multicellular shape in the plan

Shape Table

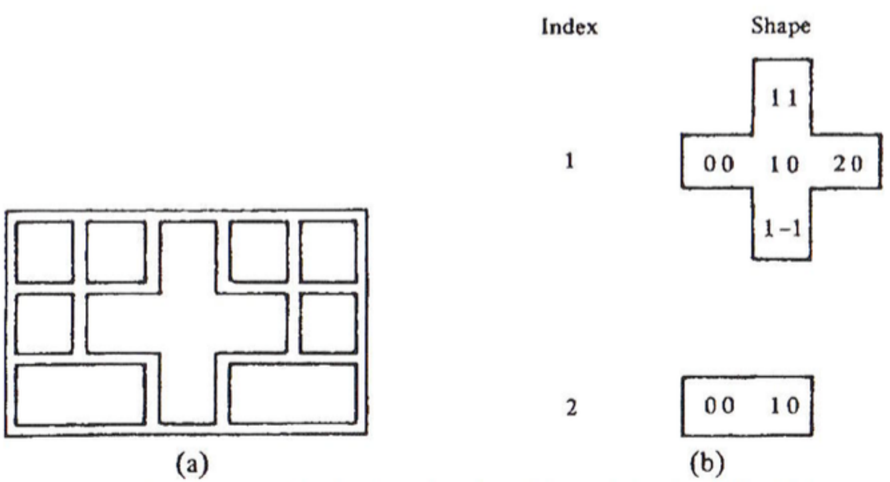
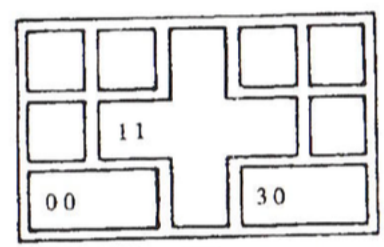


Figure 5. The shape table (b) for the plan (a) used in the Villa Malcontenta.

Occurrence Table

Shape index	Coordinates of 0 0 cell	Rotation
1	1 1	0
2	0 0	0
2	3 0	0

(a)



(b)

Figure 6. The occurrence table (a) for the plan used in the Villa Malcontenta, and (b) a pictorial representation illustrating the construction of the table.