Combing Grammars and Space Syntax: Formulating, Generating and Evaluating Designs

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This paper is concerned with how two different computational approaches to design – shape grammars and space syntax – can be combined into a single common framework for formulating, generating, and evaluating designs. The main goal is to explore how the formal principles applied in the design process interact with the spatial properties of the designed objects. Results suggest that space syntax is (1) useful in determining the universe of solutions generated by the grammar and (2) in evaluating the evolving designs in terms of spatial properties and, therefore, in guiding the generation of designs.

1. Introduction

It has been shown by Duarte how shape *grammars and description grammars*, coupled *with heuristic search* can be used to generate designs within a language that match given criteria, thereby forming a *discursive grammar* [1] [2]. The new framework was called discursive grammar because it provides the means to generate syntactically correct designs – the new design is within the language, as well as semantically correct designs – the new design matches given criteria.

From the operative viewpoint, a discursive grammar is composed of a *programming grammar* and a *designing grammar*. The programming grammar takes user and site data and generates the *housing program* or *design brief*. The designing grammar takes the housing program and generates a *design solution* that satisfies the brief. From the technical viewpoint, both the programming and the designing grammars are composed of a description grammar, a shape grammar, and a set of heuristics. The relationship between these definitions is such that both the programming and the designing grammars have description and shape components.

The concept of shape grammar was invented by Stiny and Gips [3]. A shape grammar specifies how designs can be composed with shapes starting with an initial shape and then proceeding recursively by applying shape rules. An *initial design* and a set of *shape rules* define a shape grammar; the set of designs that can be derived from the initial shape by applying the rules define a *language of designs* or a *style*. The concept of description grammar was developed by Stiny to account for features of designs not covered by shape grammars [4]. A description grammar describes the design in terms of other features considered relevant according to some criteria of interest. The relation between shape grammars and description grammars is such that for each shape rule there is a corresponding description rule. As the grammar rules are applied to the evolving design, the corresponding description rules are applied to the evolving description. Stiny further suggests that the description grammar can be considered a grammar of another language and that it is possible to translate back and forth between the two languages. The discursive grammar uses such a translation mechanism to obtain the design from a goal description (the housing program). The set of heuristics is used to guide search through the space of solutions until one that closely matches the goal is encountered. This is accomplished by selecting at each step the rules that bring the description of the evolving design closer to the goal description.

Duarte illustrates the concept of discursive grammar by developing a specific grammar called PAHPA-Malagueira. In this specific discursive grammar, the programming grammar, called PAHPA, adapts both the rules of the Portuguese housing program guidelines [5], and the rules of the Portuguese housing evaluation system [6] as developed by Pedro. One goal of the present work is to use space syntax to describe and evaluate spatial

properties – depth, contiguity and control – and to predict their use. The idea is that space syntax will provide the accurate means to describe such properties, and therefore, will increase the likelihood of generating solutions that closely correspond to the user's requirements. In the PAHPA-Malagueira grammar, the designing grammar encodes Siza's rules for the design of Malagueira houses. One of the main difficulties in designing this grammar was to determine the exact universe of design solutions: on the one hand, one wanted the grammar to generate a large set of design solutions to increase the potential of generating customized designs; and on the other, one wanted to make sure that the grammar only generated designs in the Malagueira style. The other goal of the current work was to use space syntax to determine whether a design is in the language thereby solving this paradox and fixing the contents of the grammar.

Section 2 describes the discursive grammar. Section 3 presents the universe of design solutions. Section 4 summarizes the results of the space syntax analysis. Section 5 discusses the results, and presents the main findings, suggesting how grammars together with space syntax can be used to generate criteria matching designs.

2. Discursive grammar

The generation of a design in the discursive grammar is a two-step process. The first is concerned with the generation of a symbolic description of the desired house (the housing program) from user input data. The second step is concerned with the generation of a housing solution that matches the housing program.

2.1. The PAHPA programming grammar

The programming grammar is concerned with the generation of a symbolic description of the desired house (the housing program) from user input data by manipulating only symbolic descriptions. A crucial issue in the development of symbolic descriptions is that of fixing the contents of the description, that is, which categories to include. The PAHPA grammar used a hierarchy of qualities based on Pedro [6] performance criteria organized into a decision tree (Figure 1, top). The description includes a variable description (α) and a fixed description (β). The features of the variable description are organized into three main groups. The first group includes contextual, typological, and morphological features. This group is called constraints because the values of its elemental features are specified by the user and cannot be changed by the programmer. The second group includes function-spatiality and topology-and aesthetics-whose single feature is proportion regarded by Siza as important. The user can assign weights to these qualities to express their relative importance, and to determine the overall quality. The third group includes only the construction cost. Constraints, qualities, and cost frame the problem as "design a house with

► Figure 1.Top: Part of the description. some features are not shown such as building elements (windows, doors, walls, pavements) and history (rule application order). Bottom: Programming grammar rule. Features that are not manipulated by the rule are omitted.

Description	Main	Groups	Features	Elemental features	
Variable	Constraints		Context	Lot	α_0
				Urban context	α_1
				Solar orientation	α_2
			Typology	Customization	α_3
				Users	α_4
				Bedrooms	α_5
				Quality	α_6
			Morphology	Housetype	α_7
				Floors	α_8
				Balconies	α_9
	Quality	Function	Spatiality	Capacity (dwelling)	$\alpha_{10\text{-}13}$
				Capacity (spaces)	$\alpha_{10\text{-}13}$
				Articulation (spaces)	$\alpha_{10\text{-}14}$
				Spaciousness s(dwell. &spaces)	$\alpha_{15\text{-}16}$
			Topology		α_{17}
		Aesthetics	Proportion		α_{22}
	Cost		Building		α_{24}
Fixed	Floor dimensions			Width	β_1
				Height	β_2
				Area	β_3
	Section dimensions			Floor thickness	β_4
				Floor height	β_5
	Cost				β_6

Rule g83: Adding a lavatory bathroom to the current list of spaces

$\alpha_4 \rightarrow \alpha_4$, $n_{users} = \alpha_4$
$\alpha_6 \rightarrow \alpha_6$, $q_{level} = \alpha_6$
$\alpha_{11} \rightarrow \alpha_{11} + <$ [lavatory, $\varnothing$, 0] $>$
$\alpha_{13} \rightarrow \alpha_{13} + <$ [ba, id_{lv}, $\varnothing$, (hygiene), (lavatory, 80), (isolated, 100), (q_{level}, 0),
$\qquad\qquad\qquad w_{lv}$, h_{lv}, a_{lv}] $>$
$\qquad\qquad\qquad n_{bathrooms} = 2 \wedge q_{level} - max \wedge n_{users} \in \{6, 7, 8, 9\}$, $id_{lv} = max(id) + 1$
$\alpha_{14} \rightarrow \alpha_{14} +$ sleeping (id_{lv}, a_{lv})
$\alpha_{15} \rightarrow \alpha_{15} + <$ available, (0, $-a_{lv}$, 0, $-a_{lv}$), (0, 0, 0, 0), (0, $-a_{lv}$, 0, $-a_{lv}$), 0$>$
$\alpha_{16} \rightarrow \alpha_{16} + <$ used, (0, a_{lv}, 0, a_{lv}), (0, 0, 0, 0), (0, a_{lv}, 0, a_{lv}), - $a_i / a_u + (a_i / a_u + a_{lv})$ $>$
$\alpha_{17} \rightarrow \alpha_{17} + <$ [id_{lv}, id_{fl}, on, 100] $>$
$\alpha_{24} \rightarrow \alpha_{24} + a_{lv} \cdot$ cm2
$\beta_1 \rightarrow \beta_1$, $w_{lv} = w$ (ba, lv, q_{level})
$\beta_2 \rightarrow \beta_2$, $h_{lv} = h$ (ba, lv, q_{level})
$\beta_3 \rightarrow \beta_3$, $a_{lv} = a$ (ba, lv, q_{level})
$\beta_7 \rightarrow \beta_7$, cm2 = cost_m2 (q_{level}, covered)

the specified qualities, within the given constraints, without exceeding the cost." The features of the fixed description have fixed values that the user cannot change. Due to space constraints, it is not possible to show the complete set of rules in detail. Therefore, one rule is shown as a way of illustration (Figure 1, bottom).

2.2. The Malagueira Designing grammar

The designing grammar is concerned with the generation of a housing solution that matches the housing program by manipulating both symbolic

and shape descriptions. To make it easier for the reader to understand the formal properties of the grammar, we show a very simplified set of shape rules and the partial generation of a layout using such rules in Figure 2.
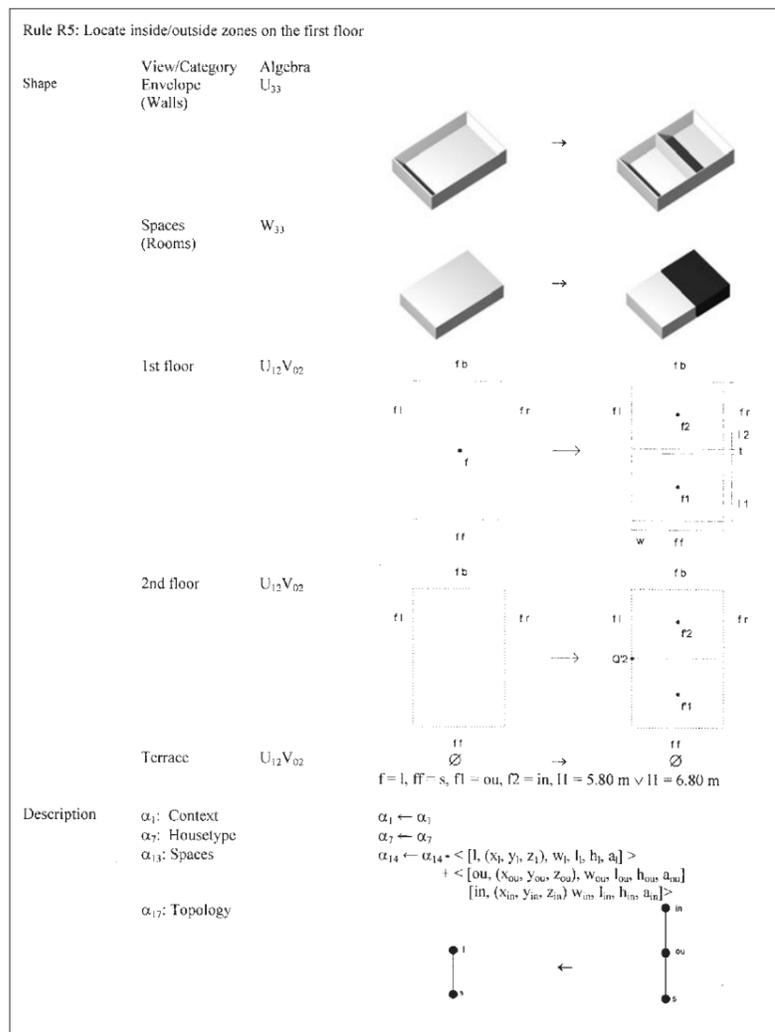

Simplified shape rules

Simplified partial derivation
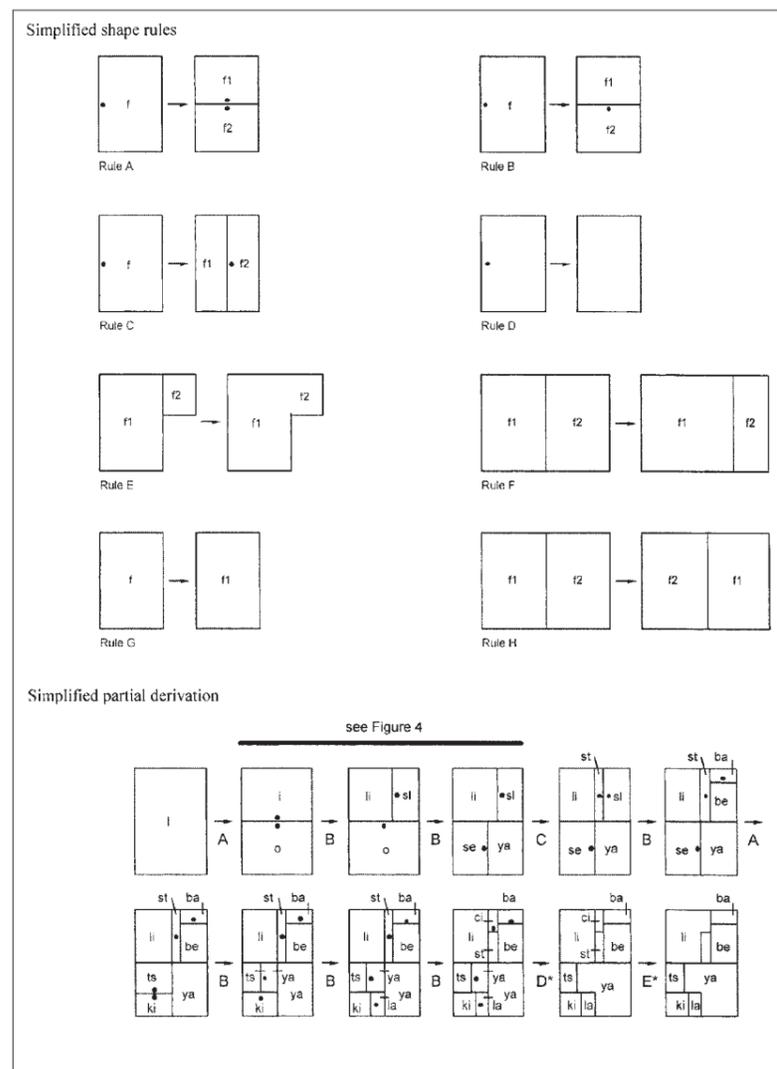
◄ Figure 2. Top: Simplified Malagueira shape rules. Bottom: Partial derivation of an existing layout. There are rules for dissecting (A, B, and C), connecting (E), and extending (F) rectangles. The remaining rules are for deleting a marker (D), assigning a function (G), and permuting functions (H). Legend: l – lot, i – inside zone, o – outside zone, li – living zone, sl – sleeping zone, se – service zone, ya – yard zone, be – bedroom, ba – bathroom, ki – kitchen, ts – transitional space, la – laundry, pa – pantry, ci – circulation, st – stairs. The asterisk means that the same rule was applied several time.

In brief, the generation of a Malagueira design is based on the manipulation of rectangles using rules for dissecting, connecting, and extending rectangles, as well as rules for assigning and changing the functions associated with them. The generation of basic layouts with these rules comprises two steps. In the first step, the lot is first divided into the four functional zones-patio, living, service, and sleeping-thereby obtaining a basic pattern, and then a staircase is added thereby defining a stair pattern

and the housetype. In the second step, these zones are divided into rooms to obtain the layout. The labels "fn" denote the functions of the rooms that the rectangles represent. The dot • is a label that identifies the last line placed and indicates on which side the next dissection may occur: on both sides (Rule A) or only one side (Rule B). In rules A and B, dissections are perpendicular to the bigger side of the rectangle, whereas in Rule C it is perpendicular to the smallest one. Rule D deletes the label (, preventing further dissections. Rule E concatenates two adjacent rectangles to form a larger room. Rule F, extends a room at the expense of an adjacent one. Rule G assigns a function to a room. Finally, Rule H permutes the function of two adjacent rooms.

The actual designing rules are further more complicated as they include a shape part and a description part. To make it possible for the reader to understand the complexity of the designing grammar and the usefulness of introducing space syntax, we show a more detailed rule in Figure 3. The original shape part uses various shape algebras to represent several viewpoints-plans, elevations, axonometrics, but we only show four of such viewpoints-envelope, space, first and second floors layouts. Using the standard shape grammar notation, the algebras are identified by a capital letter followed by two subscript numbers. The letter represents the type of algebra – U for shapes, W for weights (color, shade, line thickness), and V for labels. The first number specifies the dimension of primitive shapes – 0, 1, 2, or 3 dimensions for points, lines, planes, and solids, respectively – and the second number tells the dimension of the space in which these primitives are combined in the algebra. For instance, $U_{12}V_{02}$ is an algebra defined in the Cartesian product of two algebras; the first is formed by all the shapes that can be defined by combining lines on the plane; and the second is formed by the set of all the labels that can be created by combining symbols on the plane. For a detailed discussion on algebras and weights see [7] and [8].

The description part includes the same categories used in the programming grammar, but we only display four-context, housetype, zones, and topology. The contribution of space syntax will come about by expanding the topology category to include not only the adjacency graph as in the original grammar, but also syntactic measures such as depth, contiguity and control, as explained further below. The rule is parametric: "f = 1" and "ff = s" specify the conditions that must exist on the design for the rule to apply – the shape on the first floor is the lot and the street is at the front – and "f1 = ou, f2 = in, ll = 5.8 m ∨ ll = 6.8 m" specify the result of its application – the lot is dissected into inside and outside zones by a line distancing 5.8 or 6.8 m from the street. In Figure 4, we show a few moves in the generation of a design. Due to space limitations, only the first floor view in the the shape part is shown. The shown moves define a basic pattern and correspond to the part of the derivation highlighted in Figure 2. It should help to clarify the relation between shapes and descriptions, and

◀ Figure 3. Simplified discursive rule combining shapes and descriptions. The shown rule includes only some of the views and some of the features in the original grammar and it depicts the case in which the outside zone is located at the front of the house, adjacent to the street – s. The feature "spaces" include [use (x,y,z) width length area] where use is the function associated with the space (e.g. lot – l, inside – in, or outside zone – ou(; (x,y,z) is the insertion point, and w, l, h, and a are the dimensional features.

the role of heuristics in guiding the generation. In step 3 the layout is divided into inside and outside zones using the rule shown in Figure 3. In step 4 the outside zone is divided into the yard zone and an unnamed zone that can become any of the remaining three functional zones – sleeping, living and service zones. There is no doubt in assigning the yard zone because the description specifies that the housetype is frontyard. In steps 5 and 6 the layout is divided into four functional zones in all possible ways and the six resulting candidate solutions are rated. In steps 7–12 the worst patterns are eliminated one by one and the best pattern is selected to proceed with the derivation.
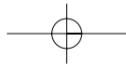
► Figure 4. Some steps in the derivation of a house within the PAHPA-Malagueira grammar (please compare with Figure 2). The feature "context" is <front, left, right, back> where front, left, right, and back indicate whether the lot is bordered by a house – h, or a street – s on each of its four sides.
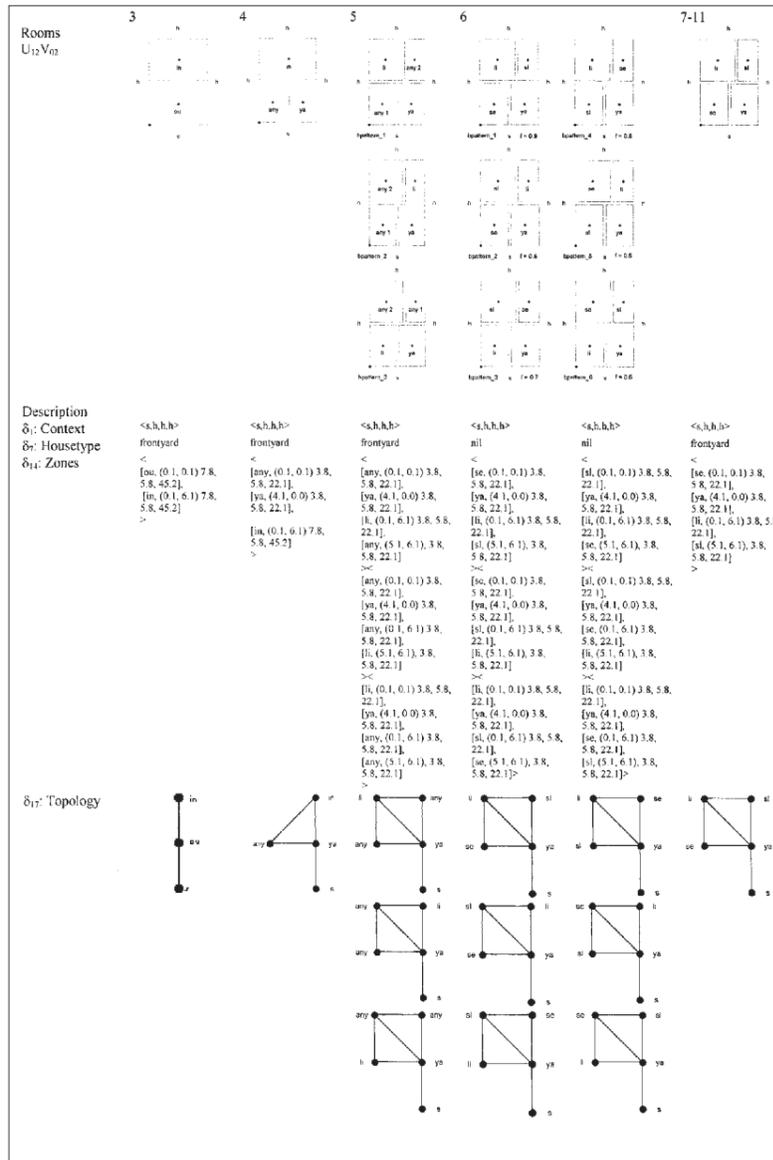

3. Universe of design solutions

As mentioned in Section 1, designing the grammar created an apparent paradox. On the one hand, one needed a grammar that generated a large set of design solutions to increase the potential of generating customized designs. On the other hand, one wanted to make sure that the grammar only generated designs in the Malagueira style and that a solution could be

found in practical time. In the first stage, the grammar was developed after
a relatively small (35) number of different houses in the following way. The
first design conceived by Siza (type Ab) was analysed. The analysis of this
design lead to a hypothesis of what the grammar could be. The analysis of a
subsequent design required one to´refine the hypothesis, and so on. This
analytical procedure mirrored Siza´s design procedure, who after conceiving
an initial, paradigmatic design conceived others as variations of the first.
Going through several of the analytical cycles, showed that the hypothesis
was being refined by unrestricting the grammar and raised the question
whether one should continue doing so. One could restrict the grammar to
generate only analysed designs, but this conflicted with our goal of using the
grammar to generate new, customized designs. The grammar was further
unrestricted thereby entering a new stage in its development, which
encompassed three steps. The first step was to develop the exhaustive set
of rules that could be derived from the compositional principles of
dissecting and concatenating rectangles, which seemed to rest behind Siza´s
rules, at a very abstract level. The corresponding universe of design
solutions is partially diagrammed in Figure 5. The second step was to limit
such an exhaustive set of rules whenever it seemed that it would oppose
Siza's compositional rules; doing this implied to distinguish between *legal* and
illegal designs, that is whether designs were or not in the style. For
instance, Figure 5 shows the 8 geometric patterns that can be derived from
Siza's dissecting rules but only patterns with a dot • correspond to houses
designed by Siza. Figure 5 also shows 24 out of 192 topological patterns
that can be derived from the 8 geometric patterns, following a broad
interpretation of Siza's design rules. Patterns with a dot • correspond to
houses designed by Siza and patterns with a dot O are patterns considered
in the final grammar. The remaining patterns were excluded from the final
grammar for a number of reasons; they were thus considered *illegal*. The
third step was to generate new designs with a closed set of rules and then
ask Siza whether he considered them to be in the grammar. A set of rules
is closed if it is possible to generate complete designs within the set. This
procedure presented several difficulties. First, Siza's responses denoted
several degrees of stylistic compliance: it is almost legal; it is legal but Siza
would not have designed it for idiosyncratic reasons; and it is legal and Siza
could have designed it. Second, the process was time-consuming and Siza
was not always available. Third, it was prone to error because one could
generate only a small set of solutions and, therefore, one could only guess
what Siza would think in the remaining cases. Our goal in using space
syntax was to develop an additional, rigorous tool that could help us in
defining the universe of solutions, that is, that could help us to clarify
whether a certain layout design was in the style. With this tool, we could
relax the grammar, as Duarte did, but rely on space syntax to increase the
likelihood of generating stylistically compliant designs. The use of space

► Figure 5. The universe of potential
solutions in the Malagueira grammar.
Each level in the tree represents a
single step in the derivation. Due to
space limitations, only the steps
required for the derivation of
dimensioned stair patterns are shown,
and only one branch is expanded to
the level below. The symbol • identify
patterns that correspond to houses
designed by Siza. The symbol o identify
patterns considered in the final version
of the grammar but not used by Siza.
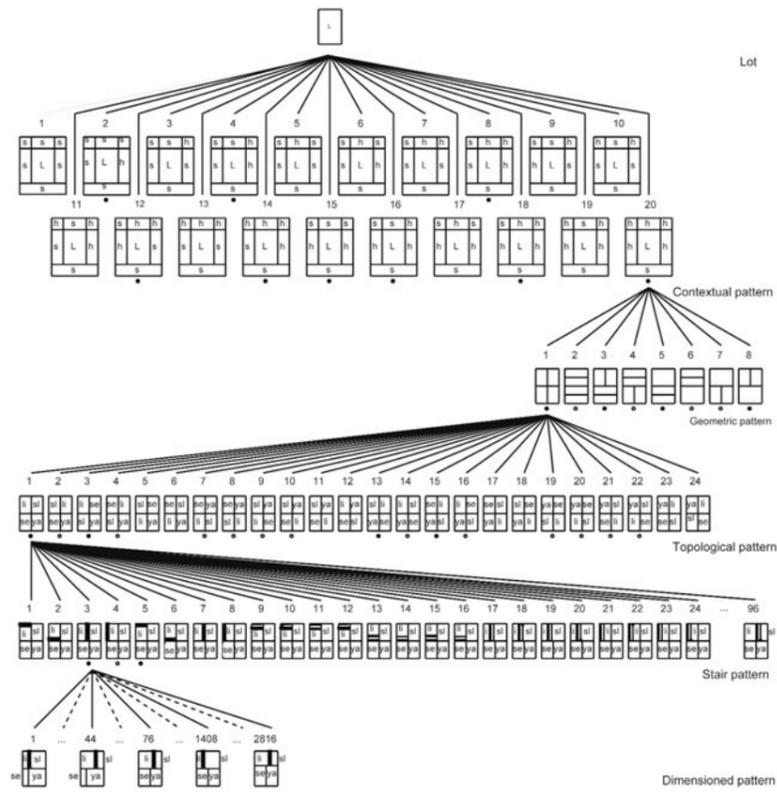
syntax seemed suitable because it captured the spatial and social structure
encoded in layouts without specifying form. The idea is to use syntactic
measures to prevent an uncompliant design being generated by discarding
uncompliant partial designs – those with a lower syntactic rank – as
candidate solutions during derivation. For further information on the role
of heuristics in derivation of designs by a discursivre grammar, please see
Duarte [2].

4. Space syntax

4.1. Concepts

Space syntax is a descriptive technique of spatial and configurational analysis
that allows a consistent identification of spatial-functional patterns [10].
Space is studied in terms of abstract properties of topological nature, i.e.
the pattern of connections among spaces and the connections of each space
to all others, rather than in terms of geometric measures. These

configurational properties are *depth*, *contiguity* and *control*. Consider *v* to denote any space. Depth of space *v* is the distance of v to all the others spaces in the system; Contiguity of space *v* refers to the number of spaces directly connected to v. Control of space *v* denotes the importance of *v* as a route relatively to all the other spaces.

The basis for the analysis of spatial configurations in buildings is a graphical transformation called convex map. Convex maps are planar connected configurations obtained by breaking up the system into the set of the fewest convex elements. They are introduced to allow a non-arbitrary and reproducible representation as well as a quantitative analysis of the spatial system. These objects provide information concerning the topological properties. To make them suitable for computation they are converted into a set of discrete elements, which take the form of a graph: the 'convex' graph [10]. The convex graph of a convex map is a graph in which vertices correspond to spaces; two vertices are connected if and only if the corresponding spaces of the convex map are adjacent. These graphs carry information about the connections of each space to all other spaces in the map.

Hillier and Hanson [10] also introduced the so-called 'justified' graph as a graphical representation for visually clarifying the structure of both the convex and the axial graph. The justified graph is no more than a particular representation of the convex and axial graph in which a particular vertex is selected as the root and the vertices in the graph are then aligned above it in levels, keeping the graph as shallow as possible to the root. The shape of the justified graph captures a depth distribution from a point in an overall shape.

Depth is used in a more developed and quantitative form, which is called integration. The integration value of space v expresses the relative depth of that space from all others in the system. The integration value of a space thus expresses numerically a key aspect of the shape of the justified graph that is constructed from that space.

4.2. Methodology

The methodological approach used in this study was to analyse houses within the PAHPA-Malagueira grammar from the space syntax viewpoint and then to compare the results with assumptions made in the development of the grammar. Syntactic description was applied to uncover configurational properties embedded in the rules used to generate both existing and new houses within the grammar. Four sets of single-family houses were considered forming a total of 46. The first two sets include houses designed by Siza (Set 1: 24 houses) or by its collaborators (Set 2: 2 houses). These sets correspond to the corpus of houses used in the development of the grammar. The third set comprises houses generated by the author of the grammar following the grammar rules in a random manner (set 3: 4 houses).

► Figure 6. Space syntax analysis of a house in the corpus. Top: Plan, section and elevation. Bottom left: Convex map obtained by partitioning the plan into convex spaces. Bottom right: Justified graph analysis in which the exterior is taken as the root, each vertex is labelled by the functional sector to which it belongs; and functional sub-complexes are reduced to single vertices and connected to each other by the remaining links, originating a compact sector's graph.
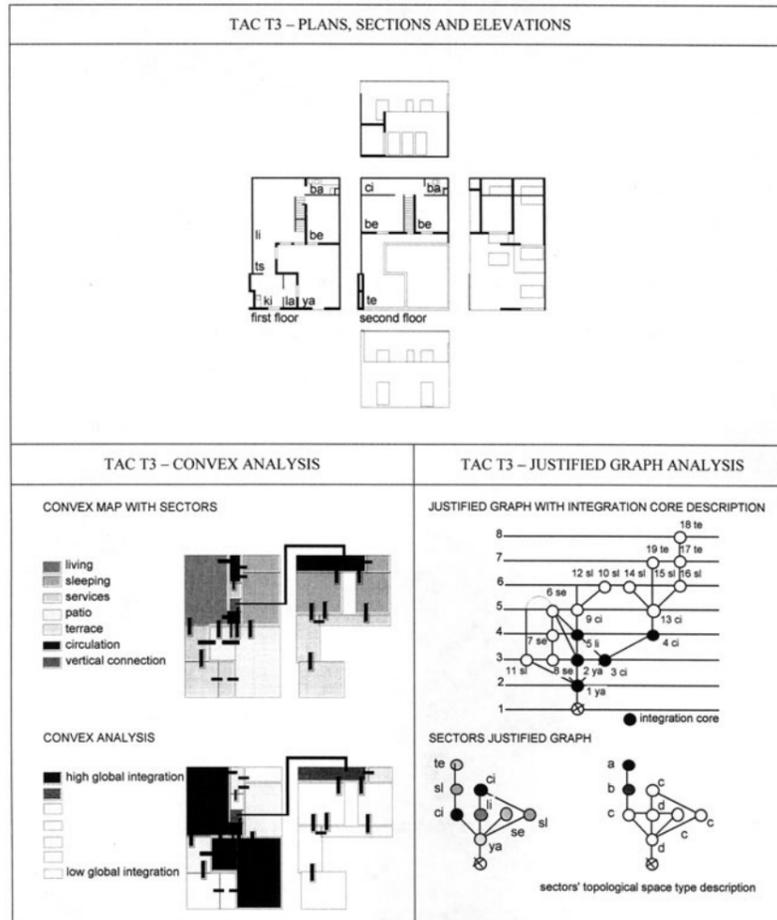
The fourth set encompasses houses generated by other authors using the grammar rules to match criteria given a priori by clients (set 4: 16 houses).

To achieve the two goals stated at the end of Section 1, we reframed them in the following way:

1. The shape grammar organises the functional space into zones; is this confirmed through syntactic analysis? If it is, one can use syntactic analysis to describe and evaluate spatial properties.
2. Does the syntactic analysis of new houses relate to the syntactic analysis of Siza's? If they do, it is possible to use syntactic analysis to determine the likelihood of an unknown design being in the language.

Configurational properties are analysed using space syntax techniques, which proceed by representing spatial complexity by means of *convex maps* and *justified graphs*, taking the exterior as the root. Convex maps are examined by exploring syntactical attributes such as depth, contiguity and

control, by identifying the *most integrated spaces*, and by determining the *integration core* – defined as the set of the 20% most integrated spaces. Graph descriptions consider *topological size* (number of nodes), *depth* (number of levels), *and topological types*. As shown in Figure 6, Hillier [11] classifies the spaces in a graph into four topological types: *a-types* (links =1; dead-ends); *b-types* (links >1; lying on a chain or on a tree); *c- types* (links >1; lying on a ring) and *d- types* (links =2; lying on at least 2 rings). The space-use condition was assessed based on the complemented configurational analysis of the domestic functional model using a '*sector(s) analysis*' technique as defined by Amorim [12]. This technique consists of three steps. Firstly, it assigns each space to the corresponding functional sector; secondly, it determines whether the classified spaces form continuous functional fields;and thirdly, it develops a series of syntactic analysis aiming at characterizing the configurational properties of the sectors such as number of nodes, depth, integration, and topological types. Functional sectors were labelled yard (1st floor) or terrace (2nd floor), living, service, sleeping, and circulation, according to the designations assigned to zones in the PAHPA-Malagueira grammar.
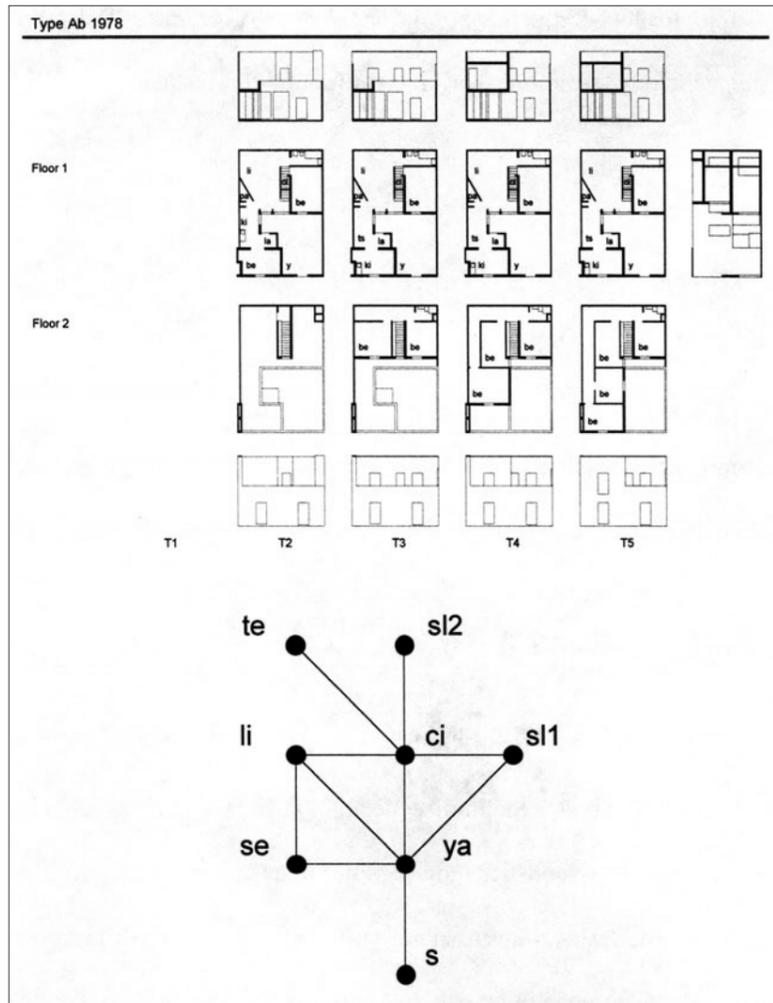
4.3. Analysis

Grammar rules

The grammar rules define adjacency features concerning the domestic functional organisation (Figure 7). Such features were already present in the first design by Siza, the paradigmatic design from which all the others were designed as variations and the grammar was initially inferred, as described in Section 3. Due to space limitations, the plans of the remaining houses used in the analysis are not shown in this paper but they can be found in [9]. The corresponding graph shows 8 nodes and 10 links performing a tree-like configuration with rings-in-rings. The yard has the highest connectivity value, being connected to all the other sectors. The service sector is directly connected to the living sector, which is connected to the circulation sector (horizontal and vertical circulation). The sleeping sector is connected to the living sector through the circulation or through the yard. The terrace is accessed through the circulation sector. The yard is the shallowest and most integrated node, being included in different rings as a d-type space. It also shows the strongest control over the other sectors thereby suggesting that it plays an important role in the functional organisation of the house. The circulation and the living sector follow the yard. They are included, at least, in one ring, being c- or d-type spaces. The service, sleeping, and terrace sectors are the less accessible ones. The service and the sleeping sector on the first floor (sl1) are included in rings, being c-type spaces. The sleeping sector on the second floor (sl2) and the terrace are a-type spaces.

   As Hillier has shown [10], d-type spaces are depth minimisers. Hence, the yard, the living, and the circulation sectors have the role of globally

► Figure 7. Plan of the first housetype designed by Siza (top) and the syntactic description of the corresponding functional organisation (bottom), which formed the basis of the functional organisation embedded in the grammar.


integrating the system. The links between the yard, and the service and living sectors support social activities in the house, while promoting the integration of major domestic spaces within the system. The results of the analysis are summarized in Figures 8 and 9 and in Table 1.

Set 1: Existing houses designed by Siza (24 houses)

This set comprises 24 houses of which 21 are grouped into 5 types named A through E. Each type has four or five variations, ranging from 1 or 2 up to 5 bedrooms. The variations are named tn where n is the number of bedrooms. The remaining 3 houses constitute single cases of variations t3 or t4.

These houses have an average topological size of 19 spaces, ranging from 13 up to 24 convex spaces. In 83% of the houses, the sleeping sector is the
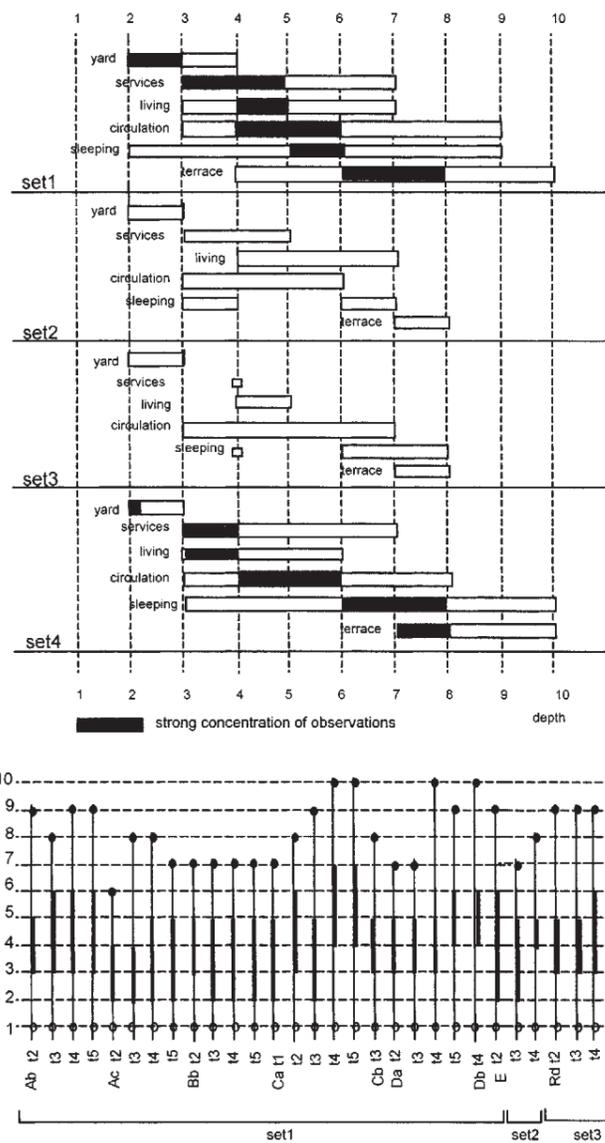
◄ Figure 8. Top: Sectors depth distribution concerning the four sets of houses. The dark areas show the levels with the strongest concentration of observations. Bottom: Integration core distribution showing the number of levels and its relative position in the justified graph.

largest sector, with an average of 6 convex spaces per house, ranging from 3 (types Ca and Da – t2) up to 8 spaces (type Bb – t5). Circulation has an average size of 5 spaces, ranging from 2 up to 7 spaces. The service sector has an average size of 3 spaces. The living sector has an average of 2 convex spaces, ranging from a single living/dining room (types Da and Ac – t2) to 3 convex spaces (types Ab, Bb, Ca, Cb and E). The yard is mostly composed of 2 convex spaces.

► Figure 9. Sets 1 through 4: sector graphs
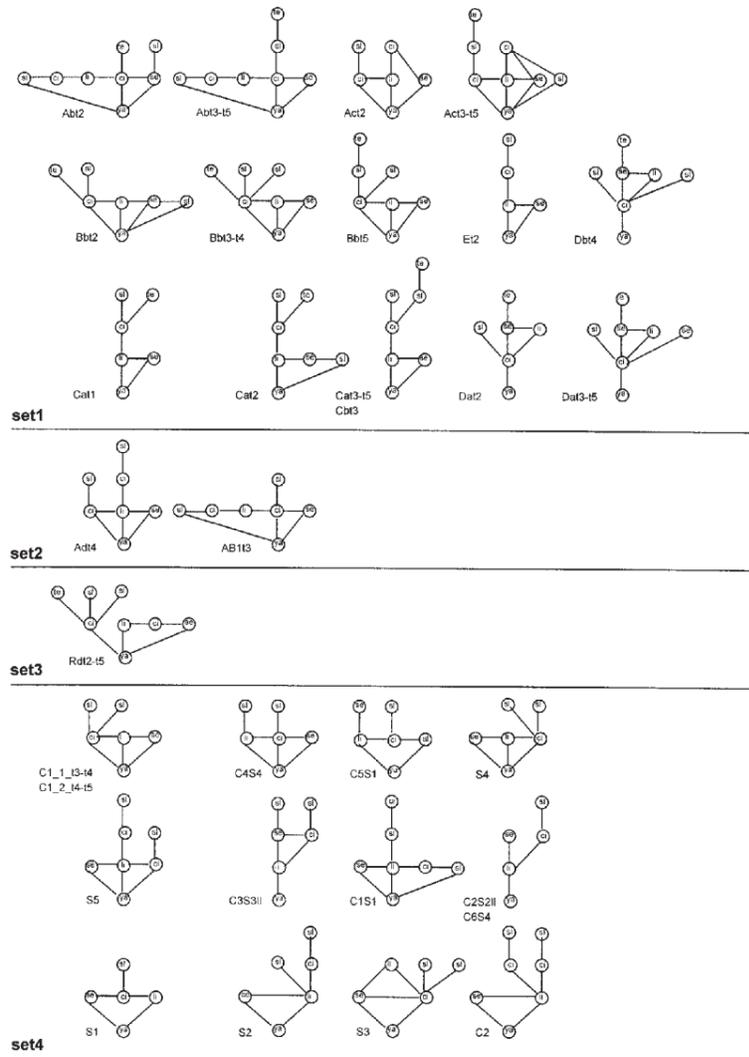
In terms of configuration, the graphs show a tree-like shape with rings, composed of either a single ring (30%) or a sequence of interconnected rings (70%). Justified graphs show an average of 8 levels, ranging from 6 up to 10 levels. They reveal a complex structure, mostly formed by rings-in-rings on the ground floor and a tree structure on the upper floor. The yard spaces are the shallowest spaces and the sleeping and the terrace spaces are the deepest ones.

Mean integration values range from 0.624 (s = 0.160) up to 0.971 (s = 0.270), with an average value of 0.827 (s = 0.081). Using the coefficient of variation (s/x) as a measure of spread, they range from 0.160 up to 0.300.

Set / sample	set1 / 24	set2 / 2	se3 / 4	set4 / 17
convex spaces				
mean	19	24	19	21
max	24	28	20	24
min	13	20	19	18
rank order (by sectors)	sl> ci>se>li>ya>t	sl>ci>se>li>ya>t ci>li>sl>se>ya>t	ci>sl>se>li>ya>te	ci>sl>se>li>ya>te
depth				
mean	8	8	9	8
max	10	8	10	10
min	6	7	9	7
graph configuration	tree + rings	tree + rings	tree + rings	tree (12%) tree+rings (88%)
integration				
mean	.827	.841	.763	.781
st. dev.	.081	.047	.021	.867
max	.971	.874	.788	.665
min	.624	.808	.746	.056
int. core				
configuration	chain (42%) tree (12%) tree+rings (38%) ring (8%)	tree tree+ring	chain	chain (59%) tree (41%)
composition	(ci +li) + ya (80%)	(ci +li) + se (ci +li) + ya	(ci +li) + ya (25%)	ci +li
position	shallow (63%) centralized (47%)	shallow centralised	shallow	centralised (53%) shallow (47%)
topological types				
a- mean; (s) max ; min	34%; (.09) 56%; 27%	20%; (.01) 21%; 20%	39%; (.02) 42%; 37%	45%; (.06) 57%; 27%
b- mean; (s) max; min	21%; (.13) 46%; 9%	17%; (.10) 25%; 10%	25%; (.02) 26%; 21%	28%; (.09) 47%; 9%
c- mean; (s)s max ; min d-	33%; (.13) 52%; 0%	41%; (.18) 55%; 28%	20%; (.005) 21%; 20%	19%; (.11) 39%; 0
d- mean; (s) max ; min	12% (.19) 31%; 0%	22% (.12) 32%; 15%	16% (.004) 15%; 15%	8% (.06) 20%; 0
sectors				
rank order (int)	ci>li>ya>sl>se>t (50%) ci>ya>li>sl>se>t (33%) li>ya>ci>sl>se>t (13%) ci>li>sl>se>ya (4%)	ci>li>ya>sl>se>t ci>ya>li>sl>se>t	li>ci>ya>sl>se>t (75%) ci>li>ya>sl>se>t (25%)	ci>ya>li>sl>se>t (35%) ci>li>ya>sl>se>t (29%) li>ci>ya>sl>se>t (18%) ci>li>sl>se>ya>t (12%) ya>ci>li>sl>se>t (6%)
topological type				
yard	b- (21%) c- (25%) **d- (55%)**	c- d-	c-	b- (18%) c- (29%) **d- (53%)**
living	**c- (58%)** d- (42%)	c-+a- d-	c-	b- (35%) c- (12%) **d- (53%)**
sleeping	b- + c- (33%) a- + c- (29%) a + b- (17%) **a- (67 %)**	a- + c- a- + b-	a-	**a - (88%)** a- + c- (12%)
services	**c- (75%)** d- (25%)	c-	c-	a- (18%) **c- (76%)** d- (6%)
circulation	b- (30%) c- (25%) **d- (45%)**	c- c+b-	b- c-	b- (23%) **c- (65%)** d- (12%).
terrace	**a- (88%)** c- (12%)	a-	a-	a-

▲ Table 1. Summary of syntactic analysis results
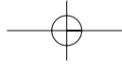
Therefore, one may conclude that size does not affect integration values. Circulation assumes a central position in the overall configuration of the houses since the highest values of integration tend to be concentrated in circulation spaces or in the adjacent ones. The ground floor circulation space is the most integrated space in 71% of the houses, and adjacent spaces show the highest value of integration in the remaining 29%: the yard in 17%, the staircase in 8%, and the living-room in 4%.

The integration core tends to be positioned slightly over the medium depth level inside the houses. It spans over an average of 4 levels and its form assumes three different configurations: single chain (42%), tree-like cores (12%), tree-like cores with one or two rings (38%), and single rings (8%). The circulation spaces, as well as living spaces, are always included in the integration core. The yard is part of the integration core in 80% of the houses. The sleeping and the service spaces tend to be secluded from the integration core; the former is included in only 17% and the latter in 4%. This seems to be an effect of their configuration, which draws integration to itself. When circulation spaces are removed, the living sector tends to be the centre of the house in 75% of the cases, whereas the yard assumes the central position in the remaining 25%. The sleeping and the service sectors show the most segregated values in all cases.

In terms of topological type, the yard is a b- (21%), a c- (25%), or a d-space type (55%). When it assumes a b- type, the distributor role is assigned to the circulation sector. The living and the service sectors are always found within rings as c- or d-types. The circulation sector is found in three different space-types: b- (30%); c- (25%) and d- (45%). The sleeping sector is non-continuous (with one bedroom on the ground floor and the remaining on the 2nd floor) in 75% of the houses, being found as a b- and c- type in 33%, as an a- and c-type in 29%, and as an a- and b-type in 17%. The sleeping sector is continuous in the remaining 25% of the houses, being an a-type. The predominance of a-types (dead-ends) in both the non- and the continuous cases denotes an intention to isolate this sector. In addition, when a sleeping space is found as a b-type it always provides access to the terrace, which is then an a-type. When a sleeping space is a c-type (embedded in a ring), they are simultaneously adjacent to circulation spaces and to the yard, which also promotes the spatial isolation of the sleeping sector relatively to the other sectors in the ring.

Set 2: Existing houses designed by Siza's collaborators (2 houses)

Set 2 includes 2 houses of variation t3 (Ab1) and t4 (Ad), which have 28 and 20 convex spaces, respectively.

House Ad t4 shows a pattern similar to those of houses in Set 1. The sleeping sector is the largest sector, with 6 convex spaces; the living sector is composed of a single living/dining room; the service sector has 3 spaces;

circulation has 5 spaces, and the yard is composed of 2 spaces. The justified graph shows a tree-like shape with rings, spread along 8 levels and a mean integration value of 0.874 (s = 0.268). The integration core is located in the middle of the system and assumes a tree-like shape composed of two circulation spaces (corridor and staircase), the living/dining room and the kitchen. The sector's graph is also similar to the previous ones. It shows a tree-like shape with two interconnected rings. The living sector shows the highest integration values.

House Ab1 t3 reveals some differences. The topological size is over the average size due to an increase in the number of living and circulation spaces. The circulation sector is the largest one (9 spaces) followed by the living (6 spaces) and the sleeping (5 spaces) sectors. The justified graph shows a tree-like shape with a sequence of interconnected rings, spread along 7 levels. Its mean integration value is 0.808 (s = 0.221). The integration core assumes a tree-like shape with one ring distributed along 4 levels. It is composed of three circulation spaces (corridors and staircase), the living room and the yard and it tends to be located towards the shallowest levels. The sector's graph is similar to the previous ones although the living sector is split in two (a- and c- types).

Set 3: Random design (4)

This set is composed of 4 houses of variation t2 up to t5. Variations t2, t3, and t4 have 19 convex spaces and variation t5 has 20 spaces. Being designed as one type, they have an identical basic pattern, and vary in the number of sleeping and terrace spaces.

Considering the number of convex spaces, the circulation sector is always the largest sector, followed by the sleeping sector. In terms of configuration, graphs show a tree-like shape with three interconnected rings spread along 8 (T2, T3 and d T4) and 9 levels (T5). The yard occupies the shallowest positions while sleeping spaces and the terrace are on the deepest levels.

The mean integration values range from 0.788 (s = 0.219) to 0.746 (s = 0.212). The circulation spaces show the highest values, followed by the living room. The integration core takes a chain configuration extended along 4 levels (from level 3 to 4) containing circulation spaces and the living room. It tends to be slightly biased towards the shallowest spaces. The sector graph shows a tree-like shape with a single ring composed of 4 nodes: yard, living, circulation, and service sectors. The sleeping sector and the terrace are found as a-type spaces, connected to the yard through a sequence of circulation spaces.

Set 4: Criteria matching design (17)

This set includes 17 houses. Five of them define types (C1_1 – variation t3 up to t5; C1_2 – variation t4 and t5) whereas the remaining are single cases

of variations t3 (1 house), t4 (5), t5 (5), and t7 (1).

The topological size of these houses ranges from 18 to 24 convex spaces, with an average of 21 spaces. The sleeping sector is always the largest sector, with an average number of 8 convex spaces per house, ranging from a minimum of 6 in variation t3 up to a maximum of 11 in variation t5. It is followed by the circulation sector, with an average number of 5 convex spaces, ranging from 3 up to 8; and the service sector, with an average size of 4 convex spaces, ranging from 2 up to 5. The living sector has an average of 2 convex spaces, ranging from a single space up to 4 convex spaces. The yard is mostly composed of a single space. The terrace exists in only 7 houses (40%), with a single convex space. In the remaining houses, terraces were transformed into balconies and integrated into the sleeping spaces.

In terms of configuration, graphs show a tree-like shape (12%) or a tree-like shape with rings, composed of either a single ring (20%) or a sequence of interconnected rings (80%). Justified graphs have an average of 8 levels, ranging from 7 to 10 levels.

Mean integration values range from 0.665 (s = 0.176) to 0.867 (s = 0.267), with an average value of 0.781 (s = 0.056). Circulation spaces maintain a central position in the configuration, showing the highest values of integration. In 53% of the houses, the staircase is the most integrated space. In the remaining 47%, this position is assumed by the ground floor circulation space. The integration core tends to be deeply inside the houses. It takes two different configurations: a single chain (59%) and a tree-like shape (41%). In its composition, it always includes circulation and living spaces. The yard, as part of the integration core, is only present in 2 houses (C1_1_t3 and C1_2_t5), although it tends to be included within the 50% more integrated spaces. In 4 houses (23%), the yard is secluded from the house core, being within the set of the 20% more segregated spaces. The sleeping, the service, and the terrace spaces are always within the 50% more segregated spaces.

In terms of space-type, the yard is found as a b- (18%), c- (29%) or d-type (53%). When the yard assumes a b- type, the living sector operates as a distributor. The living and the service sectors are mostly found within the same ring (82%), as a c- or d-type. In the remaining, the service sector is found as an a-type and the living sector as a b- or c-type. The circulation sector is also found in three different space-types: b- (23%), c- (65%) and d- (12%). The sleeping sector and the terrace are found as a-types. There is only one exception (C5S1) of a sleeping sector being found as a c-type of space. It refers to a case where this sector is non-continuous and part of it is embedded in a ring, adjacent to circulation spaces and to the yard.

5. Discussion and conclusions

Syntactic analysis was able to reveal some effective configuration regularities among the four sets of houses, confirming apparent features and emphasize

new, less apparent ones, such as:

- The separation of the public and private domestic functions, due to the spatial isolation of the living sector from the sleeping and service sectors.
- The seclusion of the terrace as a secondary family sector.
- The suitable location of the service sector, and the kitchen in particular; close to well-integrated dinning areas, but with a clear degree of segregation within the house.
- The double role of the circulation sector, whether promoting the isolation (maximising depth as a b- or c- type) or the access among sectors (as a d-type), through the strategic location of small transitional and threshold spaces, between functional sectors, which becomes clear in the convex break-up.
- At the level of public interface (dwellers/visitors) the spatial system is a movement generating system that supports social solidarity, and at the private level (interface between dwellers) it becomes a more controlled system.
- The separation of the living spaces from the sleeping and service spaces promotes a controlled experience of the house since visitors can be prevented from grasping the more private areas.

Space syntax also revealed the complex relations in the house and the logic underlying the spatial structure and the relations between functions:

- Set 1 and 2 systems are mainly movement-based systems that provide a multiplicity of movement choices between the interior and the exterior spaces of the houses. This because the main public spaces, such as the living/dinning spaces and the yard tend to be d-type spaces, lying at the intersection of the major rings in the system. (type of spaces mean% Set 1: a-=34%; b-=21%; c-=33%; d-=12%; Set 2: a-=20%; b-=17%; c-=40%; d-=23%).
- Set 3 and 4 systems loose part of their ringiness (Set 1: mean sl=1.04.; s=.104; min=.84; max=1.25; Set2: mean sl=1.16; s=.02; min=1.15.; max=1.17; Set3: mean sl=1.03; s=2.5; min=1; max=1.05; Set4: mean sl=.995; s=7.7; min=.809; max=1.15). Nevertheless, Set 3 and 4 become more controlled by means of the transformation of d-type of spaces into b- and c- types which means more segregation and control in terms of the social character of the domestic space (type of spaces mean% Set 3: a-=40%; b-=25%; c-=20%; d-=15%; Set 4: a-=44%; b-=28%; c-=19%; d-=9%). Systems 3 and 4 also become more sequential, as it is clear in the justified graphs, where movement becomes more programmed. The higher levels of integration within the whole system tend to move to the centre of the houses thereby increasing the segregation of the private areas. The yard is still on the shallowest levels, thereby being an inevitable passage through the house. Although its integration value

decreases, it is arranged to promote a controlled experience of the house, i.e., a space where visitors could be received without direct contact with the rest of the house.

In summary, syntactic analysis yielded positive answers to the two research questions outlined in Section 4, thereby achieving the two goals stated in Section 1:

1. Space syntax sector analysis is consistent with the division of the house on the first floor into four functional zones and circulation as proposed in the grammar. It revealed some cases of functional ambiguity, that is, spaces that can either be considered part of one zone or part of another. For instance, in the layout shown in Figure 2, the bathroom is included in the sleeping zone from the grammar viewpoint, but it can also be considered as part of the living zone from the space syntax viewpoint. This ambiguity can be explained by the shape rules as resulting first from the dissection of the sleeping zone to create a bathroom, and then by the erasing of the wall between the living zone and the circulation to facilitate the access of the bathroom from the living room. Therefore, it space syntax is consistent with the grammar.

2. Space syntax also confirmed that the designs in the corpus (Sets 1 and 2) and the new designs (Sets 3 and 4) present very similar syntactic structures, thereby supporting the idea that they are in the same style. In other words, the language of designs created by the grammar seems to be stylistically compliant. The new designs are, nevertheless, less complex than the corpus as they present a more clear separation among functional zones. This can stem from the satisfaction of user requirements, which supports the idea that the grammar is flexible enough to generate customized designs. It can also be explained by the fact that the authors of these designs were less familiar with the grammar and, therefore, they were not as skilled as Siza in the manipulation of the rules to generate functional ambiguity. Functional ambiguity is important because it permits to satisfy two or more

► Figure 10. The revised contents of the description with space syntax features included as topological features.

Quality	Function	Spatiality		
		Spatiality	Capacity (dwelling)	$\alpha_{10\text{-}13}$
			Capacity (spaces)	$\alpha_{10\text{-}13}$
			Articulation (spaces)	$\alpha_{10\text{-}14}$
			Spaciousness (dwell. & spaces)	$\alpha_{15\text{-}16}$
		Topology	"Adjacency"	α_{17a}
			Depth	α_{17b}
			Contiguity	α_{17c}
			Control	α_{17d}
	Aesthetics	Proportion		α_{22}

otherwise conflicting functional requirements. For instance, in the example above, the bathroom serves both the living room and the bedroom.

Following the conclusions above, we suggest adding space syntax analysis as features in the description as shown in Figure 10. The idea is to use these features in the evaluation function together with topological user requirements when generating designs to ensure that they possess the same syntactic features detected in corpus designs. Thus, topology would include one user-controlled feature, "adjacency", defined as the relation between any two spaces (e.g. away, close, adjacent, window, door, passage, and merged), and three syntactic features: depth, contiguity, and control. Depth is the topological distance of one space to all the others. Contiguity is the number of connections of a space to adjacent ones. Control takes into account relations between a space and its immediate neighbours. For instance, it indicates whether a space is accessed through another space. The use of syntactic features would control the spatial configuration of the solutions, by imposing additional restrictions on the top of user-prompted requirements. In practical terms, space syntax would permit to characterize the adjacency graphs generated by Duarte's grammar in terms of those syntactic features. This would enable the discursive grammar to evaluate and rank partial candidate solutions in terms of their spatial configuration at various steps during design derivation. The best partial design would then be selected so that it increased the likelihood of the grammar to generate a stylistically compliant design at the end.

Space syntax, however, is suitable to architectural layout design. The combination of grammars and space syntax can be extended to encompass other design contexts as long as syntactic features are relevant, such as urban design. Further design contexts will require different strategies to guarantee stylistic compliance. For a discussion of the difficulty in determining the universe of design solutions in a different design context, that of a traditional Chinese roof sections grammar, please see [13].

Future work will be concerned with the following issues: (1) the syntactic analysis of the design briefs used in the generation of the houses in Sets 3 and 4 to reveal the relation between the briefs and their solutions; (2) the syntactic analysis of houses designed by other authors at Malagueira without following the grammar, but following the regulations defined by Siza; and (3) the practical implementation of the extended discursive grammar proposed in this paper.

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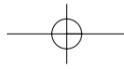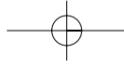
Diffusion of Creative Design: Gatekeeping Effects

Ricardo Sosa and John S. Gero