Combining grammars and Space Syntax:
Formulating, evaluating, and generating designs

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Teresa Heitor, José Pinto Duarte and Rafaela Marques Pinto
Instituto de Engenharia de Estruturas, Território e Construção do Instituto Superior Técnico, Portugal

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Abstract
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, evaluating, and generating 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.

Keywords
Discursive grammar, programming grammar, designing grammar, syntactic description, customised designs

teresa@civil.ist.utl.pt
jduarte@civil.ist.utl.pt
rmarquespinto@yahoo.com

1. Context

Previous work (Duarte 2001) has shown how description grammars and shape grammars, coupled with heuristic search can be used to generate designs within a language that match given criteria, thereby forming a discursive grammar. 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 design brief. The designing grammar takes the design brief and generates a design solution that satisfies the brief. From the technical viewpoint, both the description grammar 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 shape grammars have description and shape components.

The concept of shape grammar was invented by Stiny and Gips (1972). A shape grammar specifies how designs can be composed with shapes starting with an initial shape and then proceeding recursively by applying shape rules. The concept of description grammar was developed by Stiny to account for features of designs not covered by shape grammars. (1981). 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 set of heuristics is used to guide a 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 PHAPA-Malagueira. In this specific discursive grammar, the programming grammar, called PAHPA, adapts both the rules of the Portuguese housing program guidelines (Pedro 1999), and the rules of the Portuguese housing evaluation system (Pedro 2000). 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 customised designs; and on the other, one wanted to make sure that the grammar only generated designs in the Malagueira style. The other goal of this work was to use space syntax to determine whether a design is in the language thereby fixing the contents of the grammar.

Section 2 describes the discursive grammar. Section 3 presents the universe of design solutions. Section 4 summarises the results of the space syntax analysis. Section 5 discusses the results, and presents the conclusions, 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 (2000) performance criteria organised into a decision tree (Figure 1a). The description includes a variable description (α) and a fixed description (β). The features of the variable description are organised 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 exception is the quality level, which is updated by the programmer after the user changes other features. 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 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 by way of illustration (Figure 1b).

Figure 1: The contents of the description and a programming grammar rule

Features that are not manipulated by the rule are not shown in the rule.

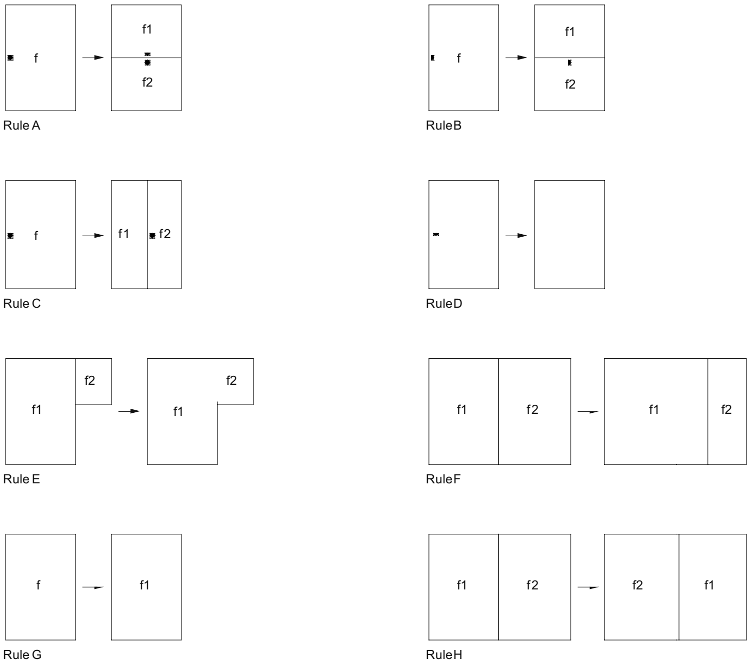
	(a) Description					(b) Rule
	Main	Groups	Features	Elemental features		g83: Adding a lavatory bathroom to the current list of spaces
VARIABLE	Constraints		Context	Lot	α_0	
				Urban context	α_1	
				Solar orientation	α_2	
			Typology	Customization	α_3	
				Users	α_4	$\alpha_4 \rightarrow \alpha_4$, $n_{users} = \alpha_4$
				Bedrooms	α_5	
				Quality	α_6	$\alpha_6 \rightarrow \alpha_6$, $q_{level} = \alpha_6$
			Morphology	Housetype	α_7	
				Floors	α_8	
				Balconies	α_9	
	Quality	Function	Spatiality	Capacity (dwelling)	$\alpha_{10\text{-}13}$	
				Capacity (spaces)	$\alpha_{10\text{-}13}$	$\alpha_{11} \rightarrow \alpha_{11}$ + < [lavatory, $\varnothing$, 0] > $\alpha_{13} \rightarrow \alpha_{13}$ + < [ba, id_{lv}, $\varnothing$, (hygiene), (lavatory, 80), (isolated, 100), (q_{level}, 0), w_{lv}, h_{lv}, a_{lv}] > $n_{bathrooms} = 2 \wedge q_{level} = max \wedge n_{users} \in \{6, 7, 8, 9\}$, id_{lv} = max(id) +1
				Articulation (spaces)	$\alpha_{10\text{-}14}$	$\alpha_{14} \rightarrow \alpha_{14}$ + sleeping (id_{lv}, a_{lv})
				Spaciousness (dwell. & spaces)	$\alpha_{15\text{-}16}$	$\alpha_{15} \rightarrow \alpha_{15}$ + < 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}), $- a_i / a_u + (a_i / a_u + a_{lv})$>
			Topology		α_{17}	$\alpha_{17} \rightarrow \alpha_{17}$ + < [id_{lv}, id_{f1}, on, 100] >
		Aesthetics	Proportion		α_{22}	
	Cost		Building		α_{24}	$\alpha_{24} \rightarrow \alpha_{24} + \alpha_{lv} \cdot cm2$
FIXED	Floor dimensions			Width	β_1	$\beta_1 \rightarrow \beta_1$, w_{lv} = w (ba, lv, $q_{level,}$)
				Height	β_2	$\beta_2 \rightarrow \beta_2$, h_{lv} = h (ba, lv, q_{level})
				Area	β_3	$\beta_3 \rightarrow \beta_3$, a_{lv} = a (ba, lv, q_{level})
					β_4	
	Section dimensions			Floor thickness	β_5	
				Floor height	β_6	
	Cost				β_7	$\beta_7 \rightarrow \beta_7$, cm2 = cost_m2 (q_{level}, covered)

2.2 The Malagueira Designing grammar

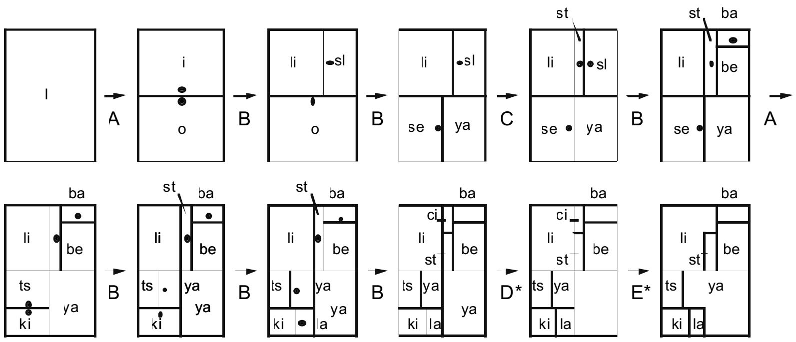
The designing grammar is concerned with the generation of a housing solution that matches the housing program by manipulating both symbolic and shape descriptions. To make it easier for the reader to understand the formal properties of the grammar, we show a very simplified set of shape rules and the partial generation of a layout using such rules in Figure 2.

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 house type. 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 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 two of such viewpoints—envelope and space. The description part includes the same categories used in the programming grammar, but we only display four—context, house type, zones, and topology. In Figure 4, we show the first six steps in the generation of a house, until a stair pattern is defined. It should help to clarify the relation between shapes and descriptions. We refer the curious reader to the detailed examples available on-line at http://www.civil.ist.utl.pt/~jduarte/malag/.



(a) Simplified shape rules



(b) Partial derivation

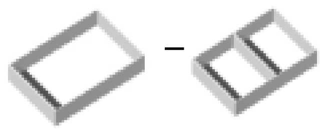
Figure 2: Simplified Malagueira shape rules

(a) and partial derivation of an existing layout (b). 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 times.

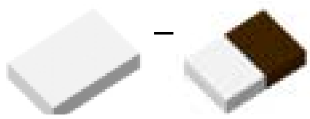
R5: Locate inside/outside zones on the first floor

Shape | View/Category | Algebra

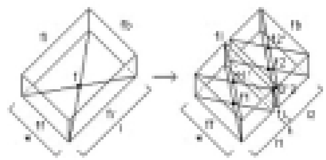
View/Category: Envelope (Walls) — Algebra: U_{33}



View/Category: Spaces (Rooms) — Algebra: W_{33}



Algebra: $U_{13}V_{03}$



f = l, ff = s, f1 = ou, f2 = in, l1 = 5.80 m ∨ l1 = 6.80 m

Description

α_1: Context — α_1 _ α_1

α_7: Housetype — α_7 _ α_7

α_{13}: Spaces — α_{14} _ α_{14} - < [l, (x_l, y_l, z_1), w_l, l_l, h_l, a_l] >
+ < [ou, (x_{ou}, y_{ou}, z_{ou}), w_{ou}, l_{ou}, h_{ou}, a_{ou}]
[in, (x_{in}, y_{in}, z_{in}) w_{in}, l_{in}, h_{in}, a_{in}]>

α_{17}: Topology

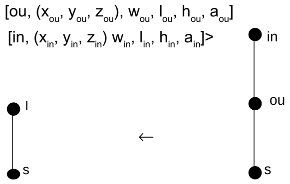
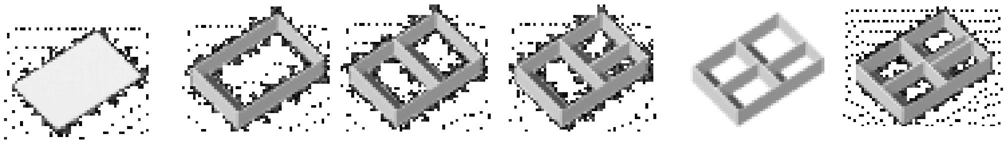


Figure 3: Simplified discursive rule combining shapes and descriptions.

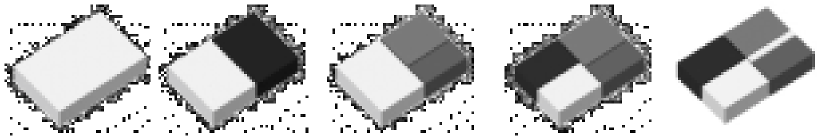
The shown rule includes only some of the views and some of the features in the original grammar and it depicts the case in which the outside zone is located at the front of the house, adjacent to the street—s. The feature “spaces” include [use (x,y) width length area] where use is the function associated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

	1	2	3	4	5	6

wall



Rooms



	1	2	3	4	5	6
	Ø					
α_1: Context	<s,h,h,h>	<s,h,h,h>	<s,h,h,h>	<s,h,h,h>	<s,h,h,h>	<s,h,h,h>
α_7: Housetype	nil	nil	frontyard	frontyard	frontyard	frontyard
α_{14}: Zones	Ø	< [l, (0.1, 0.1) 7.8, 11.8, 92.04] >	< [ou, (0.1, 0.1) 7.8, 5.8, 45.2], [li, (0.1, 6.1) 7.8, 5.8, 45.2], >	< [ou, (0.1, 0.1) 7.8, 5.8, 45.2], [li, (0.1, 6.1) 3.8, 5.8, 22.1], [sl, (5.1, 6.1), 3.8, 5.8, 22.1] >	< [se, (0.1, 0.1) 3.8, 5.8, 22.1], [ya, (4.1, 0.0) 3.8, 5.8, 22.1], [li, (0.1, 6.1) 3.8, 5.8, 22.1], [sl, (5.1, 6.1), 3.8, 5.8, 22.1] >	< [se, (0.1, 0.1) 3.8, 5.8, 22.1], [ya, (4.1, 0.0) 3.8, 5.8, 22.1], [li, (0.1, 6.1) 3.8, 5.8, 22.1], [sl, (5.1, 6.1), 2.8, 5.8, 16.2] [ci, (4.1, 5.1) 0.8, 5.8, 4,6], >

α_{17}: Topology

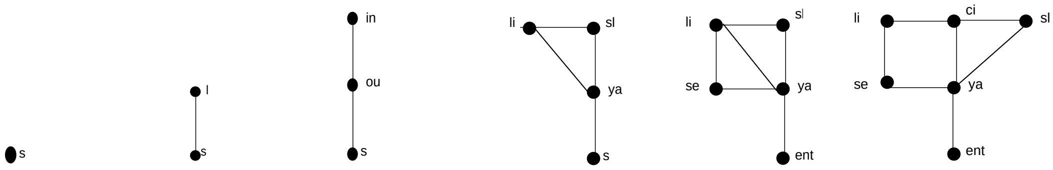


Figure 4: First six steps in the derivation of a house within the PAHPA-Malagueira grammar. The feature "context" is <front, left, right, back> where front, left, right, and back indicate whether the lot is bordered by a house—h, or a street—s on each of its four sides.

3. Universe of Design Solutions

Designing the grammar created a paradox. On the one hand, one needed a grammar that generated a large set of design solutions to increase the potential of generating customised 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. To overcome this paradox, three steps were followed in the design of the grammar. The first step was to develop the exhaustive set of rules that could be derived from the compositional principles of dissecting and concatenating rectangles. The corresponding universe of design solutions is partially illustrated 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. 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 ◦ are patterns considered in the final grammar. The remaining patterns were excluded from the final grammar for a number of reasons. 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 was not always available. Second, it was time-consuming. 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 design was in style.

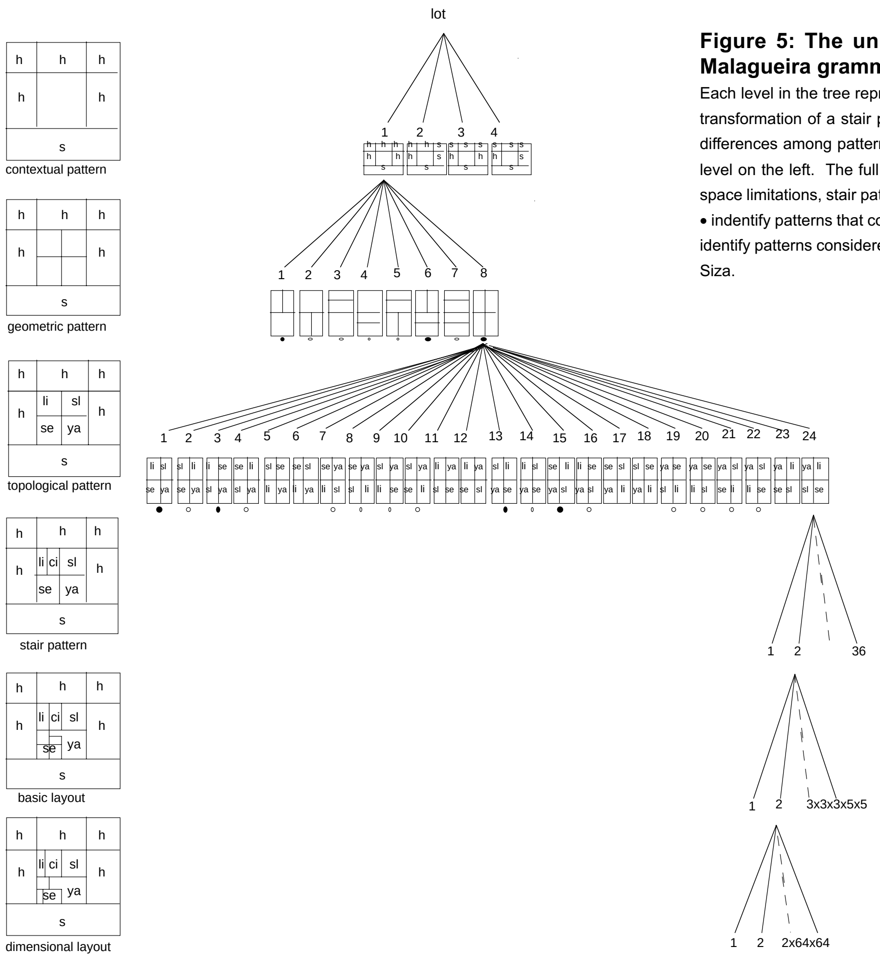


Figure 5: The universe of potential solutions in the Malagueira grammar.
Each level in the tree represents a single step in the derivation, except for the transformation of a stair pattern into a basic layout. To make it apparent the differences among patterns on different levels, one pattern is shown on each level on the left. The full set of patterns is diagrammed on the right. Due to space limitations, stair patterns and basic patterns are not shown. The symbol • indentify patterns that correspond to houses designed by Siza. The symbol ° identify patterns considered in the final version of the grammar but not used by Siza.

4. Space Syntax

4.1 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 shape grammar rules used to generate both existing and new houses. 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). 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).

Two main issues were addressed:

(1) The shape grammar organises the functional space into zones. Is the shape grammar confirmed through syntactic analysis?

(2) Does the syntactic analysis of new houses relate to the syntactic analysis of Siza's?

Configurational properties are analysed through the convex dimension according to space syntax techniques: representing spatial complexity by means of convex partitioning (convex map) and justified graphs, taking the exterior as the root. The convex data is examined by exploring syntactical attributes, by observing the most integrated spaces and by locating the configurational centre of the house (integration core), defined by the set of 20% most integrated spaces.

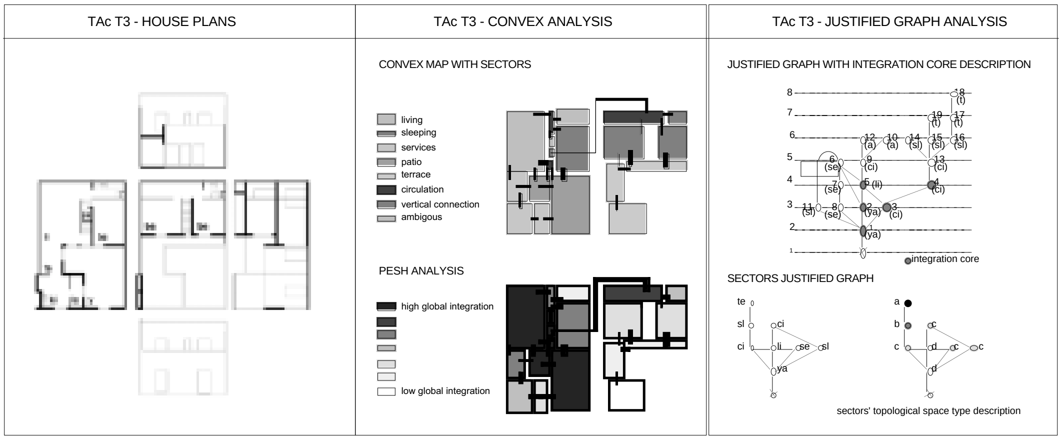


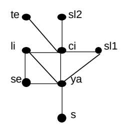
Figure 6: Space Syntax analysis of House type: example TAc T3

The graph description considers the topological size (number of nodes), depth, and the topological types of space by which they are formed. As shown in Figure 6, Hillier (1996: 321) identifies 4 topological types of spaces: -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). We assessed the space-use condition based on the complemented configurational analysis of the domestic functional model using a 'sectors analysis' technique as defined by Amorim (1999). Functional sectors were labelled yard; living; services; sleeping; circulation; and terrace - according to designations assigned in PAHPA-Malagueira grammar to zones.

4.2 Analysis

The grammar rules define adjacency features concerning the domestic functional organisation as described in Figure 7. The corresponding graph shows 8 nodes and 10 links forming 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 one or through the yard. The terrace is accessed through the circulation. 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 being apparent that it plays an important role in the functioning 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 former is included in, one ring being a c-type space while the others are a-type spaces when it promotes the access to the terrace.

As Hillier (1996) has shown, d-type spaces are depth minimisers, therefore the yard, the living and the circulation sector have the role of globally integrating the system. The link between the yard and the service and the living sectors supports the social activities held in the house while promoting the integration of major domestic spaces within the system.



	syntactic description: rank order
integration rn	yard = circulation > living > sleeping > services> terrace
control	circulation > yard > living > services > sleeping > terrace
connectivity	circulation > yard > living > services > sleeping > terrace
r3	yard = circulation > living > sleeping > services> terrace

Figure 7: Syntactic description of the functional organisation considered in the grammar

The results of the analysis are summarized in Figures 8 and 9 and in Table 1, at the end of this section.

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

This set comprises 24 houses of which 21 are grouped in 5 types of four or five variations each, depending on the number of bedrooms. The remaining 3 houses constitute single cases of variation t3 (3 bedroom spaces); variation t3 (3 bedroom spaces) and variation t4 (4 bedroom spaces), since they are not included in any type.

The topological size of these houses ranges from 13 to 24 convex spaces, with an average of 19 spaces. In 20 cases (83%), the sleeping sector is the largest sector, with an average of 6 convex spaces per house, ranging from 3 (types Ca and Da - t2) to 8 (type Bb -t5). Circulation has an average size of 5 spaces, with a maximum of 7 and a minimum of 2. 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 (series Da and Ac – t2) to 3 convex spaces (types Ab, Bb, Ca, Cb and E). The yard is mostly composed of 2 spaces. 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, taking the exterior as the root, show an average of 8 levels, ranging from 6 to 10 levels. They reveal a complex structure, mostly governed by rings-in-rings on the ground floor becoming 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 rang from 0.624 (s = 0.160) to 0.971 (s = 0.270), with an average value of 0.827 (s = 0.081). Using the coefficient of variation (s/$\bar{x}$) as a measure of spread, they range from 0.160 to 0.300, and one may conclude that the size does not affect the integration values. Circulation assumes a central position in the overall configuration of the houses. The highest values of integration tend to be concentrated in these spaces or in the adjacent ones. The ground floor circulation space is the most integrated space in 17 houses and the remainder show the highest value of integration positioned in adjacent spaces: the yard (4 houses), the staircase (3 houses) or the living-room (1 house). The integration core tends to be positioned slightly over the medium depth level inside the houses. It occupies 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%). In terms of composition, it always includes circulation spaces as well as living spaces. The yard, as part of the integration core, is present in 19 houses (80%). The sleeping and the service spaces tend to be secluded from the integration core; the former is only in 4 houses (17%) and the latter in one. 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 houses (75%), in the remaining 25%, the yard assumes the central position. In all cases, the sleeping and the services sectors show the most segregated values. In terms of space-type, the yard is found as a b- (21%), c- (25%) or 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 in 75% of the houses, being found as a b- and c- type in 8 cases (33%); as an a- and c-type in 7 cases (29%) and as an a- and b-type in 3 cases (17%). In the remaining 6 houses (25%), it forms a continuous sector being a-type. The predominance of a-types (67%), that are dead-ends in the system, assigns a purpose of isolation to this sector. When the sleeping sector is found as a b-type of space it is always related with the access to the terrace, which is always found as an a-type. When sleeping spaces are embedded in a ring (as c-type), they are always adjacent to circulation spaces and to the yard, promoting the spatial isolation of this sector relatively to the others sectors in the ring.

Set2: Existing houses designed by Siza's collaborators (2 houses)

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

House Ad t4 shows a pattern similar to the previous ones: 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 (horizontal and staircase), the living/dining room and the kitchen. The sectors 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 with a multiplication of both the living and the circulation spaces. The circulation sector is the largest one (9 spaces) followed by the living (6 spaces) and the sleeping sectors (5 spaces). 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 and 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 being positioned biased towards the shallowest levels. The sectors 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 to t5; C1_2 - variation t4 and t5) and the remaining are single cases of variations t3 (1), 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 of 8 convex spaces per house, ranging from 6 (t3) to 11 spaces (t5). It is followed by the circulation sector - with an average size of 5 convex spaces, ranging from a maximum of 8 to a minimum of 3) - and the service sector - with an average size of 4 convex spaces, ranging from 2 to 5. The living sector has an average of 2 convex spaces, ranging from a single living/dining room to 4 convex spaces. The yard is mostly composed of 1 single space. The terrace is only present in 7 houses (40%), with one 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 houses' configurations, 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 ground floor circulation space. The integration core tends to be deep 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 spaces and the terrace 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-space 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 spaces. In the remaining, the service sector is found as an a-type of space and the living sector as a b- or c-type of space. 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-type of spaces. 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.

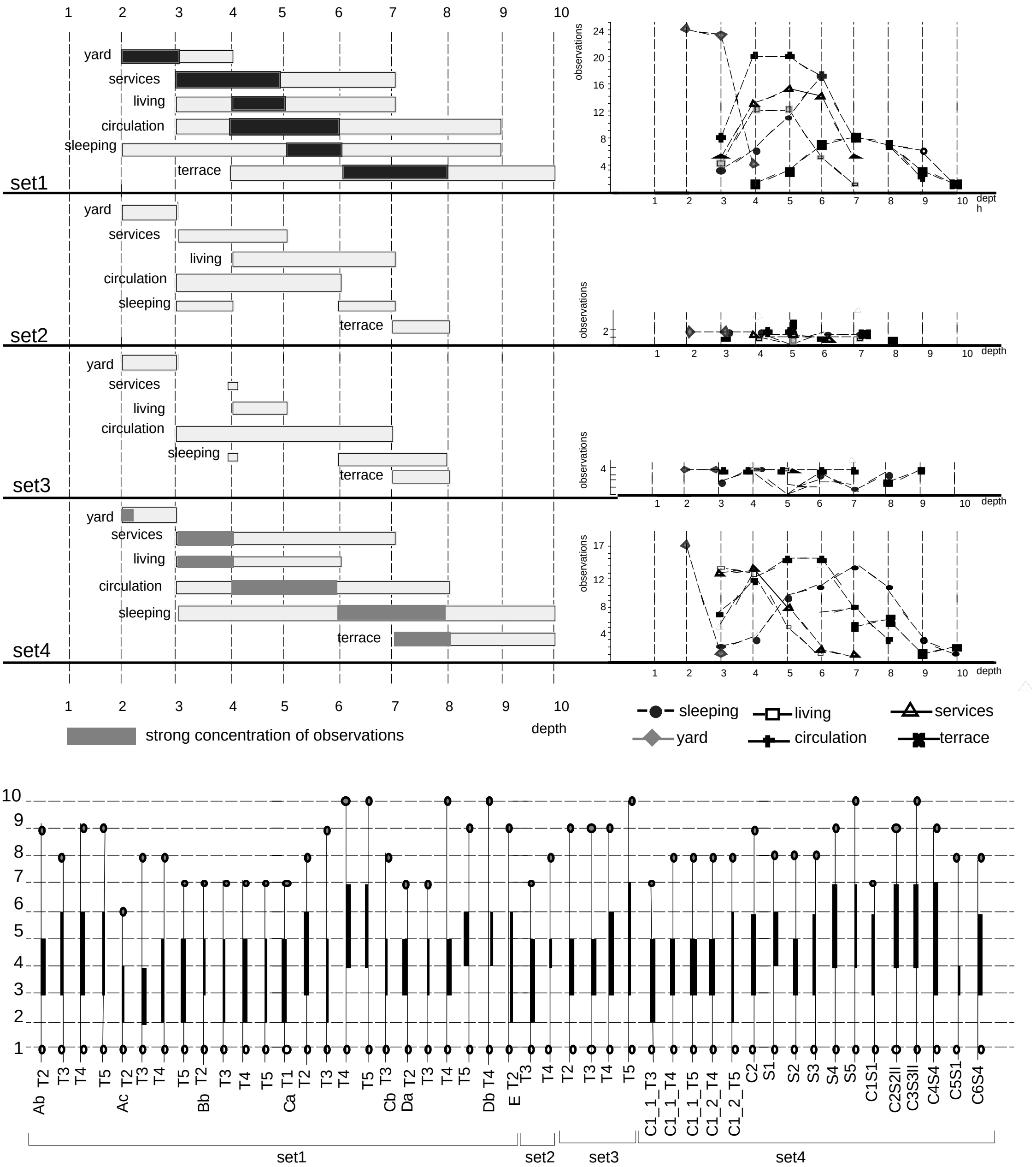


Figure 8: Sectors depth distribution

(a) _and integration core

(b) _number of levels and its relative position in the justified graph

Figure 9: Set 1 to 4: sector graphs

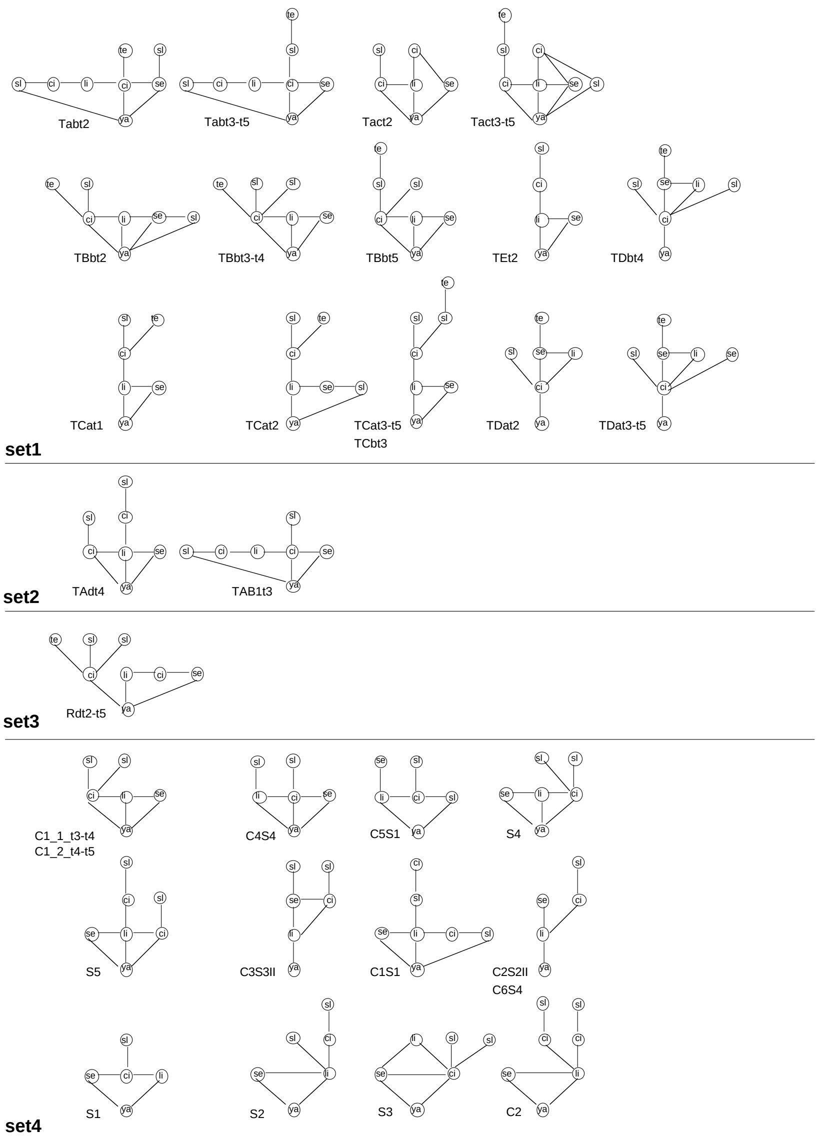


Table 1: Summary of syntactic analysis result

	set1	**set2**	**se3**	**set4**
sample	24	2	4	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>sl>se>li>ya>te	ci>li>sl>se>ya>t	ci>sl>se>li>ya>te
depth				
mea	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%)

Space types				
a-				
mean; (s)	34%; (.09)	20%; (.01)	39%; (.02)	45%; (.06)
max ; min	56%; 27%	21%; 20%	42%; 37%	57%; 27%
b-				
mean; (s)	21%; (.13)	17%; (.10)	25%; (.02)	28%; (.09)
max; min	46%; 9%	25%; 10%	26%; 21%	47%; 9%
c-				
mean; (s)s	33%; (.13)	41%; (.18)	20%; (.005)	19%; (.11)
max ; min d-	52%; 0%	55%; 28%	21%; 20%	39%; 0
d-				
mean; (s)	12% (.19)	22% (.12)	16% (.004)	8% (.06)
max ; min	31%; 0%	32%; 15%	15%; 15%	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%)
space 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-

5. Conclusion

Syntactic analysis was able to reveal some effective configurational regularities among the four sets of houses, confirming apparent features and emphasising 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 dining 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 approaching 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/dining 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 lose 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 issues outlined at the beginning of Section 4:

(1) Space syntax sector analysis is consistent with the division of the house on the first floor into four functional zones plus 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, 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 grammar. 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 makes it possible to satisfy two or more 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, 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.

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

Quality	**Function**	**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}

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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