
Available from: http://dx.doi.org/10.1177/0265813516665618

© 2018 Reprinted by permission of SAGE Publications.

Accessed from: http://hdl.handle.net/1959.13/1391214
A Justified Plan Graph (JPG) grammar approach to identifying spatial design patterns in an architectural style

Ju Hyun Lee¹, Michael J. Ostwald¹ and Ning Gu²

¹School of Architecture and Built Environment, The University of Newcastle, Newcastle, Australia
²School of Art, Architecture and Design, University of South Australia, Adelaide, Australia

Abstract
This paper presents a hybrid approach that selectively merges aspects of both the theories of Shape Grammar and Space Syntax to investigate spatial design patterns. The paper describes the development of a generic Justified Plan Graph (g-JPG) grammar. This grammatically nuanced, syntactically derived approach is then demonstrated through a more specific JPG (s-JPG) grammar to identify spatial design patterns in the rural domestic architecture of Glenn Murcutt. The results are then discussed in terms of Murcutt’s architecture from four perspectives: grammatical transformation of syntax, epistemological questions, similarity or disparity and finally in terms of JPG variations. The findings of this paper suggest that the combined analytic approach facilitates the exploration of both the grammatical and syntactical genotypes of sets of architectural designs.

Keywords
Shape grammars, space syntax, spatial analysis, design methods, Justified Plan Graph grammar
INTRODUCTION

The earliest technologically-enabled, computational approaches to architectural analysis and generation are conventionally traced to the 1960s and 1970s (Alexander, 1964; March and Steadman, 1971; Steadman, 1983). Amongst the most enduring theories that were proposed at this time were two that pursued complementary, but divergent agendas. The first of these focused on architecture as form, examining the logical relationships between elements in the two or three-dimensional shape of a building (Stiny and Gips, 1972). The second was more concerned with spatial relations, regardless of the forms that defined them (Hillier and Hanson, 1984). Using the linguistic analogies of the era, these two were described, respectively, as pertaining to the grammar of architectural shape and the syntax of architectural space. Applications of the two were similarly diverse, the former being applied to develop rules to describe or generate a design, whereas the latter was used to understand spatial topologies and social relations. Both theories have since been extensively refined and promulgated through many projects and publications (Prats et al., 2006; Rashid, 2012). However, despite their apparent complementarity, they have rarely been successfully combined to consider both the grammatical and syntactical features of architecture.

One of the few previous examples that exist of the combination of these methods commences by developing a Shape Grammar which defines all of the form-generating rules that are apparent in a particular set of works. A Space Syntax technique is then used to decide which combinations of these rules are most significant in the set (March, 2002; Heitor et al., 2004). Such an approach starts with a grammatical process for generation and ends with an analysis and evaluation using graph theory. Importantly, by adopting shape as the starting point this approach effectively privileges form over function. Çağdaş (1996) proposes an alternative method wherein an architectural language is formed by both syntactical and formal analysis.
and its vocabulary is then transformed into a Shape Grammar. Çağdaş uses this method to define the space of possible designs using a syntactic system.

In contrast to this past research, the present paper describes a new approach that identifies both the grammatical patterns of the syntactical properties of architecture and the syntactical patterns. The rationale for this method, and the advantages of combining both grammatical and syntactical approaches to analysis, are illuminated in a case study of ten rural houses by Pritzker Prize winning architect Glenn Murcutt. Previous computational studies of Murcutt’s domestic architecture (Hanson and Radford, 1986a; 1986b; Ostwald, 2011a; 2011b; Vaughan and Ostwald 2014) have identified significant spatial and formal properties, but have never been able to combine the two and thereby characterize his architectural style and its development. The new approach described in this paper adds a grammatical dimension to the syntactical analysis of combined social and spatial relationships. Through this process, the contribution of both space and form to the set of potential design outcomes in a particular style can be characterized. Furthermore, because the method is innately grammatical, it also provides a potential generative sequence or logic which, while not necessarily the one used by the architect, still provides a unique insight into the broader range of formal possibilities that may have been available to Murcutt. In the present paper, the results of this approach enable us to critically understand Murcutt’s architecture in terms of four perspectives: grammatical transformation of syntax; epistemological questions; similarity or disparity; generating variations.

This new way of thinking about architectural spatial patterns involves a reconceptualisation of the architectural plan in terms of functional zones and their relationships that are determined prior to any form generation. These zones and relationships can be schematically represented using nodes and links. The former (nodes) comprising the set of functionally
defined spaces or zones required of a building and the latter (links) being the connections between them. Although there are differences, such a schema is conceptually reminiscent of the convex space analysis technique that analyses visually defined zones using a justified permeability graph (Hanson, 1998) or the functional analysis of space using a Justified Plan Graph (JPG) (Ostwald, 2011a; 2011c). Both of these related approaches have also been used in the past to identify the spatial design patterns present across sets of designs (Lee et al., 2013; Bafna, 1999; Hanson, 1998; Ostwald, 2011b), confirming the usefulness of graph-based (node and link) logic for this purpose.

This new, syntactically-derived and grammatical approach to analysing architectural spatial patterns starts by working towards the production of a “generic shape grammar” (Costa and Duarte, 2015), which consists of a set of algebraic rules that are able to be used to create any type of JPG. Hence, the paper firstly develops and illustrates the so-called “generic JPG (g-JPG) grammar”. Designers and researchers can then customise the g-JPG grammar into a more specific JPG (s-JPG) grammar, which identifies distinctive properties of a family of designs or of a style. The second half of the paper applies a s-JPG to a distinct stylistic set of works by Murcutt, presenting the analytical results and a discussion of their implications. This paper concludes by outlining the contribution of the research and further directions.

The present research has several practical limitations including its focus on the analysis of architectural plans (rather than, for example, sections or elevations). Furthermore, to limit the scope of the study, the paper does not consider the full social implications of the syntactical approach or the complete set of all possible procedures required to apply the g-JPG grammar to a much larger or more complex body of work. Notwithstanding these practical limitations, the paper’s intention is to demonstrate a computational approach to grammatical and syntactic analysis, using a distinctive, but still relatively concise method.
A GRAMMATICAL, SYNTACTICALLY-DERIVED APPROACH

Conceptual Foundations

The design process is conventionally conceptualised and explained as a progressive or staged sequence of actions with only a limited number of recursive steps (Lawson, 2005). The recursive stages are typically regarded as either corrective, being used to return a design process to its ideal path, or to assess the degree to which a design fulfils its functional or aesthetic goals (Anderson, 2011). Furthermore, when the building that results from the design process is analysed, it is usually understood as exhibiting the architect’s true and unexpurgated design intention, regardless of how it was actually produced (Pressman, 2012). Thus, even if the process was intuitive or non-linear, the resultant building is taken to represent a reasoned, consistent or optimal set of design decisions by an architect. This assumption is at the core of many computational models of design analysis and generation. Such approaches accept that design is not necessarily a straightforward process, but argue that architecture can, nevertheless, be usefully examined on this basis.

An example of this way of thinking is found in the Shape Grammar method which specifies a set of rules delineating how a design can be composed from shapes, by starting with an initial one and then proceeding iteratively by applying rules or modifiers to that shape until an end-state has been reached (Knight, 1994). In this process, form-making is assumed to be a rigorous and possibly sequential procedure. Such a generative model of compositional design is central to many famous grammatical studies (Çağdaş, 1996; Koning and Eizenberg, 1981; Stiny and Mitchell, 1978). Thus, whereas designs may arise in a manner which is independent of a logical sequence of operations (Stiny, 1990), Shape Grammar reasoning of this kind allows researchers to rigorously capture possible generative processes to design (Economou, 2000; Knight, 2003).
Space Syntax methods highlight the relationship between spaces and the social patterns which necessitate or sustain such relations (Hillier and Hanson, 1984). These same spatial relationships could also be understood as arising from stages in the design process which respond to the need to provide socially compliant spatial relations. Thus, combining a grammatical method with a syntactical variation, provides a means of highlighting rules that are derived from a building’s space and which describe how it might have been, or could be, logically generated.

This subtle shift in reasoning, which is central to the JPG grammar method presented in this paper, is reflected in models of the design process which use “bubble diagrams” and “proximity matrixes” to determine the basic spatio-functional relationships in a plan (Balmer and Swisher, 2012; Seonwook, 2012). It further follows that the process of generating and defining a set of functional zones in a plan, along with their levels of connectivity, could be regarded as a general design stage. This alternative way of conceptualising the process is especially important for the design of housing, where certain patterns of spatial relations reveal the basic social values or aspirations of a region or an architect (Hanson, 1998; Hillier, 1999). Such studies and models tacitly assume that *form* follows *function*, or at least that decisions about the broad functional zoning of space, coupled with those about permeability (connections between spaces), typically precede any decision about the shape of a building.

The idea of viewing syntactical relationships grammatically is an especially important one for design. For example, research into spatial relations often relies on the development of an “inequality genotype”, being a list of programmatically defined spaces that are ordered in accordance with their integration values, as derived from a JPG (Bafna, 2001; Hillier et al., 1987). Along with the statistical archetype (an average condition derived from a set of genotypes), the inequality genotype offers a means of understanding the recurring
relationship between functional elements in a set of architectural plans (Bafna, 1999; Ostwald, 2011b; 2011c). But, if the functionally-defined JPG is reconceptualised as a set of rules that can be used to formally define spatial relations, then the inequality genotype and the statistical archetype could be thought of as reflecting the rules which are most dominant in a set. From this position it is possible to review the JPG not just syntactically, but grammatically. The sequence and frequency of the rule application as well as the generative results and alternatives that arise from the application, as illustrated in the grammatical analysis, provide a unique insight into the possible formal design operations and outcomes that may have been available to the architect. Such outcomes are especially beneficial for architectural historians and theorists with an interest in understanding and interpreting different stylistic approaches to design. This conceptual shift in thinking about design syntax and grammar is at the core of the new approach presented in this paper. In the following sections, the generic version of the approach is presented.

THE JPG GRAMMAR

Nodes and Links

The two key operations that underpin the JPG grammar approach — configuring functional zones (nodes) and their connectivity (links) — are described in Table 1. The first involves identifying significant spatial groupings and defining them as nodes. While in syntactical research this process is traditionally focussed on identifying convex spaces or room functions, the present paper adopts Amorim’s (1999) concept of dwelling ‘sectors’ to more broadly define zones within a plan. The second operation defines the connectivity or relationship between these sector nodes, typically expressed in a graph. In combination, the sector nodes and links are used to create a type of JPG, the structure of which reflects both a type of spatial relationship (accommodating, in a simplified way, both permeability and
adjacency) along with the sequence (a reflection of underlying rules) in which decisions about sector relationships (expressed in a JPG) are made.

**Table 1. Notations of the two key concepts: node and link.**

<table>
<thead>
<tr>
<th></th>
<th>Node</th>
<th>Link</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Definition</strong></td>
<td>Convex spaces (sectors)</td>
<td>Spatial connection (adjacency)</td>
</tr>
<tr>
<td><strong>Description</strong></td>
<td>C, H, P</td>
<td>(C, H), (H, P)</td>
</tr>
<tr>
<td><strong>Graph</strong></td>
<td><img src="image" alt="Graph" /></td>
<td><img src="image" alt="Graph" /></td>
</tr>
</tbody>
</table>

**Formulating the JPG Grammar**

The various approaches to developing a permeability graph from an architectural plan are well documented (Hanson, 1998; Hillier and Hanson, 1984; Ostwald, 2011c). They typically commence with the partitioning of a plan, using a predetermined protocol, into a series of spaces and the connections between them. The protocol determines whether the analysis is of rigorously defined convex spaces (Hillier and Hanson, 1984) or programmatically defined areas (Bafna, 1999). The protocol also determines the nature of connections between each space (including different approaches for ‘trivial’ or ‘non-trivial’ loops) (Dawes and Ostwald, 2013). For the new approach described in this paper, nodes and links represent, respectively, ‘functional sectors’ and ‘adjacency’. This implies that instead of extracting convex spaces or programmatic areas from a plan, zones with similar programmatic needs are grouped into sectors. Furthermore, rather than defining doors as links in a graph, sector-based zoning defines a link representing adjacency; that is, at least one, but possibly multiple, direct connections exist between sectors. While a convex-plan-based approach of the JPG grammar could more explicitly consider visually defined spaces or permeability, in this paper it is
restricted to the consideration of relations between functional sectors.

Because connectivity between sectors is less clearly defined than it is between rooms or spaces, this approach is also informed by Hiller’s notion of four topological types of spaces (Hillier, 1999). Hiller explains that the a-type (cut-link) is associated with occupation, whilst the b-type (tree-link) is more relevant to movement. Ring-link nodes are divided into a single ring-link (c-type) and a multiple ring-link (d-type). These categories allow for different types of sector relations to be defined.

Once the graph of functional sectors and adjacency is prepared then the Total Depth ($TD$), Mean Depth ($MD$), Relative Asymmetry ($RA$), integration ($i$) and Control Values ($CV$) are calculated (Hillier and Hanson, 1984; Ostwald, 2011c). These mathematical values can be used to identify a genotype, or to support an understanding of a range of topological types (Heitor, et al., 2004; Ostwald, 2011b). For example, using only four domestic sector types (Exterior, Hall, Common and Private) it is possible to demonstrate three topological types (Figure 1). Each common sector node in this example is represented by C and located at the second order of depth (D2 in Figure 1). In each case, it has a different spatial relationship and the syntactic values depend on the number of nodes and links. The JPGs for plans (b) and (c) in Figure 1 are similar with the exception of one additional link. These differences are readily apparent in the mathematical results (Figure 1). From this syntactical review of the JPG, it is then possible to derive a series of rules that describe the graph grammatically.
A JPG consisting of nodes and topological links can be described using algebra, for example, 
\[ x \rightarrow x, y, (x, y), \] where \( x \) and \( y \) are nodes and \((x, y)\) is a link between the two nodes. Using this method, the typological links between every node in the sector-adjacency JPG can be coded as a series of rules. In this way, the JPG grammar can be regarded as a graph grammar that generates planar mechanisms. Graph grammars (Freudenstein and Maki, 1979; Li and Schmidt, 2004; Schmidt and Cagan, 1997) consisting of vertices (links) and edges (joints) deal with the structural and functional relations required for generating machine designs. These graphs are regarded as a source of information from which to generate plans (Grasl, 2012; Krstic, 2015) and three dimensional shapes (Lee et al., 2015). Thus, two grammars are needed to develop the JPG for plans or 3D shapes. In addition, Grasl and Economou (2013)
highlight the way in which shapes can be represented as graphs. They introduce a part-relation graph consisting of maximal lines and points to nodes (two different types of nodes), and relations to edges. This graph representation allows for the recognition of emergent shapes and the development of parametric shape grammars.

In contrast, in a JPG grammar the symbol of a vertex is a node representing a sector (or a convex space) and the edge is a link that connects between nodes. In order to code such a grammar, we draw on the work of Li and Schmidt (2004), which has parallels with context-free grammar codings (Hopcroft et al., 2006), to define four components: Grammar $G = (V, T, P, S)$, where $V$ is the set of variables (non-terminal), $T$ is the terminals, $P$ is the set of production (rules), and $S$ is the start symbol. Thus, the JPG grammar is represented by

$$G_{JPG} = (\{x, y\}, \{N, c, E\}, P, S),$$

where $x$ and $y$ are non-terminal symbols. Terminal symbol $N$ denotes a set of nodes, terminal symbol ‘c’ denotes a ‘core node’ (see $R_1$ and $R_2$ in Table 3) and terminal symbol ‘E’ denotes an exterior node (see $R_6$ and $R_7$ in Table 3). Similarly, $P$ is the set of production (rules) and $S$ is the start symbol. A JPG is described as a set of nodes and links and any graph, $g_a$, generated by applying the JPG grammar is represented by

$$g_a = (N, L),$$

where $N$ is a set of nodes and $L$ is a set of links represented as $(i, j)$ when $i$ and $j$ are nodes of the graph.

Four basic schemas are required for the JPG grammar to define the sectors present in a set of designs and to assign nodes. These four schemas in Table 2 are as follows, represented both in the generic JPG form and then a specific JPG variant for the Murcutt analysis later in the paper. There are two ways to define the nodes in the JPG grammar. The first is that designers
or clients assign nodes manually, which is described as ‘programming’ an invariable sequence in the architectural design process (Wade, 1977). The second involves the automatic generation of nodes that are numerically dominant in a set of designs or conversely those which are regarded as being dominant in the theoretical framing of these designs. This paper considers both approaches, but follows the second way in the example analysis in the following section.

**Table 2. Four schemas defining the sectors**

<table>
<thead>
<tr>
<th>Step</th>
<th>Schema</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Identify the set of functional sectors.</td>
</tr>
<tr>
<td>2</td>
<td>Group ‘visually enclosed’ convex spaces into a sector.</td>
</tr>
<tr>
<td>3</td>
<td>Configure transit (T) sectors. Transit spaces are intermediate zones between interior and exterior, or occasionally between two interior spaces.</td>
</tr>
<tr>
<td>4</td>
<td>Configure second functional sectors. If there are two or more spatially separated instances of the same functional sectors, each is separately numbered. This is because each functional sector can include multiple small spaces (alcoves, bathrooms, toilets, utility cupboards) within its larger grouping.</td>
</tr>
</tbody>
</table>

*Generating the g-JPG Grammar*

The JPG grammar commences by generating a core node (see (i) core node generation in Table 3). This core node, has a similar grammatical function of the ‘core unit’ (Koning and Eizenberg 1981). This step differs from the traditional graph grammar approach which is often used to solve mechanical design problems. To develop JPGs representing the spatial structures of architectural designs, decision making about a set of nodes can refer to one of the significant processes and also effects the application of the following rules.

**Table 3. Generic JPG grammar.** (Key: $L$ represents a level, $n$ indicates the location of a level, $S$ is the start symbol, $c$ is a label indicating a core node, $N$ is a set of nodes)
A g-JPG grammar consists of eight general rules which are illustrated in Table 3. Thus, a
shape (JPG) is divided into parts to form a description (Stiny, 1994). The first step commences with the core node generation. Each core node, like the ‘head’ of a phrase (Chomsky, 1995; Corbett et al, 1993), may also determine the syntactic type of the graph because it usually develops the structure of the JPGs. The grammar, furthermore, considers both local and global syntax of JPGs which allows for the investigation of the two types of social relations (Hillier and Hanson, 1984) – the first one is the relation between inhabitants and the second is between inhabitants and visitors. After the g-JPG grammar develops local connectedness at a topological level (local configuration), the global connection step commonly deals with the relationships between the exterior and interior topologies. In the grammar an exterior sector node (E) represents the outside world signifying the potential for ingress and egress relationships. The global connectedness for a building can then be extended between two different levels or storeys. Thus, the grammar facilitates the development of three syntactic patterns – the head of a graph, local and global syntax – that may not be easily discerned in a more straightforward graph developed just from plan layouts.

The g-JPG grammar itself is, by definition, able to be applied to virtually any plan. In contrast, based on the algebraic rules in Table 3, “specific shape grammars” (Beirao et al., 2011; Costa and Duarte, 2015) can be developed using non-terminal symbols representing sectors in a set of cases. The specific-JPG (s-JPG) grammar can capture the spatial design patterns in the set of designs as well as generate variations maintaining stylistic, syntactic consistency. Furthermore, to enhance the usefulness of the process, the JPG grammar could adopt a wider set of rules including ones for the modification of a core node and the subtraction of nodes and links, however, this is beyond the scope of the present paper.
CASE STUDY

Developing a s-JPG grammar

The g-JPG grammar approach (Table 3) is applicable to analysing a distinct architectural style, the works of an individual designer, or to a socially or culturally defined building type. An application of the grammar is able to reveal and articulate the common characteristics of a set of architectural works, in terms of their syntactic structures, as well as to generate a family of designs. Taking as its starting point the generic method (described in the previous section) the paper now develops a specific JPG grammar (s-JPG) from a distinct set of Murcutt’s architectural works. The set comprises ten cases; single-family houses, on isolated rural sites, which were constructed between 1975 and 2005. Each house has a modernist, linear, pavilion plan, often with an extensive external, covered veranda space. Figure 2 illustrates each of the ten cases in isometric projection along with their JPG diagrams.

The development of the s-JPG grammar firstly involves defining a set of nodes in a design from possible sector nodes, eg., H, C, P, T and G (see Table 4). For Murcutt’s domestic buildings, including the second functional sectors, the node set, $N$, which is used to generate the ten cases, is represented by

$$N = \{E, H, C, P, T, G, C^2, P^2, T^2\}.$$
Table 4. Four schemas defining the sectors for Murcutt’s rural domestic architecture

<table>
<thead>
<tr>
<th>Step</th>
<th>Schema</th>
</tr>
</thead>
</table>
| 1    | **Identify the set of functional sectors.**  
For the generation of Murcutt’s domestic designs, six functional sectors are required (C, P, H, G, T, E). |
| 2    | **Group ‘visually enclosed’ convex spaces into a sector.**  
The primary four sectors are: Common (C) areas, which include living rooms, dining rooms, foyers and kitchens; Private (P) areas contain bedrooms and bathrooms; Hall (H) includes corridors, hallways and other types of linking spaces; and Garage (G) is for the storage of cars, including workshops, laundries and service areas. |
| 3    | **Configure transit (T) sectors.**  
In Murcutt’s architecture, transit sectors are usually roofed and semi-enclosed, but are still open to weather conditions. |
| 4    | **Configure second functional sectors.**  
In Murcutt’s architecture, for example, a grouping of entry foyer, living room and gallery might be a common space (C), while in a separate part of the same plan an additional grouping of dining room, kitchen and music room, might be a second common space (C²). |
Figure 2. Isometrics and Justified Plan Graph (JPG) diagrams for the ten cases.
Figure 3 describes the syntax derivations that are grammatically segmented and generated through the s-JPG grammar. These are distinctive to the specific syntactic structure of Murcutt’s ten houses. While the nodes or links configured by each rule include the previous results that are a conditional part of each rule, Figure 3 only shows the derivations emerging from that rule to simplify it and it also omits the termination rule ($R_8$). The JPGs of cases are produced in the specific rule sets and they are described hereafter.

Figure 3. The syntax tree generated by each rule set of the specific Justified Plan Graph (s-JPG) grammar of Murcutt’s domestic buildings.
This first rule set ($L_0R_1$) of the s-JPG grammar transforms a start symbol ($S_0$) into a core node at the ground level ($L_0$). As for the family of Murcutt’s domestic buildings, the s-JPG grammar defines a sector including the main entrance as a core node because it is commonly located in the middle of the long-narrow form, as well as mostly linking to more than two sectors. In five cases a hall sector, $H_{C0}$, is regarded as the core node. In the other three a transit sector functions as the core node, $T_{C0}$. In the remaining two cases a common sector, $C_{C0}$, is the core node. Thus, $L_0R_1$ consists of three rules: $S_0 \rightarrow H_{C0}; S_0 \rightarrow T_{C0}; S_0 \rightarrow C_{C0}$.

The second rule set ($L_0R_2$) generates nodes and links adjacent to a core node. This rule set can be regarded to defining a syntactic head in a graph, which is one of the topologically significant steps in the grammar. In order to better understand the patterns of links generated by this step, the links are categorised into three main patterns (Table 5). There are three sets of links that connect from three core nodes, $H_{C0}, C_{C0}$ and $T_{C0}$, respectively. $L_0R_2$ in the s-JPG grammar tends to generate two or more links and therefore they sequentially form a tree-like structure in the resultant JPG. Seven cases each generate two links in this step, whilst only two cases (2 and 7) generate one link. The dominant rule set is $H_{C0} \rightarrow H_{C0}, C, (H_{C0}, C)$ and $H_{C0} \rightarrow H_{C0}, P, (H_{C0}, P)$. This implies that a hall sector node as a circulation zone tends to link to both common and private sector nodes, which would be a common pattern in domestic buildings. However, the feature that many links are generated from the common and transit sectors (as core nodes) can be understood as a more distinctive pattern, which may characterise a particular style element in Murcutt’s domestic designs.
Table 5. Three main patterns of links generated by $L_0R_2$.

<table>
<thead>
<tr>
<th>Core node</th>
<th>$HC_0$</th>
<th>$CC_0$</th>
<th>$TC_0$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Link</td>
<td>$(HC_0,C)$</td>
<td>$(HC_0,P)$</td>
<td>$(HC_0,T^2)$</td>
</tr>
<tr>
<td>$F$</td>
<td>5</td>
<td>4</td>
<td>1</td>
</tr>
<tr>
<td>Total $F$</td>
<td>9</td>
<td>5</td>
<td>5</td>
</tr>
</tbody>
</table>

Key: $F$ is the frequency of each link in the ten selected cases

$L_0R_3$ generates nodes and a second set of links starting from a node generated by the previous rule set to the adjacent nodes at the next depth, while $L_0R_4$ adds only links between non-core nodes at the same depth. $L_0R_3$ deals with seven sets of derivations including 17 nodes and links, while only three sets of rules – $H, C \rightarrow (H, C)$ and $P, T^2 \rightarrow (P, T^2); P, H \rightarrow (P, H); C^2, H \rightarrow (C^2, H)$ – are developed in $L_0R_4$.

After both steps, the configuration of links is locally completed to form a local JPG representing the interior topology. Two of the Murcutt cases (3 and 10) skip these steps, while a total of 21 links are generated in the other eight cases. In a manner which is similar to the pattern of the dominant links identified from the previous step, many links (11) generated by $L_0R_3$ also start from a common sector. The reason for this may be that the common and hall sectors are generally used as circulation zones. Thus, they naturally link to the other spaces and often form a chain or loop structure. It is interesting that these features are revealed sequentially by applying the s-JPG grammar. While applying $L_0R_2$ often produces a pair of links that transform the core node into a b-type (tree-type) node, the use of $L_0R_3$ develops a node at a much deeper level, up to the third depth in the graph (see cases 2 and 6). This process identifies another feature of Murcutt’s domestic designs, which rely on the use of long corridors or passages in parallel to form circulation loops. JPGs developed through $L_0R_3$ and $L_0R_4$ are ideal for investigating local relations between inhabitants. Before the global...
connectness in the JPG grammar, \( L_{0R5} \) adds nodes that are locally-isolated, but formally-connected in the level. Only two sets of rules \(-P \rightarrow P, P^2 \rightarrow P^2, G; P^2 \rightarrow P^2, G\) are developed in \( L_{0R5} \). The local configuration ends with the fifth rule set.

\( L_{0R5} \) in the s-JPG grammar generates the exterior node (E) and adds a link between a core node at the ground level and the exterior node, while \( L_{0R7} \) adds only links between non-core nodes at the ground level and the exterior node. In order to generate these for the ten houses, \( L_{0R7} \) develops specific links from five nodes (G, \( P^2 \), C, H) to an exterior sector node. \( L_{0R7} \) is concerned with inserting a sub-entrance into a node or a garage sector node at the first depth. \( L_{0R7} \) develops 18 links altogether in eight cases, with four of these cases (7, 8, 9, 10) adding the three links, producing \{(C, E), (P^2, E), (G, E)\} or \{(C^2, E), (H, E), (G, E)\}. The dominant rule set in \( L_{0R7} \) is generating three links through \( C, E \rightarrow C, E \), \( C, E \) and \( P^2, E \rightarrow P^2, E \), \( P^2, E \) and \( G, E \rightarrow G, E \), \( G, E \).

The particular application of \( L_{0R7} \) is divided between (C or \( C^2 \), E), five times, and (G, E), five times. This is reasonable in domestic buildings because a common sector and a garage often link to the exterior. However, applying \( L_{0R6} \) and \( L_{0R7} \) of the s-JPG grammar significantly changes the syntactic feature of each JPG. Most b-type (tree-type) nodes are transformed into the ring-type (c-, d-type) nodes after the global connection.

**Syntactically-derived analysis**

The JPGs created by applying the s-JPG grammar can be investigated using both graphical and mathematical means. The graphical analysis considers the topological types of spaces (Hillier, 1999), whilst the mathematical analysis (Table 6) highlights various derived results, including \( i \) and \( CV \), for the six basic sector nodes. This process also produces a type of
inequality genotype. In order to capture the pattern of each genotype, this paper deals with only the six basic functional sectors. To do this, $i$ values in the same functional sectors are averaged.

The hall sector in the first five cases and in case 9 has the highest integration value and the greatest control value, while the exterior sector in cases 6, 7, 8, 9 and 10 are most significant in the syntactic values of Table 6. The most integrated spaces in the ten cases also exert the highest spatial influence ($CV$) because they have relatively more links to the adjacent nodes. It is also natural that the common sector is typically the second most integrated space.

The new approach used in this paper highlights that syntactic patterns could arise from the most frequently generated links, in particular by $L_0R_2$ and $L_0R_3$. For example, links from each core node, generated by $L_0R_2$, are also to the most integrated spaces in four cases (3, 4, 5, 6). Cases 4 and 5 apply $L_0R_2$ three times to generate three different links connecting the core node. The generated JPG therefore has a ‘tree-like’ structure, which results in the most integrated node ($i = 10$) and the greatest degree of control ($CV = 1.67$ and 3.50, respectively) among other nodes. In the last four cases (7, 8, 9, 10) by applying $L_0R_7$ three times the exterior sector becomes the most integrated space. That is, the repetitive application of $L_0R_2$ or $L_0R_7$ plays an important role in the formation of the syntactic patterns.
Table 6. Summary of syntactic analysis result (*denotes a value used to replace an irrational result that occurs when MD = 1.00 in a plan).

<table>
<thead>
<tr>
<th>Type</th>
<th>Exterior</th>
<th>Hall</th>
<th>Common</th>
<th>Private</th>
<th>Transit</th>
<th>Garage</th>
<th>Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case 1</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>Case 2</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>Case 3</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>Case 4</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>Case 5</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>Case 6</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>Case 7</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>Case 8</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>Case 9</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>Case 10</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
</tbody>
</table>

The distributions of the overall sector nodes of the ten houses in relation to Hillier’s categorisation of the four basic types are as follows: a-type 28%, b-type 6%, c-type 38% and d-type 28%. Therefore, the ring-type (c-, d-type) sectors are the dominant ones in these selected houses. In three cases (1, 6 and 8) only ring-type sectors are identified. Except for two tree-like complexes (cases 3 and 5), the exterior, hall and common sectors are typically arranged as a ring type (c-, d-type), which also collectively have higher $i$ and $CV$ results than other sectors (such as the private sector). The exterior sectors tend to be d-type (50%) and there are no instances of b-type. The hall sectors are mostly d-type (56%), while c-type is dominant in the common sectors. In contrast, the distributions of the private sectors are: a-type 56% and c-type 44%. Thus, the pattern wherein a hall and a common sector link to the exterior, as a core node, provides a starting point for the generation of the house plans, while
it ends with a private sector. This is sequenced broadly in line with the concept of ‘intimacy
gradients’ (Alexander et al., 1997; Ostwald 2011b), starting with the most public and ending
with the most private. Based on the integration value \( i \) of each sector, the inequality
genotypes of the ten houses are as follows:

Case 1: \( H (10) > C (5) > T (3.33) > P (2.5) > E (2) \)
Case 2: \( H (5) > C (3.33) = T (3.33) = E (3.33) > P (1.67) \)
Case 3: \( H (10) > C (1.5) = E (1.5) = P (1.5) \)
Case 4: \( H (5) > C (4.29) > E (3.75) > G (2.14) > P (2) \)
Case 5: \( H (10) > C (3.33) > P (2) = E (2) > T (1.67) \)
Case 6: \( E (5) = T (5) > G (3) > C (2.73) > P (2.5) \)
Case 7: \( H (3.33) = C (3.33) = E (3.33) > P (2) > G (1.43) \)
Case 8: \( E (10) > H (5) = C (5) = P (5) > G (3.33) \)
Case 9: \( H(7.5) = E(7.5) > C (6) > G(2.14) = P(2.14) \)
Case 10: \( E(10) > H(5) > C(3.33) > G(2) > P(1.82) \)

In seven cases (1, 2, 3, 4, 5, 7, 9) the hall sector dominates the genotype as the most
integrated space, while the private sector of six cases (2, 3, 4, 6, 9, 10) is the least integrated
space. Another pattern revealed from the data is that most of sectors in the more recent
houses (1984 – 2005) tend to connect directly to the exterior sector. This is a by-product of
the long-narrow forms often found in Murcutt’s architecture, and one of the notable findings.
The sectors of the seventh case, the Simpson-Lee House, are comparatively less integrated
(average \( i \) value = 2.29) while the eighth case, the Fletcher-Page House, has the highest
average \( i \) value (5.56).
DISCUSSION

Grammatical transformation of syntax

It is generally accepted that shape grammars can be used to simulate a version of the design process (Economou, 2000) and the applications of rules in a shape grammar provides analytic decompositions of such designs (Knight, 2003). In a similar way, the JPG grammar presented in this paper highlights three design stages that develop three syntactic patterns: the head of a graph, local and global syntax. In order to discuss the three syntactic patterns, the paper examines JPGs generated at the three grammatical stages (Figure 4). Although the generative process illustrated in this analysis may not reveal the actual process of the architect, it nevertheless provides an effective approach to revealing and exploring the formal possibilities that may have contributed to, or could contribute to, the language of designs.

Figure 4. Justified Plan Graphs (JPGs) generated by the specific JPG (s-JPG) grammar at three grammatical stages.
It is possible to hypothesise from this data that each core node might act as the head of a graph and thereby determine the syntactic type of the graph. $L_0R_2$ initiates the tree structures of the syntax by generating more than two links in eight cases. While for our purposes, a core node is considered a sector including the main entrance, but we may also consider an alternative, which defines a hall sector as a core node because in many cases the hall sector dominates the genotype as the most integrated space.

It is also evident from the data that many core nodes are at the center of the tree structures of the local syntax of the JPGs (Figure 4) and they also have the highest integration value among the local nodes (cases 3, 4, 5, 6, 7, 8, 10). However, the links to an exterior sector node (E) by $L_0R_6$ and $L_0R_7$ of the s-JPG grammar change the syntactic feature of each JPG into the ring-type structures. Thus, the final inhabitant-visitor relations (the global topology) of Murcutt’s domestic designs are different from the local relations shown in the local configuration stage of the s-JPG grammar. The local relations are isolated through $L_0R_2$ and $L_0R_3$ in the long-narrow forms of the plans, while the final syntax of each JPG becomes more integrated through $L_0R_6$ and $L_0R_7$ which increases inhabitant-visitor relations. This is an interesting finding from the application of the grammar to Murcutt, as well as showing its more general benefit to both grammatical and syntactical analysis.

**Epistemological questions**

Hanson and Radford’s (1986a; 1986b) grammatical analysis of Murcutt’s early houses concludes that their forms are largely shaped by enviromental rules, or decisions made during the design process about the way buildings should respond to orientation, topography and climate. Their result is effectively an evaluation of which rules most clearly account for the
shape of Murcutt’s architecture, without much consideration of the programmatic or social function of the design. Similarly, Ostwald’s (2011a; 2011b) syntactical analysis of a larger set of Murcutt’s houses identifies a range of indicators that formal or environmental priorities might be more important in Murcutt’s architecture than socio-spatial factors. The latter’s purely syntactical approach to the question of design priorities is limited by the fact that most Space Syntax methods only consider form as an indirect reflection of spatial results.

The JPG grammar has both advantages and disadvantages over these two traditional methods. Its primary disadvantage is that in the form presented here, it only examines larger spatial groupings, limiting its effectiveness for social analysis. However, the grammatical and syntactically-derived analysis is capable of identifying patterns in social and functional planning as expressed in design decisions which have their own innate grammar. Even though the JPG grammar prioritises functional-spatial groupings in its interpretation of the design process, it is possible to posit a different set of design values, which acknowledge both social and functional dimensions, in Murcutt’s architecture.

This method further highlights the stylistic patterns of the syntax in a body of work, which is defined as a syntactic style. A syntactic style could be a spatial and social structure reiterated and reinterpreted in design layouts by architect(s) and a particular architectural style. The presence of this particular syntactic pattern across multiple houses by an architect and on multiple occasions in the same house, seems to suggest that the architect’s syntactic style at the very least embraces this pattern, and it is certainly a characteristic element of those houses. In the case study, although such syntactical characteristics are captured in a relatively small body of work (10 design instances), it demonstrates the effectiveness of the combined grammatical and syntactic approach to architectural analysis in capturing both sets of characterisations of a language of designs or a design style.
**Similarity and disparity**

The floor plan of a building could be regarded as a reflection of the needs of the building’s users and the comparative analysis of such a plan allows for the development of a spatio-functional typology of design solutions (van der Voordt et al., 1997). Our analysis of Murcutt’s architecture through the s-JPG grammar is initially founded on a clearly delineated space of movement (associated with $H_{o0}$) which in turn provides a means of accessing a set of public or common spaces. Not only is this a dominant pattern, but at the next stage in the design process Murcutt reinforces the significance of these sector pairings by turning this simple structure into a ring or loop. For example, connecting $H$ to $C$ before finally linking to $E$. While this loop may evolve, in the penultimate stage of the design process, to include tree-like or secondary ring-like planning structures (often founded on $H$) which encompass private zones, the significance of the original ring-type is preserved by the number of exterior connections through $L_{0}R_{7}$. It is the combination of these factors, not any one of them in isolation, which is at the core of the sector-adjacency decision-making process in Murcutt’s architecture. Based on this model, Murcutt’s architecture is characterised by a clear programmatic and functional pattern of relationships between just three key parts of the plan, and a similarly strong relationship between these and the exterior.

In six cases (1, 2, 3, 4, 5, 9) the hall sector dominates the genotype as the most integrated space, although the first case consists of two pavilions and the fifth case forms one pavilion, and the topological configuration of both is similar to a genotype ($H > C > P, T, E$). The syntactic values presented in Table 6 can be further used to generate JPGs in a syntactic style. An application using this information will be able to automatically provide a range of syntactic values and suitable links. Thus, it can act as a constraint to achieving a similar
development of JPGs in terms of Space Syntax values.

The hybrid approach using the JPG grammar also provides quantitative and graphical aids to further analyse the similarities between the houses. For example, based on the charts representing the inequality genotypes described in the previous section, it is evident that the eighth case and the tenth case have a similar topological configuration (E > H, C > G, P). Conversely, the ninth case with its four exterior connections, two of which are directly through common areas and two of which loop through common and hallway zones, represents a clear doubling of this design strategy in the same house; something which would be rare in a more conventional design.

In contrast, there are disparities between the fifth and sixth cases, the Ball-Eastaway House and the Magney House. The exterior and transit sectors dominate the sixth genotype as the most integrated space and the common sector has the relatively low $i$ value compared to the other cases. The sixth case is also an interesting genotype that shows the least range of fluctuation between the maximum and minimum $i$ values. This pattern relates to the applied rules. In the sixth case, the grammar configures a transit sector which functions as a core node and it directly links to common sectors. Links with T, C, C\textsuperscript{2} and P are generated rather than those with H that are dominant in the fifth case. The application of $LoR_T$ results in more than two links to the exterior sector in the eighth case, while it is not used in the third and fifth cases. Thus, two different applications of rules form the two dissimilar JPGs (tree-type and two-ring-type) and their genotypes.

*Generating JPG variations*

The s-JPG grammar enables the generation of JPG variations and four examples of this are
illustrated in Figure 5. The first variation has nodes and links similar to that of the Nicholas House (case 2), but its exterior link, generated by $L_0R_7$, is only (C, E) instead of \{(H, E), (C^2, E)\}. The result is an unusual structure that locates the second common sector at the deepest depth. However, the second and third variations are more acceptable in terms of their syntax. The second variation is also developed by the different application of $L_0R_7$. The same node and link generation of the ninth case before $L_0R_7$, but the development of two links, \{(H, E), (G, E)\}, is applied. The node and link generation of the fourth case with three links by $L_0R_7$, \{(H, E), (G, E), (C^2, E)\} will also develop another variation (see the syntax tree of Figure 3). The third and fourth variations can be regarded as alternative JPG variations of the Simpson-Lee House. Because a grammar establishes the limits of the style (Krstic, 1999), the s-JPG grammar has the beneficial property that it can be employed to examine the possible alternatives using a holistic application of the rule sets as well as to generate design instances in the style.

Figure 5. Justified Plan Graph (JPG) variations generated by the specific JPG (s-JPG) grammar.
Economou (2000) highlights the way Shape Grammars provide a parsimonious means for constructing designs in specific languages. Thus, a JPG can be identified as a representative graph showing the syntactic style of the JPGs generated in the case study. It is developed by the dominant productions of each rule during the generation of the ten cases in Figure 3. Thus, applying the dominant rules identified from each step allows a dominant JPG to be generated, which arguably encapsulates most of the spatial relationships present in Murcutt’s architecture. Since this paper applies and examines the s-JPG grammar sequentially, the rules applied at the previous steps must be considered to effectively produce such a dominant JPG.

It is also possible to calculate the mathematical likelihood of certain rule combinations being used for the transition probabilities and conditions. We briefly summarise the generation of this dominant JPG as follows.

First, $L_0R_1$ generates $H_{C0}$ which is the most dominant node generated by the grammar. It is followed by $L_0R_2$ which produces the most frequent pair of links, $(H_{C0}, P)$ and $(H_{C0}, C)$. $L_0R_3$ is skipped (66% probability) and then $L_0R_5$ develops two nodes, $P^2$ and $G$, which are unlinked. After generating $E$ and $(H_{C0}, E)$ by $L_0R_6$ the s-JPG grammar generates $\{(C, E), (P^2, E), (G, E)\}$ through $L_0R_7$. Finally, through applying the termination rule $L_0R_8$, $g_{case10}$ is constructed (see Figure 3). This implies that of the complete set of the ten selected designs, the last case (the Walsh House), best represents the way Murcutt creates functional relationships in space.

A future application of the JPG grammar could be to calculate the transition probability and frequency indicators in order to support the generation of a more precise dominant JPG. To do this, with a larger sample group, a future study would allow for the production of results that are more statistically significant.
CONCLUSION

The new grammatical, syntactically-derived, approach presented in this paper is intended to provide both statistical and graphical support for defining and exploring spatial design patterns in any family of works. The effectiveness of this approach is illustrated in the paper through the development and application of the specific JPG grammar for ten rural houses by architect Glenn Murcutt. The discussion arising from these results, while directly applicable to Murcutt’s architecture, also contributes to research focusing on Space Syntax as an analytic-generative theory for design and to an understanding of the implications of combining Space Syntax and Shape Grammar theories on computational design analysis and generation.

The s-JPG grammar not only provides a capacity to identify spatial design patterns of a body of work, it can also suggest a new way of generating variations of these, as well as of capturing a dominant JPG in a syntactic style. Augmented with other computational design and knowledge-based systems, it can be expanded to accommodate more complex or detailed issues that are pertinent to design practice or historiography. For example, since the g-JPG grammar can be applied to develop any s-JPG grammar describing such a corpus of designs or a style, the further application allows us to syntactically and grammatically compare different families of designs. This will contribute to the global investigation of epistemological questions across local, specific JPGs. In addition, this approach, which can be regarded as a notation system at the conceptual design stage to explore both analytical and generative issues, can offer designers and students both an insight into a syntactic style and a way of producing and assessing variations of that particular style.
REFERENCE


Bafna S, 1999, "The morphology of early modernist residential plans: geometry and genotypical trends in Mies van der Rohe’s designs", in Proceedings of the Second International Symposium on Space Syntax (Brasília) pp 01.01-01.12


Çağdaş G, 1996, "A shape grammar: the language of traditional Turkish houses"

Environment and Planning B 23 443-464

Chomsky N, 1995 The Minimalist Program (The MIT Press, Cambridge)


Economou A, 2000, "Shape grammars in architectural design studio", in 2000 ACSA Technology Conference (Hong Kong)

Freudenstein F, Maki E R, 1979, "The creation of mechanisms according to kinematic structure and function" Environment and Planning B 6 375-391

Grasl T, 2012, "Transformational Palladians" Environment and Planning B: Planning and Design 39 83-95

Grasl T, Economou A, 2013, "From topologies to shapes: parametric shape grammars implemented by graphs" Environment and Planning B: Planning and Design 40 905-922

Hanson J, 1998 Decoding Homes and Houses (Cambridge University Press, Cambridge)

Hanson N L R, Radford A D, 1986a, "Living on the edge: a grammar for some country Houses by Glenn Murcutt" Architecture Australia 75 66-73

Hanson N L R, Radford T, 1986b, "On modelling the work of the architect Glenn Murcutt" Design Computing 1 189-203


Hillier B, Hanson J, Graham H, 1987, "Ideas are in things: an application of the space syntax method to discovering house genotypes" *Environment and Planning B* 14 363-385


Knight T W, 2003, "Either/or \(\rightarrow\) and" *Environment and Planning B: Planning and Design* 30 327-338


Krstic D, 1999, "Constructing algebras of design" *Environment and Planning B: Planning and Design* 26 45-57


Lawson B, 2006 *How Designers Think: The Design Process Demystified* (Elsevier/Architectural, Burlington, Massachusetts)

Seoul


Stiny G, 1990, "What is a design?" *Environment and Planning B: Planning and Design* **17** 97-103


