How designs evolve

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The last few decades have witnessed the rise of different theoretical design paradigms in architecture. Some of the most significant paradigms of knowledge in this domain were associated with the notion of Design Methodology. With a common vision, studies that looked into the configurations of shapes (shape grammar) and structures (space syntax) in architecture agree on the possibility of externalising a universal language to interpret architectural artefacts. Studies in this field were mostly focused on the spatial and social architectural artefact. No studies were known to approach how spatial relationships and shape proportions evolve during the course of design. Within the framework of protocol analysis, research was often focused on decoding design cognitive activity. The development of sketches and thoughts during the course of design could be further illuminated through syntactic and grammatical descriptions as metrics to evaluate the quantitative properties of architectural design sketches. Hence, this paper presents an attempt to bring all these lines together to outline how shapes and spatial structures coevolve with the pronounced mental activity. The premise is that there is some underlying logic that couples these different processes. This logic might be traced in how sketches develop and in models that represent verbalised design actions. For this purpose, verbal comments along with their associated hand-drawn sketches were externalised and modelled. Focus was centred on whether the partitioning of spaces in architectural drawings would coincide with regular patterns of cognitive activity. The addition of partitions marks changes to the shapes and structures of designs, but is also likely to correspond to major changes in the cognitive flow marked by making decisions. The paper discusses the invariant relationships that couple shapes and structures as they change over the course of design and tracks their associated cognitive behaviour on a linkograph. The findings yield convergent patterns of behaviour that characterise the coevolution of designs and design thinking, albeit differences in design preferences.

1. Introduction
The second half of the 20th century witnessed the birth and evolution of different theorisations on design research (Cross, 1984), and on understanding and decoding architectural and urban space, either through identifying patterns of relationships between shapes (Stiny, 1980) or through a structural relationship that couples space and society (Hillier and Hanson, 1984; Hillier, 1996). These lines of research have developed separately with hardly any attempt to bring them all together to understand how designs evolve. Architects remained sceptical about any effort made to outline models that capture what designers share when solving a particular design problem or when approaching design solutions. For the most part, cognitive1 design studies, particularly those based on protocol analysis (Goldschmidt, 1990; Ericsson and Simon, 1993), were built on taxonomical models or graphs of progressive design actions that were extracted from designers’ verbal statements whilst not alluding to the development in design sketches. Other studies have considered both mental and drawing activities in understanding design (Akin and Lin, 1996). However, due to the broader understanding of what design is, no specific case was made in the literature to reveal the change in layout configura-

Notes:
1 By cognitive design studies, we refer to studies that are focused on a higher level of abstraction of design thinking that reveals how designers make decisions whilst progressing from the problem definition stage to the solution definition stage: what type of knowledge they use and how they retrieve memory from previous experiences. This process might be traced in designers’ verbalised thoughts and in sketches.
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Joshi and Summers (2012) introduced the use of quantitative metrics such as positions and shape proportions to evaluate changes in architectural design sketches. Through capturing configurational relationships between spaces in a layout, and bridging the link between the 'perceived space' and 'conceived space', the non-discursive is said to be rendered discursive in architecture through space syntax (Psarra, 2010). The majority of space syntax studies (Hillier and Hanson, 1984; Hillier, 1996) read space as an ultimate product and place less emphasis on the process of partitioning space where spatial structures continuously transform over the course of design. An understanding of the discursive techniques implemented in changing the layout configurations throughout design is likely to illuminate critical decision points in the cognitive activity of designers (Al_Sayed et al., 2008; 2010). Similar to space syntax but lacking the social description, shape grammar was devised to recognise formal relationships in a layout. With a computational perspective to comprehend architectural form, shapes were found to have some inherent grammar that can be obtained by modelling the proportions and translations of shape components (Stiny, 1980; Mitchell, 1990). This approach was marked to be purely formal. It was based on recognising rules that govern the relationships between shapes in a given layout or a given volume. The main sets of rules that govern shape grammars could be categorised as those that recognise the state of shapes at a certain stage, rules that govern the transformation of shapes and rules that identify the final state of shapes. The transformations are usually based on geometric positioning and alterations, lacking semantic social descriptions. A study to integrate the shape grammar approach with that of space syntax (Hillier, 1996) was carried out by Heitor et al., 2003. While this work brings the two methods together in one design approach, it does not foresee a relationship between them. Instead, it applies syntactic analysis to evaluate the socio-spatial performance of possible shape variations. In order to find a sensible model that couples both descriptions, it is essential to understand how the relationship between shapes and spatial structures builds up over the course of design. It is also useful to track how mental activities are associated with major transformations of shapes and spatial structures in sketches to understand how the psychology of design thinking is materialised through its graphic product.

An interpretation of the design rationalisation that precedes design actions can be revealed through investigating how design knowledge is deployed and materialised through sketches. It is acknowledged that drawing in design is a technique to externalise design ideas in the form of visual representations (Goel, 1995; Oxman, 1997). After configuring a situated design problem, architects retrieve knowledge by recalling memories of relevant design situations or user-based experiences. They construct analogical models in which they implement memories into restructuring their experiences as users in space and adapt that to support the way they reason about their drawing actions. There is – thus far – no way of telling when architects reason about their drawing actions. Goldschmidt (1990; 1992; 1995) attempted to reveal this through devising a model that clarified how design actions link backwards to preceding design actions, and how they link forwards to subsequent ones. However, it is still ambiguous whether this reasoning process takes place before finding solutions, or whether architects build conjectures about possible design solutions and follow that by post-rationalising their design proposals. Some recent work has linked cognitive activity represented by Goldschmidt’s model to the evolution of concepts or design ‘episodes’ in sketches (El-Khouly and Penn, 2012a, 2012b; El-Khouly, 2013), and in the work of Cai et al. (2010), and of Brösamle and Hölscher (2010).
El-Khouly’s work is thought to have demarcated where creative insights are likely to be in the process of design. Further analysis is yet needed to outline how spatial relationships evolve in the process of schematic design development and whether there is some inherent relationship that couples design thinking with drawing actions.

Goldschmidt’s methodology was adapted in the current research and adjoined with with drawing activity to look into regularities in the cognitive and drawing activities of architects approaching their designs with different preferences. Thus, we take two extreme cases from a previous study (Al_Sayed et al., 2008; 2010) where one architect starts from socio-spatial preferences, whilst the other’s design preferences are based on natural lighting requirements. The two architects are compatible in terms of professional design experience. The targeted model incorporates the geometric dimension along with the configurational evolution of sketches and relates both to the linkograph as a linear plotting of the network structure of design thinking. First introduced by Goldschmidt (1990), the linkograph is a model that represents the semantic segmentation and relational structure of cognitive activity in the form of a network. The network is projected against the sequential progression of design moves as ‘acts of reasoning’ that transform the state of design, whereas Goldschmidt’s definition for design moves is based on pronounced design thoughts. The method to delimit these thoughts to distinguish design moves is subject to common sense agreement by arbitrators. This type of representation of designer’s cognitive activity will have consequences on the patterns revealed by the linkographs. Of interest is how that representation of cognitive activity links to the process of schematic development of designs.

2. On coupling cognitive and drawing actions
The scope of this paper is to introduce a novel methodological approach towards understanding the relationship between the evolution of spatial structures in sketches and the pronounced cognitive activity of designers. This is not to say there is no tacit – and perhaps more complex – cognitive activity that is internal to the design process. What we are mainly concerned with is the cognitive and physical activity that externalises design thoughts. We distinguish here between the process of cognitive activity that is pronounced through verbal comments only and the moments when drawing activity takes place. Where both activities meet, we mark periods of high productivity. The verbal externalisation of design thoughts is intermediate between the deep level of concept formation where fuzzy conceptualisation of designs is being processed through mental imagery, and the physical design actions manifested by sketches. Sketches reflect on the state at which design concepts are confirmed through design decisions. Although this state might be preceded by a verbal statement, the physical manifestation of design decisions through drawing will mark the point at which an understanding of a prior state of design problem will lead to actions that will transform the design problem. This transformation would often result with a progressive step towards better defining the problem conditions of design and the solutions to be defined. The constraints assigned to define the design problem are subject to the architect’s background knowledge and the sequence of knowledge retrieval and implementation that is applied towards defining design solutions. The prioritisation of certain constraints over others will lead to divergent approaches towards problem-solution definition. While it is acknowledged that individual differences always arise as a result of different academic or personal backgrounds, it is expected that architects will implement relevant knowledge into their design decisions. Studies were made to investigate cross-knowledge by looking at multi-constraint requirements, see Bertel et al. (2007). Unlike them, we are mainly concerned
with the within-domain knowledge and how it is utilised in filtering design solutions. The knowledge of ‘generic function’ is assumed to be the core within-domain knowledge that all architects – no matter how different their backgrounds are – implement consciously or subconsciously in design. In addition to this knowledge, architects cast other types of constraints such as lighting requirements, emergency planning and cultural idiosyncrasies in further defining design solutions.

Focus in this research is centred on outlining similarities that designers share whilst approaching a predefined design brief. On that basis, a limited number of cases were chosen to give an insight into the associations between spatial transformations and further particularities in the structure of cognitive activity. The study presents an attempt towards understanding these associations given different design preferences.

3. Design task
In this paper, 12 design cases that were studied by Al_Sayed et al. (2010) are reintroduced. A video camera recorded the drawing process and a microphone recorded the architect’s voice while describing his/her thoughts during the design process. The verbal comments were later transcribed in order to subject them to protocol analysis. The protocol analysis took into consideration the semantic expressions without including the physical acts

Table 1:
Details on the subjects’ experiences and preferences as well as the word count and duration of the design task.

<table>
<thead>
<tr>
<th>Architects</th>
<th>Experience²</th>
<th>Duration</th>
<th>Word count</th>
<th>What are your design preferences?</th>
</tr>
</thead>
<tbody>
<tr>
<td>AH</td>
<td>17</td>
<td>18m</td>
<td>1685</td>
<td>I always try to optimise circulation in relation to occupation.</td>
</tr>
<tr>
<td>LC</td>
<td>20</td>
<td>49m</td>
<td>5426</td>
<td>Thinking about the logic of circulation, and occupation. This spatial structure is hierarchical reflecting the organisation.</td>
</tr>
<tr>
<td>AB</td>
<td>13</td>
<td>38m</td>
<td>3132</td>
<td>Depending on the scale, scope of the project, client demands, and how functions determine circulation.</td>
</tr>
<tr>
<td>KS</td>
<td>11</td>
<td>32m</td>
<td>1189</td>
<td>Connecting main spaces visually. Circulation is a secondary issue.</td>
</tr>
<tr>
<td>OO</td>
<td>21</td>
<td>38m</td>
<td>2673</td>
<td>On the basis of client requirements, the context and the environment.</td>
</tr>
<tr>
<td>JG</td>
<td>11</td>
<td>11m</td>
<td>651</td>
<td>Depending on the design program.</td>
</tr>
<tr>
<td>BC</td>
<td>11</td>
<td>15m</td>
<td>1191</td>
<td>Circulation is a result of making connections between static spaces.</td>
</tr>
<tr>
<td>PE</td>
<td>11</td>
<td>27m</td>
<td>2305</td>
<td>Setting the organisational structure and grouping functions.</td>
</tr>
<tr>
<td>AN</td>
<td>11</td>
<td>18m30s</td>
<td>1118</td>
<td>Thinking about the client, the users and functional organisation.</td>
</tr>
<tr>
<td>CE</td>
<td>10</td>
<td>30m30s</td>
<td>1374</td>
<td>Space, connections, circulation are basic layers of design process; the top layer is an ideal one.</td>
</tr>
<tr>
<td>CR</td>
<td>19</td>
<td>15m</td>
<td>1819</td>
<td>–</td>
</tr>
<tr>
<td>LM</td>
<td>13</td>
<td>16m30s</td>
<td>770</td>
<td>Depending on the functions.</td>
</tr>
</tbody>
</table>

Notes:
² Academic and practical experience in architecture.
themselves. Only the final design outcomes were subject to additional quantitative evaluation. Architects were interviewed to seek information about their expertise and their general design strategies and preferences (see Table 1).

The design brief was intentionally limited to a set of functional spaces that form the basic requirements for an architect’s office. Accounting for the idea that architectural design problems are ill defined (Simon, 1977), the scope was to limit the variation on how the brief might be interpreted. The programme that sets the narratives for the relationships between these functions is likely to have impact on the spatial structure of the design outcome. The relationship between the functioning programme of a building and spatial structures is recognised in the space syntax literature (Koch and Steen, 2012). As a matter of simplification of the design task, architects were required to allocate the predefined functions in a given layout (see Table 2). The layout itself was restricted to one level rather than multi-levels in order to simplify the design problem and enable comparison of the configurational properties of design solutions. The layout was a hypothetical rectangular floor plan in a skyscraper with two access points from two cores (Shpuza, 2006). There are some challenging problems with regards to the layout settings and in relation to its massive size, the number and pattern of columns that appear, and the two cores that link it with the external environment. The size and shape would themselves present constraints over possible solutions for partitioning space3. Given these constraints, the way space is partitioned will have non-trivial effects on the social organisation that is likely to occupy the layout (Duffy, 1974; Sailer and Penn, 2009). Whether architects are aware of the consequences of their decisions on user satisfaction and performance is something that is difficult to measure, but might be traced in their verbalised thoughts – some architects were mimicking users’ experiences to inform design decisions.

### Notes:

3 See March and Steadman (1971) and Steadman (1983) for an extensive body of research on this subject.

### Table 2:

**Design task including a brief for an architect’s office and an existing layout (cited in Shpuza, 2006).**
After analysing a set of 12 design experiments performed by the subjects, two participants – KS and CR – were selected based upon two criteria. The first criterion was having divergent design preferences; CR is more reliant on discursive techniques to filter out design possibilities, whilst KS uses natural lighting as a criterion for allocating spaces in a layout. The second criterion was having a considerable amount of design practising experience. KS has 11 years of academic and professional experience in architecture. CR is an architect with 19 years of academic and professional experience. CR’s experience has involved space syntax knowledge for over 9 years of what can be recognised as mostly an academic practice. In spite of the overall difference in academic experience, the professional experience that is design-based is compatible (around 9 years each). Architects were asked to develop design solutions intuitively using sketches within a 15-minute duration. KS finished the design task within 32 minutes, whereas CR finished the task within 15 minutes.

The two design experiments performed by the selected participants were chosen for further analysis to outline temporal patterns of change on the design process and the layout’s spatial description. Both design experiments were to represent divergent design approaches starting from a predefined brief. We aim to prove that in spite of their differences, the two subjects are thought to share similarities that couple pronounced cognitive activities together with the layout description of their designs. We distinguish activities that result with drawing lines that have direct effect on the geometric and configurational structure of the design outcome. The configurational structure of a layout can be represented by a topological network of convex spaces. The breaking of a layout into convex spaces involves defining the fewest and fattest spaces (Hillier and Hanson, 1984; Peponis et al., 1997). These spaces are then mapped in a network where nodes represent spaces and links represent adjacency relationships. The geometric properties of convex spaces as shapes are mainly defined by area and proportional ratio of width to length. This may be further simplified by representing convex spaces by their longest two diagonals. These types of representations would define a parametric shape grammar model different to that of Heitor et al.’s (2003). Our proposed parametric shape grammar model would account for the generative capacity of space syntax to be coupled with the production of shapes rather than a pure evaluative tool. The generative capacity of space syntax can be explained as the mechanism in which a configurational structure directs the course of subdivisions in a layout.

4. Modelling cognitive and physical design moves
As mentioned in the introduction, attempts made to decode architectural design process have often focused on cognitive activity without much reference to how design solutions change over the process of schematic design development. In this study, we attempt to reflect on the mutual evolution of design thoughts and drawing activity. We further observe changes in shapes and changes in structures, and highlight relations in-between. We observe how reasoning and goal-driven actions contribute to decision making in design, and how and when such decisions are executed in the form of drawings. Drawing activity is considered to be ‘critical’ when lines drawn change the geometric and configurational properties of the design. We examine cognitive and physical activities and track them on a linkograph (Goldschmidt, 1992). In a linkograph model, the cognitive activity is recorded, segmented and rebuilt in a relational structure that links design moves by matching their semantic meaning. In Goldschmidt’s scheme the protocol is segmented to a set of ‘design moves’ with directed links. A ‘design move’ is explained as ‘an act of reasoning that presents a coherent proposition pertaining to
an entity that is being designed’ (ibid., p.72). Links among moves are determined arbitrarily by the observer, and are notated in a network. The design process can then be interpreted as a pattern of linked moves that comprise the graphic network of the linkograph. Goldschmidt identifies two types of directed links: links connecting to preceding moves – ‘backlinks’; and links connecting to subsequent moves – ‘forelinks’. She recognises that moves that have dense linkage connections, both forwards and backwards; namely critical moves (CM) can be considered as indicators for design productivity. The trend of sequential, critical moves represents the critical path of a design process. Each design move involves retrieval of knowledge in a process of reasoning or goal identification.

An example of a linkograph structure is represented in Figure 1. In part of this example the transcribed verbal comments have been segmented to design moves (moves 1 to 12). The segmentation of the design moves is mapped in a linkograph. Design moves are linked by nodes whenever they exhibit some association in terms of content. In this way it has been possible to map the progress of design thoughts.

Tracking the evolution of designs themselves is made possible by segmenting the hand-drawing process into sketches that correspond to coherent sets of design moves. Setting major circulation corridors exemplifies one coherent set of actions. Dividing the edges of a layout to allocate certain functions is another. Drawing in the design process under investigation is beheld as a set of progressive actions that result – in this case – with the partitioning of a given space. The partitioning allows for functional properties of occupation and circulation to be allocated in a spatial structure that links geometric shapes together. Architects partition space to fit in occupational spaces by means of optimising user access and maintaining a high level of communication between different members and groups in the prospective social organisation. On the linkograph (Figure 1), periods of critical drawing actions were marked to reveal any regularities or differences that mark the association between thoughts and acts. Within-sketching links are identified as links that connect design moves within a continuous period of critical drawing activity. Cross-sketching links connect design moves that associate critical drawing activity, but are separated by intervals of verbalised cognitive activity. The remaining links connect moves that represent verbally translated cognitive activity with no drawing undertaken. It is acknowledged that cognitive activity runs throughout the course of design. With our segmentation scheme, we distinguished design moves that are associated with drawing activity.

In order to detect regularities and distinctions in the data of the semantic transcripts, the linkography models in both design processes will be examined in direct relation to the drawing activities carried out by architects in the form of sketches. By distinguishing verbal protocol from executive drawing protocol, more substantiation on how thoughts manifest into sketches may be externalised to expose design logic.

5. Clustering of design actions in linkographs

In the original scheme of a linkograph, Goldschmidt referred to four main types. In Case 1, design moves are completely unrelated, indicating low potentials for idea development. In Case 2, design moves are completely interconnected, hinting to a fully integrated process in which successive ideas may suffer from fixation and lack of diversity; this leaves fewer chances for novel ideas. In Case 3, each design move is linked only to its subsequent move; this signifies a progression in the process with not much development in terms of ideas. In Case 4, design moves are partly interrelated, indicating a productive design process that provides plenty of opportunities for idea generation and development.
According to the office plan layout, it is a rectangular shape. Two main cores, a lot of columns. I have two main elevations left and right. I am not quite sure about this area here, is it just for the shape of the building from outside? Or is it not? What about these columns here? Are there any neighborhoods here, can I open the side, can I have open views, I need to think about these things. Regarding the inside, there is a clear network for the columns, which will affect the divisions of these functions, but I need to understand first how can I reach the functions according to the main points which will affect the circulation around the cores; and how these two cores will be working together, because I am designing something for one team or for one firm. This is in general the first impression about what I can see now.
In our cases, all moves are interrelated. Case 1 and Case 3 hardly exist anywhere in our linkographs. Case 4 is the most dominant in all linkographs, with an occasional but partial occurrence of Case 2. The only way to distinguish between Case 2 (an interconnected net of moves) and Case 4 (interrelated moves) is to suggest a kind of coding which ranges between Case 2, where you can find patches of totally integrated moves, and Case 4, where you have a diverse structure of interrelated moves. In order to highlight these differences in nodes clustering in both groups, a Nonparametric Density Estimation (NDE) feature was used to distinguish patterns in the nodes’ point density. Statistical clustering was previously investigated by Kan and Gero (2008). The bivariate density estimation projects a smooth surface that describes the density of nodes in a linkograph at each point in that surface. The nodes are mapped in a two-dimensional space, and a set of contour lines are set at quantiles in 5% intervals. The contours are rendered to show the density of nodes in a linkograph. This means that 5% of the nodes are below the lowest contour, 10% are below the next contour, and so on. The highest contour has about 95% of the points representing the nodes below it, indicating clusters that contain the highest concentration of nodes within the contour boundary; these clusters would perhaps represent moments of ‘fixation’ in the cognitive activity where architects tend to focus on solving certain problems. The nonparametric density method is computed by dividing each axis into a fixed number of binning intervals. The number of points is then counted in each bin. Following that, a smoothing kernel standard deviation is set. A bivariate normal kernel smoother is applied using a fast Fourier transform (FFT) algorithm and inverse FFT to do the convolution. Following this procedure, a contour map is created using a bilinear surface patch model. This method is explained in Rodriguez and Stokes (1998) and applied in SAS software. In this paper, the Kernel Standard Deviation was set to 6 to enable a comparison between all linkographs.

A statistical representation of clustering in the node densities was favoured over a structural description of the linkographs (Gong et al., 2009; El-Khouly and Penn, 2012a, 2012b). The latter was thought to present a wide range of variation in the structure subject to the representation of design actions. The statistical methods highlighted different patterns of clustering, ranging between highly concentrated nodes matching Case 2 and more diffused distributions matching Case 4. The resulting diagrams can be seen in Table 3. The dark spots indicate states of concentration or ‘fixation’ on particular concepts or problems (Youmans and Arciszewski, 2012). This pattern would correspond to Case 2.

In general, patterns of difference and similarities between the architects are not clear-cut. In fact, more differences can be distinguished on the individual level compared to the group level. All linkographs seem to render localised concentrations of design ideas along the X axis, which means that design moves are predominantly sequential. There are, however, bulks of ‘fixation’ that appear on a higher global level, mostly in the second half of the design process where architects are more focused on the synthesis of design ideas, hence connecting actions that they have made to configure the design problem with actions that are executed to define the design solution. This all would depend on the length of the design session. The floating bulks or patches of ‘fixation’ clusters are more likely to appear with longer design processes. One can distinguish two highlighted clusters of intense sequential design moves: one that appears at the beginning of each design process; and one that sometimes appears at the end of the design process. These clusters are likely to mark intense points at which designers attempt to configure the problem settings of their design and points at which designers define the features of design solutions.

These observations are thought to indicate that
architects exhibit two layers of intense cognitive activity: one layer is global linking problem definition with solution definition; and the other is local, affecting the sequential design moves. The clustering of the linkograph is dependent upon the measures used for estimating densities. Further empirical analysis needs to be adapted to validate these results.

Table 3:

Nonparametric Density Estimation of all linkographs.
The X axis represents the sequential progress of design moves over the period of the design session. Diagrams produced using JMP, The Statistical Discovery Software, Version 5.1.
6. How do thoughts translate into drawings?

The last section revealed some similarities amongst a population of 12 architects, looking purely at how designers share similar patterns in their cognitive activity. Further insights are needed into the regularities that couple this cognitive activity with drawing actions. Hence, this section presents a scheme to decode drawing actions and link them with cognitive actions based on the performance of two case studies: CR and KS. The two subjects explicitly expressed their intention to follow two different design paradigms in approaching solutions for the predefined problem. This sets the challenge as to whether these two divergent approaches are likely to exhibit invariant patterns of cognitive and drawing activities.

The continuities of drawing actions were delimited in the linkographs and separated by intervals where no drawing activity was undertaken. It is important to note that no hand gestures were considered. Drawing actions represent what appears to be critical drawing activity that results with partitioning, marking and linking spaces on the layout. With regards to the structure of thinking expressed verbally and executed physically through drawing, the distinctions marked on the linkographs may highlight imperative differences and similarities (see Figures 2 and 3). Some distinctions can be marked by distinguishing one aspect of the linkograph complexity, where design moves link within continuous periods of drawing activity or across these periods. By ‘periods’ we refer to time durations that cover design moves whether associated with drawing activity or not. We differentiate between links that interconnect design moves within periods of drawing and those that connect in-between separate periods of drawing activity. The first is to be named as within-sketching links and the second is referred to as cross-sketching links. In both cases, the aggregate numbers of cross-sketching links double the numbers of within-sketching links. This means that drawing actions are interlinked in terms of the semantic meaning they hold, whilst being separated by periods of pure cognitive activity.

In general, the within-sketching links are slightly higher than half the number of cross-sketching links. In CR’s design process, there are events where cross-sketching links are remarkably higher than the within-sketching links. These periods (3, 5, 6, 8) seem to include high functional activity. In KS’s case, there are two outliers where the number of cross-sketching links are by and large higher than within-sketching links (3 and 6). In both cases, the number of backlinks between sketching activity and non-sketching activity went well above the number of forelinks. In CR’s case, it tripled the number of forelinks, and similarly in KS’s case, the number of backlinks is five times bigger than the number of forelinks. This may imply the notion that before executing drawing actions, architects are likely to refer back to previous actions to accumulate a better understanding of the design problem.

It is remarkable to see that the average ratio of time consumed for verbally-explained design moves is 8 seconds per design move in the case of CR, whereas KS consumes approximately 32 seconds per design move. This means that performing one design move in the design process would take CR remarkably less time than KS. The rate of drawing performance seems to double in the case of CR compared to that of KS. CR draws twice the number of lines and twice the number of convex spaces within periods of drawing activity that KS can draw. The rates of partitioning space per time unit do reasonably distribute uniformly across the design process with the exception of the initial stage of drawing in CR’s case, where CR takes more time to define the first partitions in her design.

In what concerns the way periods of drawing activity are distributed, there are some regularities that both cases share. Both KS and CR consume one third of the total duration of the design process
to configure the design problem before undertaking any drawing activity. A differentiation can be made through noting that during the first third of the design process, the verbal statements of CR involve less than a quarter of the total design moves in the design process; whereas one third of the design moves in KS’s case are progressed through the first third of the design process. This may mean that, subject to the way architects’ thoughts were externalised, CR was less willing to express her mental activity than KS. This might be an effect of individual differences or divergent preferences.

In order to externalise the pattern in which design thinking actively engages with critical drawing actions, an evaluation is needed to reveal the degree of integrity between the design process as a whole and segments where drawing and thinking activities are associated. For this, hubs on the linkograph are marked where associations can be detected between the actual process of drawing new partitions and critical design moves (see Figures 2 and 3). According to Goldschmidt (1990; 1992; 1995), a ‘critical move’ (CM) is an indicator of productivity. We apply this definition to find design moves that have more than (5, 6, 7, 8) connections, whether backwards or forwards, or in both directions. The phases at which ‘critical moves’ are aligned to drawing activity are basically where well-connected thoughts synchronise with critical drawing actions that materialise and execute verbalised thoughts. By drawing lines on the layout, a partitioning of space takes place that would necessarily lead to changes to the spatial structure, hence evolving the design situation. Partitioning

Figure 2:

A linkograph representing the design activity of KS and marking the association between critical moves and drawing new partitions. The evolutionary stages of design as well as periods of sketching activity are attached.
space will also necessarily lead to shape fragmentation. We identify these critical drawing actions that lead to transformations of the layout structure and consequently lead to changes to the shape’s size and proportions as critical drawing actions. This process, when associated with highly linked design moves, will highlight critical decision making points where actions that transform the state of the layout correspond with higher order thinking activity that operate on a global scale. In essence, having outlined events in the design process (Figures 2 and 3), where both critical design moves and critical drawing actions appear simultaneously might prove to be very meaningful.

If we match up the occurrence of critical drawing activity with the peaks of critical moves, we can observe two patterns of design thinking and acting that appear in both design processes. In both cases, critical design moves are mostly associated with drawing activity. In KS’s case they spread along periods of drawing activity. In CR’s case, they are mainly positioned at the start of periods of drawing activity. This may suggest that CR goes through intensive cognitive activity before undertaking criti-
cal drawing decisions, whilst KS replicates these patterns during drawing activities.

7. The evolution of shapes and configurations in design

This part of the analysis is mainly focused on a quantitative evaluation of sketches as they progress over the course of design. The quantitative analysis will consider changes in shapes in relation to changes to the layout’s syntactic configurations. The aim is to see whether the spatial structure acts as a determinant factor in defining the parameters of shapes. Space syntax explains the spatial structure as the materialisation of the social organisation that occupies space. Normally, tree-like structures reflect deeper arrangements and a hierarchy in the social organisation. Conversely, the provision of interconnected rings of movement in a layout offers choices for movement routes reducing control and depth. The relation between spaces might be ‘symmetrical’ if, for example: A connects to B = B connects to A. Otherwise the relation is ‘asymmetrical’. The total amount of asymmetry in a plan from any point relates to its mean depth from that point. This is measured by its ‘relative asymmetry’ (RA). To normalise the measure, a diamond (D) value is used. With that in use, it is possible to compare graphs of different sizes by calculating real relative asymmetry (RRA). Spaces that are, in sum, topologically ‘closest’ to all spaces (low RRA) are the shallowest (most integrated) in the spatial network. They characteristically have dense movement through them. Those with high RRA are the most segregated.

Convex integration correlates with ‘occupational’ behaviour in a building. Convex spaces are spaces where all contained points are mutually visible. The convex break-up map is formed by identifying the fewest and fattest convex spaces - the fewest to prevail. The greyscale or classic spectral colours of the convex map are distributed in five bands according to their integration values. High integration is marked in darker or red colours. Within the network of convex spaces, we differentiate between different types of spaces based on their proportions. Some are more suitable for occupation and more compact, others allow for denser through-movement due to their elongated shapes. Some spaces may even contain both movement and occupational functionalities. In the arbitrary decisions about the fewest and fattest convex maps, preference was given to spaces that are recurrent in the evolutionary process of design and exhibit distinct functional particularities such as corridors or hallways, in spite of their elongated geometric properties. This sets the rules for recognising convex break-up maps as the first set of shapes in the initial structure defined by the first sketch. By considering a convex break-up map as the set of primary shapes that are ready to transform following certain parameterised rules, we expect a relationship of some kind between shapes and socio-spatial behaviour.

Although the design task was the same for both groups, the design outcomes were significantly different in terms of organisational structure. In many cases, the design teams were placed as the main function within the most integrated areas, as shown in Figure 4. However, some recognised the corridors are the most integrated space within the layout. With reference to the patterns of clustering of design actions in Table 3, there is no apparent link between the design outcomes and the cognitive activity of design. This needs to be further investigated by focusing on two case studies, examining how design thinking and drawings are coupled over time.

The general feature that might be noted from the two sequences of sketches (see Figure 5) is that elongated convex elements are generally well integrated. They are largely defined for movement as circulation pathways and corridors. They seem to be more integrated in CR’s case than KS’s. In general, fatter and larger convex spaces seem to
Figure 4: The convex map configurations of all the design outcomes.
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reside in the lower integration part. Small and fat convex spaces seem to present the lowest integration values in both cases. In terms of the evolution of geometric and configurational properties of convex spaces in the sequential sketches, it is observed that elongated large spaces with average integration values are more likely to suffer from fragmentations. We define this property as the generativity of convex spaces. It might be important to add that integration values seem to spread more normally in the sketches produced by KS compared to CR’s. This is an effect of the symmetry in the designs produced by CR. The symmetry results in an evenly distanced pattern of clusters in the diagrams. By assuming a parametric relationship between shape grammar and the overall values of spatial structure, we might be able to outline three regularities as potential rules: elongated shapes have higher integration values and tend to preserve their proportions throughout design; bigger and fatter convex shapes tend to be average in terms of integration but tend to subdivide into smaller, yet relatively compact shapes; and small compact shapes tend to have minimum integration values, preserving their proportions over the design process. These rules in their simplistic form can be inferred from the evolution of the design sketches in these studies. However, in order for them to be verified and interpreted into a model, further case studies need to be explored and tested against these observed regularities.

A separate examination of the two design processes leads to further distinctions on the individual level. While integration values spread with wider ranges in CR’s case, they tend to spread less evenly in KS’s case and compress again within a smaller range in the last sketch. To further illustrate differences and similarities between the two design processes, we plot the same ranges of integration on convex maps that are binned and represented on a grid square layer with 1-metre spacing (see Table 4). The table shows that the series of layouts produced by CR were more integrated compared to those of KS. The structure produced by CR evolves into a ring consisting of four segments and connecting the two cores. A different design approach was undertaken by KS, who created a central corridor that connects the cores and allows movement to stem from it towards occupational spaces on the edges. In general, the quantitative analysis of structural properties of sketches emphasised the idea that CR was more inclined than KS to minimise depth in her sketches (see Table 4 and Figure 5). Despite these individual differences between the two architects who initially started from divergent preferences in their designs, they both produced structures that gradually became deeper. Both structures stemmed from circulation routes and presented hierarchies towards the edges. Through calculating transformations on convex integration values on the grid layer, it was possible to outline stages at which a change in configurations in the layout were more dominant and more visible. These stages happened between sketch 2 and sketch 3, where maximum values of increase in integration can be noted in KS, and maximum values of increase and decrease of integration are also observed in CR. The extent to which these changes are visible is relative to the size, statistical distribution and number of spaces that are witnessing changes in integration values. In general, the highest 50% of observations recording a change in configurations are recorded between sketches 2 and 3. Comparing these stages to the linkographs in Figures 2 and 3, it is striking to see how a configuration change in the layout corresponds to periods of relatively low cognitive activity (low presence of critical design moves). This means that intense cognitive activity is less likely to synchronise with critical partitioning actions. Instead, the two types of activity seem to alternate. This observation is clearer in CR’s case than it is with KS. More case studies need to be examined before making any generalisations on how these processes alternate.
Figure 5: The relation between shapes and topological properties in KS's sketches.
Looking into a finer level of differentiation, we may identify changes in the counts of different types of convex spaces that are classified by exploring their topological connections in a graph-based representation. This classification was introduced by Hillier (1996) who differentiated between four types of spaces: a-types which are characterised as dead-end spaces and connect to no more than one space in the graph; b-types which connect to two or more spaces in the graph without being part of any ring; conversely, c-types are positioned on one ring; while d-type spaces must be in a joint
location between two or more rings. The positioning of these types of spaces within the local and global configurations of the whole network can determine the maximisation and minimisation of depth in a layout. The increase of a-type locally and d-type globally minimised depth, creating an integrated system, while the increase of b-type globally and c-type locally maximised depth, resulting in a segregated system.

If we plot the trends of change to the different spatial types in the different stages of design (see Figure 6), we may identify some regularities in the way spaces are partitioned. At the same time as a-type spaces witnessed an exponential increase in numbers, the count of d-type spaces increased at an early stage and then gradually decreased. That very point when d-type of spaces settled around a constant trend marked the transition point at which the layouts witnessed a sudden increase in integration values (Table 4). This could be an effect of the increase in a-type of spaces that led to an increase in the heterogeneity or asymmetry in the layout. The count of c-type spaces witnessed a slight decrease across the different sketches. KS was presenting deeper hierarchies in his sketches whereas b-types and a-types appeared early in the second sketch. Spaces of c-types and b-types appeared to be dominant throughout the process. In CR’s designs, b-type spaces only appeared in the last sketch while a high number of d-types and a-types appeared throughout the process. This meant that CR approached her design by minimising depth. She did so through connecting d-type and a-type directly. KS was less likely to do so; he started by presenting deep hierarchies from the second sketch, resulting in a deep structure towards the end. In spite of these observed differences, the number of spatial types appeared to plot parallel trends over the course of structural transformations. In order to confirm this, more data points and cases need to be observed.

8. Conclusions
This study builds on previous work (Al_Sayed et al., 2008, 2010; Al_Sayed, 2012) to further outline patterns of cognitive activity during design, along with changes to the layout configurations. The paper examined design and drawing activities by looking at the relationship between a linkograph – as a representation of design activity – and the configurations of design outcomes. Initially, we analysed 12 case studies to reveal patterns of clustering of design activity in a linkograph, and how those
clusters highlighted points of ‘fixation’ in the design process where designers concentrate on certain decisions or problems. We also analysed 12 design outcomes to reveal any differences and similarities, before moving to a more detailed description of how design thinking and drawing evolved in two design processes. The paper also showed an adapted description of the linkograph model to distinguish periods of critical drawing activity. Similarities were detected in the behaviour of two architects, despite the divergent preferences undertaken in their designs. With regards to their sketches, we have also identified relationships between the parameters of shapes and their structural configurations. Moreover, we have seen that the count of different spatial types follow similar trends. For that, we still need to define the exact metrics of similarity. More importantly, these results need to be validated by means of a larger participant population. The experiment conditions need also to be refined. In our current approach, we intentionally chose two divergent design approaches in order to rule out any identified similarities or regular patterns in design activity. CR’s preferences were to prioritise circulation and occupation, and how they shaped the social organisation that resides within the designed space. KS started with allocating spaces in relation to a maximised natural lighting and ended up by configuring circulation. These two approaches, while expected to present distinct patterns of design behaviour, countered our expectations by revealing resilient similarities.

Observations suggest that thoughts which are associated with the drawing activity are robustly interlinked throughout design. Both design behaviours exhibited a tendency towards linking to previous design moves rather than future ones. An interpretation for that might be that architects keep referring to previous design moves in order to reason about their drawing actions. Both architects spent the first third of the design process producing no depictions as they accumulated understanding of the design problem. There seemed to be a strong association between critical design moves and drawing actions in both cases. Critical design moves are spread along drawing actions in the case of KS, while CR’s critical design moves appear at the beginning of periods when drawing actions are undertaken. This may indicate that architects consume most of their cognitive activity while executing drawing actions. However, through mapping transformations onto configurational structures of design sketches, it was observed that cognitive activity is likely to intensify before and after drawing actions that result in a significant decrease of depth in the layout. It is either that cognitive activity is lower during these actions, or that designers are occupied with critical drawing actions and hence less likely to verbalise their thoughts.

In terms of schematic design development, there are three rules identified that define a parametric relationship between shapes and configurations. The first rule is that highly elongated spaces such as corridors are more likely to be the most integrated. Secondly, fat and small spaces are more likely to be segregated. Both types tend to preserve their proportions and values. The strategies by which designers allocate elongated spaces to minimise depth, increase connections and perhaps maximise the visibility of access towards small fat spaces might relate to the concept of ‘purview interface’, introduced recently by Peponis (2012). Peponis recognised purview interface as separate spaces that are more dominant in the layout and spaces that are more self-contained in such a way as to minimise steps between the two types, hence increasing layout intelligibility.

The third rule, revealed through our observations, indicates that large and relatively elongated spaces with average integration values are more likely to be generative, in that they are more likely to subdivide in subsequent stages. This simplified
reading of a parametric shape grammar by structural configurations needs to be generalised across a larger sample. Another regularity that might be inferred from the partitioning of space is that rings of movement and circulation tend to be first defined in designs. They are more likely to reduce in number on the account of an exponential increase in the number of dead-end spaces; in that, architects are inclined to define circulation first and then progress to allocate occupational spaces. In this process, hierarchies that are subject to the conditions of the organisational structure of a building type contribute to a gain in depth.

These findings are subject to limitations that concern the arbitrary segmentation of verbally interpreted design thoughts. Additionally, decisions were made to separate different stages of drawing by means of drawing order; they were set by observing stages where certain functionalities were positioned all at once. For that, more systematic procedure is needed. It must also be disclosed that convex brake-up is not a product of a unique process of reduction. Matching similar spaces was needed to construct a comparative setting across the successive sketches. It might be safe to say, however, that these inadequacies are not likely to have had serious implications on the final results, particularly regarding the convex break-up representations. It might be safe to say, however, that these inadequacies are not likely to have had serious implications on the final results, particularly regarding the convex break-up representations. This is in light of the fact that our purpose was to define similarities rather than differences between divergent design approaches.

The coupling of thoughts, shapes and configurational structures in both design processes indicates an inherent model in the structure of design thinking and doing. This needs to be confirmed by generalising the findings via a larger population and different building types. Where differences are present, they tend to serve the idea that designers are idiosyncratic and will therefore approach their own designs in a unique manner. These differences do not disqualify the argument that there is a shared way in which designers behave in making decisions and in shaping their design solutions. In essence, it was seen that globally connected decisions have an executive nature which translates into major geometric and configurational transformations in the layout, but which only happens with some time delay. In spite of apparent differences in the designers’ preferences, they seem to share particular aspects in segmenting their design solutions, rendering certain associations between shapes and structures over the course of design where both designers start from circulation and move to allocate occupational spaces following similar trends. These findings remain experimental and need to be further investigated by introducing more robust settings and metrics of evaluation into the case study. Future studies should also consider further development along the strand of configurational transformations and their utilisation in parametric shape grammar to associate the designed geometry with social meaning.

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