

# Floor Plate Shapes as Generators of Circulation

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## Abstract

I investigate the relation between floor plate shapes and systems of circulation from a configurational standpoint. I analyze spatial complexes with modular representations that take into account the difference between their occupation and circulation parts. The three-layered analysis shows the existence of certain regions of shapes from which the rest of complexes are in linear proximity. These points serve as keys for laying out the most integrating circulation system possible. Two proposed measures for describing shapes from this stance indicate the potential of shapes to generate integrating circulation patterns.

## 1 Introduction

Many design decisions, especially in the programming and schematic stages, concern the relation between parts of the building that are about movement and connection, and parts of static or occupation activities. Regardless the size of the building, corridors or spaces that act primarily for movement are instrumental in terms of influencing the intelligibility of the whole building by making remote parts accessible through visual and permeable connections. Often based on intuition, design choices bear a substantial concern with the relation of corridors with the rest of the spaces. The aim of this work is to provide an analytical description of this relation which will concern both understanding and possible applications into design procedures. I address the issue of fitting corridors, or else a circulation system, into the shape of a floor plate. What is the most intelligible circulation a shape can generate? Where does this system have to be inserted in order to capture the best a shape can offer? How can we describe shapes in order to see their potential of generating certain circulation systems? What are the design implications of modifying floor plate shapes for the outcome of the internal corridors? I depart from an existing 'space syntax' methodological platform to offer an approach that will tie to the peculiar nature of complexes of corridors and non-circulation spaces.

## 2 Defining the complex: relationship between 1D and 2D aspects of spatial layout

I define *circulation system* as the main system of corridors, in a building. This includes corridors that are clearly separated from other rooms, and major open spaces that have a clear circulation purpose. Circulation spaces inside rooms or between partitions in open plan buildings will not be included in this category. Despite considering the real dimensions of the circulation system, the focus will be given to the linear dimension of the elongated system neglecting the width. I define *floor plate* as the overall footprint of the floor in consideration.

## Keywords:

shape, circulation,  
floor plates, low  
spots, compactness,  
concavity

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Its boundary corresponds to the outer edge of the envelope of the building. Atria, courtyards and openings of such nature will be considered as holes in the floor plate. For the analysis of floor plate, its shape in a two-dimensional respect will be the focus of investigation. Further, I define the non-circulation spaces such as rooms, as *occupation spaces*. They are the result of subtracting the *circulation spaces* from the entirety of the floor plate.

It would be beneficial to address the main question of this study from a platform that analyzes both aspects of shapes and circulation simultaneously. This would require finding a common ground for analyzing two-dimensional and one-dimensional elements while preserving their relational effect on the complex. I approach the problem by utilizing a model of analysis where both shapes and circulation systems are fragmented into small modular elements. Representing shapes with constant metric modules is the only way we can capture their configuration. I will define the methodological focus of this work alongside the research on unitized elements that was first introduced in architectural discourse by March and Steadman (1971), Steadman (1983), and later developed further by Hillier (1996).

### 3 Hillier's model: unconnected corridors of modular elements

In the chapter *Is Architecture an Ars Combinatoria?* (Hillier 1996), the author analyzes the effect of adding partitions in various positions in order to study their effect on the overall distribution of integration. The experimentation has constituted rectangular shapes partitioned into a number of elementary units according to a rectangular grid by regarding permeability connections among them. In the model, each cell has been assigned its value of *total depth counts* which shows the sum of graph distances to all other cells. The *total depth* of the complex is calculated by summing up total depth counts of all cells in the complex.

The *local-to-global* effects of adding partitions or openings in a permeability complex have been thought of as design principles from which we can forecast the global effects. Four such principles have been summarized.

‘...the *principle of centrality*: more centrally placed bars create more depth gain than peripherally placed bars; the *principle of extension*: the more extended the system by which we define centrality (i.e. the length of lines orthogonal to the bar) then the greater the depth gain from the bar; the *principle of contiguity*: contiguous bars create more depth gain than no-contiguous bars or blocks; and the *principle of linearity*: linearly arranged contiguous bars create more depth gain than coiled bars’ (ibid.: 299).

Of particular interest to this paper is another experiment that is the reverse of the one discussed above. Here, openings or large spaces are introduced instead of partitions. Their effect is to reduce depth rather than increase it. It has been shown that the same principles are valid, if the idea of depth loss is substituted for the idea of depth gain. Therefore, more central openings create more depth loss than peripheral ones; the longer the openings, the larger the depth loss; openings that are contiguous result in more depth loss than the ones that are positioned apart from each other; openings that are placed in a linear way result in a greater depth loss than the ones that are coiled.

The depth minimizing moves, applied consistently over a floor plate, lead to the creation of long linear corridors, while the depth maximizing ones lead to broken corridors and irregular patterns of subdivision. The emergence of corridor like connections among cells

minimizes the total depth in a system, and is influenced by three *principles of extension, contiguity, and linearity*. According to the *principle of centrality*, corridors that are positioned centrally in a floor plate minimize depth more than peripheral ones.

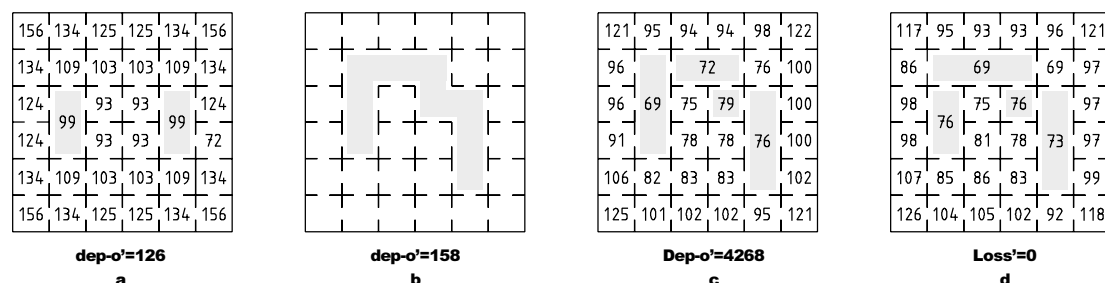
From the perspective of addressing our questions, Hillier's model has certain built-in limitations that result from the issue of maintaining convexity. In that model, open spaces have been created by means of merging original cells, figure 1a. However, open spaces are always kept convex. If we were to think of these spaces as joined to create circulation spaces, they would quite possibly form non-convex spaces, figure 1b. If we were to analyze the system that includes such non-convex circulation space, we would need to break it up into convex components. At this point the idea of a fixed and discrete convex partitions of circulation spaces does not appear fully satisfactory. This is due to the fact that alternative partitions of the same circulation system into convex segments may best represent how well this system serves to make connections between adjoining areas of occupation spaces. In a symmetrical L-shaped circulation space, each of two alternative partitions into two convex spaces may make the distance between some adjoining cells appear deeper. In figure 1c and 1d, the same circulation system is divided into convex entities in two different ways, hence resulting in different total depth values of 2912 and 2892. The arguments from *Space Is the Machine* have been developed on a model that consist on a series of segmented and scattered open spaces, in which the issue of dividing a continuous and non-convex system into convex entities has not been addressed.

#### 4 Linear depth spread: key feature of open spaces

The difficulty of the previous model consists on the fact that a single type of cell has been used to deal with both unitized regions and with open ones in the complex. After the mechanical merging of cells into larger entities, the emerged one has the same features with the ones that created it, i.e. permeability connection to the adjacent ones if a link is provided between them. I propose an alternative strategy. The underlying units of space that are part of circulation will not be allowed to merge into a single pattern of larger convex spaces, instead, their identity will be preserved. I avoid the approach of finding plausible convex break ups of the circulation system, to suggest a dynamic depth calculation, which is always unique to certain location.

From the syntactic point of view, open spaces facilitate the connection of parts in a building in such a way that no matter how far in metric terms, a region of space can have the same depth as another if they belong to a convex spatial arrangement. Thus, two parts of a spatial complex are in a convex relationship to each other, i.e. they have the same depth, if there exists an uninterrupted linear sequence of spaces to link them. The key feature of the units of space that are considered to be part of the same circulation space, is that they have the

**Fig. 1 Controversy of merging units into circulation openings according to the model of Hillier. a) detached circulation segments, b) non-convex circulation system, c), d) ambiguities of dividing symmetrical turns into convex partitions**



same depth if viewed from a certain location. There is no addition of depth as one moves along the space. Given this premise, we can think of the relations of these units with each other as being about spreading the same depth value all over a larger space. In fact, the spread of constant depth value is the defining feature of the units of space that are primarily about circulation. They are in contrast to the cells of occupation, which, like the cells used in Hillier's model, are about resistance or metric inertia. Here, units of space that are part of circulation system will be referred to as *circulation cells* or *c-cells*, and the ones that are part of the occupation part of the complex will be referred to as *occupation cells* or *o-cells*.

In order to clarify the distinction between a linear part of a circulation space to a turn, I introduce the concept of *linear depth spread*. The consequence of some *c-cells* belonging to the same convex circulation space is that they share the same depth from a certain reference point. I define the concept as follows: if the depth is spreading from *c-cell* A, which is closer to the reference point; *c-cell* B is adjacent to A; *c-cell* C is adjacent to B; and three of them have a convex relationship to each other, *c-cell* C gets the same depth value as A. Each time this condition is not satisfied, like in the case of turns, a depth increase occurs. This is illustrated from the depth calculations in figures 2e-g. Except the *linear depth spread* effect, *c-cells* share the same qualities with *o-cells*. Thus, the depth between two adjacent cells increases each time by one when: 1- a threshold is crossed between an *o-cell* and *c-cells*; 2- *c-cell* and *o-cell*; 3- two *o-cells*; 4- two *c-cells* when linearity is broken. In a few words, *c-cells* are about acceleration, spreading depth or else transferring the same depth condition to areas that belong to the same uninterrupted convex space in contrast to *o-cells*, which are about resistance or else depth augmentation. In real buildings, most corridor systems are organized, at least in certain parts of buildings, along two major axes in order to facilitate the organization of occupation spaces. Hence, two orthogonal axes are chosen as guide rulers out of the infinite possible directions that pass through locations in a shape. Therefore, the linear depth will ignore other possible linear connections in the complex unlike the isovist integration (Turner 1999). The analysis will filter all open directions that follow the two main orthogonal axes.

### 5 Three-layered model: occupation and circulation cells

The new model, similarly to the layered tessellation suggested in the chapter *Non-discursive Technique* (Hillier 1996), preserves a logical distinction between the layer that regards metric properties of shape, and the one that regards the syntactic ones. The first layer *L1*, like Hillier's model, will represent shape entirely with *o-cells* that have adjacency relations between them, figure 2a-d. The second layer *L2* will represent shape entirely with the newly proposed *c-cells*, figure 2e-h. Further to combining the analysis of two layers together, a third layer *L3* is proposed: one that uses *o-cells* and *c-cells* simultaneously. This layer represents occupation spaces in a complex such as rooms or offices with *o-cells*, and the circulation ones like corridors or halls with *c-cells*, figure 2j-n.

As part of an ongoing project, a Java applet is designed to enable drawing *o-cells* and *c-cells* in different module sizes and calculating several measures of complexes of shapes and circulation systems.<sup>1</sup> The sign (°) will be added to distinguish measures taken in *L1*, (°) for measures in *L2*, and (°°) for the measures in *L3*. For the purpose of this analysis, only measures of *N-o*, *N-c*, *Dep-o*, *Dep-c*, and *Loss* have been used, and will be described grouped in two categories:

1 - The applet may be viewed at <http://www.prism.gatech.edu/~gt7531b/Qelize/qelize.html>

## 1- Counting

$N-o$ : the number of *o-cells* in the complex. If the length of a cell is considered as a metric unit,  $N-o$  also gives the total area covered by *o-cells*.

$N-c$ : the number of *c-cells*, and also the area covered by *c-cells*.

## 2- Syntactic Depth

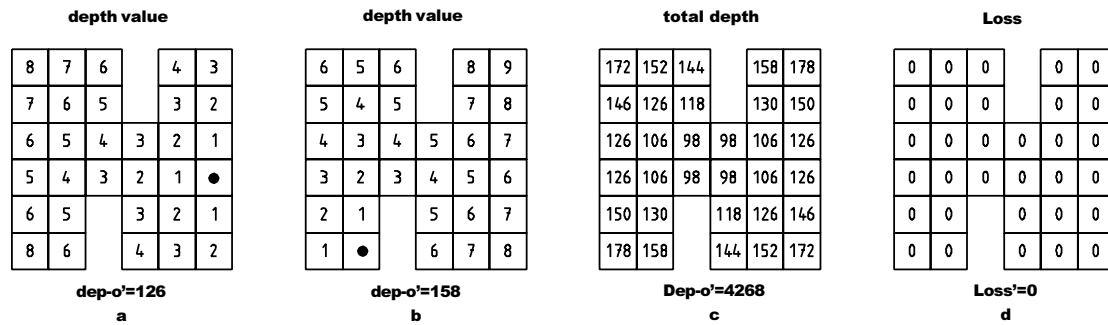
The depth calculation is based on adjacency relations when *o-cells* are concerned, and on *linear depth spread* effect in the case of *c-cells*.  $Dep-o$  represents the sum of the individual depths of all *o-cells*. The individual depths are calculated by summing up the depths of all other *o-cells* and *c-cells* from the root *o-cell*. After calculating the depths for each *o-cell* the values are assigned to each one, figure 2a-c. The individual depth of a *o-cell* is denoted by  $dep-o$ , and  $Dep-o$  is given from the expression:

$$Dep.o = \sum dep.o \quad [1]$$

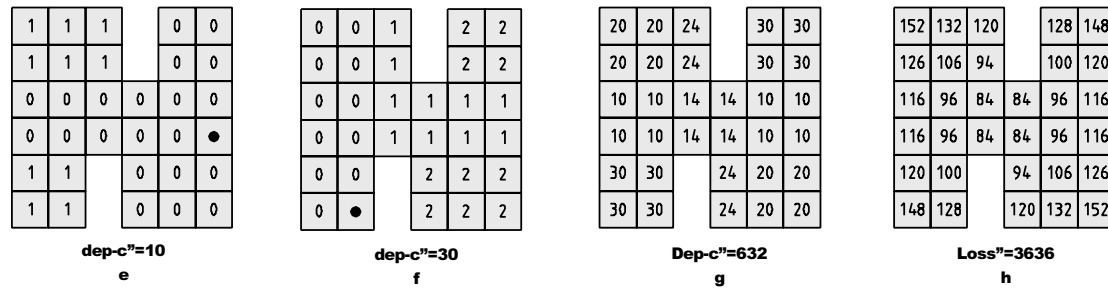
$Dep-c$  is calculated by summing up the individual depths of each *c-cell* to all other cells. The depth value is assigned to each *c-cell*, figure 2e-g. If the individual depth of a certain *c-cell* is denoted by  $dep-c$ ,  $Dep-c$  is expressed:

$$Dep.c = \sum dep.c \quad [2]$$

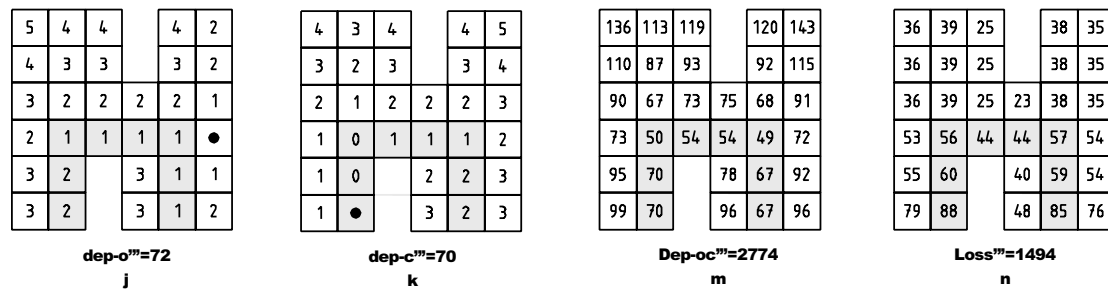
**Fig. 2 Three-layered representation of a shape and the calculation of total depth and Loss. O-cells are shown in white, c-cells are shown shaded**



**L1 representation in which the shape is mapped entirely with o-cells.**



**L2 representation in which the shape is mapped entirely with c-cells.**



**L3 representation in which the shape is mapped with both o-cells and c-cells.**

$Loss$  is defined as the difference between the total depth in the case when the effect of the corridors has been ignored, i.e. the shape is represented entirely with o-cells, to the total depth in the actual case of a combined state of o-cells and c-cells. This measure allows quantifying the depth loss, that is integration gain, effect of introducing the corridors into the system, figures 2d, 2h, 2n. Loss is calculated:

$$\begin{aligned} Loss' &= 0 & L1 \\ Loss'' &= Dep.o' - Dep.c'' & L2 \\ Loss''' &= Dep.o' - Dep.oc''' & L3 \end{aligned} \quad [3]$$

By definition, in  $L1$  there are no c-cells hence  $Dep.c' = 0$ . Likewise in  $L2$  there are no o-cells, thus  $Dep.o'' = 0$ . Therefore, the total depth of the complex in  $L1$  will be represented always only by  $Dep.o'$ , and the total depth in  $L2$  by only  $Dep.c''$ . The total depth for the complex in  $L3$  has been calculated by summing up the respective depths for the regions covered by o-cells and c-cells, figures 2j-k. Therefore, for three layers we have:

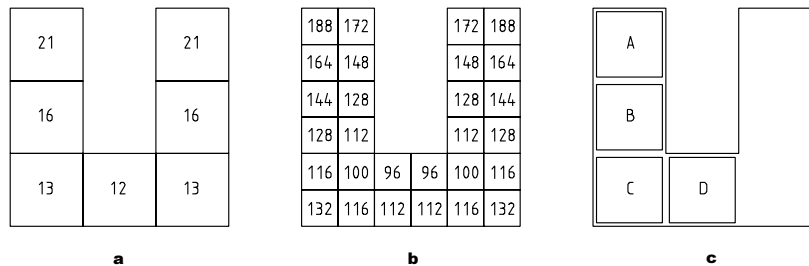
$$\begin{aligned} Dep.oc' &= Dep.o' + Dep.c' = Dep.o' & L1 \\ Dep.oc'' &= Dep.o'' + Dep.c'' = Dep.c'' & L2 \\ Dep.oc''' &= Dep.o''' + Dep.c''' & L3 \end{aligned} \quad [4]$$

### 6 Metric shape description: first analysis layer of total o-cells

$L1$  layer of analysis, where all the units have been represented with o-cells, shows how the universal distance is distributed in a shape where lower values are located in the center, and higher ones at the periphery. We can think of the total sum of universal distances as a way to describe metric properties of the shape. This would give a robust and general description. The value of universal distance, which here is calculated with the measure of  $Dep.o'$ , is due partly to the number of o-cells in the complex. It is necessary to propose a way to disregard the actual size of the units in order to characterize and compare shapes of different sizes.

A shape is represented with 7 o-cells in figure 3a and 28 o-cells in figure 3b in order to see whether there exists any consistency from one representation to the other. Two regions of the shape A and C, which are covered with one o-cell in 3a and four o-cells in 3b, are compared between each other by summing up the depth values of o-cells. In figure 3a, region A has a depth of 21, and region C a depth of 13. The sums for regions A and C in figure 3b equal 672 and 464. I compare the ratios between the depth of two regions, which are 672:21=32 for region A, and 464:13=35.692 for region C. Because of different ratios, we can conclude that by changing the fineness of the modules, certain regions of the shape are not differentiated between each other in constant degrees. There is no way we can use the measure of  $Dep.o'$  to characterize a shape in an exact manner. We would tend to think that a finer module size would show the features of the shape in more accurate way. Then, the shape is represented

**Fig. 3 L1 analysis a) representation with 7 units, b) representation with 28 units, c) regions in consideration**



with 63 and 112 *o-cells*, and the depth values of regions A, B, C and D are compared with each other. We can see that the densification of the units results in greater similarity between ratios for certain regions. For instance, while the ratios between 28:7 representations for regions A, B and C have values of 1, 0.897 and 1.03, for 112:63 ones they come much closer to each other at 1.001, 0.99 and 1.001, therefore giving a consistent differentiation between regions of shape. Thus, despite the differentiation between regions, each densification of the grid gives better approximation. An empirical modification seems to give promising results. I call the modified measure *compactness* as it captures this property of the shape:

$$compactness = \frac{Dep.o'}{N.o^{2.5}} \quad [5]$$

The modified value practically does not change at all for higher number of units. For instance, for the shape analyzed with 7, 28, 63 and 112 units, the modified *Dep-o'* changes from 0.846 to 0.8995 to 0.896 to 0.896.

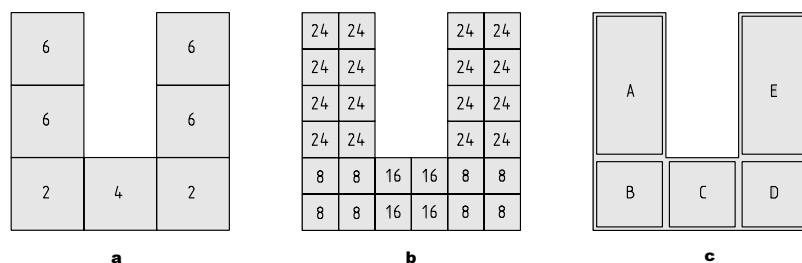
I investigate how the modified measure of *Dep-o'* changes from one shape to another. A sample of 8 shapes has been analyzed entirely with *o-cells*, and the values of *compactness* are shown below each one, figure 5. The case 5g has the highest value at 1.38, followed by 5a at 1.028, which reinforces the fact that these two shapes are the most elongated ones in the sample. The compact shape 5f is positioned in the lowest end with *compactness* at 0.685. By taking out the effect of the number of units in the shape, it is possible to express the intrinsic property of the shape in regard to minimizing the universal distance.

## 7 Linear convex shape description: second analysis layer of total c-cells

When the issue of fitting circulation systems into floor plates is raised, the distribution of universal distances offers little help. In order to grasp the spatial properties of floor plates rather than the metric ones, we need to treat the relations between units in a way that reflects the features of spatial configuration of the shape. The *linear depth spread* effect is fundamental in regard to capturing the structure of relations between regions of space since it is the key condition that unites parts of space into single convex entities. We can analyze the relation of each unit to all others in the complex by means of representing shapes totally with *c-cells*.

Figure 4 shows the analysis of the same shape that was analyzed above in *L1*, now represented entirely with *c-cells* in *L2*. The shape is analyzed entirely with 7 *c-cells* and with 28 *c-cells*, and the regions with distinct depths are labelled separately. We can see that, for instance in figure 4b, *c-cells* of region B have depth of 8 because there are 8 *c-cells* one linear step away 8x1. Region E *c-cells* have a depth of 24 because of regions A, B, and C are not in convex relationship with E, hence 24=8x1+8x2. The value of *Dep-c''* has a built-in component of the number of *c-cells*. The effect is twofold: first because the individual total depth reflects how many *c-cells* are in a certain depth from it, and second because of how many *c-cells* add

**Fig. 4 L2 analysis a) representation with 7 units, b) representation with 28 units, c) regions in consideration**







their individual depth in the overall measure. Thus,  $Dep-c''$  has to be modified by taking out the effect of  $c$ -cells twice, thus dividing it by  $N-c$  in the power of two. The modified measure will be referred to as *concavity* of the shape and will be calculated from the formula:

$$concavity = \frac{Dep.c''}{N.c^2} \quad [6]$$

We can see that the value of *concavity* for this particular shape remains the same at 0.653 regardless of the modular grid. By investigating the examples in figure 5, we can see that shapes that have no wings, i.e. that are entirely convex such as 5k and 5r have a *concavity* equal to zero. As the shape is compound of more parts that are not aligned, the *concavity* increases further. Comparing one shape to another from the sample, we can see that as we add more wings, or else as the number of turns increases, more differentiated regions are created. Of special interest is the presence of distinct and separate areas with low depth values. In contrast to the first layer of analysis with  $o$ -cells where the integrated core constitutes a single entity that lies around the gravity center, here the integrated areas are disjoint from each other, and are scattered in the shape corresponding to the junctions of the wings. These regions will be referred to as *low spots* because of the low depth and their position in the shape. The junctions from where all the regions and wings in the shape are in linear access have a depth equal to zero, figure 5k, 5m, 5n, 5r. The depth value of a region increases as more areas in the shape fall in a linear shadow from it.

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### 8 Combined shape description: third analysis layer of $o$ -cells and $c$ -cells

In this layer of analysis different parts of the complex are represented as  $o$ -cells and  $c$ -cells depending on the occupation or circulation function they have. Attempts to disregard the effect of the number of cells in the value of  $Dep-oc$  meet a twofold obstacle. First the number of cells effects the two components  $Dep-o$  and  $Dep-c$  in different exponents of the order 2 and 2.5. Second, the effect of two components in the summed depth is complicated from the different percentages and the configurational position of the circulation system in the floor plate. Thus, we cannot expect to find an exact expression that would discard the effect of size or number of modules in the shape. This can be easily verified by comparing the depth values of two corresponding regions of a shape represented with different modules. From an alternative viewpoint, the combined floor plate of  $o$ -cells and  $c$ -cells can be thought as an intermediate state between a shape that is covered entirely with  $o$ -cells to a shape where  $c$ -cells have taken over entirely. In other words, layer  $L3$  can be considered as a state between the extremes of layers  $L1$  and  $L2$  of representation. Thus, I propose to measure the relativized state of the actual depth, which will be termed  $RelDep-oc$ , as the percentage of the actual combined state to the range between two extremes:

$$RelDep.oc = \frac{Dep.oc''' - Dep.c''}{Dep.o' - Dep.c''} \quad [7]$$

The minimum depth is achieved when the complex is covered completely by  $c$ -cells, i.e.  $Dep-oc''$  of  $L2$ , and the maximum depth results when the whole is covered by  $o$ -cells, that is  $Dep-oc'$  of  $L1$ . By replacing the component from [4]:

$$\begin{aligned} Dep.oc'''_{min} &= Dep.oc'' = Dep.c'' \\ Dep.oc'''_{max} &= Dep.oc' = Dep.o' \end{aligned} \quad [8]$$

From the definition of  $Loss$  from [3]:

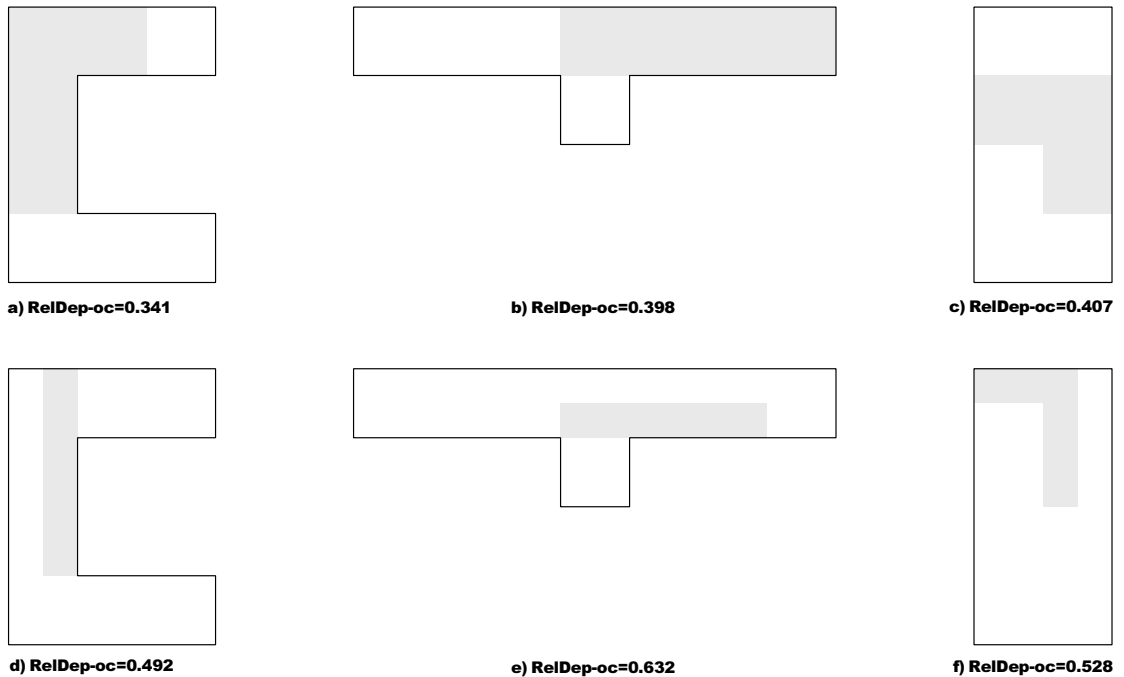
$$Dep.o' = Dep.oc''' + Loss''' = Dep.o''' + Dep.c''' + Loss''' \quad [9]$$

Replacing the components in [7], we express  $RelDep-oc$  only with measures in L1 and L2:

$$RelDep.oc = \frac{Dep.oc''' - Dep.c''}{Dep.o' - Dep.c''} = \frac{Dep.o''' + Dep.c''' - Dep.c''}{Dep.o''' + Dep.c''' + Loss''' - Dep.c''} \quad [10]$$

where  $Dep.o'''$  is the depth of  $o$ -cells in L3,  $Dep.c'''$  is the depth of  $c$ -cells in L3,  $Dep.o'$  is the depth of  $o$ -cells in L1,  $Dep.c''$  is the depth of  $c$ -cells in L2, and  $Loss'''$  is the difference of overall depth values between L1 and L3. Some combined complexes have been analyzed using different size of modules as shown in figure 6. Despite the fact that the value of  $RelDep-oc$  changes according to fineness of the grid, we can see that for finer modules the changes become smaller and the measure gets towards a stable state. The value of  $RelDep-oc$ , which ranges between 0 and 1, expresses the percentage of depth loss of the complex when compared to the state without circulation system. For instance, a value of  $RelDep-oc$  at 0.341 in the case 6a shows that the complex becomes 66 percent more integrated as a result of introducing the circulation system. While keeping the same floor plate shape, I carry out a comparison of complexes in figures 6a, 6b and 6c, with complexes where the circulation system amounts for twice the size of the earlier, figure 6d, 6e and 6f. In the first cases, half of the area of the shape has been covered by  $c$ -cells. We can see that the values of modified depth range between 0.34 and 0.4. Cases in figures 6d, 6e and 6f the area covered by  $c$ -cells has dropped into nearly one fifth of the overall area. Thus, as the circulation systems become shorter or thinner, the relativised depth becomes higher falling between ranges of 0.5 to 0.63. However, the changes are by no means proportionate to the reduction of the circulation, and that relation seems to be complex judging from the shapes of circulation systems. While the ratio between  $o$ -cells to  $c$ -cells changes from 1:1 to 4/5: 1/5, the depth values change only a fraction from a mean of 0.35 to a mean of 0.5. I can suggest that the effect of  $c$ -cells in the complex in regard to the depth minimization is distinctively large. A small number of aligned  $c$ -cells in a corridor-like

**Fig. 6 Combined representation of shapes with different circulation systems**



shape result in major depth loss in the system. The experiment above hints that the system of *c-cells* has a major role in the overall configuration of the whole since a small opening accounts for large depth losses.

The consequences of extending, fattening, of moving circulation openings conform to four principles that were proposed by Hillier. However, when investigating combined systems as close approximations of real buildings, it is not clear how to account for all of the four principles as they operate jointly. For example, it is not clear how to quantify a complex circulation system with regards to how linear and how central it is at the same time, as these two trends might work in opposite directions for a certain case. By means of using the measure of *Rel/Dep-oc*, it is possible to offer a robust and generic way to capture their overall configurational properties, and the peculiarities of their embedding into floor plates.

### 9 Low spots: principles of fitting circulation systems into floor plates

Here I suggest some ways to answer the questions asked on the beginning. Let us adopt the criterion of having the best possible integration of the complex as a principle for fitting circulation into floor plates throughout the following experiments. Circulation systems are crucial in regard to enforcing their structure onto the rest of the complex, therefore, we have to aim first at using circulation structures that are integrated themselves, and second to find ways of embedding them into the shape so as to achieve the best possible integration. In other words, we must aim at including as many areas of low depth as possible as part of the circulation system while also aiming at producing the maximum depth loss through the placement of circulation. *Low spots* that were detected from all *c-cell* second layer analysis seem to provide the clue for solving the problem. As it was discussed in section 7, *low spots* emerge at the intersections of wings, or linear parts of the shape. They have a distinct significance in terms of capturing positions from where a considerable portion of the shape is in linear access. The lower the value of a certain area, the larger the proportion of the shape that is in linear access from it. Areas that have a depth equal to zero have linear access to the entire shape. *Low spots* primarily capture the extension of linearity in the shape given the *linear depth spread* effect where their depth calculation is based. Thus, intuitively, we can think of them as the pivotal points through which the circulation systems must pass if the condition of providing best integration of the overall complex is imposed.

I carry out a number of experiments of fitting circulation systems in several shapes by means of changing the status of certain cells in a floor plate from *o-cells* into *c-cells*. I operate in *L3* of combined cells, being guided from findings that come from two other layers. The criterion of finding the most integrated solution is equivalent to finding the highest value for the measure of *Loss*. A change is preserved each time a higher *Loss* value is achieved, reversing all the moves that have given a lower *Loss*. First, the shape is analyzed on the first layer entirely with *o-cells*, figure 7a. Then, it is analyzed entirely with *c-cells* in order to see the location of *low spots*, figure 7b. I start from the cell that coincides with the most integrated *low spot* in *L2* with the depth value 51, which is shown with letter A in figure 7c. Because of the *principle of contiguity*, the next *o-cell* to be converted has to be adjacent to A. The move A1 gives a higher *Loss* at 723 than A2 with a *Loss* at 704. So the next step is to try the cells adjacent to A1. It is obvious from the *principle of linearity* that A11 would be a better solution than A12, as it is reinforced from the result of analysis where the *Loss* for A11 at 1479 is higher than the one of A12 at 789. A linear corridor in the bottom of the shape is thus seen emerging. As I extend it further we see how it connects to the other position that coincides with the *low spot* B with

**Fig. 7** Generating a circulation system in a shape by means of connecting its low spots

depth value 51. Because of the *linear depth spread* effect, the first line of circulation not only connects the first *low spots* in the rank, but it also covers all other *low spots* with depth values next to the lowest. Therefore, connecting first *low spots* guarantees that we do the best move to obtain the highest integration for the number of converted cells. After the first line of circulation system is completed, I continue on adding other *c-cells* into the shape. Because of apparent central position, it may seem obvious that the next move would be connecting C with D, as shown in figure 7d, which gives a *Loss* at 6392. On the contrary, connecting A to the next lowest *low spot* E with depth value in *L2* at 76, figure 7e, is the best option with *Loss* higher than CD at 7460. This holds true for all next moves. Thus, from here I propose the first principle of fitting circulation systems into a shape:

511	476	445		395	394	395		445	476	511
470	435	404		354	353	354		404	435	470
509		377		353		353		377		509
550		352		326		326		352		550
593		329	310	295		295	310	329		593
638		328	309	294	295	294	309	328		638

a)  
**L1 analysis showing the depths for each o-cell**

109	113	76		87	122	87		76	113	109
109	113	76		87	122	87		76	113	109
150		84		94		94		84		150
150		84		94		94		84		150
150		74	86	78		78	86	74		150
150		51	63	57	66	57	63	51		150

b)  
**L3 analysis showing depth values for each c-cell**

+	+	+		+	+	+		+	+	+
+	+	+		+	+	+		+	+	+
+		+		+		+		+		+
+		+		+		+		+		+
+		A2	A12	+		+	+	+		+
+		A	A1	A11				B		+

c)  
**A - B connection**

+	+	+		D	+	+		+	+	+
+	+	+			+	+		+	+	+
+		+				+		+		+
+		+				+		+		+
+		+				+		+		+
+		+				+		+		+

d)  
**C - D trial**

+	+	E		+	+	+		+	+	+
+	+			+	+	+		+	+	+
+				+		+		+		+
+				+		+		+		+
+				+		+		+		+
+				+		+		+		+

e)  
**A - E connection**

+	+			+	+	+		F	+	+
+	+			+	+	+			+	+
+				+		+			+	+
+				+		+			+	+
+				+		+			+	+
+				+		+			+	+

f)  
**B - F connection**

+	+			G	+	J		+	+	
+	+				+			+	+	
+									+	
+									+	
+									+	
+									+	

g)  
**C - G and H - J connections**

+	+			G	+	J			+	+
+	+				+				+	+
+									+	
+									+	
+									+	
+									+	

h)  
**K - L connection**

*P1 Connecting positions that coincide to low spots, as detected from all c-cells analysis of a shape, in a hierarchical order starting from the ones with lowest depth, gives the most integrated solution for the same number of converted cells in a combined complex of o-cells and c-cells.*

Once there are more than two equal values of *low spots* in the rank, which one of them to connect first becomes an issue. To illustrate this, I analyze the shape in figure 8, which, due to a number of symmetries, shows eight *low spots* with the same depth value of 21 in the second layer of all *c-cells*. From principle *P1*, the first moves would be to connect two *low spots* with a five cell long line. Hillier's *principle of centrality* seems to offer the best answer to the problem. As it is shown from the tentative trials in figures 8c, 8d, 8e and 8f, the best solution is CE in the latest with a *Loss* at 1884. The connection CE has the most central position as it

**Fig. 8** Generating a circulation system in a shape in which several low spots have the same depth value

304	282	262	238	216	216	218	216	216	238	262	282	304
310				222				222				310
318				230				230				318
310				222				222				310
304	282	262	238	216	216	218	216	216	238	262	282	304

a)  
L1 analysis showing the depths for each o-cell

21	34	34	34	21	34	34	34	21	34	34	34	21
42				42				42				42
42				42				42				42
42				42				42				42
21	34	34	34	21	34	34	34	21	34	34	34	21

b)  
L3 analysis showing depth values for each c-cell

B	+	+	+	+	+	+	+	+	+	+	+	+
				+				+				+
				+				+				+
				+				+				+
A	+	+	+	+	+	+	+	+	+	+	+	+

c)  
A - B trial

B				C	+	+	+	+	+	+	+	+
+				+				+				+
+				+				+				+
+				+				+				+
+	+	+	+	+	+	+	+	+	+	+	+	+

d)  
B - C trial

+	+	+	+	C	+	+	+	+	+	+	+	+
+								+				+
+								+				+
+								+				+
+	+	+	+	D	+	+	+	+	+	+	+	+

e)  
C - D trial

+	+	+	+	C				E	+	+	+	+
+				+				+				+
+				+				+				+
+				+				+				+
+	+	+	+	+	+	+	+	+	+	+	+	+

f)  
C - E connection

+	+	+	+	C				E	+	+	+	+
+								+				+
+								+				+
+								+				+
+	+	+	+	D	+	+	+	+	+	+	+	+

g)  
C - D trial

B				C					+	+	+	+
+				+				+				+
+				+				+				+
+				+				+				+
+	+	+	+	+	+	+	+	+	+	+	+	+

h)  
C - B connection

								E				F
+				+				+				+
+				+				+				+
+				+				+				+
+	+	+	+	+	+	+	+	+	+	+	+	+

j)  
E - F connection

				C								
+								+				+
+								+				+
+								+				+
+	+	+	+	D	+	+	+	+	+	+	+	+

k)  
C - D connection

29.13

can be seen from the all *o-cells* analysis in 8a. The centrality of connections is tested from the sum of depth values of corresponding cells that the connection covers in the first layer of all *o-cells*. For instance, connection AB covers a sum of  $1546 = 304 + 310 + 318 + 310 + 304$  in *L1*, and connection CE covers a sum of  $1082 = 216 + 216 + 218 + 216 + 216$ . Hillier's *principle of centrality* for fitting circulation systems can be restated as follows:

*P2 When there are more than two alternative low spots with the same depth value in the shape, the most central connection between them gives the most integrated solution. The most central connection is guaranteed from covering cells which corresponding ones in the first layer of all o-cells have the smallest depth sum.*

Although global in their significance, *low spots* represent local clues in terms of showing where to pass the circulation system in order to achieve the best integration. In contrast, the measure of *concavity* offers a robust description of shapes, and is strongly tied with the potential of introducing a circulation system. As the *concavity* increases, shapes offer more differentiation between certain regions, therefore the choice of inserting the circulation system is channeled through *low spots*. Concave shapes would determine to a large extent the nature of the circulation system to be inserted. In contrast, convex shapes, would present no differentiation for fitting a circulation system. While metric concerns are not addressed, they would offer no obvious choice for a particular circulation, which in turn would be independent from the shape itself. In such case, fitting the circulation would resemble an inserting that is guided only from geometrical constraints. At the same time, the hierarchical influence of circulation to the combined complex would be more significant.

When generating a shape through enhancing an existing circulation system, *low spots* also determine the placement of *o-cells* according to five principles. A further discussion on this can be seen in (Shpuza 2000).

## 10 Conclusions

The findings presented in this paper are the result of investigating shapes from the standpoint of capturing their potential to generate circulation patterns. Once improving integration was set as an essential criterion, shapes displayed unambiguous properties that dictated the configuration and geometry of circulation systems which emerged from them. While only a schematic representation of the built environment, and thereby disregarding metric properties at certain stages of analysis, there emerged a clearer picture of how configurational concerns negotiated between the particular nature of circulation and occupation spaces. The intrinsic feature of circulation systems which facilitates linear movement and increases intelligibility, was used as the foundation for the analysis model. Furthermore, the linear properties of two-dimensional shapes translated the outer boundaries of the shape into the internal organization of the building. Therefore, they offered the key to achieving a unity between two sides of the 'duo' shape and circulation by means of extracting from the shape the potential to generate a complex of connected segments of circulation.

Analyzing shapes of floor plates employing this particular theoretical base and methodology with regard to issues of programming and schematic design in architectural practice, serves a two-fold strategy. Fitting circulation schemes into floor plates and enhancing a chosen circulation pattern is the first stage of this process. The second stage is an analytical understanding of properties of complexes comprising of circulation and shapes, enormously widening the possibility of intuitive choices. A building where schematic design is conceived in this manner, would achieve a unity, in syntactic terms, between the two-dimen-

sional floor plate and the one-dimensional system of internal corridors. The proposed model would regard this complex simultaneously without a hierarchical preference. Its elastic units would switch state from occupation to circulation and *vice versa*, opening an avenue of generating spatial complexes either by the enhancement of preferred circulation schemes, or by the placement of certain syntactic features as constraints on conventional shape-generating models.

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### Bibliography

- Harary, F. 1969. *Graph Theory*, Addison-Wesley, Reading, Massachusetts  
Hillier, B. 1996. *Space is the Machine*, University Cambridge Press, Cambridge  
March, L., Steadman, P. 1971. *The Geometry of Environment*, RIBA Publications, London  
Shpuza, E. 2000. *Floor Plate Shapes as Generators of Circulation*, Qualifying Paper, PhD Program, COA, Georgia Institute of Technology  
Steadman, P. 1983. *Architectural Morphology*, Pion Ltd, London  
Turner, A., Penn, A. 1999. 'Making isovists syntactic: isovists integration analysis'. *Space Syntax 2nd International Symposium*, Universidad de Brasilia, Brazil