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The influence of traditional Indian architecture in Balkrishna Doshi's IIM Complex at Bangalore: A comparative analysis using fractal dimensions and lacunarity

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Abstract

Initiated in 1977 and completed in 1992, the Indian Institute of Management (IIM) Complex at Bangalore is generally accepted as one of the most significant turning points in the career of the Indian architect Balkrishna Vithaldas Doshi, as well as one of the key works in the history of contemporary Indian architecture. As declared by the architect himself and interpreted by scholars, the complex's design, in particular its sophisticated spatial order, was significantly influenced by and closely resembles some key specimens of the traditional Indian architecture: the Royal Complex of Fatehpur Sikri (a specimen of Mughal architecture), the Meenakshi-Sundereshwara Temple Complex, and possibly the Sri Ranganatha-Swamy Temple Complex (both are examples of Hindu architecture). However, these qualitative claims and commentaries have remained mostly unverified in a quantitatively measurable manner. Thus, the present paper uses comparative fractal dimension and lacunarity analysis to mathematically calculate the visual complexity and spatial heterogeneity of these architectural works, focusing on the site plans as the best device to efficiently and comprehensively represent the spatial orders two-dimensionally. While the lacunarity analysis shows a relatively low heterogeneity of the IIM Complex compared to the traditional counterparts, the fractal dimension analysis indicates a relatively high concurrence between the visual complexities of the spatial orders of the IIM Complex and both the Hindu temple compounds. This finding confirms Doshi's preference for a more unorthodox spatial fabric of Hindu architecture compared to the more straightforward order of Mughal architecture.

Keywords
Balkrishna Vithaldas Doshi, Fractal dimension analysis, IIM Complex at Bangalore, Indian architecture, Lacunarity analysis.

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1. Introduction

Designed from 1977 to 1979 and completed in 1992, the architect Balkrishna Doshi's Indian Institute of Management (IIM) Complex at Bangalore is now considered one of the architect's most acclaimed masterpieces. The IIM Complex marks a transition in Doshi's evolution of architectural approach, at which time his earlier works, which had been heavily influenced by Western Modernism, transformed into a new kind of architecture which was (and still is) more sensitive and responsive to the contemporary Indian context. It was during this time that Doshi re-learned Indian culture and philosophy and took inspirations from the Indian architecture from the past. In this regard, the remarkable influence of traditional Indian architecture in the IIM Complex is undisputable; it is admitted by Doshi himself (Doshi, 2012a) and noted by a number of scholars (Curtis, 1987; Curtis, 1988; Mukerjin & Basu, 2011; Hoof, 2019; Subramanian, 2019) that the design of the complex was inspired by a number of ancient Indian masterpieces, such as the Royal Complex of Fatehpur Sikri, the Meenakshi-Sundereshwara Temple Complex, and possibly the Sri Ranganatha-Swamy Temple Complex.

In particular, these structures share a mutual key characteristic with Doshi's IIM Complex at Bangalore: an advanced, intricate spatial order. Scholars have observed how the IIM Complex resembles those ancient masterpieces: the labyrinthine, fluid sequence of spaces, the interweaving of indoor and outdoor area, the shifting axes forming an unorthodox yet balanced type of symmetries, and the arrangement of hierarchical layers, resulting in ambiguous and mysterious spatial experiences. These are the very traits which characterize the complexity of traditional Indian architecture in particular, and the complexity of Indian culture and life in general; a complexity which Doshi has been continuously attempting to capture through his works. Nevertheless, these commentaries on the IIM Complex's formal properties rely heavily on qualitative strategies, such as poetic description, interpretive analysis, or phenomenology; this implies a need to investigate such claims and observations in a more quantitative, mathematically measurable manner. This study aims to provide such mathematical evidence which may confirm (or disprove) these views on the influence of the traditional Indian architecture in Doshi's IIM Complex at Bangalore by using an alternative method for quantitative formal inquiry in architecture: fractal dimension analysis and lacunarity analysis.

The concept of fractals and fractal dimensions was first coined by Benoit Mandelbrot (1977); in principle, fractal dimension analysis is a method to mathematically quantify the visual *complexity* of an image or an object. This method has been conducted in various areas, such as medical studies (Asvestas, et al., 2000), economy (Andronache, et al., 2016), and geology (Blekinsop & Sanderson, 1999). Since the 1990s, the idea of fractals has been more frequently utilized as both a quantitative technique for analyzing architecture (Rian, et al., 2007; Vaughan & Ostwald, 2008; Ostwald & Ediz, 2015; Qin, et al., 2015) and a generator for computational, algorithm-based architectural designs (Ediz & Çağdaş, 2004; Ediz, 2009; Sakai, et al., 2012; Sedrez & Pereira, 2012).

The notion of lacunarity was initially observed by Mandelbrot as well (1983). In short, lacunarity analysis is a method to mathematically quantify "gap distribution" or the s*patial heterogeneity* of a geometric structure. Researches utilizing lacunarity analysis have been conducted in various areas such as landscape ecology (Malhi & Román-Cuesta, 2008) and biology and medical studies (Gould, et al., 2011). In the field of built environment, lacunarity analysis is proven useful for spatial analysis in urban studies (Barros Filho & Sobreira, 2005; Alves Júnior & Barros Filho, 2005; Kaya & Bölen, 2017). Moreover, lacunarity analysis has also been utilized to produce inputs and feedbacks for computational-generative urban design (Gürbüz, et al., 2010; Swaid, et al., 2016).

This present paper commences with a short biography of Balkrishna Doshi and how his approach in architecture has been (and still is) influenced by both Modernism and Indian context, followed by a description of the IIM Complex at Bangalore in relation to the Indian architectural works from the past which might influence Doshi in designing the complex. Afterwards, overviews of fractal dimension and lacunarity analysis as well as the applications in architectural researches are presented, followed by brief descriptions of the variables and settings of analysis used in this study. Finally, the results of fractal dimension and lacunarity calculations are presented, followed by mathematical analysis and interpretive discussions of those quantitative results.

Before progressing, there are some issues that must be clarified. First, with no purpose to understate the broader and more abstract significance of the IIM Complex and other architectural works investigated in this study, be it historical, cultural, or philosophical, such aspects are not directly considered in this paper. This study is focused on two of the formal properties of these works; namely, the visual *complexity*, measured in the form of *fractal dimension,* and the *spatial heterogeneity*, measured in the form of *lacunarity.* Second, as described further in following sections, the analysis is focused on the *spatial order* of the architectural works. Consequently, other formal properties, such as the elevational expression or the layout of building masses, are not investigated in this study; nevertheless, such aspects may be evaluated in future researches.

2. Architect Balkrishna Vithaldas Doshi

Born in 1927 in Pune, India, Balkrishna Vithaldas Doshi began his architectural education in Bombay; however, it is the chance for working with two Modern masters, Le Corbusier (from 1951 to 1955, both in Paris and in India) and Louis Isadore Kahn (in 1962, for the design of the Indian Institute of Management in Ahmedabad, together with Indian architect Anant Raje) that might be considered as the real learning experiences for him. Reasonably, the earlier works of Doshi display strong characteristics of Western Modernism, influenced by the two masters.

Nevertheless, the time finally came for Doshi to feel that, up to that point, his works seemed out of place and significantly lacked a much-needed Indian identity. This was a period during which time Doshi looked back upon the past; in addition to observing the traditional Indian architecture, he also studied the literatures, culture, and in general the Indian philosophies. Doshi's continuous learning and searching establishes him as one of the most respected contemporary architects in India, and in 2018, he was awarded the Pritzker Architecture Prize. His mature works embody his idea of architecture as a reflection of the complexity and nuanced aspects of the relationship between human and environment; an idea of architecture as a "celebration of life" (Doshi, 2012b).

3. The Indian Institute of Management (IIM) Complex at Bangalore and the possible influence of traditional Indian architecture

The Indian Institute of Management (IIM) Complex at Bangalore is one of the four national institutes of management envisaged in the early 1960s by the government of India, the others being at Ahmedabad, Calcutta, and Lucknow. The complex at Bangalore was designed from 1977 to 1979 by Doshi in collaboration with James Allen Stein, Jai Rattan Bhalla, and Achyut Kanvinde, and was constructed between 1977 and 1992.

The IIM Complex at Bangalore is one of the key works from the period of a significant transition in Doshi's architectural career, during which time Doshi felt that his previous works "somehow have a foreign look" and "appear not to have their roots in the soil", and that he had to develop a new kind of architecture which is more appropriate to the vision of the new India; a kind of architecture which is more sensitive and responsive to the "people, their tradition, and social customs and the philosophy of life" (Doshi, 1981: 67). Taking inspirations from Indian architecture of the past, the IIM Complex at Bangalore is an appropriate example of such new kind of architecture. The enormous complex was designed in such a manner that resembles a city, a whole "environment" or *vastu*, more than a "free-standing" building (Curtis, 1988: 29), and in this sense, the influence of large ancient Indian palaces and temple complexes is undeniable.

On numerous occasions, Doshi did express his admiration for traditional Indian architecture and urban design in general, and he also explicitly stated that the design of the IIM Complex was inspired specifically by two large ancient Indian complexes: the Royal Complex of Fatehpur Sikri near Agra and the Meenakshi-Sundereshwara Temple Complex at Madurai (Doshi, 2012a: 14); this was also observed by other scholars (Curtis, 1987; Curtis, 1988; Mukerjin & Basu, 2011; Hoof, 2019; Subramanian, 2019). Besides, on an occasion, while describing his opinion on the importance of spatial experience in Hindu temples, he mentioned specifically the Temple City of Srirangam (Doshi, 1989), at which the Sri Ranganatha-Swamy Temple Complex is located. While Doshi did not mention any explicit connection between the temple and the IIM Complex, its spatial resemblance to the Meenakshi Temple makes it a potential, influential comparison worth to investigate.

Constructed between 1571 and 1585, the Royal Complex of Fatehpur Sikri is a superb example of Mughal architecture (Pandya, 2014: 26); meanwhile, both the Meenakshi-Sundereshwara and the Sri Ranganatha-Swamy Temple Complexes (built in 17th century and c.10th CE, respectively) unmistakably display the key features of Indian Hindu architecture (Hari Rao, 1976; Pandya, 2014: 112). On one side, it is evident that Doshi borrowed the idea of numerous interlocking between building masses and courtyards, the ambiguous border between indoor, outdoor, and all the interstitial spaces (Curtis, 1987: 36), as well as the concept of multiple axes and local symmetries which sometimes clash each other, restraining the whole complex from becoming too formal and too monumental and instead feeling surprisingly humane (Curtis, 1988: 29), from the Royal Complex of Fatehpur Sikri, with its multiple nuclei formed by numerous building masses and courtyards surrounded by galleries and colonnades, declaring each own spatial and formal arrangement, yet harmonious as a whole. On the other hand, the IIM Complex's more intricate and complex fabric of spaces and architectural elements (Subramanian, 2019: 37), the hierarchical structure of "layers" and "overlays" (Curtis, 1988: 29), and the experiential sense of rhythm and progression which frequently interrupted and denied by changes and shifts in vistas or axes (Hoof, 2019: 185), also bring to mind the Meenakshi-Sundereshwara and the Sri Ranganatha-Swamy Temple Complexes. In conclusion, those features which mutually characterize Doshi's IIM Complex and these three major structures may be summarized as one common formal property: a sophisticated, if not unorthodox, spatial order.

Thus, it is the *formal relationship between* Doshi's IIM Complex and these three influential Indian architectural complexes from the past which becomes the focus of this study. In particular, this study investigates the visual complexity, i.e., the density of the visual information found in the spatial order of these architectural works, and the spatial heterogeneity, i.e., the distribution of such visual information. To examine this relationship in a quantitative and mathematically measurable manner, this study utilizes alternative two complementary methods for analyzing formal properties in architecture: fractal dimension and lacunarity analysis.

4. Research methods

Researches based on the idea of applying quantitative and mathematically measurable approach to analyze certain architectural properties are being more frequently conducted, complementing the more abstract and occasionally poetic qualitative analyses. The examples of such inquiries are the study by Şener & Görgül (2008), wherein a particular algorithm is proposed to investigate the shape grammar of classical Ottoman mosques, and the research by Ye and Van Nes (2014) in which space syntax, spacematrix, and mixed-use index are utilized to analyze the New and Old Towns of Songjiang in a comparative manner. Similar to the latter study, this present paper proposes a premise of comparatively analyzing new architecture and its traditional counterparts; yet in this case, the quantitative approach is focused to the visual complexity as well as the spatial heterogeneity of these architectural works, using the methods of fractal dimension and lacunarity analysis.

4.1. Fractal dimension analysis

Fractal dimension is a dimension in the form of *fraction* or n*on-integer value* indicating the *visual complexity* of 2-dimensional images and 3-dimensional objects, in a directly proportional relationship. For instance, a value of 1.25 indicates a 2-dimensional image with low visual complexity, whereas a value of 2.75 indicates a 3-dimensional object with high visual complexity. Mandelbrot (1982) proposed box-counting method to calculate fractal dimension, but it is Voss (1986) who is commonly credited with the first use of the method. Afterwards, researches utilizing fractal analysis have been conducted more frequently in various areas, including architecture. The focus of these studies varies from vernacular and traditional architecture (Ediz, 2003) to Modern and contemporary masterpieces (Ostwald, et al., 2008); the scale ranges from building component (Sakai, et al., 2012) to urban form (Qin, et al., 2015); and the strategy differs from analyzing past works (Ediz & Ostwald, 2012) to utilizing fractal analysis for generating future design (Çağdaş, Gözübüyük, & Ediz, 2005; Ediz & Çağdaş, 2007).

Due to the complexity in terms of its formal and visual characteristics, traditional Indian architecture has become a favoured object in a number of fractal-related researches. For example, Dutta & Adane (2014) and Sardar & Kulkarni (2015) separately conducted studies on fractal geometry in Indian Hindu temples, while Rian, et al. (2007) calculated the fractal dimension of the Kandariya Mahadev Temple in Khajuraho. Yet, it is the study by Kitchley (2003), wherein the fractal dimension of Indian architecture was compared to that of Modern piece, that might be considered most similar to this paper, in terms of the main idea of *comparative* fractal dimension calculation. However, this present paper utilizes the comparative fractal analysis in a more focused manner: a comparison between Balkrishna Doshi's IIM Complex at Bangalore and a number of major traditional Indian complexes which possibly influence the design of the IIM Complex, in terms of the intricacy of the spatial order.

4.1.1. Methodological concerns

As previously described, the most prominent mutual formal and visual characteristics and features of Doshi's IIM Complex at Bangalore and the influential Indian architectural works from the past (the Royal Complex of Fatehpur Sikri, the Meenakshi-Sundereshwara Temple Complex, and the Sri Ranganatha-Swamy Temple Complex) can be summarized under the major theme of *spatial order*. Since the fractal analysis in this paper were conducted two-dimensionally, this *spatial order* must be visualized in the form of the best possible two-dimensional drawing: the *site plans*. Compared to the elevation drawings, which give insight on the exterior forms, masses, and visual articulations but generally inform very little or nothing about the interior, the site plan drawing offer a comprehensive reading on a building's spatial network, including both indoor and outdoor spaces, in a most efficient manner. Therefore, while there are indeed possibilities to conduct fractal analysis upon the other formal aspects of the IIM Complex and these influential ancient complexes in the future works, the fractal calculations in this study are focused on the site plans.

For this study, a number of images were digitally retraced by the authors using the Autodesk AutoCAD 2018 software. The site plan of the IIM Complex (Figure 1) was redrawn based on a drawing depicting the main section of the complex, credited to Stein Doshi & Bhalla in association with Kanvinde & Rai and published in Curtis's book (1988: 99). For the Royal Complex of Fatehpur Sikri, the site plan (Figure 2a) was based on a drawing in a book by Herdeg (1990: 51). The site plan of the Meenakshi-Sundereshwara Temple Complex (Figure 2b) was redrawn based on a drawing in a book published by John Murray (1911: 646); and for the Sri Ranganatha-Swamy Temple Complex, the site plan (Figure 2c) was based on a drawing in a book by Fer-

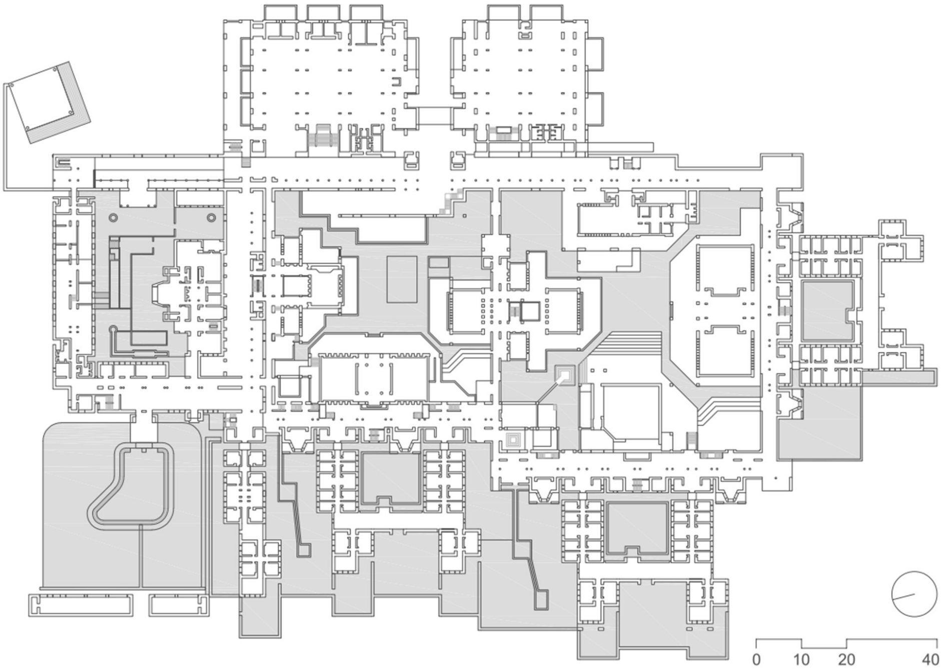


Figure 1. *The site plan of Doshi's IIM Complex at Bangalore (main section).*

gusson, et al. (1910: 368). These three site plans are depicted on the same scale and orientation. It should be noted that, in this paper, the fractal dimension analyses only measure the lines. The gray areas shown in the site plans, depicting the outdoor open spaces, are not measured, and presented here only to illustrate the differentiation between the indoor and outdoor spaces of these complexes.

Table 1. *Methodological variables and settings for fractal dimension calculations used in this paper.*

Stage	Variable	Setting	Notes
Image preparations	White space	50/50	The dimension of the field was determined by enlarging the rectangular outline of the image by the scale of $\sqrt{2}$, or approximately 1.4142; this results in the ratio of 1:1, or 50/50, between the area of the image and the white space around the image
	Image position	Centre-centre	The image was located at the centre of the field before analysis
Fractal dimension calculations	Scaling coefficient (SC)	$\sqrt{2}$:1	This is the ratio by which successive grids are reduced in size
	Grid disposition (GD)	Centre-growth	Successive grids for comparison were generated from the centre of the image
	Grid comparison	10	The number of grids/iterations
	Starting grid size	0.25 l	The first grid was generated by dividing the shortest dimension of the field by four

4.1.2. Image preparations

In principle, architectural fractal dimension analysis requires a strict representation of only the concrete, physical architectural elements of the objects in the form of *line drawings*. Thus, neither shades, colors, non-linear texture, any conventional symbols usually presented in technical drawings, nor any entourage components such as humans, vehicles, or vegetation, may be depicted on the drawings. Furthermore, for the purpose of comparative fractal analysis, all the drawings must be presented in a similar manner of depiction, with an equal level of visual complexity. Thus, in the four site plan drawings used in this study, only a limited set of elements is depicted: the outlines of the wall and columns, and the lines indicating the differences in the floor elevation. The panes, frames, and sills of the doors and windows, as well as the furniture, are not presented. Finally, the images must be produced according to certain standards (Foroutan-Pour, et al., 1999; Ostwald & Vaughan, 2013) summarized in Table 1.

4.1.3. Fractal dimension calculations

Among a number of methods developed for calculating fractal dimension, the method used in this study, i.e., the *box-counting method*, is considered as the most suitable, useful, reliable, and accurate for most results (Ostwald & Vaughan, 2016: 12). The box-counting

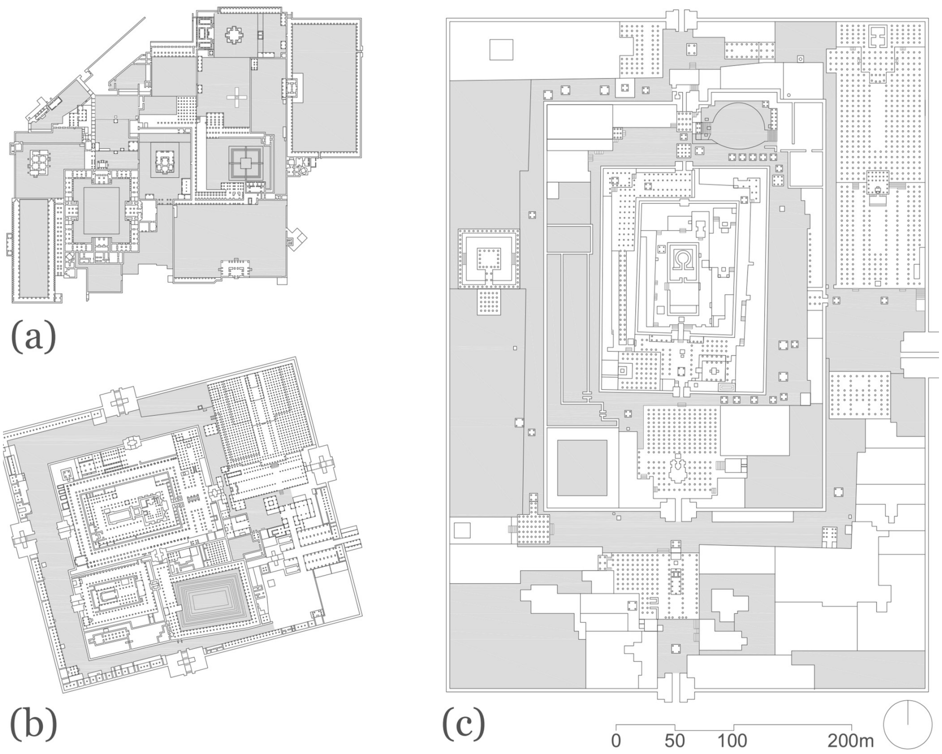


Figure 2. *The site plans of (a) the Royal Complex of Fatehpur Sikri near Agra, (b) the Meenakshi-Sundereshwara Temple Complex at Madurai, and (c) the Sri Ranganatha-Swamy Temple Complex at Srirangam, depicted on the same scale and orientation.*

method states that a number of grids containing boxes of varying numbers and sizes must be super-imposed over the images (Figure 3), and the boxes which intersect with the image must be counted; hence the name "box-counting". Since the sizes of the boxes in each of the successive grids are diminished according to certain *scaling coefficient* (SC)—which, in this case, is √2, or approximately 1.4142—this process results in different *numbers of boxes containing parts of the images* (N#, in which # = the #th iteration) for each grid. In this study, this process was iterated ten times, following the suggestion (Ostwald & Vaughan, 2016: 40–41) about the ideal number of iteration for producing accurate result. Next, *the approximate fractal dimension* (D#) is calculated using Equation 1:

Finally, the *final fractal dimension* (D) is calculated as the mean value of

$$D_{\#} = \frac{[(\log(N\#+1)-\log(N\#)]}{\log(SC)} \quad (1)$$

a number of D# values; thus, a process consisting of ten iterations produces nine D# values, from which the final D value must be derived as a mean value. The methodological variables and settings for the fractal dimension calculations are resumed in Table 1. These variables and settings are described in a more detailed manner in several publications (Lorenz, 2003; Ostwald & Ediz, 2015; Ostwald & Vaughan, 2016). For this study, a set of four images were analyzed, and a total of 40 grid comparisons were calculated, recording over 26,000 data points.

4.2. Lacunarity analysis

The concept of lacunarity may be considered as a complement to the fractal dimension, in that geometric constructions with similar or even precisely identical fractal dimension values can possess very different lacunarity values. While fractal dimension quantifies the visual complexity of geometric objects, i.e., the density of the objects' visual information, lacunarity quantifies how such visual information are spatially organized; i.e., the distribution of the density. Mandelbrot (1983) originally described lacunarity as distribution of the size/area of the lacuna or gaps (open/empty spaces) in fractal sequences; however, it is possible to calculate the lacunarity from the non-fractal geometries as well (Plotnick, et al., 1996).

Thus, lacunarity can be more precisely defined as the measurement of the spatial heterogeneity (Plotnick, et al., 1993) or the "gappiness" (Gefen, et al., 1983) of geometric structures. Similar to fractal dimension, the value of lacunarity is directly proportional to the spatial heterogeneity. Thus in a way, a higher lacunarity value indicate a more complex arrangement of gaps or spaces among the visual information of certain geometric objects.

Lacunarity analysis has been conducted more frequently in the area of urban studies. For example, lacunarity calculations as part of a comprehensive morphogenetic investigation of the city of Istanbul (Kaya & Bölen, 2017) as well as for other Anatolian cities in Turkey (Kaya & Bölen, 2006), a comparative study of morphological evolution of the Turkish city of Bursa in terms of fractal dimension and lacunarity values (İlhan & Ediz, 2019), and a development of texture-based identification system for urban slum areas in the city of Hyderabad, India (Kit, et al., 2012). Lacunarity analysis has also been utilized in computational-based, generative urban designs as in the cases of the city of Gaziantep, Turkey (Gürbüz, et al., 2010) and the city of Cosenza, Italy (Swaid, et al., 2016).

4.2.1. Methodological concerns

As previously mentioned researches demonstrate, in general, lacunarity analysis for urban studies is focused in the spatial distribution of the *open spaces*; i.e., the spaces between building masses. However, in conducting the lacunarity analysis, this present paper aims to investigate the spatial heterogeneity of these complexes in general; that is, not only the outdoor open spaces but also the indoor spaces (the spaces confined inside building masses); in short, all the spaces in general sense. Thus, while the urban studies typically use figure-ground images (buildings versus outdoor open spaces) for lacunarity analysis, this present paper uses the site plan drawings of the complexes wherein masses or volumes (walls and columns) are solid-hatched (black area), while spaces (both indoor and outdoor) are unhatched (white area). Finally, some other preparations have also been applied to the drawings, as explained in the following section.

4.2.2. Image preparations

One key properties of lacunarity is that it is scale-dependent; geometric structures which seem considerably homogeneous (indicating low lacunarity) at certain scale may seem more heterogeneous (indicating higher lacunarity) at different scale. Thus it becomes conventional to conduct lacunarity analysis at different scales or box sizes, as described in the following section. Furthermore, it is also necessary for

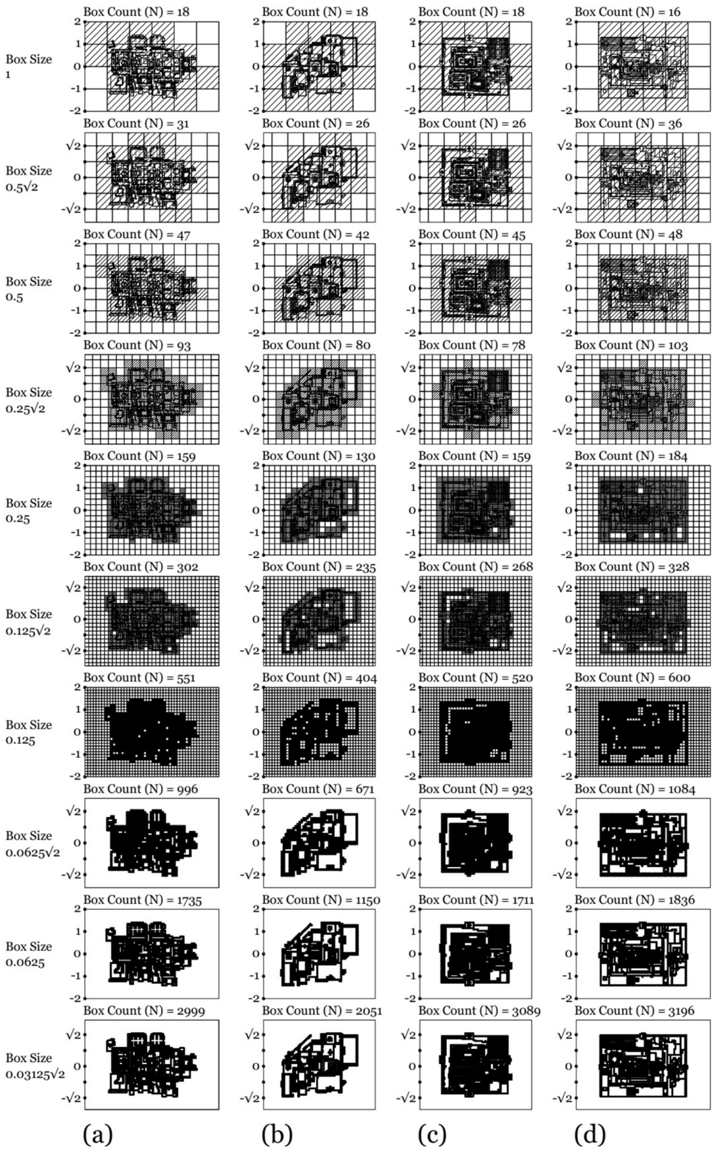


Figure 3. *Box-counting process: (a) the IIM Complex, (b) the Royal Complex of Fatehpur Sikri, (c) the Meenakshi-Sundereshwara Temple Complex, and (d) the Sri Ranganatha-Swamy Temple Complex.*

the drawings to be of identical scale. Since the IIM Complex at Bangalore and the three traditional Indian complexes differ considerably in size, prior to the analysis, each of the site plan drawings was divided into a number of parcels identical in size with the dimension of 50 m x 50 m; this is the optimum largest square unit by which each of the complexes can be divided. This procedure results in the IIM Complex of Bangalore being divided into 12 parcels, the Royal Complex of Fatehpur Sikri into 28 parcels, the Meenakshi-Sundereshwara Temple Complex into 30 parcels, and the Sri Ranganatha-Swamy Temple Complex into 108 parcels (Figure 4). Afterwards, the parcels are converted automatically to binary drawings by the program and the plug-in used for the analysis (ImageJ and FracLac). The size of each of the drawings is 500 x 500 pixels, wherein 10 pixels represent(s) a length of 1 meter. Each of these parcels then was calculated according to the procedure explained in the following section.

4.2.3. Lacunarity calculations

To conduct the lacunarity calculations, this present paper utilizes the conceptually straightforward, computationally simple *gliding-box algorithm* proposed by Allain and Cloitre (1991) and later popularized by Plotnick, et al. (1993). In this algorithm, a box of certain size (b) is placed upon a binary image, resulting in a certain number of open/empty spaces confined inside the box. The box is then shifted or "glided" both along X- and Y-axis, resulting in other number of empty spaces, which may be identical to or different from the previous result. This process of shifting or "gliding" the box is repeated until the whole image is covered completely. As demonstrated in a more detailed manner by Malhi & Román-Cuesta (2008), this procedure results in the *mean value of the numbers of the open/empty unit per box* (μ[b]) and *the standard deviation* (σ[b]). The lacunarity (λ[b]) can be calculated using Equation 2:

$$\lambda[b] = 1 + (\sigma[b]/\mu[b])^2 \qquad (2)$$

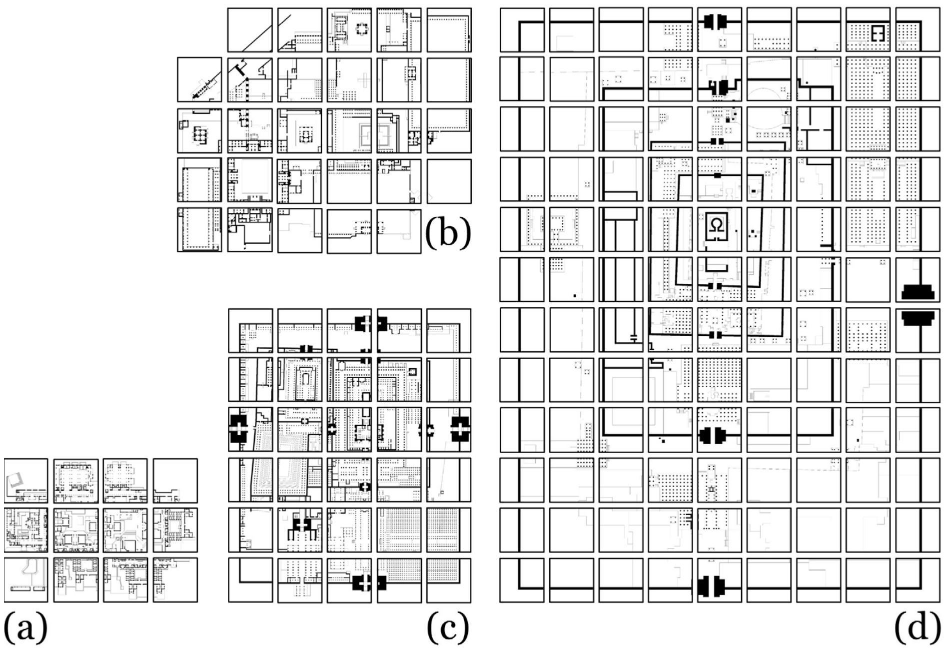


Figure 4. *The divisions of the complexes into parcels identical in size (50 x 50 m): (a) the IIM Complex—12 parcels, (b) the Royal Complex of Fatehpur Sikri—28 parcels, (c) the Meenakshi-Sundereshwara Temple Complex—30 parcels, and (d) the Sri Ranganatha-Swamy Temple Complex—108 parcels.*

This formula produces the lacunarity value resulted from gliding-box algorithm using box with certain size (b); consequently, changing the size of the box may result in different lacunarity value(s). Thus, a series of the algorithm using a certain number of different box sizes may be conducted, resulting in a series of lacunarity values. Finally, the average lacunarity value (λ_μ) may be calculated as a mean of these λ[b] values. This procedure was applied separately to each of the parcels described in the previous section; every parcel thus possesses its own λ_μ value. The final total lacunarity value (Λ) of each of the complexes was calculated as a mean of the λ_μ values of the parcels. For this paper, the ImageJ open source image processing program and the FracLac plug-in were used for the lacunarity analysis using the gliding-box algorithm (also called *sliding lacunarity* or SLac in the FracLac's glossary). The methodological variables and settings for the lacunarity calculations are resumed in Table 2.

5. Results and discussions

5.1. Fractal dimension values, comparisons, and interpretive analysis

Four fractal dimension values (D) of the site plans were produced: Doshi's IIM Complex at Bangalore (D_{IIM}), the Royal Complex of Fatehpur Sikri (D_{FS}), the Meenakshi-Sundereshwara Temple Complex (D_{MS}), and the Sri Ranganatha-Swamy Temple Complex (D_{SRS}). Likewise, the differences (Diff-D)

Table 2. *Methodological variables and settings for lacunarity calculations used in this paper.*

Variable	Setting	Notes
Scaling method	Linear (default sampling method)	Box sizes are increased by a fixed value over a range from the minimum to the maximum box sizes.
Number of box sizes	10	The series/iteration consists of 10 different box sizes.
Minimum box size	10 x 10 pixels	This size represents an area of 1 m².
Maximum box size	200 x 200 pixels	40% of the dimension of the images (500 x 500 pixels).
Slide-X	5 pixels	The boxes are shifted 5 pixels along the horizontal/X-axis.
Slide-Y	5 pixels	The boxes are shifted 5 pixels along the vertical/Y-axis.

Table 3. *Results of fractal dimension calculations.*

Settings		**The IIM Complex at Bangalore**	**The Royal Complex of Fatehpur Sikri**	**The Meenakshi-Sundereshwara Temple Complex**	**The Sri Ranganatha-Swamy Temple Complex**
Iteration	**Box Size**	**Box Count**	**Box Count**	**Box Count**	**Box Count**
1	1	18	18	18	16
2	0.5√2	31	26	26	36
3	0.5	47	42	45	48
4	0.25√2	93	80	78	103
5	0.25	159	130	159	184
6	0.125√2	302	235	268	328
7	0.125	551	404	520	600
8	0.0625√2	996	671	923	1084
9	0.0625	1735	1150	1711	1836
10	0.03125√2	2999	2051	3089	3196
Fractal Dimension (D)		**D_{IIM} 1.64008**	**D_{FS} 1.51826**	**D_{MS} 1.64956**	**D_{SRS} 1.69823**
Difference/Diff-D (%)			**Diff-$D_{(IIM/FS)}$ 12.18**	**Diff-$D_{(IIM/MS)}$ 0.95**	**Diff-$D_{(IIM/SRS)}$ 5.82**

between the fractal dimensions of Doshi's IIM Complex and the three comparisons—between the IIM Complex and the Royal Complex of Fatehpur Sikri or Diff-$D_{(IIM/FS)}$, between the IIM Complex and the Meenakshi- Sundereshwara Temple Complex or Diff-$D_{(IIM/MS)}$, and between the IIM Complex and the Sri Ranganatha-Swamy Temple Complex or Diff-$D_{(IIM/SRS)}$—were also calculated. The complete results as well as the comparisons between the fractal dimension values are summarized in Table 3.

In terms of fractal dimension analysis with architectural works as the object, it has been suggested that the fractal dimension value of ~1.8 can be considered as the upper limit of visual complexity (Ostwald & Vaughan, 2016: 62), and the value of ~1.1 as the lower limit (Vaughan & Ostwald, 2008); this implies that an average value of ~1.5 can be considered as an indication of moderate visual complexity. In this respect, the spatial order of Doshi's IIM Complex, represented by the site plan, can be considered more than moderately complex, since the fractal dimension (D_{IIM}) is ~1.64. Meanwhile, among the three major Indian complexes, the Meenakshi-Sundereshwara Temple Complex is the closest to the IIM Complex, with a fractal dimension value (D_{MS}) of ~1.65. The other temple, Sri Ranganatha-Swamy Temple Complex, is more intricate visually than the IIM Complex (D_{SRS} ~1.70), while the Royal Complex of Fatehpur Sikri is significantly less intricate (D_{FS} ~1.52).

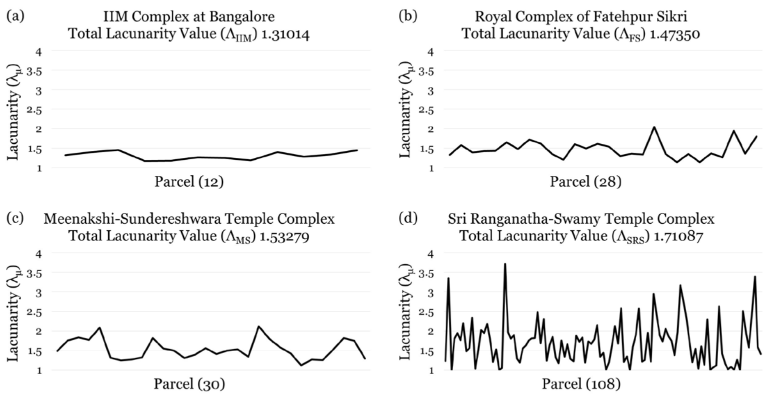
For this paper, the most significant results are the fractal dimension differences (Diff-Ds) between the IIM Complex and the three complexes. This type of difference is inversely proportional to the level of concurrency between the visual complexities of the calculated objects, and it has been suggested that, for a number of objects to be considered highly concurrent in terms of visual complexity, the difference must not exceed 1% (Vaughan & Ostwald, 2009). In this sense, the most interesting result is the difference between Doshi's IIM Complex and the Meenakshi-Sundereshwara Temple Complex (Diff-$D_{(IIM/MS)}$), which is ~0.95%. Slightly less than 1%, this value undoubtedly indicates a high degree of concurrency in terms of visual complexity. In other words, these two complexes are equally intricate in terms of the spatial order. Meanwhile, the difference between the IIM Complex and the Sri Ranganatha-Swamy Temple Complex (Diff-$D_{(IIM/SRS)}$) is ~5.82%, resulted from the fact that the temple's spatial order is more intricate than that of Doshi's IIM Complex. While this number is considerably higher than the Diff-$D_{(IIM/MS)}$ value, this suggests that a similarity in terms of visual complexity is still observable between the IIM Complex and the Sri-Ranganatha Swamy Temple Complex, albeit in a considerably lower degree. Conversely, the difference between the IIM Complex and the Royal Complex of Fatehpur Sikri (Diff-$D_{(IIM/FS)}$ ~12.18%) indicates that the latter's spatial order is undoubtedly and remarkably less intricate than that of Doshi's IIM Complex.

There is also some additional interpretations of these results. It is apparent from the mathematical evidences that, in terms of the fractal dimension values (which represent the visual intricacy of these complexes' spatial order), the resemblance among Doshi's IIM Complex and the two temple complexes is considerably higher than the resemblance between these three complexes (the IIM, the Meenakshi-Sundereshwara Temple, and the Sri Ranganatha-Swamy Temple) and the Royal Complex of Fatehpur Sikri. With fractal dimension values ranging from ~1.64 (D_{IIM}) to ~1.70 (D_{SRS}), and the average value of ~1.66, the IIM Complex and the two temple complexes is significantly more intricate in terms of the spatial order than the royal complex, with the fractal dimension value (D_{FS}) of ~1.52. This phenomenon interestingly concurs with Doshi's opinion about the difference between traditional Indian Hindu and Mughal architecture. He sensed that Mughal architecture is "simple, clear, and pure", with an "explicit" geometry, while Hindu architecture presents "apparent disorder", wherein "things would twist and turn, go up and down" (Doshi, 2012b: 35–36).

In short, in Doshi's opinion at least, Hindu architecture is considerably more intricate visually than Mughal architecture. It should be noted that this differentiation is probably more about the non-spatial aspects than about the spatial properties of both these architecture styles, such as the articulation of surfaces and building elements (Doshi, 2012b: 55). This implies that the results of fractal analysis somehow complement this notion: the contrast between Hindu and Mughal architecture can be observed *not only* in terms of the non-spatial properties, *but also* in the spatial order. However, such deduction is quantitatively reasoned from the measurements of only two specimens of Hindu architecture and one specimen of Mughal architecture (although these structures are arguably among the most impressive and representative specimens). Therefore, although this intuitive and qualitative observation about the contradictory characteristics of Hindu and Mughal architecture is potentially true, it requires more extensive sets of fractal dimension analysis upon a large number of specimens—both of Hindu and Mughal architecture—to prove (or to disprove) such commentaries quantitatively. However, this discussion is already too far beyond the scope of this paper. Nevertheless, in regards to this study, since the Royal Complex of Fatehpur Sikri is one of the masterpieces of Mughal architecture, it is neither unreasonable nor unexpected that the royal complex's fractal dimension value is remarkably lower than those of the Meenakshi-Sundereshwara Temple and the Sri Ranganatha-Swamy Temple Complexes; these two temples are among the most important specimens characterizing Hindu architecture.

While on one hand Doshi depicted this dualism of Mughal architecture's clear order and simplicity versus Hindu architecture's apparent disorder and complexity in a neutral and balanced manner of analysis, on the other hand he also has a clear preference when the times come for him to design himself; namely, the latter. Starting from the period of transition at least, Doshi has been always, and still is, more interested in a more sophisticated and more intricate, even "invisible" order—so invisible that it can also be dubbed as an "apparent *dis*order"—wherein it is possible to introduce contradictions, exceptions, and disruptions every so often, yet still in a general formal idea (Doshi, et al., 2006). Doshi does not take such approach for the sake of formalism only; it is his belief that architecture has an obligation to be more than a mere utilitarian device, even more than a superficially aesthetic object; he believes that architecture has to touch and affect human psyche, sometimes in an undefined and immeasurable manner, through experiences. In this regard, in Doshi's opinion, it is the aspects such as contradiction and ambiguity that characterize a "supreme among architectural experiences" (Doshi, 1989); the aspects found in Hindu temples.

Thus, since Doshi indeed tried to apply this type of advanced order in his design of the IIM Complex, in particular in terms of the spatial order, it is understandable that the fractal dimension of the IIM Complex considerably closely resembles those of the temple complexes, more than it resembles that of the Royal Complex of Fatehpur Sikri. While Doshi did also take inspiration from the royal complex as he himself acclaimed, in the end it is the temple complexes that more strongly influence the intricacy of the spatial order in his design of the



Total Lacunarity (Λ)	**Λ_{IIM} 1.31014**	**Λ_{FS} 1.47350**	**Λ_{MS} 1.53279**	**Λ_{SRS} 1.71087**
Difference (Diff-Λ)		**Diff-$\Lambda_{(IIM/FS)}$ 0.16**	**Diff-$\Lambda_{(IIM/MS)}$ 0.22**	**Diff-$\Lambda_{(IIM/SRS)}$ 0.40**

Figure 5. *Results of lacunarity calculations: (a) the IIM Complex, (b) the Royal Complex of Fatehpur Sikri, (c) the Meenakshi-Sundereshwara Temple Complex, and (d) the Sri Ranganatha-Swamy Temple Complex.*

IIM Complex. The Royal Complex of Fatehpur Sikri might influence Doshi's design of the IIM Complex more significantly in terms of other aspects, such as the vocabulary of the architectural components, or the interplay of building masses and open spaces. While these aspects are beyond the scope of this paper, future studies may be conducted to investigate the importance of such formal properties in a more complete set of Doshi's architectural works.

5.2. Lacunarity values, comparisons, and interpretive analysis

Four total lacunarity values (Λ) of the site plans were produced: Doshi's IIM Complex at Bangalore (Λ_{IIM}), the Royal Complex of Fatehpur Sikri (Λ_{FS}), the Meenakshi-Sundereshwara Temple Complex (Λ_{MS}), and the Sri Ranganatha-Swamy Temple Complex (Λ_{SRS}). Likewise, the differences between the lacunarity values (Diff-Λs)—Diff-$\Lambda_{(IIM/FS)}$, Diff-$\Lambda_{(IIM/MS)}$, and Diff-$\Lambda_{(IIM/SRS)}$—were also calculated. The complete results are summarized in Figure 5, with the graphs illustrating the various λ_{μ} values of the individual parcels shaping the whole images.

The direct relationship between the real sizes (ground area) and the lacunarity values of the complexes is immediately evident. The IIM Complex, being the smallest in terms of area, possess the lowest mean lacunarity value (Λ_{IIM} ~1.31). The complex with the largest area, the Sri Ranganatha-Swamy Temple Complex, possess the highest lacunarity value (Λ_{SRS} ~1.71). Meanwhile both the Royal Complex of Fatehpur Sikri and the Meenakshi-Sundereshwara Temple Complex, with the relatively similar area fall between the lowest and the highest, have lacunarity values of Λ_{FS} ~1.47 and Λ_{MS} ~1.53, respectively. This gives the difference values of Diff-$\Lambda_{(IIM/FS)}$ ~0.16, Diff-$\Lambda_{(IIM/MS)}$ ~0.22, and Diff-$\Lambda_{(IIM/SRS)}$ ~0.40.

In this case, it is not the size of the area per se that affect the lacunarity of these complexes; instead, it is more logical to interpret that, in the complex with larger ground area, there are *more possibilities to design and organize spaces* in terms of size variations and distribution arrangements. Thus in the Sri Ranganatha-Swamy Temple Complex, there can be found particularly more complex distributions of spaces differ extremely in sizes; this is indicated in the graph (Figure 5d) which shows that ~60.19% of the total parcels forming the whole area possess λ value more than 1.5, and ~21.30% have λ value more than 2. Compare this with the Royal Complex of Fatehpur Sikri (Figure 7b) wherein ~35.71% of the parcels possess λ value more than 1.5 and only ~3.57% have λ value more than 2, and with the Meenakshi-Sundereshwara Temple Complex (Figure 7c) wherein ~50% of the parcels possess λ value more than 1.5 and only ~6.67% have λ value more than 2. This indicates less extreme differences in the sizes and less complex distribution of the spaces. Meanwhile, in the IIM Complex at Bangalore, all the parcels have λ value less than 1.5 (Figure 5a), indicating the least differences in terms of sizes of the spaces as well as the least intricate arrangement of those spaces.

Thus, the relatively low lacunarity (and therefore the lower spatial heterogeneity) of the IIM Complex is less the result of Doshi's philosophical design choice than a pragmatic consequence of the complex's relatively small ground area (compared to the three traditional Indian compounds). Furthermore, due to the relatively stricter and utilitarian functional programs, most of the spaces in the IIM Complex were designed with relatively similar sizes (classrooms), resulting in smaller differences between the sizes of the spaces and less complex arrangement of those spaces. Had Doshi been given a ground area as large the Sri Ranganatha-Swamy Temple Complex, it would not be impossible for him to more freely experiment with spaces extremely contrasting in sizes and more heterogeneously distributed all over the area, giving a significantly higher lacunarity value.

Finally, it is interesting to particularly investigate the Royal Complex of Fatehpur Sikri and the Meenakshi-Sundereshwara Temple Complex. These two compounds have relatively similar ground area as well as circumferential sizes, and thus it is possible to compare the lacunarity values of both these complexes. It is immediately evident that the Meenakshi-Sundereshwara Temple Complex is spatially more heterogeneous (Λ_{MS} ~1.53) than the Royal Complex of Fatehpur Sikri (Λ_{FS} ~1.47), with the difference of ~0.06. This concurs with Doshi's notion that Hindu architecture is inherently more complex than Mughal architecture; more specifically, in Hindu architecture, spaces are designed and distributed more heterogeneously than in its Mughal counterparts. Indeed, in this particular case, despite the rich differences in terms of the sizes, the spaces in Fatehpur Sikri are organized in a more orderly fashion, in which the large courtyards are placed in a grid-like arrangement surrounded by colonnaded corridors consisting of rows of small spaces relatively identical in sizes. By contrast, in the Meenakshi-Sundereshwara Temple Complex, the spaces do not only differ contrastingly in sizes, but are also organized in a more heterogeneous, less rigid arrangement. Indeed, these characteristics can also be found in the Sri Ranganatha-Swamy Temple Complex; however, it should be noted that the latter is far greater in size than the other complexes, resulting in greater range of possible complex spatial organizations.

5.3. Summary

Figure 6 illustrates the relationship between fractal dimension and lacunarity values of the architectural works being analyzed. For the three traditional Indian complexes, this relationship is straightforwardly proportional: the higher the fractal dimension value, the higher the lacunarity value. However, this is not the case for the IIM Complex, with the considerably high fractal dimension value nearly equal to the Meenakshi-Sundereshwara Temple Complex, yet the lowest lacunarity value. This demonstrates that the measurements of spatial complexity proposed here, i.e. the density and the distribution of visual information, are indeed two different parameters to measure visual complexity. A relatively dense amount of visual information found in a geometric structure is not necessarily

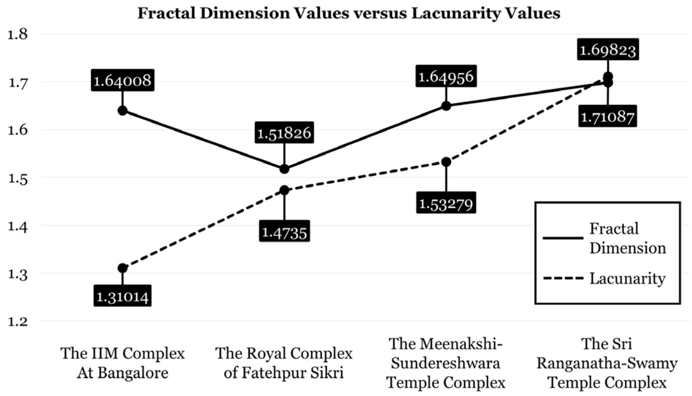


Figure 6. *Comparison between fractal dimension and lacunarity values.*

distributed in a heterogeneous manner, and vice versa. However, in this particular case of the IIM Complex at Bangalore, it is likely that the seemingly contradictory high density and low heterogeneity are actually complementary results of common causes: certain programmatic requirements and relatively limited site area. The amount of multiple functions and facilities, combined with Doshi's strategy of orchestrating various architectural elements, results in the dense visual information in the IIM Complex's site plan. However, a necessity to accommodate multiple spaces of relatively identical sizes, an inherent orderly spatial pattern of the functional typo-morphology of an educational facility, and the constraint of the site area result in a spatial distribution less heterogeneous than the three traditional Indian complexes.

6. Conclusion

Balkrishna Doshi himself, along with a number of scholars, have acknowledged the significance of the influence of several major traditional Indian architectural works in his design of the IIM Complex at Bangalore. This paper examines this proposition by utilizing fractal dimension and lacunarity analysis to quantify the visual and formal properties of these works. While the lacunarity analysis shows the complex's relatively low spatial heterogeneity compared to the traditional counterparts, the fractal dimension analysis confirms the concurrence between the visual density of the IIM Complex and these traditional Indian structures. In particular, when comparing the fractal dimensions of the architectural works being investigated, it is also evident that, while Doshi's IIM Complex indeed closely resembles the two major temple compounds—the Meenakshi Sundereshwara Temple Complex and the Sri Ranganatha-Swamy Temple Complex—in terms of the complexity of the spatial order, the IIM Complex is also remarkably more intricate than the Royal Complex of Fatehpur Sikri. This also confirms Doshi's preference for designing a more sophisticated and unorthodox type of formal order generally found in Hindu architecture, compared to the simpler and more straightforward Mughal architecture.

Finally, whether these results may indicate a more general trend in Doshi's body of work, particularly during and after his period of transition, is not yet discovered. It would be interesting and insightful to quantitatively compare the relationship between Doshi's earlier works and, say, the works of Le Corbusier and Louis Kahn, with the relationship between Doshi's later, more mature works and the vernacular Indian houses or ancient cities and villages. Thus, future works may investigate a larger set of Doshi's masterpieces, as well as other architectural works which might be considered influential to him—both traditional and Modern—to understand how his strategy for devising spatial order as well as other formal aspects evolved, both over time and in response to the architecture which might inspire him.

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