Measuring Fallingwater:

A computational fractal analysis of Wright's Kaufman House in the context of his theories and domestic architecture.

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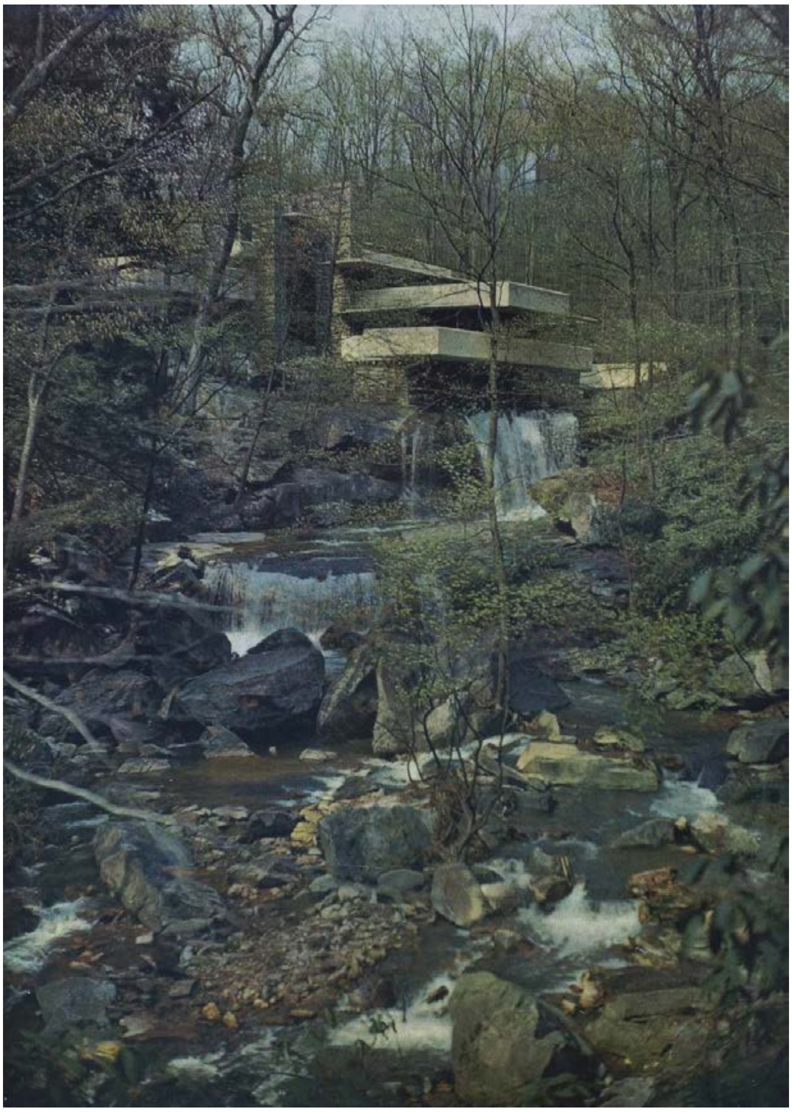

Figure 1.1 "Fallingwater in Springtime" (Zevi 1965: 29)

Statement of Originality
I hereby certify that the work embodied in the thesis is my own work, conducted under normal supervision.

The thesis contains no material which has been accepted for the award of any other degree or diploma in any university or other tertiary institution and, to the best of my knowledge and belief, contains no material previously published or written by another person, except where due reference has been made in the text. I give consent to the final version of my thesis being made available worldwide when deposited in the University's Digital Repository, subject to the provisions of the Copyright Act 1968.

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I hereby certify that the work embodied in this thesis contains published papers/scholarly work of which I am a joint author. I have included below, as part of the thesis a written statement, endorsed by my supervisor, attesting to my contribution to the joint publications/scholarly work.

Between 2009 and 2016, Josephine Vaughan (the candidate) and Professor Michael J. Ostwald (primary supervisor), jointly published 25 papers and a co-authored monograph, developing the basic analytical method and some of the arguments used in this dissertation. Sections of these jointly authored publications form the basis for several chapters in this dissertation, although all have been modified and revised for this purpose.

In accordance with the University of Newcastle policy, this statement is to confirm that the sections of these past publications which are used in this dissertation are those for which the candidate led the primary authoring and/or intellectual development. Notwithstanding this general statement, Chapter 1 provides a complete list of the sources for any sections or ideas, fully referenced to the original authorship and place of publication. Furthermore, for Hypothesis 1, the method was jointly developed, and the results were solely produced and analyzed by the candidate. For Hypothesis 2, the candidate solely developed the method, the results and completed the subsequent analysis.

Josephine Vaughan (candidate) Professor Michael J. Ostwald (supervisor)

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Abstract

Sited above a waterfall on Bear Run stream, in a wooded gulley in Mill Run, Pennsylvania, the Kaufman house, or *Fallingwater* as it is commonly known, is one of the most famous buildings in the world. This house, which Frank Lloyd Wright commenced designing in 1934, has been the subject of enduring scholarly analysis and speculation for many reasons, two of which are the subject of this dissertation. The first is associated with the positioning of the design in Wright's larger body of work. Across 70 years of his architectural practice, most of Wright's domestic work can be categorised into three distinct stylistic periods—the Prairie, Textile-block and Usonian. Compared to the houses that belong to those three periods, *Fallingwater* appears to defy such a simple classification and is typically regarded as representing a break from Wright's usual approach to creating domestic architecture. A second, and more famous argument about *Fallingwater*, is that it is the finest example of one of Wright's key design propositions, Organic architecture. In particular, Wright's *Fallingwater* allegedly exhibits clear parallels between its form and that of the surrounding natural landscape. Both theories about *Fallingwater*—that it is different from his other designs and that it is visually similar to its setting—seem to be widely accepted by scholars, although there is relatively little quantitative evidence in support of either argument. These theories are reframed in the present dissertation as two hypotheses.

Using fractal dimension analysis, a computational method that mathematically measures the characteristic visual complexity of an object, this dissertation tests two hypotheses about the visual properties of Frank Lloyd Wright's *Fallingwater*. These hypotheses are only used to define the testable goals of the dissertation, as due to the many variables in the way architectural historians and theorists develop arguments, the hypotheses cannot be framed in a pure scientific sense.

To test Hypothesis 1, the computational method is applied to fifteen houses from three of Wright's well-documented domestic design periods, and the results are compared with measures that are derived from *Fallingwater*. Through this process a mathematical determination can be made about the relationship between the formal expressions of *Fallingwater* and that of Wright's other domestic architecture. To test Hypothesis 2, twenty analogues of the natural landscape surrounding *Fallingwater* are measured using the same computational method, and the results compared to the broader formal properties of the house. Such a computational and mathematical analysis has never before been undertaken of *Fallingwater* or its surrounding landscape.

The dissertation concludes by providing an assessment of the two hypotheses, and through this process demonstrates the usefulness of fractal analysis in the interpretation of architecture, and the natural environment. The numerical results for Hypothesis 1 do not have a high enough percentage difference to suggest that *Fallingwater* is atypical of his houses, confirming that Hypothesis 1 is false. Thus the outcome does not support the general scholarly consensus that *Fallingwater* is different to Wright's other domestic works. The results for Hypothesis 2 found a mixed level of similarity in characteristic complexity between *Fallingwater* and its natural setting. However, the background to this hypothesis suggests that the results should be convincingly positive and while some of the results are supportive, this was not the dominant outcome and thus Hypothesis 2 could potentially be considered disproved. This second outcome does not confirm the general view that *Fallingwater* is visually similar to its surrounding landscape.

Prelude

Figure 1.2 Approaching Fallingwater *(Photographs by the author)*

The approach to *Fallingwater* is famous for its drama and the immersion in nature it requires (fig. 1.2). At the end of a long walk through the forests of Bear Run Nature Reserve, the visitor finally reaches their destination. It is a real moment of revelation, as the valley opens out along the Bear Run watercourse and *Fallingwater* is revealed in its majesty, like something that has grown out of the site. This is the house that Wright commenced designing for the Kaufmann family in 1934.

Its appearance would have been unlike that of any other building of the era; its bulk both poised above and stacked on the site (Maddex 1998). Broad concrete horizontal outdoor spaces are layered around its core, projecting beyond the rising walls of rough-cut stone which enclose small private rooms. Geometrical patterns of dark red window frames hold glistening glass, creating a space somewhere between inside and outside, reflecting the dampness of the forest.

This is a house that seemingly evokes the mystery and power of its setting. The approach through the landscape to *Fallingwater* can be considered as a demonstration of a key principle of Wright's architectural strategy, to create a clear relationship between a building and its setting. According to historian Gwendolyn Wright, *Fallingwater* exploits 'the startling dramatic potential of a precarious slash of rock that extended over a waterfall, epitomizing the interplay of daring technologies and theatrical gestures' (1994: 85).

Part I: Frank Lloyd Wright and *Fallingwater*

Chapter 1

Introduction

> Fallingwater is a great blessing – one of the great blessings to be experienced here on earth. I think nothing yet ever equaled the coordination, sympathetic expression of the great principle of repose where forest and stream and rock and all the elements of structure are combined so quietly that really you listen not to any noise whatsoever although the music of the stream is there. But you listen to *Fallingwater* the way you listen to the quiet of the country (Wright quoted in Pfeiffer 2004: 53).

Frank Lloyd Wright designed *Fallingwater* in the 1930's as a county retreat for the Kaufmann family. Hailed as a significant architect for his domestic buildings decades previously, many scholars have noted that when Wright designed *Fallingwater,* he had received no major commissions for several years (Kaufmann 1986; McCarter 1999; Storrer 2006). The last designs Wright had completed prior to *Fallingwater* were, the *Lloyd Jones House* in 1929—the final work of his Textile-block period—and in 1933 a small residence in Minnesota, an early example of his Usonian period. The stock market crash of 1929 had halted the built realisation of many of Wright's grand designs until 1934, when the Kaufmann family invited him to design a new country house for their woodland property. In 1937 their house—dubbed by Wright *Fallingwater*—was completed.

The site of *Fallingwater* is part of a thickly forested area of Pennsylvania through which the Bear Run creek flows. Located above this stream, the three storey house—*Fallingwater*— is made from what Aaron Green describes as a 'unique' combination of specially cut and laid local stone, stacked with large rendered concrete cantilevering balconies and levels (1988: 136). Dramatically, the waters of Bear Run travel under the house and then emerge from beneath the living room terrace, pouring down a series of waterfall ledges and flowing out of the west of the site. Bruce Brooks Pfeiffer explains that

> [a]t *Fallingwater*, the entire house is composed of these projections from and above the rock ledges. The rooms themselves, with their adjacent outdoor terraces, are all a part of broad-sweeping balconies reaching out to the branches of the surrounding trees, and over the stream and waterfalls below (Futagawa and Pfeiffer 2003: 10).

The house, despite ongoing structural problems associated with its dramatic concrete cantilevers, seasonal flooding and constant damp, held an enduring place in the lives of the Kaufmann family and continues to captivate the public imagination and scholarly interest today. When describing *Fallingwater*, architectural historians frequently provide two commentaries; the first being that it is a stand-alone house, unique among Wright's domestic oeuvre, what Diane Maddex describes as a 'one-of-a-kind' design (1998: 7). The second commentary regarding *Fallingwater* is that the building's form is a visual reflection of its natural setting. For example, Paul Laseau and James Tice describe *Fallingwater* as a 'most splendid example' of a place 'where the landscape is beautifully woven into the structure'; a place where the '[r]esultant composition effectively unites architecture and nature as one' (1992: 94-95).

These two, well represented positions, reflect twin arguments which concern the relationship between *Fallingwater* and Wright's other houses, and the relationship between *Fallingwater* and its context or setting. These scholarly interpretations of Wright's work are typically based on qualitative assessments of both his buildings and theories. When he died in 1959, Wright left behind a legacy of over 500 completed buildings. Additionally, he published many books and articles and his public lectures were frequently transcribed for posterity. As a result of this volume of output, there is a wealth of information available to support qualitative analysis, even though his buildings are often complex and his writing is notoriously difficult to interpret. For example, Norman Crowe outlines the central problem of studying Wright's work, as that his 'architecture is clouded by details of his life, his clients, the times in which he worked, his own misleading rhetoric, and by an elaborate taxonomy of his stylistic inventions and their subsequent influences on later architects and architecture' (Crowe 1992: vii).

The following section introduces *Fallingwater* and its background, before these two scholarly arguments about *Fallingwater* are examined in more detail. While the mathematical and computational analysis used in the present dissertation are based on quantitative data, the broad range of qualitative information and interpretation of Wright's work serves as a guide for this research, providing a basis from which to draw the framework of the methodology.

1.1 History and Setting of *Fallingwater*

In the aftermath of the great depression, Wright maintained an income by setting up the 'Taliesin Fellowship' in 1932, where fee-paying students worked alongside Wright in his architectural practice, absorbing his architecture, philosophy and lifestyle. One member of this 'fellowship' was Edgar Kaufmann Junior, who joined the group in early 1934. Not particularly interested in becoming an architect, Edgar Junior—like his parents Liliane and Edgar Kaufmann—had an interest in contemporary art, architecture, design and philosophy, and he joined the fellowship to round out his education. Edgar Junior, full of enthusiasm for Wright's architecture, introduced his own family to the philosophy and architecture of Frank Lloyd Wright. The Kaufmanns shared many similar philosophical views with Wright, including the enjoyment of spending time in nature (Cleary 1999). To this end the Kaufmanns would regularly visit their own holiday cabin in the woods, near a locality called Mill Run, about 100km southwest of their home in Pittsburgh, Pennsylvania. In the early 1930s the Kaufmanns began thinking of building a more refined holiday home, and with Edgar Junior's encouragement, they invited Wright to inspect the site, which he did in December 1934.

It is cold in Mill Run in December, the average temperature at that time of year in the 1930s was a high of 3ºC and a low of around -7 ºC. The tall trees, mostly deciduous, lose their leaves in December, and the Great Laurel Rhododendrons are some of the few plants in the understory to hold their greenery in the winter months. At that time of year snow can blanket the area and the creek can freeze over. The effect of winter is that the landscape is less clothed in greenery, and the shape of the land can be seen more easily than in the deeply forested valley in spring. Edgar Kaufmann Junior recalls the day Wright came to their site when the 'mountains put on their best repertoire to him—sun, rain and hail alternated; the masses of native rhododendrons were in bloom' (1983: 69), and he remembers how the weather that day 'accentuated the rugged terrain' (1986: 36).

Figure 1.3 Bear Run stream in its forested setting (Photograph by the author)

The Kaufmann's land was located in a thickly forested area of Pennsylvania, adjacent to Ohiopyle State Park and Bear Run Nature Reserve. It was over 1500 acres in size, but the landforms were steep on the part of the property that they had in mind for the house. This was 'a wooded glen […] characterized by large sandstone outcroppings that exhibited a rustic, even ancient, appearance' (Smith 2000: 21). The land itself was full of life, with a dense forest canopy above of 'red maple, oak black cherry, tulip poplar, and black birch' and below the 'shrubs are evergreen, including mountain laurel and rhododendron' (Cleary 1999: 38). On the forest floor there was a 'rich mat of ferns and mosses and a variety of wild roses, mountain roses, and native bulbs' (Cleary 1999: 38). A special feature of the site, and a place the Kaufmanns spent a lot of time, was the Bear Run stream (fig. 1.3) which enters the site from the east, running through a valley of the ancient 'Pottsville sandstone' geological formation, the stream drops over the many sandstone slabs, creating waterfalls as it passes down the mountains, flowing out of the west of the site to feed into the Youghiogheny River, which eventually merges into the Monongahela River, running right into Pittsburgh city.

On the day Wright first visited the property it would have been far too cold for swimming in the creek, which was 'swollen' while above, the falls were 'thundering' (Kaufmann 1983: 69). However, after showing Wright the site they had in mind for the house, somewhat up the hill above Bear Run, the Kaufmanns showed him the special spot in the creek where they loved to swim, and the rock that they loved to sunbathe on. After staying all day on the site, Wright requested 'a survey of the terrain around the falls [asking that] large boulders and large trees were to be marked on it' (Kaufmann 1983: 69).

When the Kaufmanns saw Wright's design for the first time in September 1935, they were surprised. Edgar Junior was similarly bewildered by the speed at which Wright had conceptualized the design and put it down on paper, just in time to show Edgar Senior when he arrived at the Fellowship studio. In an unexpected move, Wright had located the house directly over the waterfall at Bear Run, on their favoured swimming spot.

From the original concept drawings that the Kaufmanns viewed and agreed upon in September, the first working drawings were completed in January 1936, with very little change to the design (Langmead 2009). An abandoned Pottsville sandstone quarry on the property was reinstated prior to construction and the stone for the house was cut according to specific instructions from Wright. Construction of *Fallingwater* commenced in June of 1936, although the workers from the local construction firm 'needed to be trained in Wright's individual ways' (Kaufmann 1986: 44). During the construction process, Wright was based over one thousand kilometres away at Taliesin, and it was generally apprentices from Wright's office who oversaw the project. The position for the house and Wright's own structural engineering solutions which were 'pushing technology to create poetry' (Lind 1996: 27), were not found to be structurally sound by engineers privately engaged by Edgar Kaufmann Senior. Discovering that Kaufmann had engaged an engineer and additionally had extra reinforcing added to *Fallingwater* caused strain between Wright and Kaufmann, however, it seems both had enough admiration for the other that they settled their differences amicably (Hoffmann 1993; Kaufmann 1986). The house was completed by the end of 1937 and for the Kaufmanns, *Fallingwater* 'soon became part of the family's weekend experience' (54) and Kaufmann Junior enthused of the 'delight it brought to the life of its inhabitants' (1986: 49).

After being 'an old reliable friend' (Kaufmann 1986: 62) to the Kaufmann family for nearly 30 years, *Fallingwater* and the surrounding property were donated to the Western Pennsylvania Conservancy as a place for the public in 1963, and the house and its grounds are presently open to visitors and one of the most popular Architectural destinations in the world.

1.2 A Unique House in Wright's Oeuvre?

If one building appears to have consistent formal or material qualities which are similar to those of another building—or of a set of buildings—these properties are collectively defined as a *style*. Often, architects develop distinctive formal or material qualities across a set of designs, thereby creating their own particular style. Furthermore, if the architect practices over several years, they may even develop several distinguishable styles, or periods, that their buildings can be categorised into. While the term 'style', and its derivatives such as 'stylistic', may have other meanings, in this dissertation the use of the term 'style' refers to an architectural period wherein a pattern of formal or material qualities is evident.

During his career, Wright worked in periods of distinctive styles. For example, Wright initially gained international recognition with his Prairie style houses, long, low-lying buildings which were designed as a reflection of the broad expanse of the Prairie plains. All of these Prairie style houses are characterized by strong horizontal lines, over-extended eaves, low-pitched roofs, open floor plan and a central hearth. Wright's *Robie House* is widely regarded as the ultimate example of this approach.

In the period 1910-1920, Wright became involved in several large-scale developments, including his *American System Built Homes*, a standardised, affordable housing type, and the *Ravine Bluffs Development*, in Glencoe, Illinois. During this period he was also invited to Japan to design *Tokyo's Imperial Hotel*, and he designed several houses and a school which were also built in Japan.

Wright expanded his practice in California in the early 1920's and during the following decade he designed many buildings although only five houses were constructed. These five houses have since become known as the Textile-block homes. Appearing as imposing, ageless structures, these houses were typically constructed from a double skin of pre-cast patterned and plain exposed concrete blocks held together by Wright's patented system of steel rods and concrete grout.

The plain square blocks of the houses are generally punctuated by ornamented blocks and for each house a different pattern was employed. The last house of this period, the *Lloyd Jones* House in Tulsa (1929), is notably less ornamental than the others in the sequence with Wright rejecting richly decorated blocks ‘in favor of an alternating pattern of piers and slots’ (Frampton 2005: 170). The *Lloyd Jones* House was Wright’s last major completed commission before *Fallingwater*. Perhaps for this reason, when, ten years later, *Fallingwater* house was revealed to the public, it came as a surprise, being viewed as a dramatic departure from his earlier works, at variance to other architectural styles of the time (Lind 1996; Kaufmann 1986) and with a unique appearance that was ‘revolutionary in 1939’ (Futagawa and Pfeiffer 2003: 6). Bernhard Hoesli contextualises *Fallingwater* as follows.

> Looking back almost [three quarters] of a century, one still marvels at the singularity of *Fallingwater*. It appeared as a mutation sprung into existence. *Fallingwater* still stands out as a unique achievement in the career of a distinguished architect, and it would also seem that in 1936 nothing in Frank Lloyd Wright’s previous work had prepared one to expect it. There is a surprising lack of ornamental detailing in the stark plainness of the balconies extending into space and the demonstrative use of cantilever construction in the reinforced-concrete slabs that appear to hover like abstract planes in space (Hoesli 2005: 204).

However, just because it has been argued that *Fallingwater* is a clear departure from Wright’s other domestic architectural styles, this does not mean that the position is universally accepted. For example, Kathryn Smith observes that *Fallingwater* ‘has long been recognized as a unique building in [Wright’s] prodigious seventy-year career’ (Smith 2000: 1). However, she then notes that *Fallingwater* may not be as entirely unique to Wright’s repertoire as past scholars suggest. Smith (2000) compares Wright’s other designs involving water and suggests that ‘[t]he juxtaposition of building and waterfall was not new in Wright’s’ Kaufman House (2000: 1). Laseau and Tice, while acknowledging that

Fallingwater is unique in many respects, also propose that '[s]everal houses among Wright's earlier work could provide plausible prototypes for *Fallingwater'* (1992: 72). Robert McCarter (2002) also identifies a selection of Wright's previous designs which may have influenced *Fallingwater* and supports his argument with the following quote from Wright.

> The ideas involved [in *Fallingwater*] are in no wise changed from those of early work. The materials and methods of construction come through them. The affects you see in this house are not superficial effects, and are entirely consistent with the prairie houses of 1901-10 (Wright 1941, qtd in McCarter 2002: 6).

Thomas Doremus (1992) also offers the unusual opinion that *Fallingwater's* 'abrupt break with earlier work' (35) occurred because Wright was influenced at the time by the work of Le Corbusier. In particular, Doremus (1992) suggests that *Fallingwater* is directly influenced by the *Villa Savoye*.

Such debates, about the position of *Fallingwater* in Wright's larger domestic canon, can be traced in many histories and scholarly critiques. Certainly there are elements in *Fallingwater* which recall his previous designs, and which seem to prefigure his later Usonian works. As such, claims that it is unique in his oeuvre are readily disputed, but questions remain about its connection to both earlier and later styles. Was it a transition design, from the Textile-block to the Usonian period, or was it a throwback to the Prairie style?

1.3 A House Which Reflects its Natural Setting?

It is well documented that Wright's architectural theory consistently referred to the relationship between nature and the landscape on the one hand, and the building's form, on the other. Throughout Wright's career, while he did design buildings in distinct stylistic movements, his work was consistently underscored by the concept of Organic architecture; an approach or philosophy guided by the principles of nature (Wright's approach to Organic architecture is explained in section 2.2). For Wright, this was not necessarily the physical form of nature, as he differentiated between two primary forms; the physical natural landscape and a transcendent 'inner nature' (Wright 1957: 89; Cronin 1994; Spirn 2000i). The second form, 'inner nature', described architecture which was a spiritual incarnation of nature, an Emersonian concept by which 'the correlation of physical form to nature would elevate the spiritual condition of humankind' (Alofsin 1994:32). Indeed, Wright often referred to 'Nature spelled with a capital "N" the way you spell God with a capital "G"' (Wright qtd in Pfeiffer 2004: 12). However, Wright's understanding of the physical form of nature was derived from the tangible surrounding landscapes, around which Wright typically designed buildings to achieve 'an absolutely symbiotic integration with nature' (Antoniades 1992: 243). Wright used several recurring strategies to create the impression that a building is closely related to its site and these included approaches to the design of the building as well as his interpretation and often, manipulation, of the landscape (Moholy-Nagy 1959; Frazier 1995; De Long 1996).

Fallingwater is described as one of the foremost examples of Wright's houses that appear to be a part of nature, or even as a natural object itself. For example, McCarter describes the design as having 'grown out of the ground and into the light' (1999: 220). *Fallingwater* also allegedly contains many clear examples of the design strategies linking landscape and building that Wright typically used (Kaufmann 1986; Hoffmann 1993; Levine 1996). Despite the overwhelming quantity of literature supporting or repeating this claim, that *Fallingwater* echoes its natural setting, there are those who disagree, prompting an ongoing debate amongst historians and architectural scholars. For example, Donald Hoffmann accuses *Fallingwater* of being 'an intruder in the forest' (1995: 85), and Kenneth Frampton considers *Fallingwater's* purpose is to 'juxtapose nature and culture as explicitly as possible' (1994: 72). Smith suggests that the house 'differentiates itself from its surroundings and retains its identity' (2000: 25).

Famous for acknowledging the influence of nature in his personal and architectural philosophy, Wright differentiated between the physical and spiritual aspects of nature. Examining the various examples of Wright's approach to nature—provided by Wright and successive scholars—it is possible to discover specific references to how his buildings relate to their physical, tangible setting. While most scholars, and Wright himself, insist this is the case for *Fallingwater*, others disagree, suggesting the house is more of a Modernist spaceship, landed in a pristine forest. Significantly, both sets of views are from reputed, experienced Wrightian scholars, but which, if any, are correct?

1.4 Hypotheses

In scientific research a hypothetico-deductive approach is typically used to examine phenomena from the perspective of logic and causation, with the resulting hypothesis formulated by an inductive argument. However, this dissertation can not employ such a scientific approach to developing hypotheses, as there is no pre-existing or logical evidence to support the ideas being tested. In essence, these ideas are based on theories and suppositions proposed by previous scholars. Furthermore, the complexity of the possible iterations and variables in this thesis also make it inappropriate to develop and apply hypotheses in a scientific sense. Instead, the hypotheses presented here are used to carefully define the testable goals of the dissertation.

This dissertation tests two hypotheses that reflect dominant scholarly interpretations of *Fallingwater's* visual and formal properties, as set out in the previous two sections.

- **Hypothesis 1:** That the formal and visual properties of Frank Lloyd Wright's *Fallingwater* are atypical of his early and mid-career housing (1901-1955).

- **Hypothesis 2:** That the formal and visual properties of Frank Lloyd Wright's *Fallingwater* strongly reflect its natural setting.

While historians typically frame both of these hypotheses as true, almost suggesting that one necessarily follows the other, the present research treats these hypotheses as parallel or disconnected propositions. Both could be true, both false or some combination of one true and the other false. Furthermore, unlike most scholarly assessments of Wright's work, this dissertation uses a quantitative approach: a computational variation of the fractal analysis method for measuring visual complexity. In Chapter 7, these hypotheses are reframed around the mathematical indicators that will be used to test their veracity in Chapters 8 and 9.

The proposed quantitative approach will make a new range of information about Wright's architecture, and especially *Fallingwater*, available to support future research. Rather than relying on the diverse views of scholars or Wright's own—often rambling—discourse, a quantitative study provides numerical, comparable results. Wright's architectural history and various scholarly viewpoints will assist in the interpretation of results, however, the sets of computed fractal dimensions deliver definite information on levels of visual complexity in Wright's architecture. As an approach to this dissertation, when used with a rigorous methodology, the results will illuminate the hypotheses with a solid basis of data.

Table 1.0 aligns the hypotheses with the analytical method used to test them and the indicators that will be used to determine the validity of each hypothesis. The details of these processes and indicative range percentages chosen for this purpose, are explained in Part II.

Table 1.0 Formal and visual properties of Fallingwater *mapped to specific hypotheses, analytical methods and evidence required for results*

	1	**2**
Theme	Relationship between *Fallingwater* and Wright's architecture.	Relationship between *Fallingwater* and nature.
Hypothesis	That the formal and visual properties of Frank Lloyd Wright's *Fallingwater* are atypical of his early and mid-career housing (1901-1955).	That the formal and visual properties of Frank Lloyd Wright's *Fallingwater* strongly reflect its natural setting.
Method	Fractal dimension analysis of: (i) plans and elevations of *Fallingwater* (ii) plans and elevations of fifteen other houses by Wright.	Fractal dimension analysis of: (i) plans and perspectives of *Fallingwater* (ii) plans and perspective views of four natural elements of the landscape
Evidence for a positive result	The range between: (i) the mean results for elevations and plans of *Fallingwater* and (ii) the mean results for elevations and plans of the other houses, will be greater than 10% ($x \geq 11.0\%$). A positive result indicates that *Fallingwater* is different to Wright's Prairie, Textile-block and Usonian houses.	The range between: (i) the mean results for perspective views and plans of *Fallingwater* and (ii) the mean results for perspective views and plans of natural elements, will be no more than 5% ($x < 6.0\%$). A positive result is a clear indication that the formal and visual properties of *Fallingwater* strongly reflect its natural setting
Evidence for an intermediate or neutral result	The range between: (i) the mean results for elevations and plans of *Fallingwater* and (ii) the mean results for elevations and plans of the other houses, will be ≥ 6.0% and <11.0%. An intermediate result provides an unclear outcome, where *Fallingwater* is neither obviously similar nor dissimilar to Wright's Prairie, Textile-block and Usonian houses.	The range between: (i) the mean results for perspective views and plans of *Fallingwater* and (ii) the mean results for perspective views and plans of natural elements, will be ≥ 6.0% and < 11.0%. An intermediate result indicates an unclear relation between the formal and visual properties of *Fallingwater* and its natural setting; the house is neither obviously similar nor different to its setting.
Evidence for a negative result	The range between: (i) the mean results for elevations and plans of *Fallingwater* and (ii) the mean results for elevations and plans of the other houses, will be no more than 5% (x < 6.0%). A negative result is an indicator that *Fallingwater* is largely typical of Wright's Prairie, Textile-block and Usonian houses.	The range between: (i) the mean results for perspective views and plans of *Fallingwater* and (ii) the mean results for perspective views and plans of natural elements, will be greater than 10% ($x \geq 11.0\%$). A negative result indicates that the formal and visual properties of *Fallingwater* do not reflect its natural setting

1.5 Significance and Rationale

Frank Lloyd Wright is one of the most important architects of the Twentieth Century. Anthony Alofsin describes him as ‘America’s most celebrated architect’ and as being responsible for creating a ‘revolution in domestic architecture’ (2004: 281). Wright pioneered an enduringly popular, alternative version of Modern architecture that, according to Pfeiffer, ‘would change the face of architecture in the world’ (2004: 13). Such is Wright’s legacy that his works are still analysed in depth today, with hundreds of books and thousands of scholarly papers being published on his architecture, theories, principles and texts. However, the vast majority of the published research consists of qualitative interpretations of Wright’s architecture, with only a comparatively small amount of quantitative analysis of Wright’s work in existence, so that, according to Laseau and Tice, Wright is ‘the best known and least understood of American architects’ (1992: ix) whose work is ‘mysterious and difficult to decipher’ (Koning and Eisenberg 1981: 295).

The existing diverse collection of qualitative analysis is typically based on primary sources of Wright’s designs and writings, and while often informed by personal feelings or experiences of his architecture, are necessarily subjective. The diverse personal approaches and theoretical positions brought to bear on Wright’s architecture have resulted in countless assumptions about his work, many of which seem reasonable but have, thus far, resisted any form of critical testing. Further complicating matters,

> [t]he precision and grace of Frank Lloyd Wright’s architecture are rarely to be found in his writing. He wrote swiftly and with ardour, and although he revised some pieces from time to time, his ideas were so large and encompassing that he found it sufficient if his words conveyed their general shape or effect (Nordland 1988: 4).

This characteristic of Wright’s work makes it possible for the myriad of qualitative scholarly interpretations to either differ so much, or to cycle around similar themes without developing any new insight.

The unique response of this dissertation is to consider the formal and visual properties of one of Wright’s most famous works, using a computational or quantitative method, rather than a traditional historical or theoretical method. As identified by Laseau and Tice, past scholarly

> emphasis has been on the symbolic meaning of [Wright’s] architecture rather than on an understanding of its intrinsic formal structure. The assumed split between idea and form, with the higher valuation usually given to the former, has made achieving the necessary connection between the two more difficult (1992: 1).

While the interpretation of the quantitative results developed in this dissertation will be informed by conventional scholarly analysis, and indeed the hypotheses are developed from this past research, the present work will develop mathematical results to inform the discussion and future interpretation of Wright’s architecture.

The small number of quantitative studies on Wright’s designs that have been published confirm that it is not only possible to accurately study his architecture using computational means, but it is highly beneficial because of the size of the body of work he produced. Of similar importance is the fact that several of the computational or geometric studies of Wright’s architecture that have previously been undertaken have been focused on his houses, including planar diagrammatic methods to compare the forms in Wright’s designs (Seargeant 2005; MacCormac 2005), shape grammar approaches to analysing Wright’s houses (Koning and Eizenberg 1981; Knight 1994; Lee et al. 2017) and analytical illustrations to generate typological studies of the plans of Wright’s buildings (Laseau and Tice 1992). Precise geometric mapping of lines of sight within and around Wright’s architecture have been measured using a space syntax method by Behbahani et al. (2014; 2016). Ostwald and Dawes have taken this idea further by applying isovist field analysis, a computational technique, to routes through and views of Wright's domestic architecture (Ostwald and Dawes 2013; Dawes and Ostwald 2014).

Curiously, all of these geometric and typological studies have been focused on Wright's planning, albeit some in three dimensions, and there are no equivalent studies of Wright's elevations (which encapsulate the visual or formal properties of the building as they are experienced by their users or inhabitants) using similar methods. Nevertheless, a single suggestion for such an analytical approach is found in Carl Bovill's (1996) demonstration of a version of the 'box-counting' technique of fractal dimension analysis, to determine the characteristic complexity of the main facade of Wright's *Robie House.* Bovill's work, while using only an early, manual application of the method and only applied to a single facade, is the progenitor of the present dissertation. In 2008, as a precursor to the present study, the author published a paper with colleagues Michael J. Ostwald and Christopher Tucker entitled "Characteristic visual complexity: Fractal dimensions in the architecture of Frank Lloyd Wright and Le Corbusier". That publication revisited the case of Wright's *Robie House* and developed a computational method to automate the fractal analysis of architecture and to propose a protocol, or method, for the consistent analysis of domestic designs.

The method developed in that publication has since been applied to around 80 houses including designs by Modernist architects (Ostwald and Vaughan 2009a; Vaughan and Ostwald 2009b), Avant-Garde architects (Ostwald and Vaughan 2009b; Ostwald and Vaughan 2013a) and contemporary architects (Vaughan and Ostwald 2008; Ostwald, Vaughan, and Chalup 2009) and it provides the basis for the methodology used in the present dissertation. Given the method's origins in the analysis of Wright's *Robie House*, it is appropriate that the present dissertation returns to Wright to undertake a comprehensive analysis of *Fallingwater*, one of his most significant houses. Using this method it is possible to construct a comparison between different periods in Wright's domestic design and thereby test the first hypothesis.

A secondary dimension of the present research which is significant is that it offers a comparison between architecture and its setting. In a pilot study in 1994, William Bechhoefer and Bovill measured the fractal dimensions of indigenous buildings and natural land forms in Amasya, Turkey. They concluded that each of these features had similar levels of visual complexity and thus, the topography must have either influenced the design of the buildings, or alternatively all of these features were shaped by larger environmental conditions. Bovill reproduced these findings in 1996 and further suggested that one way of determining a successful regional building could be to assess whether its fractal dimensions were similar to those of the surrounding landscape or vegetation. In order to test the second hypothesis, the present dissertation will follow Bovill's lead and develop a variation of the computational method to include natural landscapes, in order to compare the visual complexity of a building and its setting.

1.6 Approach and Method

The approach taken in this dissertation is that the two hypotheses are tested using one computational method for measuring formal expression. This method, known as the box-counting approach to measuring fractal dimensions, uses mathematical algorithms to measure the level of 'typical' or 'characteristic' visual complexity in a form (such as a building). This method has been recently tested on multiple examples of domestic architecture (Vaughan and Ostwald 2011; Ostwald and Vaughan 2013a; Ostwald and Vaughan 2016) – however it has never been applied to *Fallingwater*.

This dissertation's first hypothesis asks if *Fallingwater* is so very different from other houses by Wright in the USA which share a similarity in chronology, typology and brief. To test this hypothesis, the computational method is applied to a sample of Wright's houses completed before 1955 producing comparable, numerical values, providing a gradient of similarity (or dissimilarity) between

Fallingwater and his other houses. The method for testing hypothesis one is as follows.

a. The computational method—fractal analysis (which will be described later in Chapter 4)—is applied to measuring the characteristic complexity of the four cardinal elevations, three floor plans and one roof plan of *Fallingwater*.
b. The computational method is then applied to 58 elevations and 46 plans of 15 of Wright's built houses, from three significant periods in his career. The 15 houses are the *Robie, Evans, Zeigler, Tomek* and *Henderson Houses* from Wright's Prairie Style period; the *Ennis, Millard, Storrer, Freeman* and *Lloyd-Jones Houses* from Wright's textile block period; and the *Palmer, Dobkins, Reisley, Fawcett* and *Chahroudi Houses* from his Usonian period.
c. A numerical comparison using mean dimensions and comparative ranges is undertaken between 112 major and approximately 1000 minor data points generated by the 15 houses and the equivalent data from *Fallingwater*.

The second hypothesis asks if *Fallingwater* is visually similar to its natural setting. By using a variation in the application of the computational method, the form and complexity of Wright's *Fallingwater* can be compared with its surrounding landscape. The method for testing the second hypothesis is as follows.

a. The computational method is applied to four perspective drawings of *Fallingwater* (generated from Wright's original chosen viewpoints), and to the four plans of the building.
b. Sixteen views of four natural features and four site plans of those features are selected from the Bear Run site and analysed using the same computational method.

c. The fractal dimension measurements for *Fallingwater* are compared with equivalent measurements derived from the nature analogues. The results are analysed by comparing mean values and the gaps between them.

The results of both tests are presented as charted mathematical data, in tabular and graphical format. The data is analysed and discussed in its historical context, and interpreted with an informed theoretical reading, by comparing the results with past published research and scholarly theories on Wright's work. The interpretation of the results will also be informed by past results of research into the fractal dimensions of domestic architecture (Bovill 1996; Zarnowieka 1998; Debailleux 2010; Lorenz 2003; Ostwald and Vaughan 2016).

1.7 Limitations

The methodological scope of the research is defined by four limits: characteristic complexity and fractal dimensions; the selection of subjects for analysis; the representation of the images for analysis; and the variables of the computational method.

1. Characteristic Complexity and Fractal Dimensions

In a way, the most significant limitation is that this dissertation uses characteristic complexity—measured using fractal dimensions—to compare objects. Fractal dimensions are a statistical approximation of the spread of geometric detail or information in an image. Fractal dimensions do not provide information on any other visual properties such as proportion, composition or color.

2. Subject selection.

The computational method is carried out on two-dimensional images, and to reduce the possible number of external variables that can have an impact on the data, these images are selected from a pool of similar types. The buildings analysed are only domestic structures designed by Frank Lloyd Wright. Of the several hundred houses Wright designed in his lifetime, only 16 are selected for analysis. The reason for this limited sample of houses is to maximize the potential reliability and consistency of the results, while including his major works from each period. To narrow the selection, completed houses, in preference to unbuilt works, and designs from a similar time frame and geographic distribution are selected. Thus, only domestic buildings by Frank Lloyd Wright completed in the USA after the beginning of his Prairie style (1901), or before the end of his Usonian period (1959) are considered for inclusion.

Since Bovill first undertook a fractal dimension analysis of Wright's *Robie House* in 1996, houses have been a regular subject of this research approach (Zarnowieka 1998; Lorenz 2003; Wen and Kao 2005; Debailleux 2010; Ostwald and Vaughan 2016). Houses are appropriate analytical subjects because they typically possess scale, program and materiality that are comparable to other houses. Because the architectural brief conventionally shapes the form and complexity of the design, conducting a comparison between different building types (such as a church, an apartment building and stadium) would produce results that are largely a reflection of the function of the building.

Wright designed houses of many different sizes, from tiny cottages to large housing complexes. He designed many 'modest' sized homes, single freestanding domestic type buildings with one main living area and 2-3 bedrooms. *Fallingwater* fits into this size category, and therefore all of the other houses selected for comparison also do so.

3. Image representation boundaries.

Once the buildings are selected for analysis, there must be a consideration of which representations of these buildings will be analysed. For the architectural images, only re-drawn line drawings from existing original drawings that are publically available, but not photographs or archival facsimiles, are used for analysis. Following the method published by Bovill (1996) and work completed in part by Ostwald, Chalup, Tucker and the present author (2008) for the first hypothesis, it will be one pixel-width line drawings of elevations and plans of buildings which will be analysed, rather than sections, perspectives etc. For the second hypothesis, other drawings types, for example perspectives and landscape views, will also be considered. In this way the analysis can be done in a standardised manner, and the lines selected to include in the analysis will not include a large amount of detail, only the significant lines will be reproduced. These approaches are described in more detail in Chapter 6.

4. Computational limits.

The final limitation concerns the method being used. The box-counting method has only been developed in detail for architectural research in the last decade, with many of the most significant advances occurring in the last few years (Ben-Hamouche 2009). There are several variations of the method, and some known inconsistencies. While the box-counting method was traditionally a manual exercise, the variation used in this dissertation will follow the version published extensively in the last few years (Ostwald and Vaughan 2016). This method uses a computer program (in this case, *Archimage*, a program co-developed by Ostwald, Chalup, Nicklin and the present author). The known limitations of the method are described in detail in Chapter 5.

There are three further non-methodological limitations to this dissertation; the first being the age of the buildings. This study is focussed on the visual appearance of buildings and landscapes, and the dissertation seeks to understand Wright's original influences, which are apparent in the buildings and setting at the time they were built. The houses studied range from 62 to over 100 years old today, with *Fallingwater* being 80 years old and, as such, many changes have occurred over time to these buildings. To ensure a similar state between all buildings studied, the original images produced by Wright are analysed, rather than any modifications or additions that have been subsequently designed. This applies to a particular aspect of *Fallingwater,* where detached guest quarters were later designed by Wright. As they were designed and constructed after *Fallingwater* was originally competed they are not included in the present analysis.

The second non-methodological limitation is that the distance between Australia and the USA, and the diverse location of Wright's buildings across the USA (many of which are private homes), means that the majority of the buildings studied are impossible to visit. However, a site visit was undertaken in 2012 to *Fallingwater*—and to many of Wright's publicly accessible Prairie Houses—to gather data for this dissertation. Finally, language provides a limitation, and written sources will be limited to those published in English.

1.8 Dissertation Summary

The dissertation is divided into three parts. Part I presents the hypotheses of this dissertation and provides an introduction to Frank Lloyd Wright and his architectural design and theory. Part II provides an explanation of the computational method used to test the hypotheses and Part III reports the results generated, and discusses the results and their implications, before reaching a conclusion. These three parts, and the chapters they comprise, are summarised hereafter.

Part I**: **Frank Lloyd Wright and **Fallingwater**

The present chapter, the introduction to Part I, covers the context to the research project, focussing on scholarly analyses of Wright's work which suggest clear parallels between his architectural forms and the surrounding natural landscape. In particular, the proposals of architectural theorists and historians regarding *Fallingwater,* as emblematic of a site-related building, are described, in addition to claims that *Fallingwater* is a unique work among Wright's sizeable oeuvre. This scholarly context leads to the formulation of the two hypotheses. The two hypotheses regarding Wright and *Fallingwater* are stated and explained, and the significance of this dissertation is outlined. This is followed by a brief outline of the computational method, and the methodological and other boundaries or limitations of this work.

Chapter 2 expands on Frank Lloyd Wright's background and architectural theory, presenting an overview of Organic architecture, an architectural style which is informed by nature. Wright's influence, as 'the true father of organic architecture' (Pearson 2001:39), is also explained. This is followed by a review of Wright's long career, which also reveals several important influences on his design approach. In particular, the chapter explores, through an in-depth literature review, Wright's relationship with the landscape and nature, identifying eleven design strategies that Wright used to achieve a connection between landscape and building. The final part of Chapter 2 focuses on *Fallingwater*, the house which, according to Futagawa and Pfeiffer, 'has grown to become synonymous with […] Frank Lloyd Wright' (2003:10) and the main subject of this dissertation. Placing *Fallingwater* in the larger context of Wright's career, in this chapter *Fallingwater's* history and a description of the house and the surrounding landscape is included along with any specific instances found in *Fallingwater* of Wright's eleven key strategies for connecting nature and architecture (identified earlier in Chapter 2).

Part II: Methodological Considerations

Part II begins with Chapter 3, an introduction to fractal dimension analysis, which starts with Mandelbrot's famous proposal in the late 1970s that Euclidean geometry, the traditional tool used in science to describe natural objects, is fundamentally unable to fulfil this purpose. An explanation of Mandelbrot's non-Euclidian geometry, or fractal geometry, is then offered. Thereafter an overview of the application of fractal geometry to the built environment is outlined and in particular, its application to architecture. The final section of Chapter 3 reviews cases where past researchers have identified fractal elements in the work of Frank Lloyd Wright.

Chapter 4 introduces quantifiable methods for measuring or studying buildings, along with previous computational and geometric studies of Wright’s architecture. The difference between fractal geometry and fractal dimensions is clarified, through Carl Bovill’s response to Mandelbrot’s suggestion that architecture can be measured using fractal analysis. The computational method of fractal analysis (the method used throughout this dissertation) is then explained and demonstrated with the example of Wright’s *Robie House*. The chapter concludes with a critique of existing studies using this method to measure the fractal dimension of architecture, including examples of fractal analysis of the architecture of Frank Lloyd Wright.

Chapter 5 describes the known variables and limitations of the computational method. There are many variations of the box-counting approach that respond to known deficiencies in the method. These variations in part explain the lack of consistency in the way in which previous studies have both recorded and reported their data. This chapter describes the primary issues and how the present methodological approach responds to each issue. This includes challenges with the initial representation of the subject, the pre-processing settings such as field and image properties and finally the processing issues. Proposed variables for the dissertation method are provided and these settings are applied to the example of the *Robie House*.

Chapter 6 explores the relationship between architecture and nature. Up to this point in the dissertation, the use of fractal measurement has been limited to the analysis of architecture. This chapter reviews existing calculations of the fractal dimension of nature, with an assessment of natural analogues used for fractal analysis in other fields, such as biology, medicine and ecological studies. The chapter then introduces the approach taken to the second hypothesis—the comparison between the fractal dimensions of architecture and nature. Computational comparisons between architecture and natural settings are relatively untested, with Bovill’s suggestion of a similarity between the visual complexity of particular landscapes and their architecture being the only major proposal in this area. Bovill’s claims are examined in this chapter, and the outcomes clarify a need for improved rigor in the methodology. This leads to a review of the various approaches to images used for comparing fractal dimensions which is then developed into a framework for comparing buildings and their settings.

Finally, the chapter presents the types of data that could be selected for a comparative analysis between *Fallingwater* and its natural setting. It is recorded that Wright arranged for specific surveys to be taken of the *Fallingwater* site (Kaufmann 1986), which include the landforms, the placement of rocks and the locations of trees, with notes of their specific species. Wright then utilized these surveys in his design process. It has also been noted that Wright designed directly onto photographs of his project sites (Spirn 1996). By re-drawing these items utilized by Wright and by using additional images which are commonly employed in other scientific fields, a collection of natural analogues for comparison will be created.

The final section of Part II, Chapter 7, provides a description of the methodology for testing both hypotheses. The research description is a summary of the scope of the entire data selected, followed by a summary of the data source and types. Data representation and processing methods will be explained with the steps taken for each process provided. The settings used and the specific research method will be defined.

Part III: Results

Chapter 8 begins with an outline of the architectural styles that were employed by Wright. Historians have defined three distinct stylistic periods in his early and mid-career housing; the Prairie style (generally the first decade of the 20^{th} century), the Textile-block era (the 1920s) and the Usonian era (the 1930s to the 1950s). In this chapter these periods are all described as are five significant houses from each of the periods. The computational analysis method is used to measure the fractal dimensions of four elevations of each of these houses, in addition to four elevations of *Fallingwater*. The results for all houses are then tabulated.

Chapter 8 concludes with a discussion of the results of testing the first hypothesis on *Fallingwater* and the 15 other houses from Wright's Prairie, Textile-block and Usonian periods. The discussion provides an explanation of the significance of the results in terms of the buildings and their formal similarities or differences. It will be shown that the presence of high fractal dimensions indicates greater levels of visual complexity in the buildings. Each set of buildings will be discussed to clarify the higher and lower limits of their fractal dimensions, as well as averages of these dimensions for each building. Once the fractal analysis data is clarified, any outlying results or anomalies will be highlighted and discussed. The results for all buildings and sets can then be compared numerically, and a discussion will be provided to explain what aspects of these houses and types show similarities or significant differences. This discussion will be based around several comparative techniques, such as percentage differences and result clustering. Charts and graphs are presented in this chapter along with a discussion to clarify the results.

In Chapter 9, Hypothesis 2 is considered. As determined in chapter 6, the image requirements for a fractal dimension comparison between nature and architecture differ somewhat from a straight architectural comparison as undertaken in the previous chapter. The data set for *Fallingwater* is now expanded, with plans re-presented for this different type of comparison, and elevations replaced by perspectives drawings. The line textures of the images are changed from those used in the previous chapter to the lower level of detail used in natural data sources, in order to make a more accurate comparison. Along with the new images for the house, the sets of natural analogues of the *Fallingwater* setting, initially identified in Chapter 6 and clarified in Chapter 7, are all analysed to determine their fractal dimensions. The results of the comparison between *Fallingwater* and the natural analogues are then discussed, using the same format outlined for the previous chapter. The results are presented in chart and graph formats with discussion and contextual explanation exploring not only the results but any problems or limitations that arose as part of the application of the method. Finally, Chapter 10 summarises the conclusions, outcomes of the hypotheses and possible directions for future research.

1.9 Relationship to Past Research

During the course of this dissertation, 11 journal papers, 15 chapters, and 14 conference papers on the topic were jointly published by the present author and her supervisor, Michael Ostwald. The content of several of these publications has been substantially revised as the basis for chapters in this dissertation. Furthermore, several chapters in this dissertation share content with our recent monograph, *The Fractal Dimension of Architecture* (Birkhauser 2016). In particular, Chapters 2, 3, 4, 7 and 8 all include reworked material, at least partially derived from this book. The details of this overlap are listed hereafter and are in accordance with the standards and expectations of the University of Newcastle and are acknowledged as such.

Chapter 2 includes some material previously published in: Ostwald, Michael J., and Josephine Vaughan. 2016. Organic Architecture. In *The Fractal Dimension of Architecture*, 205–242. Birkhauser.

Chapter 3 includes some material previously published in: Ostwald, Michael J., and Josephine Vaughan. 2016. Fractals in Architectural Design and Critique. In *The Fractal Dimension of Architecture*, 21–37. Birkhauser.

Chapter 4 includes material previously published in: Ostwald, Michael J., and Josephine Vaughan. 2016. Introducing the Box-Counting Method. In *The Fractal Dimension of Architecture*, 39–66. Birkhauser; Vaughan, Josephine, and Michael J Ostwald. 2010. Refining a computational fractal method of analysis: testing

Bovill’s architectural data. In *New Frontiers: Proceedings of the 15th International Conference on Computer Aided Architectural Design Research in Asia*, 29–38. Hong Kong: CAADRIA.

Chapter 5 includes material previously published in: Ostwald, Michael J, and Josephine Vaughan. 2013. Representing Architecture for Fractal Analysis: A Framework for Identifying Significant Lines. *Architectural Science Review* 56: 242–251; Ostwald, Michael J, and Josephine Vaughan. 2013. Limits and Errors Optimising Image Pre-Processing Standards for Architectural Fractal Analysis. *ArS Architecture Science* 7: 1–19; Ostwald, Michael J., and Josephine Vaughan. 2016. Measuring Architecture. In *The Fractal Dimension of Architecture*, 67–85. Birkhauser; Ostwald, Michael J., and Josephine Vaughan. 2016. Refining the Method. In *The Fractal Dimension of Architecture*, 87–131. Birkhauser; Vaughan, Josephine and Michael J. Ostwald. 2009. Refining the Computational Method for the Evaluation of Visual Complexity in Architectural Images: Significant Lines in the Early Architecture of Le Corbusier. In *Computation: The New Realm of Architectural Design: Proceedings of eCAADe27*. 689-698. Istanbul, Turkey: eCAADe.

Chapter 6 includes material previously published in: Vaughan, Josephine, and Michael J Ostwald. 2017. The Comparative Numerical Analysis Of Nature And Architecture: A New Framework. *International Journal of Design & Nature and Ecodynamics* 12: 156–166; Vaughan, Josephine, and Michael J Ostwald. 2009. Nature and architecture: revisiting the fractal connection in Amasya and Sea Ranch. In *Performative Ecologies in the Built Environment: Sustainability Research Across Disciplines*, 42. Launceston, Tasmania; Vaughan, Josephine, and Michael J Ostwald. 2010. Using fractal analysis to compare the characteristic complexity of nature and architecture: re-examining the evidence. *Architectural Science Review* 53: 323–332.

Chapter 7 includes material previously published in: Ostwald, Michael J., and Josephine Vaughan. 2016. Analysing the Twentieth-Century House. In *The Fractal Dimension of Architecture*, 135–157. Birkhauser.

Chapter 8 includes material previously published in: Vaughan, Josephine and Michael J. Ostwald. 2011. The Relationship Between the Fractal Dimension of Plans and Elevations in the. Architecture of Frank Lloyd Wright: Comparing The Prairie Style, Textile Block and Usonian Periods. *Architectural Science Research*: *ArS.* 4: 21-44; Vaughan, Josephine and Michael J. Ostwald. 2010. A Quantitative Comparison between Wright's Prairie Style and Triangle-Plan Usonian Houses Using Fractal Analysis. *Design Principles and Practices: An International Journal*, 4: 333 – 344.

Methodological refinements described in the following works are also accommodated in the approach taken in this dissertation: Vaughan, Josephine. and Michael J. Ostwald. 2014. Measuring the significance of façade transparency in Australian regionalist architecture: A computational analysis of 10 designs by Glenn Murcutt. *Architectural Science Review* 57: 249-259; Vaughan, Josephine and Michael J. Ostwald. 2009. A Quantitative Comparison between the Formal Complexity of Le Corbusier's Pre-Modern (1905-1912) and Early Modern (1922-1928) Architecture. *Design Principles and Practices: An International Journal*, 3: 359 – 371; Vaughan, Josephine and Michael J. Ostwald, 2014. Quantifying the changing visual experience of architecture: Combining Movement with Visual Complexity. In. *Across: Architectural Research through to Practice: Proceedings of the 48th International Conference of the Architectural Science Association*: 557–568. Genoa, Italy: ANZAScA; Vaughan, Josephine and Michael J. Ostwald 2010. Refining a computational fractal method of analysis: testing Bovill's architectural data. In *Proceedings of the 15th International Conference on Computer Aided Architectural Design Research in Asia:* 29-38. Hong Kong: CAADRIA; Vaughan, Josephine and Michael J. Ostwald. 2008. Approaching Euclidean Limits: A Fractal Analysis of the Architecture of Kazuyo Sejima. In

Innovation Inspiration and Instruction: New Knowledge in the Architectural Sciences, ANZAScA 08: 285-294. Newcastle, Australia: ANZAScA.

Chapter 2

Frank Lloyd Wright and *Fallingwater*

Accounts of Frank Lloyd Wright's architecture and design philosophy often include claims about connections to the natural world and his veneration of the landscape. Indeed, scholarly readings of the relationship between Wright's architecture and nature, combined with Wright's own, often unclear, pronouncements on the metaphysical properties of the natural world, have resulted in a general view that 'Wright regarded nature in almost mystical terms' (Pfeiffer 2004: 12). So strong was his nature-oriented doctrine that Wright would eventually claim a thread of the Modernist style almost entirely to himself, being known as the 'father of organic architecture' (Pearson 2001: 39). While the words *nature*, *organic* and *landscape* are often conflated when scholars talk about Wright's influence, there are important distinctions between them. For example, popular thought in the early years of the twentieth century may have conceived of nature as a spiritual, transcendent or poetic presence (Hoffmann 1995; Miller 2009), but there was also interest in the physical forms and ecological operations of the natural landscape (Olsberg 1996). The terms 'landscape' and 'nature' are pivotal to the arguments developed in this thesis and the intricacies of these terms are unpacked throughout the chapter. The essential difference between nature and landscape is significant because it has been argued that Wright typically differentiated landscape from nature (Cronon 1994: 14; Spirn 2000a: 17). This distinction is at the core of the present chapter.

This chapter commences with an overview of Wright's attitudes to nature and how they developed throughout his career. Beginning with Wright's views about landscape and how these evolved during his early years on the family farm, this chapter presents some of the history of Wright's career, focusing on those moments when the natural landscape became a driving force in his personal and architectural identity. The first section of the chapter effectively provides a background to his design philosophy, and it is included here in part as demonstration of its existence, but also as much as a means of excluding it from the scope of the present dissertation. In contrast, the second section of this chapter analyses the difference between Wright's views and attitudes to nature and landscape. Thereafter, the eleven strategies Wright used to evoke or suggest a connection between his architecture and the landscape are identified. Importantly, this section includes a review of scholarly viewpoints and documented cases which suggest *how* Wright created his famed connection between landscape and building.

The focus on landscape in the second section in this chapter is especially significant to this dissertation, as it identifies a tangible, physical and thereby potentially measurable approach to the relationship between nature and Wright's architecture. Measuring the spiritual or metaphysical connection between Wright's architecture and nature is beyond the scope of this dissertation. However, the issues raised in the second hypothesis—*that the formal and visual qualities of Frank Lloyd Wright's Fallingwater strongly reflect its natural setting*—concern the actual, malleable forms of the landscape, and not the abstract, mystical or poetic properties of nature. As such the distinction between nature and landscape is significant, because Wright describes the latter and its connection to architecture in a more tangible way.

In the final section of this chapter, the focus shifts to specific arguments about *Fallingwater*; a building where, scholars argue 'the landscape is beautifully woven into the structure' (Laseau and Tice 1992: 95). The chapter concludes with an assessment of literature that describes how the architecture of *Fallingwater* is allegedly linked to the surrounding landscape. This review of the literature is framed around the eleven key strategies identified in section two of this chapter, but now providing specific instances found in *Fallingwater*. Finally, a list of the design strategies that Wright used to connect *Fallingwater* to its natural setting, and some specific elements which are suitable for detailed analysis, are tabulated. In Chapter 6 these tables are used as the basis for discussion about testing the connection between architectural form and the forms of nature. As a requirement for testing the two hypotheses of this dissertation, the method (as described in Part II) requires visual data (line images, drawings or other equivalent information) for comparison, and this chapter commences the process of determining what data might be suitable for representing the landscape. Abstract, spiritual and ephemeral references to nature are impossible to represent, in any consistent or coherent way, in a visual form. Thus, Wright's broad, complex and evolving definition of 'nature' is beyond the scope of this study. As this thesis is concerned with *measuring* the *visual properties* of nature, only physical features of what Wright called the 'landscape', are useful for analysis.

2.1 A background to Frank Lloyd Wright

Frank Lloyd Wright's extended maternal family, the Lloyd Joneses, had lived and farmed in a fertile valley they named *Hillside*, in southwestern Wisconsin since 1845. Wright was born in 1867, and in the summers of his youth he regularly worked on the farm in this 'long valley enclosed by parallel, lobed ridges of flat-bedded limestone and sandstone that formed smaller valleys within the larger whole' (Spirn 1996: 136-7). For Wright, this setting was the backdrop for the formative years of his life. As such, it provided 'an intimate introduction to the aesthetics of nature […] whether in microcosm or in landscape' (Hoffman 1995: 3).

Wright's early beliefs and attitudes about nature were strongly influenced by those of the extended Lloyd Jones family. In particular, poet Ralph Waldo Emerson 'served as the high priest' for this close-knit clan's 'intellectual and spiritual pantheon' (Cronon 1994: 13). Emerson believed, as did Wright, that nature is an embodiment of the greater spirit of god, and that this spirit is revealed to mankind through human endeavour. Thus, it is the 'role of human beings—especially artists—to breathe life into matter by relating it to the whole of creation and thereby giving it spiritual meaning' (Cronon 1994: 13). Like the majority of Wright's later discussions about nature, Emerson focused on spiritual or mystical dimensions, an approach that Wright would eventually describe as an 'internal nature', rather than nature's more physical, or external expression in flora, fauna and landscape (Wright 1957: 89). Thus, in his late 70's, when Wright produced *An Autobiography*, he stated:

> What did they mean when 'they' used the word nature? Just some sentimental feeling about animals, grass and trees, the out-of-doors? But how about the nature of wood, glass and iron—internal nature? The nature of boys and girls? The nature of law? Wasn't that Nature? Wasn't nature in this very sense the nature of God? Somehow I had always thought when I read the word "nature" in a book or used it in my own mind that it was meant that interior way. Not the other, measly, external way. "Fools!" They have no sentiment for nature (Wright 1957: 89).

In this quote, Wright differentiates between the 'external' way of viewing nature, which he partially dismisses, but which is, nevertheless, where many arguments about *Fallingwater* eventually lead, and the 'internal' way, which is more spiritual and transcendent. Understanding Wright's Emersonian attitude to nature is especially useful for interpreting Wright's pronouncements about the world and to highlight those moments when he has looked to the 'out of doors' and is referring to nature's tangible properties.

Wright's own attitudes to nature had parallels in then contemporary society. In the USA in the 1800's, there was 'a sense that America was the land of untold opportunities' and that '[s]cience and research into the natural world expanded and touched on critical philosophical and political questions' (Ching et al. 2011: 597). Along with Emerson, Henry David Thoreau (1817-1862) and Walt Whitman (1819-1892), both 'celebrated nature and the American landscape in opposition to the miseries of the modern industrial city' (Hoffmann 1995: 96). In a nation where '[t]he more rapidly, the more voraciously, the primordial forest was felled, the more desperately painters and poets—and also preachers—strove to identify the unique personality of this republic with the virtues of pristine and untarnished, of “romantic,” Nature’ (Miller 2009: 207). The writings of Emerson, Thoreau and Whitman shaped the American psyche of the time and its response to nature.

In addition to being influenced by figures from literature and philosophy, Wright’s architectural thinking was also shaped by Eugène Emmanuel Viollet-le-Duc (1814-1879) and John Ruskin (1819-1900), both of whom held nature-based beliefs, promoted honesty in materials and felt that a spiritual or moral imperative was required in design. Thomas Jefferson (1743-1826), not only the third president of the United States but an architect and philosopher, also influenced Wright’s early ideas about how ‘architecture was directly related to social reform’ (Ching et al. 2011: 619). Thus Wright, living at a time and in a place that supported specific approaches of family, spirituality, philosophy, literature and the arts, was influenced towards a particular life-view. This ‘philosophy’ was underscored by a hands-on experience on the land and Wright reflected that this approach ‘came to me gradually and mostly by way of the farm’ (1943: 243). The combination of practical and theoretical aspects of this context assisted Wright to develop an understanding of ‘the mysterious beauties and obvious cruelties of Nature—interlocking interchanges of the universe’, these natural elements were emphasised in Wright’s view when connected to architecture, as he concluded: ‘these began to fascinate me more when I began to build’ (243).

2.1.1 Wright’s Architectural Career

Wright began his architectural education in 1885 working for Joseph Silsbee—whose ‘Queen Anne designs were very fashionable’ at the time (Storrer 2006: 3)—and then found a like-minded mentor under the employment of Louis Sullivan from 1888 to 1893. Sullivan, a key figure in the development of large-scale urban buildings of the late 1800’s, espoused ‘an emphatic rejection of any autonomous form in building which failed to take account of function and construction’ (Seidlein 1997: 326). Sullivan also famously advocated that ideally, ‘form [is] derived from nature’ (326). Through these attitudes and beliefs, Sullivan's influence over Wright's approach endured, even after Wright left the firm to start his own practice in 1893. However, Sullivan's architectural approach used a 'naturalistic decorative vocabulary' (Tafuri and Dal Co 1986: 62) which applied natural forms predominantly as a source of external ornament, whereas Wright's nature-based inspiration was less about surface treatments and more about integration throughout a design. According to Donald Hoffmann, Sullivan provided Wright with a positive example of a person who stood for 'an undiluted concept of the architect as an artist, a high intellectual regard for nature and a fervent desire to create for America an architecture of its own' (1995: 1). In part because of this, after they parted ways, Wright 'groped for an artistic ethos', struggling to develop his own ideas and producing architecture that was 'both eclectic and experimental' (Storrer 2006: 18). Nevertheless, from the beginning of the twentieth-century, Wright's theories and designs became more consistent. This advance came, according to Hoffmann, only when Wright 'turned to an idea of the land and to aesthetic standards established by natural exemplars of organised form' (1995: 50).

During this period, from 1887 to 1909, Wright's professional and domestic worlds were centred in Oak Park, at that time an outer suburb of Chicago. For Wright, the 'natural exemplar' in the Chicago region was the Eastern Tallgrass Prairie landscape, which had once flourished locally, covering 'about 80 percent of the pre-European settlement landscape of the Chicago region' (Bowles and Jones 2007: 29). Created from 'glacial material, which was deposited in the last 20,000 years' (29), the landscape featured the iconic native tallgrasses that grow up to two metres high, creating a complex series of ecosystems, 'embedded in the prairie—fens, pannes, sedge meadows, marshes, ponds, kames, sand blowouts, savannas, and prairie groves' (Robertson et al. 1997: 63).

While by the late 1800s, much of this Prairie landscape had been destroyed to make way for suburbs, some of the natural landscape remained around the outer limits of Chicago into the early nineteenth-century. Wright viewed the remnants of this natural landscape as a site of discovery and learning. As he would continue to do throughout his career, Wright took his employees from the studio out into the landscape ‘to undertake prairie weed hunting expeditions’, returning with the flowers and grasses of the landscape to decorate their workspace (Klinkowitz 2014: 20).

Such studies and experiences of the landscape shaped Wright’s formulation of his first major design approach, the *Prairie Style*. Wright emphasised the horizontality of the landscape in this approach, stating that ‘[t]he exterior recognises the influence of the prairie, is firmly and broadly associated with the site, and makes a feature of its quiet level. The low terraces and the broad eaves are designed to accentuate that quiet level and complete the harmonious relationship’ (Wright 1901: 17). In this proposition, Wright uses simple spatial and formal analogies, rather than spiritual ones, to suggest a relationship between the landscape and his architecture. Thus, while he may have previously been dismissive of the ‘external’ properties of nature, they would provide him with the most direct connections between architectural form and the landscape.

The success of the Prairie Style—combined with his growing confidence in pursuing a design methodology inspired by the local landscape—led to a significant and productive period for Wright. As his architectural career progressed and his approach evolved, his reliance on the landscape as a design generator remained a constant. Hoffmann states that Wright’s ongoing desire was ‘to redeem the lost landscape [of the Prairie] through an architecture conceived as its abstract equivalent, or analogue’ (1995: 7). The success of this approach would also shape the ‘principles that would inform [Wright’s] art for the rest of his life’ (1995: 7). Anthony Alofsin concurs with this view, stating that the ‘process of abstraction explored in these works inevitably led [Wright] to develop the modern form language that governed everything from the mass of his buildings to their ornament’ (1994: 35). Not only was the Prairie Style significant for Wright, but the designs he produced also influenced the wider architectural understanding of the concept of the ‘house’. Wright's Prairie designs ‘combined the formal order of symmetrical planning with the dynamism of interpenetrating spaces’ to create interiors that were ‘integrated with surrounding nature’, an outcome which has since ‘become the most popular characteristic of modern domestic architecture’ (McCarter 2004: 1453).

The Prairie Style houses were built between 1901 and 1910 and are generally characterized by strong horizontal lines, outstretched eaves, low-pitched roofs, open floor plan and a central hearth. Five important houses in Wright’s Prairie Style, which are examined in more detail in Part III of this dissertation, are the *Henderson House* (1901) (fig. 2.1), *Tomek House* (1907) (fig. 2.2), *Evans House* (1908), *Zeigler House* (1910) and *Robie House* (1910).

Figure 2.1 East elevation of the Henderson House

Figure 2.2 North elevation of the Tomek House

Despite its initial success, Wright’s focus on the Prairie Style began to wane after 1910. In that year, Wright toured Europe and had two portfolios of his work published, seemingly signalling the end of that particular stage in his career. In 1911 his mother purchased a lot for him in the Lloyd Jones’ valley in Wisconsin, which he named *Taliesin*, and from ‘1911 to 1959, Wright reshaped the valley to conform to his ideals and those of his family, giving form to their Emersonian philosophy’ (Spirn 1996: 137). For Anne Winston Spirn, the success of *Taliesin* is that its presence connected the ‘whole landscape of hills and valleys, buildings and roads, fields, gardens, and groves, the disparate elements unified in a sweeping composition’ (Spirn 1996: 137).

By 1912 Wright had set up his new home and studio at *Taliesin* and the next decade was spent in experimentation with form, construction methods and mass production. Perhaps inevitably, Wright’s theories on nature began to change during this time and, according to Spirn, by 1912 when he referred to nature ‘he did not mean that outward aspect that strikes the eye as a visual image of a scene or strikes the ground glass of a camera, but that inner harmony which penetrate[s] the outward form' (Spirn 2000a: 15).

With an existing interest in Japanese art and architecture, Wright made his first trip to Japan in 1913, coinciding with the Taisho period (1912-1926), an era which was 'marked by the pursuit of new architecture by the younger generation' along with a growing interest in international architecture (Yatsuka 1997: 176). Wright spent the years from 1915 to 1922 designing and overseeing the construction of the *Imperial Hotel* in Tokyo. As he toured the country, he was exposed to the Japanese concept of *Wabi Sabi*—'rusticity and minimalism'—an ethical proposition which promotes 'harmony with nature, and the rejection of the ostentatious, the gaudy, and the wilful' (Mehta and MacDonald 2011: 14). Wright admired the traditional Japanese architecture and it is notable that 'many of the structures which he saw in Japan appeared to be virtually continuous with their surroundings' (Nute 2000: 159). In addition to some 'obvious visual motifs', the Japanese influence gave Wright 'a broader appreciation of buildings as they might become part of a larger landscape.' (De Long 1996: 33-34). Indeed, when recalling his experiences in Japan, Wright 'emphasized the relationship of the buildings to their sites' leading him to view them as creating 'a unified, cultivated landscape' (De Long 1996: 34).

Returning to the United States in the 1920's and relocating to Los Angeles, Wright began to think about an alternative, masonry system of construction that was appropriate for his new location. The country he returned to in the 1920's was 'a newly mobile America, whose progressive thinkers were increasingly bound to the idea of regionalism and to the anti-urban Jeffersonian revival' (Olsberg 1996: 9). As such, Wright was not alone in his desire to engage more closely with nature. His revitalised interest in regionalism resulted in the creation of a system of interlocking, modular patterned textile blocks. In the development of these blocks, Wright created 'a fully integrated mono-material system of design and construction, a synthesis of structure and form' (Sweeny 1994: 228). The masonry buildings in this new location responded to a different, more 'sun-baked' landscape, than the one he had left behind in Chicago. For Wright, the Los Angeles landscape was an 'arid' and 'sunlit', yet 'still unspoiled desert.' Its 'tan-gold foothills rise from tattooed sand-stretches to join slopes spotted as the leopard-skin with grease-bush. This foreground spreads to distances so vast—human scale is utterly lost as all features recede' (Wright 1957: 239).

While he experimented with several similar themes in his 1920 *Aline Barnsdall House* ('Hollyhock House'), the first of Wright's true Textile-block houses—as they since became known—was the highly patterned *La Miniatura* (fig. 2.3). Wright described this 1923 design for Alice Millard, as evolving 'as the cactus grows' (1957: 239). Other significant Textile-block houses include the *Storer House* (1923), the *Samuel Freeman House* (1923), the *Ennis House* (1924) (fig. 2.4) and the relatively unpatterned *Richard Lloyd Jones House* (1929). During this period, Alofsin argues that Wright's 'explorations of technology were soon affected by a change in [his] form language. As he responded to the incipient International Style he simplified his surface patterns, a shift that marked the end of his primitivist phase' (1994: 42). Appearing as imposing, ageless structures, several of which have been compared to pagan temples, the Textile-block houses were typically constructed from a double skin of pre-cast, patterned and plain exposed concrete blocks, held together by Wright's patented system of steel rods and grout. Occasional bands of ornamented blocks punctuate the otherwise plain square masonry grid in the facades of these houses and for each client a different pattern was created for these ornamental highlight features. Despite their apparent difference in appearance to the Prairie style houses, Alan Hess and Alan Weintraub (2006) state that 'every aspect of the LA homes followed organic principles' (38).

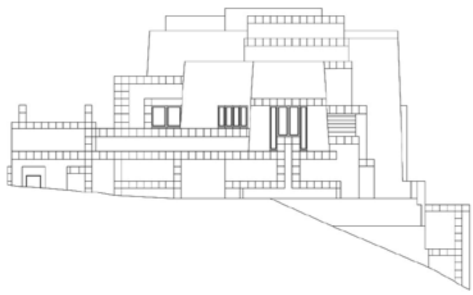


Figure 2.3 South elevation of La Miniatura

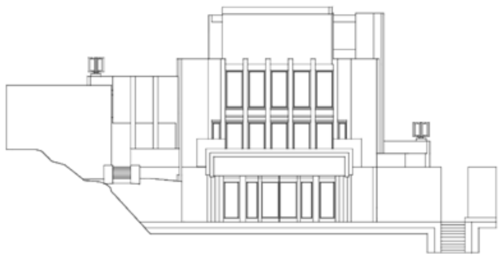


Figure 2.4 West elevation of the Ennis House

In the aftermath of the great depression, which descended upon the USA after 1930, there were few architectural commissions. Wright maintained an income by setting up the ‘Taliesin Fellowship’ in 1932, a system where students paid to learn from him. Initially the members of the fellowship lived and worked the farmlands of Wright’s *Taliesin* estate in Wisconsin. Here, once again, Wright, saw an opportunity to educate his apprentices in the cycles of nature and the processes of building and farming. The regular routines of the *Taliesin* residents included picnics in the fields and tea taken outside every day in the ‘tea circle’, an outdoor room created by circular stone benches with a leafy canopy overhead.

In the mid-1930s Wright transported the fellowship to the Arizona desert, creating *Octilla*, a temporary campsite to house the team while Wright worked on the design of *San Marcos in the desert*, an unbuilt project. In 1937, inspired by his experience in the desert landscape, Wright purchased land northeast of Phoenix where the ‘ground is hard, with rocks scattered across the surface as if cast there [… and] long heaps of loose rocks and gravel are clues to the violent force of waters that come crashing down the stony hillsides after rainstorms’ (Spirn 1996: 151). On this site, Wright and the fellowship built their winter headquarters *Taliesin West*, which, according to Wright, ‘belonged to the Arizona desert as though it had stood there during creation’ (Wright 1957: 479).

Whereas 40 years previously in Oak Park, Wright had sent his staff out to collect Prairie flowers; in Arizona, he ‘sent his apprentices out into the desert to see how

Nature designed' (Storrer 2006: xii). Wright also used this period as an opportunity for further theoretical experimentation. As part of this, he 'rethought his design procedures, and "invented" the Usonian home, a refinement of ideas already in place in the California block houses' (Storrer 2006: 55). With only one built commission between the last of the Textile-block houses (1929) and *Fallingwater* (1935), Wright's Usonian houses were built between 1935 and 1955. However, only one of the Usonian houses had been built before Wright produced two of his most 'astounding buildings of the Thirties' (Kostof 1985: 737); *Fallingwater* and the *Johnson Wax Administration Building.* The former, which was designed in 1935, is now one of the world's most known buildings. It is expressed like a stack of smooth terraces above a waterfall, anchored into the hill beside. In contrast, the latter is inwardly-focussed with tall slender, stalk-like columns creating a massive open plan workplace.

It was while these two famous works were being constructed that Wright set about designing his Usonian style, which was intended to create quintessentially American, suburban homes. Spiro Kostof describes the designs from this period as reliant on 'picturesque abstraction: hexagons and piercing points, jagged fragmentation, scaly surfaces. It is a private, romantic, transcendental vision, kept in check to the last through Wright's geometric command and his unfaltering sense of scale' (1985: 740). For Wright, the Usonian house was intended to embrace the elements of nature and make them 'a companion to the horizon' (Wright 1957: 493). Following the philosophical approaches of Jefferson and Ruskin, the houses were designed to be 'integral to the life of the inhabitants' and truthful in their material expression; 'glass is used as glass, stone as stone, and wood as wood' (Wright 1954: 353). Hoffman describes the archetypal Usonian house as 'a simplified and somewhat diluted Prairie house characterized by the absence of leaded glass and the presence of […] very thin wall screens with a striated effect from wide boards spaced by recessed battens' (1995: 80). While there were multiple variations on the Usonian house, several were based on an underlying equilateral triangular planning grid and are known as 'triangle-plan' houses. Five of the triangle-plan houses—the *Palmer House* (1950), *Reisley*

House (1951) (fig. 2.5), *Chahroudi House* (1951), *Dobkins House* (1953) (fig. 2.6) and *Fawcett House* (1955)—are examined and measured in Part III of this dissertation.

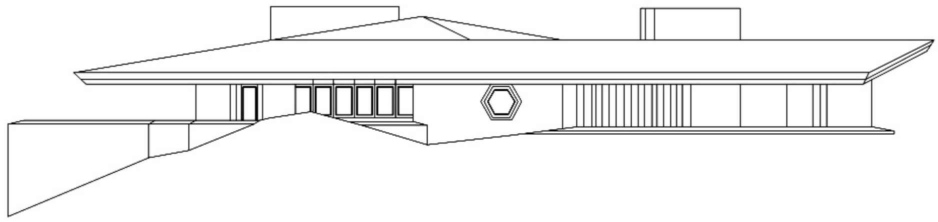


Figure 2.5 East elevation of the Reisley House

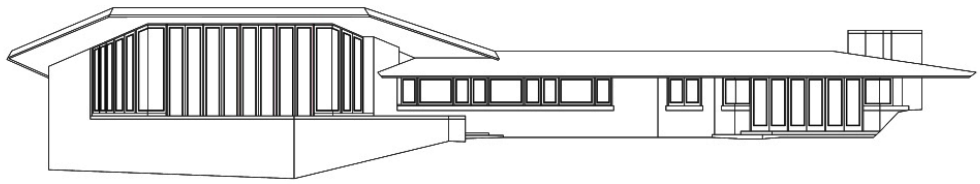


Figure 2.6 South elevation of the Dobkins house

While continuing to produce Usonian buildings for the remainder of his career, Wright, in his 'astounding capacity for self-renewal' (Lampugnani 1997: 369) began the design, in 1943, of his final iconic work, the *Solomon R Guggenheim Museum*, which Kostof describes as his 'great swansong […] a gift of pure architecture – or rather of sculpture' (1985: 740).

2.2 Style and Philosophy of the Era: Organic Modernity

The formal expressions found in Frank Lloyd Wright's architecture have been grouped into several distinct types, and yet over his long career, from 1886 to 1959, he consistently called his approach 'Organic architecture'. With almost five hundred built works, Wright 'was a key player in the development of modern architecture yet constantly at odds with it. He shared the goals of many other modernists, yet his work was often very different' (Alofsin 1994: 32). For example, Hess and Weintraub describe Wright's Organic approach as leading to the production of ‘a fresh Modern architecture that engaged both contemporary machinery and the ageless natural landscape’ (2006: 6).

Descriptions of the formal properties of Organic Modern architecture vary considerably (Joedicke 1997; Kuhlman 2008) and Farmer, noting the confusion, suggests that the movement is often associated with architecture of a ‘freer geometrical approach’ (1996: 124). Indeed, many buildings with a curvilinear appearance have been categorized as examples of the style, despite Wright’s use of rectilinear forms (Laseau and Tice 1992: 114; Nute 2008: 51). However, the architecture of this movement is less characterised by form than it is by its underlying philosophy. ‘Not all Organic buildings look alike’ state Hess and Weintraub, ‘[w]hat they have in common is the concept of seeing a building’s design, structure, use, and life as an organic thing – that is, as a thing that grows form the germ of an idea into a fully articulated, variegated and unified architectural artifact’ (2006: 6). Wright states that ‘Organic architecture is a natural architecture, the architecture of nature, for nature’ (Wright 1953: 245).

In the early 1900’s the Prairie school of architecture ‘laid the foundation’ (Hess and Weintraub 2006: 6) for Organic design and by the 1930’s Organic architecture had become intertwined with the emergence of Modernism, when a series entitled ‘Modern Architecture’ was published in 1930. This set of publications include contributions from key figures of the modern movement, Bruno Taut, Henry-Russell Hitchcock, Phillip Johnson, Catherine Bauer, Lewis Mumford, Alfred Barr and Frank Lloyd Wright. This was Wright’s first published book and in it he repeatedly refers to his influence on Modernism as well as Organic architecture, and regardless of whether his ‘self-promotion as fountainhead’ (Levine 2008: xix) of the entire Modern movement is correct, there are connections between the Functional and Organic Modernists. For example, according to Kuhlmann, ‘the Aristotelian ideal of an organic whole has pervaded modern architecture, even the theories of architects who never used natural forms in their designs’ (2008: 40). Farmer proposes that the key difference between the two approaches is that ‘Organic theories had sources not only in science but in poetic thinking too' (1996: 124). While Organic architecture is often considered 'synonymous with the buildings and writings of Frank Lloyd Wright' (Farmer and Richardson 1996: 124), there were several other key proponents of the style in the United States who had worked with Wright. These include Rudolph Schindler, Bruce Goff, John Lautner, Alden Dow and Frank Lloyd Wright's son, Lloyd Wright.

2.3 Identifying Separate Definitions of Landscape and Nature

Identifying precisely what Wright meant when he spoke of 'nature' can be difficult. As Spirn observes, 'Wright used the word "nature" in several senses' including as 'an essential quality, material reality and divine force'. Indeed, he 'often moved from one sense of the word to another without transition' (2000b: 15). Wright practiced architecture and published many written works over a period of seven decades. This extended period provided ample time for him to develop and then revise his thoughts about nature (Hoffmann 1995). For example, Wright's proclamations about Organic architecture clearly change throughout his long career. Another substantial difficulty in interpreting Wright's thoughts on nature is that his written words, and transcripts of his lectures and interviews, are notoriously ambiguous and tend to ramble in vague or ill-defined ways. Sibyl Moholy-Nagy describes Wright's verbal expression as being a 'well-known mixture of poetic pantheism […] ranting attack […and] unabashed self-glorification' (1959: 319). Wright's ideas and arguments were often so extensive that he 'found it sufficient if his words conveyed their general shape or effect' and not their specifics (Nordland 1988: 4). The consequence of this approach is that a complex mythology has grown around Wright and his philosophy of nature. For example, a common argument is that for Wright, the 'central idea often came from nature' (Bovill 1996: 6). Such a description, while useful and valid when forming an overall understanding about Wright's theory and design, is neither specific nor tangible enough for the purpose of this present study. However, whereas Wright's proclamations about nature are difficult to decipher and interpret, he had a different attitude to the landscape, which he tended to describe in more concise terms. For example, according to Spirn, ‘Wright revered nature, not landscape, and his use of the two words was distinctly different. When Wright spoke of nature, he spoke of principles, of authority for architectural form, and his words were abstract. He rarely mentioned landscape; when he did describe a landscape, his language focused upon recurrent features or pattern rather than idiosyncratic variables’ (2000b: 15). The following sections in this chapter focus on Wright’s approaches to designing in response to nature’s most tangible presence, the landscape.

2.3.1 Wright’s Methods for Designing Buildings with Landscapes

By setting aside Wright’s somewhat spiritual and often nonspecific views on *nature* and focusing instead on the more defined topic of *landscape*, particular methods that he employed to create the ‘building-of-nature’ effect have been consistently observed by scholars. However, even this process is not without its challenges. For example, Nicholas Olsberg suggests that Wright has a strong ‘discipline with which he analysed […the] forms and processes’ of the American wilderness. Unfortunately, Olsberg does not provide a detailed description of Wright’s ‘deep reading of terrain’ (1996: 10). Nevertheless, some authors have attempted to identify the precise design strategies which Wright used to contribute to the impression that his buildings are directly connected to their settings. This section looks at two of these responses to the landscape: design strategies and site integration.

Design strategies

Six interconnected and recurring design strategies, for linking Wright’s architecture to nature, have been identified by historians, scholars and critics. The six are: his approach to the ground; the formal mass of the building; the roof; the openings; any intersections with natural features of the location; and the material palette. Each of these are examined hereafter.

- The first of Wright's recurring design strategies involves the relationship between the ground floor and the landscape. The 'ground-hugging' (Frazier 1995: forward) appearance of many of Wright's buildings is a property which has been repeatedly emphasised by scholars (Richards 1970; Hoffmann 1995; Frazier 1995; McCarter 2004). While there are several common ways of providing foundation support for a building—such as being set up on piers, stilts or cantilevered—Wright's buildings were generally built using a slab-on-ground technique. This approach typically involves 'a concrete slab with integral edge beams' being 'placed on the ground', where it 'provides the base and floor structure for the building' (Milton 1994: 227). This common building method does not, in itself, provide strong evidence of a special connection of the building to the landscape. If this was the case, the frequency of its use would mean that most architects today could be regarded as 'building with nature'. What is specific to Wright is the creation (and expression) of a wide, firm, concrete, rock or earth-berm like firmament, as an integral element. This element is often emphasised by long, low masonry walls along with porches, terraces and horizontal planters. The effect can be seen in his Prairie Style houses, and especially the *Robie House*. The extended and emphasised solid plinth for a design, often executed in a contrasting color or material to the walls, usually results in the lowest floor level being raised above ground level, but still being firmly connected to it. This design strategy expressed a 'grip on the earth' (Hoffmann 1995: 10), a sense which was further emphasised by Wright's use of accentuated linear form—particularly parallel horizontal lines—throughout his buildings, not just on the surface or facade (Hoffmann 1995; Maddex 1998). In combination, these formal strategies created the sense of a building that 'embraced the ground of which it should seem to grow' (Frazier 1995: forward).

- The second of Wright's design strategies that sought to emphasise the connection to nature involves massing. One of Wright's most common approaches to architectural form was to shift the planes of his buildings, to dissolve their footprints, rooflines, and general massing, such that they seem to 'penetrate the landscape even as the landscape penetrates the building' (Moholy-Nagy 1959: 327). This approach can be seen in many of Wright's plans, which appear to have sections cut out of them, and at the same time, other sections extrude beyond a typical perimeter (Giedion 1959; McCarter 2004). This effect can be seen in *Taliesin West*, which is 'notched, and knit' into the landscape, with walls that are 'cut into, extend above [and] reach out to the immediate terrain' (Spirn 1996: 152). While less specific, Paul Laseau and James Tice suggest that when the formal symmetry of Wright's work is broken up in accordance with this strategy, it gives a building a more 'natural' feel (1992: 70). Wright's approach to massing, in which the landscape and building work together as physical volumes interacting or intersecting in three dimensions, is what scholars (and Wright himself) refer to as an architectural 'weave'. Laseau and Tice observe this geometric tapestry in Wright's buildings where typically the 'predominantly horizontal spatial weave was complimented by a vertical spatial weave' (1992: 94). John Sergeant highlights Wright's strong development of this 'warp and woof' approach to form in the Textile-block houses, which were usually set on steep sites, thus enhancing Wright's three-dimensional weave, which 'allows nature in the form of the demands of the site to penetrate Wright's geometric grid […] and to coexist there with the solid elements of the house' (Sergeant 2005: 195).

- The third of Wright's recurring design strategies involves the extension of his rooflines into the landscape. This strategy, which often involves extensive cantilevered roofs, surprised many, including Wright's clients the Tomeks, who requested that posts be added to their cantilevered roof because it looked too precarious. When he first developed this strategy during his Prairie Style period, Wright stated that 'the broad eaves are designed to accentuate that quiet level [of the prairie] and complete the harmonious relationship' (Wright 1901: 17) between the building and the landscape. The effect, suggests

Hoffmann, worked to transform the 'necessary into the poetic' (Hoffman 1995: 12).

- The next of Wright's regular design strategies is concerned with retention and containment. On multiple occasions Wright retained existing geological and botanical parts of the site within his buildings (Gideon 1959; McCarter 2004; Moholy-Nagy 1959; Antonaides 1992). For example, in one of his first buildings—his *Studio and home* in Oak Park, Chicago—he retained an existing willow tree, building the hallway around it, so that in moving down the passageway, people had to brush by its trunk. Existing rock boulders from the site were retained in the *House for Chauncey Williams* (1895) and the *Boulder House* (1951). These strategies worked alongside the others in this section to create an effect wherein 'the house and the landscape were inextricably bound to each other' (McCarter 2004: 1453).

- In comparison with today's architecture, the volume of glass and external doorways that Wright designed in his buildings might seem quite ordinary, but in the early 1900's, Wright was a pioneer of large glazed areas which allowed direct lines of sight from the interior to the exterior. This fifth design strategy provided extensive areas of glass which 'mirrored passing clouds and the flutter of foliage [….]. As though to render landscape paintings superfluous, the casements gave definite pictorial structure to outward vistas' (Hoffmann 1995: 21). In contrast, Queen Anne style and Victorian architecture in the USA in the late nineteenth and early twentieth-centuries was often internally dark, having small windows and cellular planning arrangements which restricted views of the exterior. By the time Wright was designing Usonian houses in the 1920's, his use of glazing had become a critical element. For example, in the *Samuel Freeman House* corner windows run the full height of the building. As noted by McCarter (2004), the effect of ample glazing in a building connects someone inside the building to outside, both visually through light and view, but also when the windows/doors are open, by the air movement, heat (or lack of) as well as smell and sound.

Hoffmann also observes that these windows which feature so prominently in Wright's work, are 'both vital and articulate; they open outward and break free from the uniform plane' (Hoffmann 1995: ix).

- The final design strategy is associated with materiality. According to Anthony Antoniades, '[m]aterials and their use express the character, the attitude toward eternity, and the love of nature' of an architect (1992: 211). Wright's approach to building materials positions him as a precursor to the Regionalist movement of the 1950's and 1990's, wherein architects used local materials to emphasise the physical experience of living in particular spaces (buildings) within defined locations (regions and landscapes). Wright was inspired by Ruskin's late twentieth-century writings on 'the physical and material rationale that underlies architectural reasoning' (Ching et al. 2011: 652), equating to a belief in the truth implicit in material expression. Wright insisted that an architect should '[r]eveal the nature of the wood, plaster, brick, or stone' in their designs, 'they are all by nature friendly and beautiful' (Wright 1908: 156). As such, Wright often used materials that were 'related' to the site in some way or somehow reflected the poetry and essence of the landscape that they were employed within (Giedion 1959; Frazier 1995). This effect was enhanced by Wright's preference for a raw finish which is 'sympathetic to the touch' (Scully 1960: 20). Thus, brickwork was uncovered and timber was usually stained rather than painted. Wright preferred local stone, which was often roughly cut rather than shaped into blocks, to give a less structured and less artificial appearance (Maddex 1998, Frazier 1995; Gideon 1959).

Site Integration

Past research identifies five recurring strategies Wright used to support the integration of his architecture into the landscape, creating a perception that 'his buildings cannot be divorced from their site' (Moholy-Nagy 1959: 327). These strategies are; site interpretation, locality character, site characteristics, landscape alterations and site intensification.

- The first of these strategies involves interpreting the site by means of site documentation. According to Nicholas Olsberg, it was Wright's belief 'that the critical observation of natural forms was the key to all expression in built ones' (1996: 11). Through a close analysis of Wright's design drawings scholars have identified some of the processes he used to interpret the landscape. For example, Bruce Brooks Pfeiffer notes that in 1895 when Wright designed the *Wolf Lake Amusement Park*—an entertainment facility proposed to wind its way around a picturesque section of a Chicago lake—he utilised detailed site plans, an unusual process at the time, with most designs of the era being 'placed on the site, not of it, and rarely related to it in any way' (Futagawa and Pfeiffer 1987c: 24).

  In architectural practice, one site plan does not always show the same details as another. As defined by Hans Milton, it is a 'plan of a site, showing site features, existing and/or proposed buildings or structures, and the distribution of major services' (1994: 226). The number of features and the level of detail depicted in a site plan are dependent on the compiler, or the request of the architect or client. The site plans that Wright used throughout his career may have been supplied by the client or specifically requested by Wright. However, Wright used site plans that typically included existing roadways, waterways with nautical contour lines, height data and/or topographical contours, existing tree locations (sometimes including canopies and species names) and significant items such as large stones or wells. Wright would often draw his primary designs over the top of the site plan (Futagawa and Pfeiffer 1987c; Green 1988). He also directly traced his plans over aerial photographs of the site for some projects, including *Lake Tahoe* and the *A.M Johnson Desert Compound.* Photographs of landscape panoramas were also used in this way and archived examples can be found in his design for *Taliesin West* (De Long 1996). The practical connection to the site can also be seen in Wright's sections, elevations and perspectives, which often include as much of the surrounding landscape as the building itself, showing the geometry of the landscape, with existing or proposed full grown trees and extensive plantings usually depicted.

As well as his drawings for the *Wolf Lake* project, which show a 'careful study and understanding of the waterfront and land protrusions, and the best way in which the building can blend with them' (Futagawa and Pfeiffer 1987c: 24), other examples of Wright's method of designing on a detailed topographic plan include the *Coonley House* and the *Hollyhock House*. In the latter case, the site plan depicts all trees on the site, including those noted as 'dead'. De Long (1996) suggests that it is only by identifying these features, that Wright could achieve a 'compositional unity' of his buildings with their landscapes. This method of drawing with the building 'laid out on the site illustrates an important aspect of Frank Lloyd Wright's Organic Architecture: the relationship of the building to the terrain' (Futagawa and Pfeiffer 1987c: 24).

- The second approach Wright used to respond to the landscape presents a less tangible, but still important connection. It is concerned with the way Wright interpreted the sense—or 'innermost character' (Moholy-Nagy 1959: 326)—of a locality in his architecture. Moholy-Nagy argues that while Wright created *Fallingwater* as 'the northern Mountain Fortress', the 'Robie House and the other Prairie houses are predicted on the horizontality of the Plains country' and 'the sun-cured wood framework of Taliesin West is the sparse soul of the desert' (1959: 326). Nordland ascribes these achievements to 'Wright's unusual sensitivity to the available plot of ground for a given structure' arguing that Wright 'designed and built entirely differently for the urban street than for the country acre, the open glen, the desert, and the oceanside' (1988: 2).

Wright's ability to identify this essence of a place, to observe nature—in a way perhaps overlooked by others—was one of his most celebrated achievements. From Wright's own recollections, this way of interpreting the landscape was something he could do since childhood. In the opening paragraph of *An Autobiography*—which Wright published at the age of 76—he remembers his impressions of the landscape, from his early years on his uncle's farm.

> A light blanket of snow fresh-fallen over sloping fields, gleaming in the morning sun. Clusters of pod-topped weeds woven of bronze here and there sprinkling the spotless expanse of white. Dark sprays of slender metallic straight lines, tipped with quivering dots. Pattern to the eye of the sun, as the sun spread delicate network of more patterns in blue shadows on the white beneath (Wright 1957: 3).

In such accounts, Wright interprets the landscape as a set of abstracted patterns, or as a painting or collage, interwoven, dimensional and coloured. Reinforcing this notion is the content of Wright's 1943 letter to Jens Jensen, an influential Prairie Style 'natural' landscape designer. In the letter, Wright explains his own 'experience in the study of structural Form as interpretation of nature', stating that he is 'an abstractionist seeking the pattern behind the realism' (Wright 1984: 104). This leads to his third strategy for designing buildings, wherein Wright identified individual aspects of the site which might be reinterpreted, re-used or reflected back to the viewer in the appearance of the building.

- Wright's third strategy emphasised the importance of unity between the visual appearance of the landscape and the built form, often drawing inspiration for colours, materials, forms and imagery from each individual site. He proposed using building materials which reflect the features of the site, creating the impression of houses 'growing from their site in native materials, no more "deciduous" than the native rock ledges of the hills, or the fir trees rooted in the ground, all taking on the character of the individual in perpetual bewildering variety' (Wright 1927, qtd in De Long 1996: 61).

The physical shape of the landscape surrounding the building was also to play an important role in Wright's design methodology. He was adamant that a 'building should appear to grow easily from its site and be shaped to harmonize with its surroundings if Nature is manifest there, and if not, try to make it as quiet, substantial and organic as She would have been were the opportunity Hers' (Wright 1908: 156). Wright proposed several rules for achieving this outcome, including that 'no house should ever be on any hill or on anything. It should be of the hill, belonging to it' (Wright 1957: 225). He argued that the house 'should appear to be part of the site and not a foreign element set up boxwise on edge to the utter humiliation of every natural thing in sight' (Wright 1894: qtd in Hoffmann 1995: 10). The characteristic shapes found in the locality could be adapted or applied directly in the design, as in the temporary *Octilla*, where the geometry of the surrounding mountain ranges, and the talus at their junctures, formed a one-two proportioned triangle. This geometry was then 'used in planning the camp, […] in the general form of all the cabins as well as their general plan' and in their 'eccentric gable' decoration which was scarlet coloured, to reflect the 'ocatillo bloom' (Wright 1957: 311). Here, as he did elsewhere, Wright used the colors of the local ecological landscape in his design, just as he had done earlier in his career when he advised architects to 'go to the woods and fields for color schemes' (Wright 1908: 156).

- The fourth strategy for Wright's approach to landscape integration is his attitude towards landscaping. In the majority of cases, scholarly interpretations of Wright's buildings tend to discuss the manner in which the character of the site is reflected in the architecture. However, some critical thinkers, including Olsberg (1996), David DeLong (1996) and Spirn (1998; 2000a), suggest an alternative. They argue that Wright shaped the landscape around the building, dramatically increasing the way the landscape seems to fit the architecture. These authors argue that Wright's particular talent in connecting buildings and landscapes lies in his underemphasised abilities as a landscape architect. It was not just Wright's eye for mass and volume, line and colour and their effect on the viewer that made his buildings appear to fit so well. Wright massaged his sites so that they melded into the architecture. It was this combined capacity, arising from the way he read the shape of the land, that allowed the building to become, in effect, a harmonious addition to the landscape, or as Jodidio suggests of *Fallingwater*, a 'feature of the landscape' (2006: 7). According to Spirn, 'Wright saw "land as architecture" and shaped its outward appearance to express his vision of its inner structure', which explains the fact that 'some of Wright's greatest works are large compositions of buildings and gardens, roads and waterways, fields and groves' (Spirn 1998: 127). This alternative reading of Wright's strategy suggests that he not only designed a building within its constructed footprint, but designed the entire setting—building, landscape and beyond—'as contributing elements in the larger order of both the landscape and the city' (McCarter 2004: 1453). This desire to shape and enhance the natural landscape is in accordance with Wright's Emersonian values and lessons, which proscribed that 'the purpose of art and architecture was not slavishly to copy external nature, but to use it […] as the occasion for exploring inner nature and thereby expressing universal spirit. For the artist, nature was raw material awaiting transformation into some greater vision of a still more divine ideal' (Cronon 1994: 14).

- Not only did Wright design the landscape, but in his final site strategy, he employed a particular approach to enhance the qualities of the site by means of emphasis in his architecture. Thus, Wright proposed that his designs for the Prairie should '*accentuate* this natural beauty, its quiet level' (Wright 1901: 17, author's italics). Olsberg notes that from the design of *Fallingwater* onwards, Wright left 'behind his earlier attempts to build in sympathy with the land' and within the landscape, instead his 'built forms that would indeed "*intensify*," and perhaps complete, the natural structures' (1996: 10). In a similar way, McCarter notes that even in an urban setting 'the outriding walls and overhanging eaves' serve to 'layer the house into the earth, giving the suburban site a geometric order so that the house and the landscape were inextricably bound to each other' (2004: 1453).

2.3.2 Summary of Identified Design Approaches

In total, eleven of Wright's strategies for connecting architecture to the landscape are identified in the preceding sections and these are summarised hereafter (Table 2.1). These are not only informative for understanding the basis on which claims and about Wright and nature have been made, but they also provide a basis for the analytical methodology used in Part II of this dissertation.

Table 2.1 Wright's strategies for connecting architecture and nature

Strategy	Element	Typical Approach	Selected Scholars
Design	Ground floor	Prominent, plinth-like slab on ground which visually exaggerates or celebrates the connection between the building and the site.	Richards 1970 Frazier 1995 McCarter 2004
	Formal Mass	Bulk of the building reduced by shifted formal planes, blurring the boundary between building and landscape.	Gideon 1959 Laseau & Tice 1992 Sergeant 2005
	Roof	Horizontal roofline which extends well beyond the interior edge of the building, reaching it out into the setting.	Hoffmann 1995 Maddex 1998
	Containment	Buildings envelop or are perforated by trees, rocks or natural features.	Moholy-Nagy 1959 Hoffmann 1995
	Openings	Large openings placed specifically to accentuate connection between internal and external landscape.	McCarter 2004 Storrer 2006
	Materials	Locally sourced, raw or minimally finished materials, expressing natural materials in the building.	Gideon 1959 Scully 1960 Antonoides 1992
Site Integration	Site Interpretation	Designing directly over site plans and photographs, with key landscape features identified	Futagawa and Pfeiffer 1987c Green 1988 Olsberg 1996
	Locality Character	Identification of the 'essence' of a local area	Nordland 1988 McCarter 2004 Read 2016
	Site Characteristics	Identification of the characteristic natural shapes of a location: via topography, ecology, geology. The reinterpretation, re-use or reflection of these in the built form.	De Long 1996 Jodidio 2006
	Landscape Alterations	Extensive site works used to reshape the landscape to make the building more integrated with the setting.	De Long 1996 Olsberg 1996 Spirn 1998
	Site Intensification	Architecture used to intensify, or emphasise the surrounding landscape, whether urban or natural.	Cronin 1994 Olsberg 1996 McCarter 2004

2.4 Scholarly Interpretation of *Fallingwater*

Significantly in the present context, from the earliest accounts, *Fallingwater* has been discussed by architectural critics in terms of its response to nature (Mumford 1938), and at the same time Wright himself described the house as 'an extension of a cliff beside a mountain stream' (Wright 1938:36). Ever since these initial publications, the typical descriptions of *Fallingwater* note that it is a building which displays an 'unparalleled integration of architecture and nature' (Levine 2005: 250). Such claims are, in part, the trigger for the present dissertation, which asks how did Wright achieve this effect of connecting Fallingwater to its natural surroundings? The final section of this chapter begins to explore this question through review of scholarly interpretations of *Fallingwater*, using the eleven part framework set out previously in this chapter to identify specific evidence of Wright's methods for integrating *Fallingwater* with its natural landscape. While multiple sources are examined in this section, three major sources have explored this issue in depth. Donald Hoffmann, Edgar Kaufmann Jr, and Neil Levine all provide tangible or at least direct augments about the strategies used to achieve this synthesis, rather than just providing general overviews or claims.

Design

- The first of Wright's usual design strategies noted previously, was to unite a house with the earth by way of a deep plinth to form the base of the home, seemingly resting it solidly on the ground. However, the case of *Fallingwater* is different because there is no solid ground directly underneath the majority of the house (fig. 2.7). Despite this lack of landmass beneath, many scholars still find *Fallingwater* to be 'a building that seemed part of the earth' (Frazier 1995: viii), or 'rooted in the earth' (Lind 1996: 21). By modifying his approach for *Fallingwater*, Wright 'set the building firmly' (Kaufmann 1986: 178)—or 'anchored' it—into the hillside (Mumford 1938: 206; Hoesli 2005: 214). The result is that the house still has a 'sense of the ground' (Wright 1938: 1), of being connected directly to the earth on its northern side, where it is 'seemingly embedded into a knuckle of rock' (Fell 2009: 87). This strategy also provides a firm foundation from which to project the cantilevered floors. Although the structural implications of this move are not the focus of the present research, many scholars argue that these cantilevers appear as an extension of the rocky glen, reflecting its natural setting in such a way that the house 'seems part of the rock formations to which it clings' (Storrer 2006: 236).

Figure 2.7 Fallingwater *cantilevering over Bear Run (Photograph by the author)*

- Wright's second typical design strategy of creating building forms which seem to extend a building out into the landscape using furcate planning was modified in *Fallingwater,* no doubt also because of the site constraints (Andropogon 1997: 37). Confined to a small, level area between the rocky cliff-side and the flowing water of Bear Run, Wright designed each floor plan in a typically square shape, with some subtractions and additions, but not to the extremes found in some of the shifted formal massing displayed in the plans of several of Wright's previous buildings like the *Coonley Residence* or *Taliesin*. While Sergeant notes that the planning of *Fallingwater* is` 'a particularly lyrical example of the penetration of nature into the field of the house' (Sergeant 2005: 196), it is in section and the third dimension that the strongest sense of Wright's manoeuvring of building mass into the landscape is seen. In three dimensions the form composition allegedly reflects the ‘fractured, stepping system of walls and volumes that roughly follow the line of the rock ledge to the rear’ (Laseau and Tice 1992: 68). Instead of being one singular mass, the volume of *Fallingwater* is expressed as a segmented layering of forms, where Fell notes that ‘the cantilevered balconies […] jut out into and become part of the enveloping woodland’ (2009: 88). This claim reflects Wright’s own description of ‘cantilever slabs overhanging each other leaping out from the rock ledge behind’ (Wright 1938: 41). Levine echoes this view, describing *Fallingwater* as ‘a plastic interaction of sculptural elements that push and pull in relation to the dark depths of the hillside’ (2000:50). As the terraces reach out, they provide cave-like nooks and niches which nature, in the form of rocks, plants and water, elements may enter into, pass through or under. Levine notes this ‘sense of almost complete dematerialization’ of the edges of the cantilevered planes. (Levine 2000: 50). Because of this ‘dematerialization’, the result is very much a case of Wright managing to fulfil one of his architectural aims, which was, to ‘destroy the box’ (Luke 1992: 84).

Figure 2.8 Fallingwater, *view from main bedroom over living room terrace and bridge(Photograph by the author)*

This three-dimensional composition of built and natural elements is an example of Wight's architectural 'weave' (fig. 2.8). Laseau and Tice describe *Fallingwater* as featuring the 'most splendid example of this kind [of weave]' (1992: 94); where the stream, the rock ledge and the trail though the forest are all woven spatially into the physical structure of the house so that the 'resultant composition effectively unites architecture and nature as one' (95). Levine also observes that this power of the weave is amplified by the melding of the interior and exterior elements, whereby the cantilevered terraces, or 'trays, bounded by curved parapets, weave through the vertical stone structure to provide the living spaces for the house and are continuous inside and out' (Levine 2000: 37).

Figure 2.9 Fallingwater, *southeast aspect (Photograph by the author)*

- Wright's next design approach—from the Prairie houses onwards—of reaching out into the environment with a long roofline, or rooflines, which run parallel to the horizon line, is used found in *Fallingwater*. However, *Fallingwater* does not feature a typical pitched roof with 'two sloping surfaces […] meeting at a central ridge' (Milton: 183). At *Fallingwater* the internal spaces have a topmost surface that matches only the purest description of a 'roof', being a 'weatherproof upper enclosing element of a building […] which protects the interior spaces against the external environment' (Milton 1994: 209). For each level, the 'roof' is actually the floor of the outdoor terrace above, and only the very top of *Fallingwater*, which is much reduced in area, is actually a non-trafficable (yet flat) roof. As a three-dimensional object set within a landscape of varying heights, 'Fallingwater was to be seen from above as well as from below. It was meant to recede into and emerge from the landscape' (Levine 2000: 50). Arguably it is the terracing in *Fallingwater*, rather than Wright's more conventional pitched roofing, which reaches out into the site in response to this design strategy (fig. 2.9).

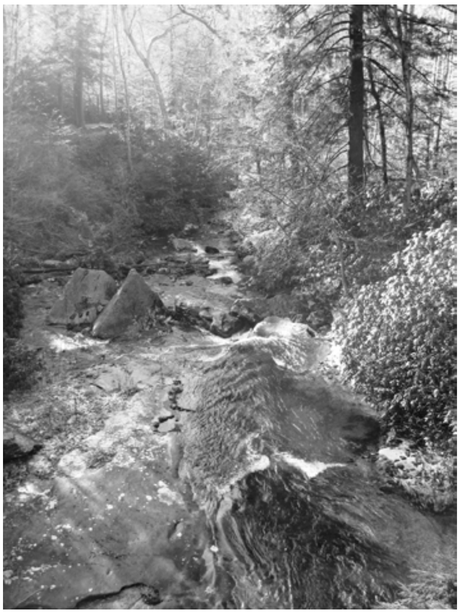


Figure 2.10 Water, rock and trees: Bear Run below Fallingwater *(Photograph by the author)*

- The fourth of Wright's design strategies is containment, the literal inclusion or capturing of nature in architecture, or architecture in nature. *Fallingwater* is one of the prime examples of Wright's approach to perforating architecture with nature. In particular in *Fallingwater,* three local natural elements achieve this effect; water, rock and trees (fig. 2.10). Wright deliberately designed in ways which would allow these natural elements to enter and be part of the building. Wright's name for the house emphasises one of the primary natural elements which is directly integrated into the building in multiple ways. The house famously includes the ‘lyrical integration of a waterfall as part of the architectural composition’ (Smith 2000: 1). According to Levine, ‘Wright’s prime objective was to make the relationship between the house and waterfall as intimate as possible’ (2000: 37). More specifically, at *Fallingwater*, Wright achieves this connection with water in two distinct ways. First, not only is the building located above a waterfall, but the siting and planning of the building and the roadway deliberately create an engagement with the Bear Run watercourse. This happens from the moment a visitor, approaching by the road, first espies the stream flowing down the gully, then as the waterway is crossed at the stone bridge, an integral part of the overall design. This is the starting point of the process whereby ‘[w]ater and building repeatedly conjoin’ (Kaufmann 1986: 124). These places of connection exist throughout the design; before the house is entered, a small fountain of water is continuously pumped up from the stream for ‘hand-rinsing after a ramble through the woods’ (99). Another diversion of the water from Bear Run creates a plunge pool against the side of the house, separated from the stream by a stone wall. This pool is connected to the bedrooms upstairs by a hidden external stairway. The second way of connecting with water is associated with the fact that from within the house, the ‘stream can be viewed in layers of spatial transition’ (Smith 2000: 25), which is most obvious when viewed from the terraces and within the living room—where an unusual glazed portal hatch opens from an aperture in the floor plate down to a set of stairs leading directly to the surface of Bear Run. Levine argues that this relationship is not only visual but a ‘combined visual, tactile, aural and olfactory sensation of water in contact with stone’ (Levine 2000: 61) and that the ‘sound of running water permeates the air of Fallingwater’ (Levine 1996: 124).

Figure 2.11 'native stone rising from boulders of the same stone' (Wright 1938:37). Some of the foundations of Fallingwater *(Photograph by the author)*

Figure 2.12 North passageway at Fallingwater*. New stone wall meets existing cliff rock face, a window joining the two different stone walls (Photograph by the author)*

In addition to containing water within the design, and a part of the same design strategy of containment, Wright also made use of the geological and the botanical elements of the site and, as shown in the very first drawings of *Fallingwater*, these became 'integral to its composition' (Cleary 1999: 4). Wright's design emphasises the rock shelf, the 'native stone rising from boulders of the same stone' (1938: 37). The foundations of the house are built directly over the stone ledges and boulders of the creek and gully (fig. 2.11). In some places the rock was cut back to allow for the building to be sited, but in other places Wright designed for the rocky outcrop to be retained and used. For example, externally 'the cliff face of the driveway becomes part of the entry' (Kaufmann 1986: 124) as it does within the building, as seen in the northern passageway where a rock outcrop sits within the stone walls (fig. 2.12). One large boulder, the very rock the Kaufmanns used to soak up the sun's heat, was transformed into the hearthstone for the fireplace in the living room. The Kaufmanns appreciated the symbolic reference, as Kaufmann Junior reflected: '[e]ven absorbed in Fallingwater as it now is, the boulder top, rising unadulterated above the floor, emanates a dense and powerful air of nature in the raw' (Kaufmann 1986: 124).

Figure 2.13 Tree growing though designed nook in trellis, Fallingwater. *(Photograph by the author)*

Wright also designed the house so that existing trees could be retained. The original survey plans included positions, species names and trunk sizes of several trees on the site. On the location chosen for the house, the site plan shows 'oak', 'tulip', 'cherry' and 'maple' trees. Photographs of the site also show Eastern Hemlocks (*Tsuga canadaensis*) and the Great Laurel Rhododendrons (*Rhododendron maximum*). Wright proposed to retain several of these and designed the house so that they would be an integral part of the design. For example, the concrete beams of the entryway trellis in *Fallingwater* are curved around the trunk of a tulip poplar (*Liriodendron tulipifera*) and the black cherry (*Prunus serotina*). The western terrace was designed with gaps for the existing Scarlet oak trees (*Quercus coccinea)* to emerge through it. But, due to discrepancies between the site plan and the actual position of the trees, and contrary to Wright's intentions, the oaks did not survive the construction process. Despite this setback, the trees in the entry arbour do grow up through their specially designed slots (fig. 2.13) and they were replaced when they reached maturity, so that they continue to 'interweave with the design of the house, [their] slender verticals accenting the bold concrete parapets' (Kaufmann 1986: 124).

Figure 2.14 Window and skylight above doorway down to Bear Run, Fallingwater *Living room. (Photograph by the author)*

- The fifth design strategy is associated with the volume and location of openings. Windows, skylights and doors are key elements in *Fallingwater* which—as they do in many of Wright's other houses—connect the interior and exterior, relating the house to its natural site (fig. 2.14). Ample doorways opening from the interiors out to the terraces facilitate the movement of inhabitants from indoors to outdoors, an effect which evokes the feeling that '[a]lmost every room in the house is continued outside, reaching freely into nature without infringement' (Kaufmann 1986: 116). The doors to the outside are generally glass, framed in thin russet-coloured steel frames. The windows are visually consistent with the doors, and both are generally framed together as a set. There are, however, some special frameless windows, where the glazing is set directly into a niche in the stonework, without any traditional window stile, these glazed areas 'create the illusion that no window exists there at all' (Fell 2009: 93). Significantly, the windows and doors form wide bands of glazing, particularly on the southern elevation which runs the length of the creek.

These window sections have no masonry interruption between the topmost dado point and the ceiling, the section being entirely made of framed glass. As a result of creating this uninterrupted vista, 'the canopy of trees […] becomes, by extension, the exterior walls and roof of the house' (Levine 2000: 64). This idea, that the openings in the house allow nature to form part of the structure or decoration of the interior, has been observed by several scholars. For example, Mumford describes the glazing at *Fallingwater* as:

> emphatically horizontal, giv[ing] an almost unbroken outlook, though the light that comes into the rooms is softened by the wide overhangs; the rocks, the trees, the big rhododendron bushes, the swirling water form the main decoration (Mumford 1938: 207).

The window detailing also serves to provide a sense of ordering or curating nature, like a painting, 'framing the leaf patterns of the trees' (Fell 2009: 93). Kaufmann makes a similar point when he notes that the 'the long bank of windows looks out on near shrubbery, framed to make a decorative screen' (Kaufmann 1986: 87).

Figure 2.15 Bedroom window, Fallingwater *(Photograph by the author)*

As well as wide horizontal glazing, Wright also used dramatic, long, narrow vertically-glazed corner windows at *Fallingwater* (fig. 2.15). These windows run up through several floors, with the floor plate remaining clear of the vertical glazing. These corner windows—including the section in the main bedroom—have casement apertures, opening away from the frameless corner, and thus when open, the room remarkably lacks any side seam. The effect is to ‘offer an even wider unrestricted view of the verdant scenery’ (Fell 2009: 93) providing ‘an unobstructed view of the natural surroundings […] and an opening up of the interior space to the outdoors’ (Meehan 1984: 49). In an interview in 1953, Wright reflected back on this effect in *Fallingwater* as part of his intention to break down the conventional, enclosed orthodoxy of Victorian architecture.

> [T]he corner window came in as all the comprehension that was ever given to that act of destruction of the box. The light now came in where it had never come before. Vision went out and you had screens instead of walls-here walls vanished as walls and the box vanished as a box (Meehan 1984: 48).

Figure 2.16 Direct access to Bear Run from within the living room at Fallingwater *(Photograph by the author)*

Other openings in *Fallingwater* that have received more specific treatments include a glazed portal to the creek below, through the living room floor (fig. 2.16). This allows direct access to the water, but also provides a visual and aural connection to it. Looking straight at this stairway, a view is provided of the water below, and looking through the glazing immediately ahead, the tree line can also be seen, so that ‘both sky and water are brought simultaneously into the house’ (Kaufmann 1986: 80). Likewise, Levine notes that this opening ‘links the tree/leaf imagery to the stone/water imagery at the point where the house is most fully understood as being suspended between earth and sky’ (Levine 2000: 64).

Several unusual windows are also located halfway over planter boxes, so in a passageway, half an ornamental garden is inside the house, and then separated by a pane of glass, the same garden appears to carry on outside. In the living room, a planter box sits just inside a window, so looking through it, one sees the live plants inside, and the living landscape beyond. Upstairs, the technique is reversed; a planter is set just on the outside of the window. The slight variations in this strategy might be evidence of Wright’s intention to constantly challenge the relationship between the inside and outside, or the synthetic and the natural, using a range of opening types.

- The final design strategy is associated with use of materials. In *Fallingwater* Wright repeats his general approach to building materials. The predominant building elements in the house are stone, concrete, glass, timber and steel. These materials are allegedly ‘appropriate’ in a structural or pragmatic sense, but they are also used to ‘develop a poetic sensibility’ (Laseau and Tice 1992: 66). Describing the house, Wright stated that ‘shelter took on a definite masonry form while still preserving protection overhead for extensive glass surface[s]’ (1938: 36). Scholars argue that the materials chosen by Wright represent his distillation of the overall essence of a site. According to Alofsin, ‘[e]ach material—stone, glass, concrete—

was assigned a function, yet each was consonant with the site over a waterfall' (1994: 46) and Mumford also proposes that the 'stones represent, as it were, the earth theme; the concrete slabs are the water theme' (Mumford 1938: 207).

Figure 2.17 'Native stone' beside Fallingwater
(Photograph by the author)

Figure 2.18 Cut stone as laid in the walls at Fallingwater
(Photograph by the author)

Figure 2.19 Cut stone as arranged in the outdoor terraces at Fallingwater
(Photograph by the author)

Wright had long expressed views about the capacity of stone to evoke the essence of nature. In 1928, in his essay *On the nature of materials-stone*, he reflected that in the history of humankind, the ancient Mayans worked with stone where 'the effect resembled naturally enriched stone surfaces such as are often seen in the landscape' (352). Wright, reflecting Ruskin's views, laments that modern, machine-honed stone is 'without joy or creative impulse behind it' (353). Wright proposes that the modern builder or architect should examine natural stone to 'see the principle that "builds", in nature, at work in stone. […] Read the grammar of the Earth in a particle of stone! Stone is the frame on which his Earth is modelled, and wherever it crops out – there the architect may sit and learn' (356).

The water course that runs beneath the Kaufmann house is the descendant of a large alluvial waterway system of the Paleozoic era, which deposited a 'wedge-shaped conglomeratic sequence'—known as the Pottsville Formation—across four states of America, including Pennsylvania (Meckel 1967: 233). This formation has many named segments, including the 'Bear Run member', and its rocky sandstone outcrops are visible on the surface in several locations, including the steep gully in which *Fallingwater* is located (fig. 2.17). It is the sandstone from this section of the Pottsville Formation that the stone elements of *Fallingwater* were quarried on the property, and Wright often emphasised its indigenous character by referring to it as 'native stone'. The stone was used in three different ways, and for each purpose the rock received a unique treatment. First, the quarried stone was used as a rough texture for the walls, second it was used as a smooth surface for the floors, and finally some boulders were left in-situ and exposed inside the house.

For the first of these three, it is notable that the stone walls were hand cut in narrow lengths and then stacked to express a rough-hewn finish, evoking their 'powerful natural forms' (Lind 1996: 27) (fig. 2.18). Significantly, Wright requested that they were laid in a very particular way and the stonemasons were thus 'guided by the irregular layering that occurs naturally in cliffs on the property' (Kaufmann 1986: 109). William Cronon proposes that to enhance the impression of the natural stone formations in *Fallingwater*, Wright used his 'favourite trick [… of using] colored mortar to disguise vertical joins and raking out horizontal joins to mimic the natural strata of sedimentary rock' (1994: 15). This approach was used both for the exterior and interior walls. According to Levine, the 'exterior surfaces were to reflect the environment just as its interior was to reveal the actual traces of it' (2000: 50).

The flooring, both inside and outside the house, is also stone, and for this purpose, large, flat—yet not completely level—slabs of stone were selected and when used inside, finished with a waxed polish (fig. 2.19). The overall impression it gives is a primal one, of rocks under water

(Alofsin 1994). The wet, rippling effect of the stone floors also contrasts with the dry-looking rocks of the walls, which appear as a lighter, softer grey.

As mentioned previously, there are parts of the house where the actual boulders of the site have been incorporated into the plan, the most significant being the boulder that forms the living room hearth. Levine enthuses that this rock ‘emerges in its raw, natural state as the base of the living room fireplace, its role in anchoring the composition is transformed from a literal to a figurative one’ (Levine 2000: 43).

Figure 2.20 Rough stone, smooth concrete; top floor of Fallingwater *(Photograph by the author)*

In stark contrast with the rough, raw texture of the stone is Wright’s use of concrete, a smoother, more plastic material (fig. 2.20). At *Fallingwater* Wright exposes the concrete in particular areas to emphasise the way spaces flow together or are folded into each other. For example, the interior ceilings are exposed, rendered concrete, and these continue, uninterrupted—by remaining the same height, color and texture—as the exterior ceilings for the covered terrace, where they fold up and over to create the balustrade parapet of the terrace above. This modelling of the concrete emphasises a flow from deep inside the house to its outer extremities in the landscape. The concrete itself was rendered throughout in an ochre colour which Wright found similar to the dried leaves of the great laurel rhododendron plants, a predominant species in the landscape (Levine 2000: 61). McCarter suggests that it is Wright's combination of cast concrete and local stone that provides for the house's 'famous combination of internal intimacy and external expansion into nature' (2005: 328).

While timber is not a dominant material in *Fallingwater*, redwood was used (but not exposed) in some of the flooring structure (Wright 1938: 36), and North Carolina black walnut was used in some non-structural internal detailing (Storrer 2006: 337). Overall, Laseau and Tice argue that Wright's material palette in *Fallingwater* emphasizes the 'nature of materials' and 'an attitude that attempted to harmonise all aspects of the design with nature', leading to their conclusion that as a result of this *Fallingwater* is a 'supreme example of the synthesis of materials and architectural expression' (Laseau and Tice 1992: 100).

Site Integration

- The second set of design strategies identified previously in the chapter is concerned with site integration. Wright's approach to site interpretation, through sources such as plans and photographs, is the first of these strategies. Wright's process of using topographic maps to aid his comprehension of the site is well documented and several versions of the topographic maps that Wright used have been reprinted. In particular, Wright received a topographic site plan for the potential location of *Fallingwater* from the Kaufmanns in March 1935. It records contour lines and heights, boulder locations and outlines, with some boulder heights included. The site plan even differentiates four categories of rock formations: 'boulder', 'rock', 'ledge" and 'rock ledge'. The stream, Bear

Run—shown enhanced with stylised nautical contour lines—runs diagonally through the top half of the surveyed area. Over 50 trees are recorded on the plan, with their species noted (including oak, cherry, tulip, beach, maple, rhododendron) and an approximation of the canopy size is depicted around each trunk. The placement of the roadway, bridge and existing retaining wall along the road are all shown. The map's central area is the location Kaufmann had chosen for the house, but Wright's focus was to the top right corner of the plan, where a small flat area was bounded by the roadways, bridge and waterfall. This section of the map was retraced and later rescaled in Wright's studio. Wright's new, more focussed site plan retains representations of the boulders and rock ledges, as well as contours, heights and sounding lines. Notably, not all of the trees were transferred over to the new plan, only six of the larger ones are retraced and the canopy sizes are not included, but the species names are. Furthermore, several marks can be seen on Wright's plan around the position of the tree trunks, as if there was some uncertainty about their actual locations.

When Wright drew his initial concept for the house, he laid tracing paper over this new site plan and then drafted the outline of the proposed house as well as the position of the water, the main boulder (now located in the living room) and the rock ledge. On the set of preliminary design drawings presented to the Kauffman family in September 1935, the stream, contours and boulders are also present along with the larger tree trunks, several with location adjustments and details.

After the building was complete a final set of drawings was produced for publication in a special edition of *The Architectural Record* in 1938. In the drawing of the living room level, a large area of the surrounding landscape is shown. These beautifully executed drawings reintroduce all of the detail of the original topographic survey in a drawing incorporating the living room level plan and the wider site. The trees are now all shown with trunk diameter and canopies rendered in different styles to represent their species: however, the information is all transmitted graphically; the names of trees, contour heights and any other nomenclature are not included.

While the Kaufmanns were initially surprised at the alternative location Wright had identified for the house, Wright must have started to conceptualise the building on the alternative location on the first day he visited the site. As Cleary notes, 'Wright's schematic drawings shed light on his design process' (1999: 41). Importantly, Wright requested that the area around the falls, well away from the original site suggested by the Kaufmanns, be included in the contour plans. He similarly made it clear that he wanted the large trees and boulders to be included in the first contour plan in great detail, as if he was already considering their incorporation in the design. Cleary also suggests that 'Wright's awareness of the [...] trees as three-dimensional entities is demonstrated by indications of their canopies as well as their trunks in the plans. Their importance was in the initial conceptualisation of the house rather than in the construction' (41).

- As well as using externally sourced documentation to gain an insight into the landscape, Wright's second site strategy involved extracting the more ephemeral properties of the site, including its 'essence'. This approach involves Wright's 'sensitivity' to nature (Nordland 1988: 2) and is harder to assess. In *Fallingwater*, Wright allegedly sought to create a building that was 'radiant and right for its forest place' (Hoffmann 1993: 3) and where 'the dynamic spirit of the building is in keeping with the spirit of the wild and rugged woodland' (Simonds 1983: 21). Likewise, Charles and Berdeana Aguar find that 'Fallingwater evokes a responsive sense-of-place absolutely in keeping with the rugged character of the massive rocks, the turbulence of the waterfall, and the natural persona of the forested site' (2002: 230). Perhaps, as suggested, this strategy involves determining an overall *character* of the locality, and it is Wright's next strategy, which identifies the individual *characteristics* of the place, characteristics that when combined form an overall character, but when disassembled, provide a set of properties which might provide tangible evidence to demonstrate how *Fallingwater* relates to its location.

- Thus in his next strategy, the third of his site approaches, Wright identifies the 'unique characteristics of the site' at *Fallingwater* and 'exploit[s them] fully' (Riley 1994: 104). Characteristics of the natural forms at the *Fallingwater* site emerge from four key areas of the site: the Pottsville sandstone exposure, the forest, the gully, and of course, Bear Run stream.

Figure 2.21 Sandstone outcrop on the site(Photograph by the author)

The Pottsville stone formation was a major influence on the design of *Fallingwater* (fig. 2.21). The shape and dynamic poise of the existing rock forms caused Wright to reflect that '[n]ature cantilevered those boulders out over the fall … I can cantilever the house over the boulders' (Wright, qtd in Levine 2000: 37). In a 1953 interview with Hugh Downs, Wright gave a similar answer, when asked, 'How did you relate the site to the house?' Wright's response was, 'there was a rock ledge bank beside the waterfall and the natural thing seemed to be to cantilever the house from that rock bank over the fall (Wright qtd in Meehan 1984: 36).

Other scholars emphasise the visual similarity between the site's sandstone geomorphology and the building's appearance, several proposing that the house *echoes* the site, meaning perhaps that the building visually recalls various elements of the site, albeit in a slightly more understated or somewhat distorted way. For example, Derek Fell suggests that the *Fallingwater*'s terrace '*echoes* the geometry of the moss-and lichen-covered cliff' below it (2009: 11, my italics), and for Kaufmann, '[l]ayered stone outcroppings are features of the terrain, their character *echoes* in the stone walls of the house and in the rippled flagging that covers its floors' (1986: 124, my italics). For Levine, '[t]he horizontal lines of the stone walls of the house […] *echo* the strata of stone ledges in the walls of the glen, while the rippling effect of the cliff is picked up by the staggered vertical slots in the rear wall of the house' (Levine 2000: 61, my italics). While these scholars use the term 'echo' in a visual sense, it is interesting that this term also serves an aural purpose. Thus, during the design process, Wright wrote to Edgar Kaufmann after the 'visit to the waterfall in the woods' describing a melodious resonance where 'a domicile has taken vague shape in my mind to the music of the stream' (Wright qtd in Smith 2000: 21).

The parallels between the horizontal structure of the landscape's sandstone shelves and the house's cantilevers are emphasised by many scholars. For example, in a general discussion of cantilevers, Hoffmann uses *Fallingwater* as an example of these 'horizontals of nature' which are present 'in rock ledges, such as those that helped inspire the house on Bear Run' (Hoffmann 1986: 19). Kaufmann also argues that the structural nature of both the house and the geomorphology provide a sound basis for a good fit within the site. He states that he views the house '*as an irregular web of forces skilfully balanced to create floating horizontal levels. It is proper for such a structure to be inserted amid horizontal rock ledges naturally settled by similar adjustments of forces' (Kaufmann 1986: 90).*

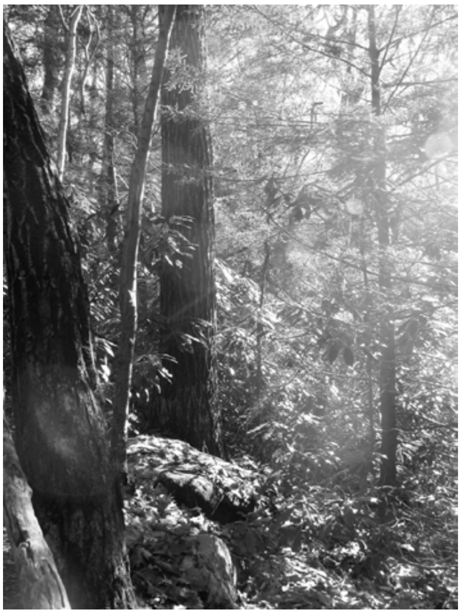


Figure 2.22 Mesophytic forest gully surrounding Fallingwater*(Photograph by the author)*

Kaufmann also emphasises that the ‘major relationship of the house and site arises from setting the building within the valley’ (1986: 124). The valley where *Fallingwater* is sited is a typical ‘dramatic gorge’ of the Appalachian plateau and mountain range of south-western Pennsylvania (Andropogon 1997: 37). Wright identified this site characteristic when he explained that *Fallingwater* is ‘a design for living down a glen in a deep forest’ (Wright 1938: 41), and described a photograph of the valley as ‘the glen in which the house dwells [… with] rocks, oaks, maples and rhododendrons’ (1938: 46). This ‘deep forest’ that Wright designed for, is a ‘typical successional Mesophytic Forest’ (Andropogon 1997: 27), which is a ‘deciduous forest biome where the abundant rainfall of the temperate climate, well distributed throughout four seasons, allows a tall, predominantly broadleaf forest to develop’ (26) (fig. 2.22). The options for locating the house within this steep landscape—as opposed to the long flat prairie landscape or the rolling low hills of *Taliesin*—are utilised by Wright to further effect, as noted by Kaufmann, whereby ‘setting the house deep in the declivity Wright was assuring its integration with the natural features’ because an alternative positioning such as ‘lifting it higher would evoke feelings of dominance and separation' (1986: 124). Likewise, Gwendolyn Wright notes how the building does 'respond perfectly to the natural landscape, nestling comfortably into the particular contours' (1994: 80).

This forested ecosystem creates the particular landscape setting to which Wright responded with *Fallingwater*. As well as directly integrating living trees into the building, as mentioned previously in Wright's design strategies, scholars also note the influence of the forest on the form and texture of the building. For example, Levine observes that the long narrow columns of stone—as they appear on the eastern façade—'merge into the background of tree trunks' (2000: 64) and the manner in which Wright merged the forest into the house.

> The beams that tie the house into the cliff become an arbor-like trellis [which] shades the path, giving a dappled light. Wright reinforced the analogy by allowing two tulip poplars to grow through the trellis, bending the concrete beam around them. Their trunks shared the rugose texture and dark color of the wall and thus appeared to be one in nature with it (Levine 2000: 61).

Figure 2.23 Bear Run gushing though the valley(Photograph by the author)

Throughout the immediate site of the house, and partially responsible for its unique majesty, the water itself provided a final set of characteristics to inspire Wright (fig. 2.23). Kaufmann imagines Wright being ‘fascinated by the torrent pouring over the fractured ledge’ and seeing ‘a great opportunity for architecture’ (1986: 36). Scholars propose that the staggered steps of the waterfall provide a visual characteristic repeated in the building. Smith suggests that the house ‘mimic[s] the form of the waterfalls in the building’ (2000: 25), and Levine agrees, declaring specifically that it is ‘the trays, with their upturned, rounded edges, [that] read as […] the overflowing pools of a cascading fountain’ (2000: 55). Wright described *Fallingwater* as a house that comes ‘[o]ut of the stone ledges over the stream’ (Wright 1938: 36). The waterfall itself is not a neat, picture book waterfall—the two main drops cross ‘the stream on the diagonal’ and are ‘not uniform’, and because of ‘the irregularities of the broken ledges, the falls did not have a formal appearance’ (Smith 2000: 21). This irregularity emphasises that the waterfall is ‘wild’ or ‘natural’, not a perfect, artificial item.

Running water is something that is completely refreshed every second, it is dynamic, the very essence of nature. It is never resting and it can be high or low, raging in flood, sticky when dry or frozen solid. According to Smith, ‘Wright endowed waterfalls with architectural weight and presence, they also carried with them associations of the water cycle—the infinite progression of evaporation, condensation, and precipitation that completes the circle of nature’ (Smith 2000: 26). Smith proposes that *Fallingwater* ‘compresses all these levels of meaning into one powerful metaphor’ (26). Levine agrees, proposing that the water element of the house ‘embodies an image of nature in flux’ (Levine 2000: 32).

As highlighted by Hoffmann (1986) and Levine (2000), the shape of the waterway influenced the form of *Fallingwater*. The way Wright set out the basic forms of *Fallingwater* on the landscape lines the house up with the angle of the stream, producing an 'oblique orientation' (Cleary 1999: 41) to which Wright draws attention in his captioning of a plan, 'showing relation of building to bank, bridge and stream' (Wright 1938: 45). Smith suggests that this positioning strategy, wherein *Fallingwater* was placed in-line with the directions of the geological fissures, creates a fascinating effect (fig. 2.24)

> [where]when viewed from a central vantage point downstream, the two waterfalls appear to flow at ninety-degree angles to each other. This configuration in repeated in the projecting living-room and bedroom parapets, which crisscross at a ninety-degree angle echoing the waterfalls below (Smith 2000: 25).

Figure 2.24 Relationship of terrace angles to waterfall, Fallingwater*(Photograph by the author)*

- The next strategy Wright typically used to integrate a building into a site, was 'a willingness to modify the landscape to conform to a pattern of work' (Riley 1994: 99). This strategy of altering the landscape to help the building to 'fit in' was not the case at *Fallingwater*, where Wright did little landscape alteration as ‘there are practically no gardens or special plantings; nature is the garden’ (Kaufmann 1986: 127). Fell notes Wright’s use of large-scale landscaping in many previous designs, but says that for *Fallingwater* it was different. ‘Wright considered the building so skilfully integrated with its surroundings, he advised [the Kaufmanns] not to change the natural landscape since it could not be improved upon’ (Fell 2009: 18). Instead, as far as landscape considerations go, Wright focused on his final strategy of using architecture to emphasise or intensify various properties of the site of *Fallingwater*. In this situation, with such a powerful landscape, Wright did not need to manipulate the site physically as he had done with other projects. For *Fallingwater*, Wright enhanced the characteristics of the site with the building. As Fell argues,

> it is the artful way Wright dovetailed his design for human shelter into a pristine natural environment that makes Fallingwater iconoclastic and a landscaping triumph. At Fallingwater it is the brilliant—and revolutionary—placement of the house itself that constitutes the landscaping (2009: 91).

Kaufmann specifically points to the terraces, which ‘seem to sublimate the great native rock ledges, echoing, completing, and ordering them’ (1986: 124). Other scholars suggest it is the boldness of the architecture that emphasises the landscape, so that it is the building that ‘reveals and dramatizes the forms and functions of the place’ (Andropgon 1997: 36). In this way, Gwendolyn Wright notes that *Fallingwater* ‘assert[s] a strong architectural statement that heightens the effect of the surroundings’ (1994: 80) and Smith suggests that while Fallingwater ‘retains its identity as a man-made object, it is perceived as a compliment to nature; and a result, each ennobles the other by its presence’ (2000: 25).

2.5 Strategies at *Fallingwater*

Tables 2.2 and 2.3 list the design and site strategies that Wright typically used to connect a building to a site and summarises the particular connections found in *Fallingwater*. Table 2.2 describes the six design strategies and Table 2.3 the five site strategies. For both tables, the typical elements and approach that connect landscape and architecture in Wright's work—as identified initially in this chapter—are presented in conjunction with a summary of how this approach was (or was not) applied by Wright at *Fallingwater*. In addition to these summaries, the table's 'evidence' column proposes a verification of how much (or little) the strategy is demonstrated at *Fallingwater*, including a symbol to represent the degree to which this evidence can be found, where '–' refers to very little if any at all, '+' indicates some evidence, and '++' shows that Fallingwater is a prime example of the strategy. As Hypothesis 2 of this dissertation analyses features of the landscape surrounding *Fallingwater* and compares the results to aspects of the building, the final 'data' column considers if the element has any features that could be analysed by measuring and comparing fractal dimensions. The initial process of of analysing Wright's approach to designing with nature is to identify pairs of forms, natural and synthetic, which historians, critics or Wright himself have linked together. In order for these features to be analysed using fractal dimensions, the data sources for pairing need to be quantifiable and comparable. The 'data' column proposes the usefulness of the element for fractal analysis, with three options. First are those elements which are eliminated due to lack of evidence at *Fallingwater* '–'. Second are those for which no specific items could be compared using fractal analysis, 'x'. The final data type, '✓', indicates the potential for the element to be analysed using fractal analysis (see Part II).

*Table 2.2 Wright's **design strategies** for connecting nature and architecture at Fallingwater*

Design Element	**Typical Approach**	**Fallingwater Approach**	**Evidence**	**Data**
Ground floor	Plinth-like slab on ground	*Fallingwater* is anchored at its side to natural rock, and then floors are cantilevered out over the water. This is a departure from Wright's conventional strategy.	No evidence _	_
Formal Mass	Bulk reduced by shifted planes	*Fallingwater* features layered, overlapping floor plates and high degree of variation of interior and exterior spaces. This broadly complies with Wright's standard strategy.	Evidence found in *Fallingwater* plans demonstrate this element. ++	x
Roof	Horizontal roofline	*Fallingwater* does not have a conventional horizontal roofline, instead it has a series of horizontal terraces, with only a small upper level roof. This partially complies with Wright's standard strategy.	Evidence found in elevations demonstrate this element to some extent. +	x
Containment	Buildings perforated by natural features	*Fallingwater* is perforated by rocks, trees and water. This complies with Wright's standard strategy.	Evidence found in building demonstrates this element. ++	x
Openings	Large openings placed specifically	*Fallingwater* has both large openings and those which dematerialise the separation between interior and exterior. The approach to openings conforms to Wright's standard strategy.	Evidence found in building demonstrates this element. ++	x
Materials	Regionalist, unfinished materials.	*Fallingwater* uses local sandstone quarried on site, untreated on walls, waxed on floor, merged with unpainted timber, tinted concrete, glass and steel. This complies with Wright's standard strategy.	Evidence found in building demonstrates this element. ++	x

*Table 2.3 Wright's **site strategies** for connecting nature and architecture at Fallingwater*

Site Element	**Typical Approach**	**Fallingwater Approach**	**Evidence**	**Data**
Site Interpretation	Drawing directly over site plans and photographs, key landscape features identified	Original plans show Wright's process of drawing over a very detailed topographic map of the site. This complies with his standard strategy.	Evidence found in Wright's original documents demonstrates this element ++	x
Locality Character	Identification of essence of local area.	Typically difficult to quantify, scholars support the idea that Wright captured the essence of the Bear Run valley.	Relies on scholarly interpretation +	x
Site characteristics	Reflection of characteristic natural forms	Evidence of reinterpretation of specific elements of surrounding landscape can be found in *Fallingwater*	Based on scholarly interpretation, could be further supported by analysis. ++	✓
Landscape alteration	Extensive site works	There are minimal site works and landscaping interventions at *Fallingwtaer*. This is contrary to Wright's standard strategy.	No evidence. –	–
Site Intensification	Landscape enhanced by architecture	Several scholars note the intensifying effect that *Fallingwater* has upon the landscape.	Relies on scholarly interpretation +	x

Of the eleven strategies identified previously in this chapter, only two (marked '–') cannot be found at *Fallingwater*, while there is evidence of nine of Wright's strategies for connecting architecture and nature. Of those, six provide excellent examples of a strategy (marked '++'). Of the somewhat weaker examples (marked '+'), some rely on claims made by scholars, rather than tangible or precise details. While all of the strong examples of strategies that Wright used to connect *Fallingwater* and the landscape can be verified by observation of the building itself or architectural drawings, the majority are not measurable using any means.

Only one strategy is measurable using fractal dimensions. This is because the method requires sets of data sources that can be compared in terms of characteristic visual complexity. The site element that provides this opportunity is 'site characteristics'. For example, as this chapter demonstrates, multiple people have drawn direct connections between the appearance of the steep topography of the valley, with its layered, projecting rock outcrops, and the form of *Fallingwater*, with its cantilevered, horizontal terraces, tied to its steep vertical stone walls. Similarly, *Fallingwater*'s profile, massing or silhouette, has been likened to that of the valley. Such features of both the architecture and the landscape are measurable using fractal analysis, and claims of their similarities are therefore testable, and suited to this study.

Conclusion

Throughout his life, Wright consistently espoused an Emersonian philosophy of nature, which in turn had a profound influence on his own approach to designing in response to the natural landscape. It was in Wright's development of the Prairie style, in the early 1900's, where he used an abstracted reference to the natural landscape, that Wright truly found his design style. For the rest of his career, Wright typically used these abilities to delve into the natural, or even urban setting, capturing its essence and reflecting this back in his architecture.

This chapter has defined the approaches—classified into eleven strategies—that Wright took in order to achieve the effect of integrating a building with its setting. The previous section of this chapter examined the evidence that Wright used these approaches in *Fallingwater* to create a house that has become emblematic of a building that fits with its natural setting. The chapter concluded with an assessment of the features identified as 'site characteristics' that might be able to be measured and tested to assess arguments that have been made about *Fallingwater*. These features will be further investigated in Chapter 6.

The following chapters form Part II of this dissertation. They will describe the methodological considerations for analysing several periods of Wright's architecture, as well as the approach to a specific study of the characteristic complexity of *Fallingwater* and its natural setting.

Part II Methodological Considerations

Chapter 3

Fractals and Architecture

The two hypotheses which are the catalyst for this research require a quantitative methodological approach to measuring and assessing Frank Lloyd Wright's architecture. Chapter 1 revealed that a suitable quantitative method for the analysis of Wright's work is fractal analysis. This computational method is based on—but differs to—fractal geometry. Part II, consisting of Chapters 3 to 6, presents a background to this approach and its architectural application.

While this dissertation includes as one of its hypotheses a comparison of data derived from architectural form with data derived from natural form, this is very much approached from an architectural perspective, using an architectural viewpoint to understand the influence of nature upon the design of the built environment. Therefore, the theoretical backgrounds in Chapters 3, 4 and 5 emphasise the architectural aspects of the method and its application. The final chapter of Part II, Chapter 6, then expands this premise to consider how a comparative analysis of formal complexity in *Fallingwater* and its immediate landscape context could be undertaken.

The present chapter commences with an introduction to the theory of fractal geometry, followed by an examination of the way architects—including Frank Lloyd Wright—and scholars have incorporated fractal geometry into the design and interpretation of the built environment. However, the influence of fractal geometry on architecture is not the focus of this dissertation, and as such, this chapter is primarily included to provide a background to wider applications of fractal geometry that will *not* be used in this thesis. Instead, it is the application of fractal dimensional analysis that will be applied to answer the hypotheses posed. The following chapters will further define the method of fractal analysis used in this study.

3.1 Defining a Fractal

The word ‘fractal’ is derived from the Latin word *frangere*, meaning to break or fragment. In mathematics the word ‘fraction’ is derived from the Latin *fractus*, which is the past participle of *frangere* (Mandelbrot 1977). A fraction is both a number produced by dividing one into another, and a fragment of a larger whole. The meaning of the word fractal is drawn from both the original Latin and the mathematical variant. In conventional use, the word fractal is used in two contexts, the first to describe a type of irregular dimensionality and the second an infinitely deep geometric set. In order to understand what a fractal dimension is, and the difference between *fractal dimensions* (the topic of this dissertation) and *fractal geometry* (the shapes often adopted by architectural designers), it is necessary to briefly delve into the theory of dimensions and the history of fractals.

Architects and designers conventionally talk about and conceptualise shape and form in both two and three dimensions. That is, from the first stages in their education, designers understand that objects (including cities, buildings and furniture) are three-dimensional, although their properties are typically described using two-dimensional representations (plans, elevations, sections and various perspective and isometric views). While this way of thinking about flat representations as ‘two-dimensional’ and physical objects as ‘three-dimensional’ is in common use in society, the theory of dimensionality is actually much more intricate and diverse (Aull and Lowen 2011). As a starting point to understanding this theory, it is first necessary to clarify some of the basic terminology and concepts used.

Mathematicians and scientists sometimes call the world in which we physically exist ‘Euclidean space’, philosophers describe it as the ‘material world’ and architectural theorists define it as ‘lived space’ or ‘experiential space’ (Juhos 1976). This dimension is physically tangible (it can be touched and otherwise sensed) and it has practical material and scale limits, meaning it cannot be infinitely divided or enlarged. To use an architectural example, a building in the material world can be touched, it provides physical shelter and it is made of substances that lose their structure if they are sufficiently weathered. In contrast, the theorised or imagined world is described by mathematicians as ‘topological space’, by philosophers as ‘abstract space’ and by architectural theorists as ‘geometric space’ (Wagner 2006). This imagined space has no direct physicality and no practical limits, but it can still be studied in valuable ways. To use another architectural example, a computer model of a building cannot be touched, it has no capacity to provide shelter from the elements and it can be made infinitely small, or large, without any impact on its geometry. Both the material world (of the building) and the abstract world (of the CAD model) are rigorously defined, dimensional spaces, but as we will see, while architects view them both as three dimensional, mathematicians and scientists see them differently.

Technically, a dimension is a topological measure of the space-filling properties of an object (Manning 1956). Thus, a dimension is an abstract but still accurate gauge of the extent to which an object occupies space. While architects talk about only two different dimensions—two-dimensional representations and three-dimensional objects—for a mathematician, a large number of hypothetical dimensions (*n*) exist in topological space. Mathematically, the relative membership of an object in a dimensional set is determined by calculating the number of coordinates required to define the location of a point on that object. Thus, for example, the corner of a planar surface can be located in space with only an *x* and *y* coordinate, while the corner of a cube requires *x*, *y* and *z* coordinates. For the first of these examples $n = 2$ and for the second $n = 3$; that is, they are respectively in two-dimensional and three-dimensional space (Sommerville 1958). Because infinite mathematical dimensions are possible, mathematicians typically talk of space as being *n*-dimensional (Pierpont 1930; Manning 1956).

Until the early 1970s, mathematicians accepted that *n* was necessarily a whole number (for example, 1, 2 or 3). Moreover, the Euclidean world was thought of as necessarily a geometrical three-dimensional space, with all other dimensions existing only in abstract space. However, the idea that multiple dimensions may exist simultaneously in Euclidean space has become known as the 'theory of general dimensions' (Edgar 2008; Pears 2008). One of the catalysts for this development was the growing realisation that whole number or integer dimensions are incapable of describing the full complexity of the material world. Probably the most famous of the general dimensions, and the first to methodically develop non-integer values, is the fractal dimension.

In *Les Objects Fractals*, Benoît Mandelbrot (1975) built on the work of Gaston Julia (1918) to suggest that Euclidean geometry, the traditional tool used in science to describe natural objects, is fundamentally unable to fulfil this purpose. While historically science considered roughness and irregularity to be an aberration disguising underlying systems with finite values, Mandelbrot suggests that the fragmentation of all naturally occurring phenomena cannot be so easily disregarded. In order to solve this dilemma Mandelbrot (1982) proposed that certain natural structures may be interpreted as lying in the range between traditional whole number dimensions. He argues that, for example, if we look at a snowflake under a microscope, it fills more space than a line ($n > 1.0$), yet far less than a surface ($n < 2.0$), therefore its actual dimension is a fraction which is more than one but less than two. Mandelbrot calls such fractional, non-integer dimensions, fractal dimensions. Mandelbrot's (1977) technical definition of a fractal has been widely paraphrased as *a set for which one has Hausdorff-Besicovitch dimension greater than topological dimension* and he demonstrated this definition of a type of irregularity using a series of geometric constructions which parametrically repeat themselves to produce evocative and infinitely complex images. In this process Mandelbrot used fractal geometric sets to explain fractal dimensions and vice versa.

It is this early combination of fractal dimensions and fractal geometry that caused much of the later confusion and even forced Mandelbrot to revise his definition. In hindsight, this misunderstanding was almost to be expected, because for a mathematician dimensions are necessarily topological or abstract and should not be confused with the measures used to describe the material world. However, such was the extent to which non-mathematicians assumed that fractal dimensions and fractal geometry were the same things that Mandelbrot was forced to retract his original definition (Feder 1988). Mandelbrot (1982) eventually revised his definition because he was dissatisfied with the way it excluded many mathematical sets from the material world that are visually reminiscent of fractals but which failed to fulfil the precise topological conditions he originally set. Furthermore, some completely chaotic topological sets (those lacking any degree of order) complied with his original definition even though they were not in its spirit. For this reason, by the 1980s Mandelbrot was forced to differentiate between fractal *geometry* and fractal *dimensions*. The former refers to particular geometric sets that only exist in topological space and exhibit high levels of self-similarity, while the latter is a more general term describing the space-filling properties of irregular objects which may be in either topological or material worlds.

A fractal geometric figure is one that is generated by successively sub-dividing or growing a geometric set using a series of iterative rules. This process produces a figure that has parts, which, under varying levels of magnification, tend to look similar, if not identical, to each other. For example, if the starting geometric set is an equilateral triangle, and the rule says that the middle third of each face of that triangle is replaced by a new equilateral triangular extension, then once the rule is applied the first time, the starting figure transforms from a triangle into a six-pointed star (like an outline of the Star of David). If the same rule is applied to this new shape, it takes each of the twelve faces, again identifies the middle third, and uses it to generate a new triangular extension, which it adds to the face. By now, the new figure has forty-eight faces, and it has begun to resemble a geometric snowflake. Furthermore this operation can be repeated an infinite number of times, generating an endless sequence of geometrically identical, though increasingly smaller-scaled, triangular additions. This special geometric set is known as the Koch Snowflake and whatever scale you magnify it to, the geometry looks the same (fig. 3.1).

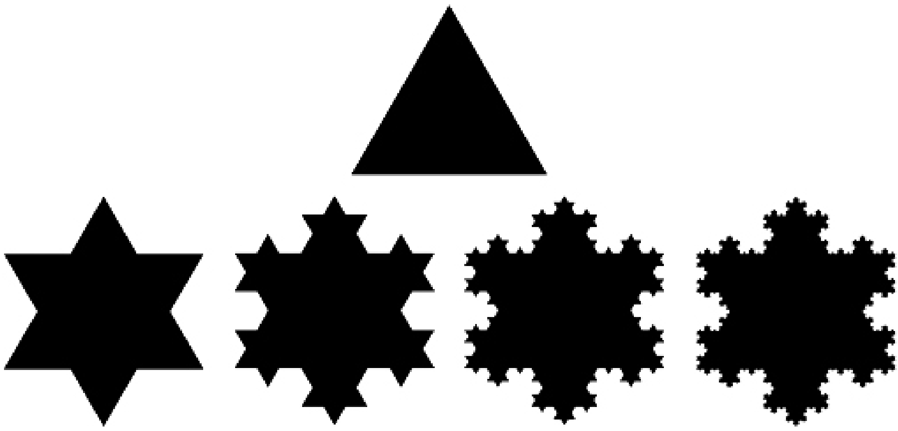


Figure 3.1 The Koch Snowflake fractal set; starting figure (above) and first four iterations (below)

There are many well-known fractal sets like the Koch Snowflake which feature infinitely deep and repetitious shapes. These are often called 'ideal fractals' because they can only exist in computer simulations or as algorithmic processes. Nevertheless, these fractal geometric sets have many interesting properties. For example, the Koch Snowflake may have an infinite number of surfaces, but it will never be bigger than a square drawn around its first iteration. Thus, the Koch Snowflake has an infinite boundary length but an area that is forever approaching, but does not reach, a fixed figure. Despite this paradoxical quality, the Koch Snowflake does have one fixed property, its characteristic irregularity, and it is possible to use mathematics to accurately calculate how consistently spiky it is. This characteristic irregularity is the fractal dimension of the Koch Snowflake, and using mathematics we can determine that its spikiness has a dimension (D) of 1.26186 (Mandelbrot 1982). While the method used to measure this irregularity is discussed in greater detail over the following few chapters, the message here is that there is a major difference between fractal geometry (an infinitely deep form, generated by the consistent application of a rule) and fractal dimension (a measure of the characteristic roughness or complexity of an object).

Mandelbrot (1982) defined fractal geometry as a type of deep geometric phenomena that arises from the application of a system of repetitively applied feedback rules – also known as Iterative Function Systems or IFS (Peitgen and Richter 1986). As a product of the IFS, the resultant geometric figure, when examined at increasingly fine scales, is seen to be self-similar, that is, at a variety of ranges, the object in question tends to resemble itself (Kaye 1989). This property is known as ‘scaling’. For Mandelbrot, any set may have a fractal dimension, but only sets with a defined scaling pattern can be described as instances of fractal geometry. This distinction is a critical one in architectural analysis where the two are rarely differentiated and widespread confusion exists about whether or not a building can be fractal (Jencks 1995). From a pure mathematical perspective, buildings may have fractal dimensions, but they are never, in the material world at least, examples of fractal geometry (Ostwald 2001; 2003). Moreover, buildings are actually part of a general class of objects called multi-fractals, a class that covers most natural and synthetic objects in the material world (Stanley and Meakin 1988). Before returning to the distinction between geometry and dimensionality, the multi-fractal is worthy of a brief diversion.

Ideal mathematical fractals, such as the Koch snowflake or Sierpinski triangle (fig. 3.2), possess infinite scalability and singular stable dimensions, and as such they are sometimes called ‘uni-fractals’. In contrast, a ‘multi-fractal’ is an object that simultaneously possesses a range of dimensions, each of which is relatively consistent over several scales, but is not continuous (Alber and Peinke 1998). For example, a tree in the material world has several distinct scales at which it exhibits levels of characteristic complexity. Buildings and cities are also multi-fractals; every building has several levels of stable dimensionality, ranging from the cellular, granular, and material to the textural, constructional and formal (Ostwald 2001; 2003).

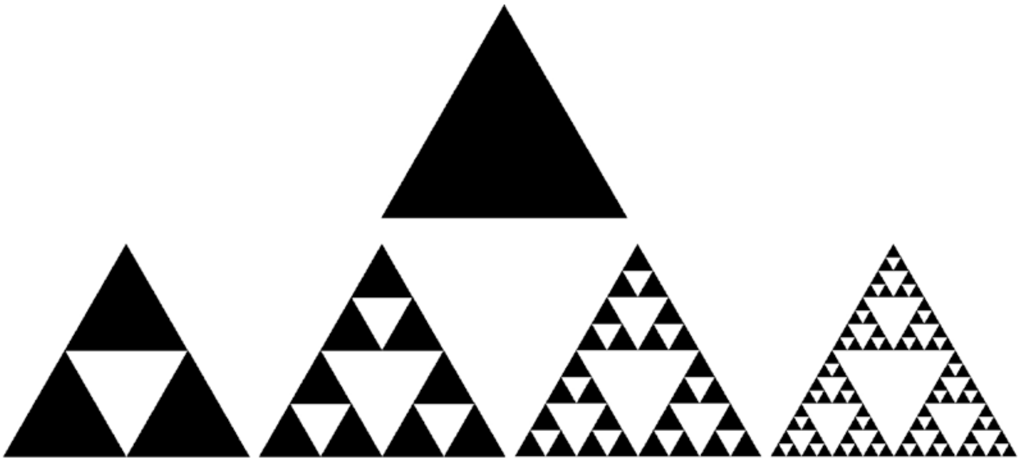


Figure 3.2 The Sierpinski Triangle fractal set; starting figure (above) and first four iterations (below)

Returning to the previous point, the distinction between geometry and dimensionality is important because it differentiates between two separate mathematical processes. The first of these, which includes models like the IFS, is used to identify the structure of a fractal geometric set. The second, made up of a range of related analytical systems, can be used to determine the fractal dimension of a set. While these two methods are independent, a small number of fractal sets effectively have matching structures and dimensions and are therefore ideal for the calibration of analytical methods (Da Silva et al. 2006; Górski et al. 2012). The Koch Snowflake is one such set as it has both a defined IFS and a fixed fractal dimension.

3.2 Fractals in Architectural Design and Critique

This dissertation is primarily about the analysis of architecture—and additionally about the possible influence of nature upon architecture—using fractal dimensions. This method and its application are described in detail in the following chapters, but it must also be acknowledged that the relationship between fractals and architecture has traditionally been both more diverse and controversial. For thirty years architectural scholars and designers have opportunistically appropriated images and ideas from fractal geometry along with concepts broadly related to fractal dimensions and non-linear dynamics, and used them for a wide variety of purposes. Some of these appropriations have been motivated by the desire to advance architecture or to offer new ways of understanding design, but many others have a seemingly more superficial or expeditious agenda (Ostwald 1998). There are sometimes frustrating connections that have been proposed between architecture and fractals, however likewise there are a large number of examples where architecture and fractal geometry have been used as a catalyst for discussion of the broader nature of this complex and creative association.

Fascinated by its mathematics and imagery, or drawn to possible natural or mystical connections, some architectural writers and designers have promulgated a range of often idiosyncratic interpretations of fractal geometry. Because of the diverse range of motives for adopting fractal geometry, there is neither an agreed upon definition nor a common title for works that use fractals for inspiration, design rationale or form generation. For example, several portmanteau descriptors exist which merge multiple, often dissimilar properties. Probably the best known of these is Charles Jencks's (1995) 'Architecture of the Jumping Universe', an evocative title for an eclectic set of ideas cherry-picked from science, philosophy and art. Similarly, the 'New Baroque' (Kipnis 1993) and the 'Architecture of the Fold' (Eisenman 1993) freely merge concepts from fractal geometry with themes from the writings of Deleuze and Guattari, philosophers who once used fractal geometry as a metaphor for political theory (Ostwald 2000; 2006). The repeated use of other classifications including 'Fractalism', 'Complexitism', 'Complexity Architecture' and 'Non-linear Architecture' have led scholars like Yannick Joye to argue that 'a systematic, encompassing, scholarly treatment of the use and presence of this geometrical language in architecture is missing' (2011: 814).

Despite ongoing confusion over definitions, there are many examples of possible connections between fractal geometry and architectural design, ranging from inspiration to structure, from construction to surface treatment and from applied ornament to algorithmic generator. More than two hundred examples of designs that have been inspired by, or allegedly designed in accordance with, fractal geometry have been identified and analysed (Ostwald 2001). These include works which explicitly acknowledge a debt to fractal geometry, even though the resultant architecture may not have such a clear relationship. Some of the architects and firms that have either made explicit reference to complexity science, or have been linked to fractals include architectural firms from—the USA: Asymptote, Peter Eisenman, Kenneth Haggard and Polly Cooper, Steven Holl, Morphosis, Eric Owen Moss—from Europe: Bolles Wilson, Kulka and Königs (Germany), Coop Himmelblau (Austria), Jean Nouvel (France) Aldo and Hannie van Eyck, Van Berkel and Bos (Netherlands), Philippe Samyn (Belgium)—from the UK: Zaha Hadid, Ushida Findlay—from Japan: Arata Isozaki, Kisho Kurokawa, Fumihiko Maki, Kazuo Shinohara—as well as Charles Correa (India), Carlos Ferrater (Spain), and Plan B (Colombia). In some cases the influence of fractal geometry in a particular architectural project may be obvious, whereas in others it is less clear what the connection is. For example, one of Charles Correa's designs for a research facility in India features a landscaped courtyard that is tiled in a representation of the fractal Sierpinski triangle. This is an obvious and literal connection that might be appropriate, given the function of the building, but it is potentially little more than an ornamental application (Ostwald and Moore 1997). In contrast, Ushida Findlay produced a three-dimensional map of the design themes they had been investigating at different stages during their joint career. This map, a nested, recursive structure which traces a spiralling path towards a series of design solutions, is visually and structurally similar to a strange attractor; an iconic form in complexity science (Ostwald 1998).

More commonly, architecture that explicitly acknowledges a connection to fractal geometry is inspired by some part of the theory or its imagery even though it does not employ a scientific or mathematical understanding of the concept. Thus, in architecture the fractal tends to serve as a sign, symbol or metaphor representing a connection to something else. For instance, a large number of architectural appropriations of fractal forms are inspired by the desire to suggest a connection to science, nature or ecology. An example of these motivations found in *the Botanical Gardens of Medellin*, jointly designed by Plan B Architects and JPRCR Architects, where the architects admit to being ‘inspired to attempt a fractal composition’ (Martignoni 2008: 55). Architects Haggard and Cooper also use fractal geometry for its ‘holistic characteristics and endless scales aiming at the creation of sustainable architecture’ (Sedrez and Pereira 2012). In both of these cases, geometric scaling is deployed to evoke a connection to nature; a link which might be reasonable in symbolic or phenomenal terms, but does not support any genuine ecological agenda.

There are also other designs which have, purportedly at least, been intuitively led to use fractal geometry, often many hundreds of years before the theory was formulated. This category includes works that demonstrate either intuitive or subconscious evidence of an understanding of the geometric principles underlying fractal geometry. For example, Ron Eglash (1999) notes the similarities between the geometric patterns found in indigenous African design and the self-similar shapes of fractal geometry. Gerardo Burkle-Elizondo (2001) offers a parallel argument drawing connections between fractal geometry and ancient Mesoamerican pyramids. Several architects and mathematicians have observed that the thirteenth-century plan of Frederick II’s Castel del Monte (fig. 3.3) possesses self-similarity at two scales, thereby suggesting the start of a sequence of fractal iterations (Schroeder 1991; Götze 1996).

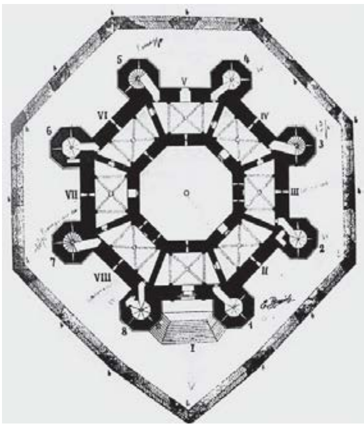


Figure 3.3Plan of Frederick II’s Castel del Monte *(Fallacara and Occhinegro 2015: 38)*

Each of these examples is an instance of scaled, geometric repetition which is superficially similar to the geometric scaling found in ideal mathematical fractals. In contrast, researchers have identified fractal properties in the way the classical Greek and Roman orders have been iteratively constructed (fig. 3.4) (Crompton 2002; Capo 2004; Bovill 2009). Gert Eilenberger (1986), Peter Fuller (1987), Sheila Emerson (1991), Manfred Schroeder (1991), Andrew Crompton (2001), Wolfgang Lorenz (2011) and Albert Samper and Blas Herrera (2014) all suggest that Gothic architecture has various connections to fractal properties or can be interpreted in terms of fractalesque geometry (fig. 3.5).

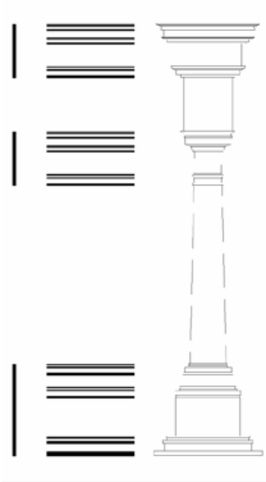


Figure 3.4 Iteration of classical orders (Capo 2004:34)

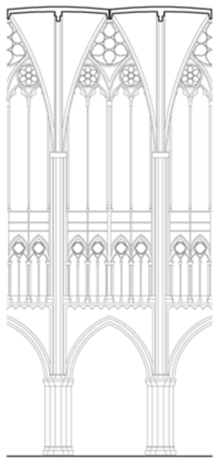


Figure 3.5 Fractal iterations in a French Gothic Cathedral (Samper and Herrera 2014: 262)

Joye (2011) even proposes that the Gothic cathedral offers one of ‘the most compelling instances of building styles with fractal characteristics’ (2011: 820). George Hersey (1999) identifies examples of fractal-like iteration in Renaissance architecture, in eighteenth-century Turkish buildings and in the Neo-classical work of Jean-Nicolas-Louis Durand. In the nineteenth century, in addition to Mandelbrot’s case for the fractalesque features of the Paris Opera, he is also one of multiple authors to suggest that the Eiffel Tower could be considered structurally fractal, at least for up to four iterations (Mandelbrot 1982; Schroeder 1991; Crompton 2001). Indian temples provide a more compelling case for an intuitive connection between fractal geometry and architecture (fig. 3.6), in part because they actually possess, to a limited extent, scaled, self-similar geometric forms that follow a seemingly clear generative process (Trivedi 1989; Kitchley 2003; Lorenz 2011; Sedrez and Pereira 2012).

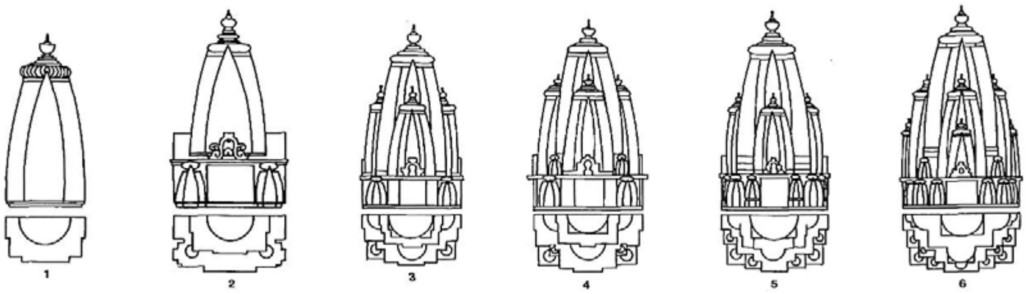


Figure 3.6 Self-similar iterations in Indian Temple Shikharas (Trivedi 1989: 252)

3.3 Frank Lloyd Wright and Fractal Geometry

In the early years of the twentieth century, and in parallel with the rise of interest in organic metaphors for design, several architects, including Frank Lloyd Wright and his mentor Louis Sullivan, began to produce works which were suggestive of fractal geometry in their experiential, planning or ornamental qualities (Kubala 1990). Bovill finds clues to Wright's possible instinctive fractally-inspired thinking in his writing and designs. According to Bovill;

> Wright clearly used nature for inspiration, but his buildings do not look like trees or bushes. He was looking beyond the outward appearance of the natural forms to the underlying structure of their organization. This is a fractal concept. Natural forms do have an underlying organizational structure, and fractal geometry provides a clear method of understanding and describing that structure (Bovill 1996: 128).

Furthermore, Bovill (1996) proposes that 'Wright's buildings are a good example of this progression of self-similar detail from the large to the small scale' (1996: 116). Leonard Eaton also found that Wright's architecture provides an example of the inspiration of fractal geometry in design. Eaton was convinced that

> Wright used nature as the basis of his geometrical abstraction. His objective was to conventionalize the geometry which he found in Nature, and his method was to adopt the abstract simplification which he found so well expressed in the Japanese print. Therefore, it is not too shocking perhaps that is this quest his work would foreshadow the new mathematics of nature: fractal geometry (Eaton 1998: 24).

Eaton argues that Wright's architecture only became more perceptually complex after the completion of the Textile-block house *La Miniatura*; a building which Eaton feels has no strong fractal presence or expression. But in terms of the geometry of the plan, Eaton (1998) suggests that Wright's Usonian work of the 1950s and 1960s features a 'striking anticipation of fractal geometry' (1998: 31). Eaton's rationale for this argument is derived from the recurring presence of equilateral triangles, at different scales, in the plan of Wright's *Palmer House* (fig. 3.7). Forms in this house, ranging from the large triangular slabs of the cast concrete floors down to the triangular shape of the fire-iron rest are noted. Eaton counts 'no less than eleven scales of equilateral triangles ascending and descending from the basic triangle' (1998: 32) leading him to conclude that the *Palmer House* has 'a three-dimensional geometry of bewildering complexity' (1998: 35).

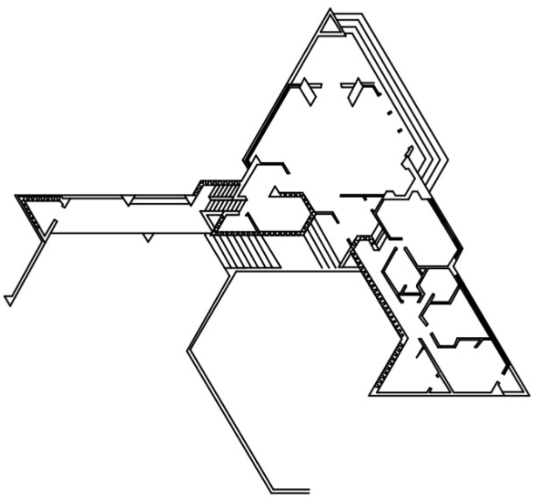


Figure 3.7 Palmer House Plan, redrawn from Storrer (1993: 352)

Yannick Joye agrees with Eaton's assertion that the 'Palmer House seems to be the culmination point' (Joye 2007: 312) of Wright's intuitive use of fractal geometry in architecture. In a similar vein, Daniele Capo (2004) uses Eaton's analysis of Wright's domestic architecture to build on his own fractal analysis of architecture, suggesting that Wright's architecture combined smaller elements to create larger works which show fractal similarities to Palladio's architectural orders. Giovanni Ferrero, Celestina Cotti, Michela Rossi, and Cecilia Tedeschi also accept Eaton's conclusion that fractals can be found in the Palmer House (Ferrero et al. 2009). However, before Eaton's work was published, Michael Ostwald and John Moore (1996) rhetorically demonstrated that even the most Euclidean of buildings, like Mies Van Der Rohe's *Seagram Building*, can have more than 12 scales of conscious self-similarity and that this does not make them, or the *Palmer House*, fractal (Ostwald 2003). James Harris also disagrees with Eaton's simplified analysis of the Palmer House, saying that Eaton's paper 'points out the misconception that a repetition of a form, the triangle in this case, constitutes a fractal quality. It is not the repetition of the form or motif but the manner in which it is repeated or its structure and nesting characteristics which are important' (Harris 2007: 98). Harris proceeds to apply an iteration method (IFS) to a triangle, in an attempt to produce a similar plan to the *Palmer House*, finally creating a design with some similarities in plan to the final design by Wright. Harris concludes that Wright's architecture may not be as strongly generated by fractal geometry as Eaton suggests. However he finds the relationship to be 'analogous' (Harris 2007:98). The word analogous is appropriate because Eaton proposes the existence of a symbolic or metaphoric relationship between fractal geometry and repetitious forms in the plan of the *Palmer House*. Grant Hildebrand's (2007) analysis of the *Palmer House* also effectively dismisses Eaton's argument about scaling and triangular geometry, preferring to stress the more phenomenal or experiential connections to nature and complexity.

While these scholars write directly about Wright's possible relationship with fractal geometry, there are others (including Wright himself) whose words do not mention fractals but do suggest a fractalesque approach to design, particularly noting repeated, scaled iterations, or pattern-seeking geometry, and this is based on natural pattern. These proposals emerge from Wright's source of inspiration in nature, and the manner of his design process, where according to Carla Lind, Wright 'dipped into the stream, looked into the treetops, stretched out like branches from a tree, and used nature's own color palette' (1996: 21). Neil Levine provides an example of this process in *Fallingwater*, which he describes as being 'ultimately about the cumulative effect of stone, water, trees, leaves, mist, clouds, and sky as they interact over time' (2000: 57-58).

Many authors emphasise Wright's own declarations that 'design is abstraction of nature-elements in purely geometric terms' (Wright 1957: 181). For example, Diane Maddex considers Wright's architecture as an expression where 'geometry synthesized nature to its very essence' (1998: 9), and David Hertz also notes Wright's 'careful observation of natural pattern' (1993: 2). According to Olsberg, Wright was attempting 'to discover an abstract language of forms—a language in sympathy with natural laws' the output of which did not have to necessarily present as 'naturalistic' (1996: 11).

While the observation of a pattern in nature may lead to the development of fractal-like geometry, as David De Long points out, it is just as possible to find Euclidean patterns and geometry this way:

> For Wright, the ideal order of the universe was thus Euclidian by nature, and this order could be represented by combinations of Euclidian shapes organized according to a larger field of gridded modules. (1996: 119)

The change from Euclidean to fractal geometry can be found in the repetition or iteration of the forms, over different levels of physical dimension. This idea of 'scaling', while not mentioned in conjunction with fractals, is alluded to by many

Wright scholars, so that while De Long finds Wright's work to be extracted Euclidean shapes, his description of their use could be considered fractal.

> [Wright] sought universal meaning though attachment to place, varying his geometries not only to achieve an indivisible bond with each specific location, but, more importantly, to complete that locations underlying structure, so that each place became more fully revealed as an indivisible part of an ordered cosmos (De Long 1996: 120).

Other authors describe the scaling effect more clearly, explaining that Wright 'developed the notion of inner geometries, concealed within larger forms' (Olsberg 1996: 12). According to Jeanne Rubin, '[f]rom the smallest interior detail to the largest exterior statement, Wright is well known to have developed his structures outward from within, through repetitive extensions of a central motif' (2002: 111). Howard Robertson defines Wright's Organic style as an architecture where 'everything in and about the building should be fully integrated, part of the design […] It means that the expression, the exterior details, the planning for requirements, are all built-in and built-up, producing an organic whole' (1952: 174). Finally, whether or not evidence of fractal properties can be detected, Wright himself, in his usual rambling way, declared that:

> Reality is spirit—the essence brooding just behind all aspect. Seize it! And–after all you will see that the pattern of reality *is* supergeometric, casting a spell or a charm over any geometry, and is such a spell in itself. Yes, so it seems to me as I draw with T-square, triangle and scale. That is what it means to be an artist—to seize the essence brooding everywhere in everything, just behind aspect (1957: 157).

Conclusion

Despite the fascinating possibility that Wright may have developed an instinctual understanding of the *fractal geometry* present in nature, this dissertation does not explore this avenue of research any further. While this chapter has been concerned with the way *fractal geometry* and associated imagery and ideas have been used by architectural designers and scholars, this notion has been presented as a precursor to this study’s more rigorous basis, the application of a quantifiable approach to measuring and analysing Wright’s architecture using *fractal dimensions*. The two approaches offer different ways of considering the relationship between design and geometry, for there is no explicit connection between fractal measurement and a design that seeks to evoke—through form, texture or tectonics—fractal geometry. Thus, while it is possible to measure the fractal dimension of a building that is inspired by fractal geometry, the two processes, measurement and inspiration, are fundamentally unrelated. The former, measurement, is a universal set of actions, following a strict protocol, which can be repeated for multiple similar objects. The latter, inspiration, is an intricate and potentially poetic process, which is typically unique to an individual. Both of these processes are valid and useful, but they should not be confused.

Chapter 4

Measuring Buildings and the Box-counting Method

This chapter commences by considering the value of a quantitative approach in the context of an architectural study. It then reports on the few mathematical or geometric studies previously undertaken on Wright. The quantitative method used in this dissertation is then introduced—fractal dimension analysis.

The box-counting method is the approach used for fractal analysis in this dissertation. In this chapter, the most basic variation of the box-counting method for calculating the fractal dimension of an image is demonstrated by applying it to Frank Lloyd Wright's *Robie House*. Thereafter the chapter provides a background to the application of the box-counting method in architectural and urban analysis—including applications to Frank Lloyd Wright's work—and describes the analytical intent and conclusions of this past work.

4.1 Measuring Wright

This thesis presents the results of analysis of sixteen of Frank Lloyd Wright's houses and a study of the natural landscape surrounding one of these houses, *Fallingwater*. The majority of these sixteen designs have been repeatedly published and analysed by scholars (Alofsin 1994; Behbahani et al. 2016; Dawes and Ostwald 2014; Frazier 1995; Hildebrand 2007; Hoffmann; 1978, 1995; Koning and Eizenberg 1981; Lampugnani 1997; Laseau and Tice 1992; Levine 1996, 2000, 2005; McCarter 2004, 2005; Pfeiffer 2004; Scully 1960; Storrer 2006; Sweeny 1994). Like the majority of designs that have been identified by historians as canonical works, the houses analysed in this thesis are understood almost exclusively in *qualitative* terms. That is, the properties that make them special or significant are documented and communicated using textual descriptions, supplemented by photographic or graphic media. In these cases, the media is not usually scrutinised or analysed, it only provides a visual reference for the house, rather than an explanatory reference, leaving the descriptive text to provide the reader with an understanding of these designs. Such texts are invariably presented using a combination of comparative and denotative terms. Thus, these designs are characterised by historians and scholars as having, ‘wider eaves’, ‘deeper balconies’ and ‘natural materials’ (Alofsin 1994; De Long 1996; Storrer 2006). They are ‘richly textured’ and ‘grow out of their sites’ (Kaufmann 1986; Maddex 1998). These examples are typical of the qualitative descriptions used to explain the characteristics of architecture and the significance of these buildings in a larger historical context. Variations of these phrases are repeated in almost every major architectural reference work. They represent a combination of professional judgment, informed personal opinion and received wisdom (Koning and Eisenberg 1981; Stamps 1999; Laseau and Tice 1992). For example, Koning and Eisenberg emphasise that ‘such descriptions do not explicitly inform us as to how […] houses are constructed, and consequently provide little help in designing’ (1981:295). There is nothing wrong with this way of constructing the history and theory of architecture, but there are valuable alternative approaches that can be used to question the traditional classification of these buildings and promote a new way of understanding them.

Frank Lloyd Wright’s architecture is a perfect example of a body of work which has been extensively documented by twentieth century historians using qualitative techniques (Futagawa and Pfeiffer 1984; 1985a; 1985b; 1985c; 1987a; 1987b; Cronon 1994; De Long 1996; Cleary 1999; Storrer 2006; Hoffmann 1978; 1993; 1995; Levine 2005; Fell 2009). Despite such examples, Wright’s architecture has only rarely been subjected to any type of quantitative—generally computational or mathematical—analysis. Even though researchers have repeatedly identified Wright’s predilection for geometric systems and have carefully quantified and categorized his works into clear stylistic period (Koning and Eizenberg 1981; MacCormac 2005; Dawes and Ostwald 2014; Behbahani et al. 2016; Lee et al.

2017), the vast majority of what is known about Wright's architecture remains qualitative in nature. Nevertheless, a small number of quantitative studies do exist and they confirm that it is not only possible to study Wright's architecture using computational means, but it is highly beneficial because of the size of the body of work he produced. Importantly, several of the computational or geometric studies of Wright's architecture that have previously been undertaken have been focused on his houses. For example, John Sergeant proposes that Wright's flexible use of planning grids is the common link between the Prairie Style, the Textile-block period and the Usonian house period. Sergeant suggests that the Prairie Style houses were designed on a 'tartan grid' where a 'vocabulary of forms was used to translate or express the grid at all points – the solid rather than pierced balconies, planters, bases of flower urns, clustered piers, even built-in seats were evocations of the underlying structure of a house' (2005: 192). The Textile-block houses, typically set in the steep topography of the Los Angeles foothills, necessitated a development in Wright's use of the grid which signals, according to Sergeant, the moment when Wright first extended his planning grid into a vertical axis.

Richard MacCormac uses a different, but equally planar diagrammatic method to compare the forms of 11 of Wright's early buildings with the shapes of the Froebel's Gifts; a three-dimensional educational device which Wright used as a child. MacCormac concludes that the Froebel discipline can be found in all of Wright's early work as a 'certain continuity of principle' (2005: 132). Hank Koning and Julie Eizenberg agree that 'MacCormac was right in the idea that there is a consistent underlying structure informing Wright's work' however, they find MacCormac's method and approach to be limited by a sense of order 'as if order must in some way be tied up with measurable geometry'(Koning and Eizenberg 1981: 296). Koning and Eizenberg propose that a shape grammar approach is more suitable to the analysis and modelling of Wright's organic design approach. Utilizing the shape grammar approach to analyse six of Wright's prairie houses, Koning and Eizenberg conclude that 'the composition of Wright's prairie-style houses is based on a few simple spatial relations between parameterized three-dimensional building blocks of the Froebelean type' (Koning and Eizenberg 1981: 296). They further propose a three-dimensional parametric shape grammar to demonstrate the design of new ‘Wright-style’ buildings. Terry Knight builds on the work of Koning and Eizenberg with a comparative shape grammar analysis of Wright’s Prairie and Usonian styles. Knight believes that the elemental ‘composition of Prairie houses provide[s] the basis for the basic composition of the later Usonian houses’ (1994: 222). Knight produces a shape grammar for six of Wright’s Usonian houses, and compares these with ‘a simplified version of Koning and Eizenberg’s earlier [Prairie] grammar’ (1994: 224), concluding that ‘[a]lthough the outward appearance and spatial organization of Usonian houses seems substantially different from that of the Prairie houses, the underlying composition of Usonian designs is closely related to that of Prairie designs’ (1994: 236). Most recently, Lee et al. (2017) have returned to Koning’s and Eizenberg’s original grammatical reading of the Prairie Style, and using a combined syntactical and grammatical method, identified a statistical archetype for this period of Wright’s architecture.

In the largest plan-analysis study undertaken into Wright’s works, Paul Laseau and James Tice reject the standard historical focus on ‘underlying principles’ and aim for a balanced approach that employs analytical illustrations to generate typological studies of the plans of 131 of Wright’s buildings. Laseau and Tice’s formal analysis demonstrates a categorisation of Wright’s work into three typological, rather than chronological, thematic groups; the atrium, the hearth and the tower (1992).

Precise geometric mapping of lines of sight within and around Wright’s architecture have been measured using a space syntax method by Behbahani et al. (2014; 2016). Ostwald and Dawes have taken this idea further by applying isovist field analysis, a computational technique, to investigate Hildebrand’s architectural version of Prospect-Refuge theory as applied to routes through and views of Wright’s domestic architecture (Ostwald and Dawes 2013; Dawes and Ostwald 2014).

4.2 Fractal Dimensions

The quantitative methods described in the previous section all provide calculable, comparable results, which broaden the techniques available to architectural scholars. Another, similarly rigorous method—fractal analysis—is the quantitative, mathematical and computational approach chosen for the present study, giving it a distinctive starting point from which to selectively rethink the properties of some of Wright's most famous buildings.

Fractal analysis measures the fractal dimension of a plan, elevation or other representation of a design. A fractal dimension is a rigorous measure of the relative density and diversity of geometric information in an image or object. This property, which is described as either 'characteristic complexity' or 'statistical roughness', is simply a determination of the amount (meaning volume) and distribution (meaning how it is spread over many scales) of geometry in a form. In architectural terms, it could be seen as a mathematical calculation of the extent to which lines, regardless of their purpose, are both present in, and dispersed across, an elevation or plan.

The method for calculating the fractal dimension of an object was first proposed by mathematicians in the 1980s (Eilenberger 1986; Peitgen and Richter 1986; Keller et al. 1987; Feder 1988; Vos 1988; Kaye 1989). Many hundreds of scientific and medical studies (for example, Peebles 1989; Chen et al. 1993; Asvestas et al. 2000; De Vico et al. 2009) have been published using variations of the fractal analysis method to measure and compare complex objects, but it is still—despite important past research—poorly understood by architectural scholars and almost completely unknown amongst design students and practitioners. Part of the reason for this situation is that these other fields (engineering, biology, astronomy, geology and medicine) have had a long-term interest in measuring the properties of complex objects and have thus developed stable versions of the method. However, in architecture and design, despite progress in the 1990s, the most accurate and useful variant has only recently been identified. For this reason, Part II contains a clear description of the process of using fractal dimensions for measuring, along with a demonstration of its application, a review of its methodological variables and a discussion of its limits.

4.3 Measuring Fractal Dimensions

There are multiple ways of mathematically calculating the fractal dimension of an image (where $1.0 < D < 2.0$) or object (where $2.0 < D < 3.0$). For example, Mandelbrot (1982) describes three alternatives, the first of which, the box-counting approach, relies on overlaying different scales of grids and comparing the amount of detail present in each. Often credited to Richard Voss (1986; 1988), technically the box-counting method calculates the Minkowski–Bouligant dimension. In practice though, the method has become so widely accepted that the result is described as either the box-counting dimension or the fractal dimension. Mandelbrot (1982) also presented a second way of calculating the approximate fractal dimension of an image using overlapping circles of different radii and a comparison between the capacities of these circles to cover the outline of an image. The third method described by Mandelbrot was the packing dimension which is based on the capacity of a series of circles to cover an irregular line around an image. This third version imagines that a range of circles, of increasingly reducing size, are iteratively packed inside the borders of that image. A comparison is then constructed between the number of circles, of different scales, needed to 'fill' the object.

Since Mandelbrot first proposed that fractal dimensions were measurable, seven major permutations or approaches have been identified. The first two are the *box-counting* method and the *differential box-counting* method. The other five are the *power spectrum* method, the *power differentiation* method, the *difference statistics* method, the *Kth nearest neighbour* method and the *covering blanket* approach (Ostwald 2013). All of these versions have been evaluated and compared with the outcome that, for most results (1.2 < *D* < 1.8) the box-counting method is the most accurate and useful (Asvestas et al. 2000; Li et al. 2009). Nirupam Sarker and B.B. Chaudhuri (1994) concur, arguing that despite some known issues with higher range (*D* > 1.8) results, the box-counting method remains the most reliable approach. This particular issue arises from the fact that for very complex dimensions, the box-counting method begins to lose accuracy at the most complex extreme (Asvestas et al. 2000). This observation is of less concern for architectural analysis than for some other fields, because architecture and most correctly pre-processed urban forms, do not fall into the range where *D* > 1.8 and if they do, the level of error does not become substantial until *D* >1.9 (Ostwald et al. 2009; Ostwald and Vaughan 2013a) and the majority of past research into methods of measuring fractal dimensions have confirmed that the box-counting approach is the most accurate and useful (Xie and Xie 1997; Yu et al. 2005).

4.4 The Box-counting Method

The box-counting method for determining the fractal dimension of an image is probably the best-known approach, in any discipline, for quantifying characteristic visual complexity. This method has been studied extensively and applied in the sciences and mathematics and, over time, several variations of it have been developed for use in different fields. While there are different ways of measuring fractal dimensions, the box-counting variant is the most stable and repeatable, and thus, over time, it has become synonymous with ‘fractal analysis’.For example, specific versions have been developed for biology (De Vico et al. 2005), neuroscience (Jelinek et al. 2005), mineralogy (Blenkinsop and Sanderson 1999), geology (Grau et al. 2006) and physics (Kruger 1996). The reason these variations exist is that the box-counting method is known to have particular strengths and weaknesses in certain ranges of dimensions and for particular image types. As a result of this, scientists and mathematicians have identified several mathematical refinements, along with a range of methodological and data variables that, in combination, can be optimised to meet the needs of different disciplines.

The box-counting method was first adopted for architectural and urban analysis in the 1990s (Batty and Longley 1994) and since that time has been used for the analysis of a growing number of buildings, ranging from ancient structures to twentieth century designs (Bovill 1996; Burkle-Elizondo 2001; Rian et al. 2007; Ostwald and Vaughan 2009; 2010; 2013). A stable computational version was first presented in 2008 (Ostwald et al. 2008) and the box counting method is now the accepted version in architectural scholarship as it is 'easy to use and an appropriate method for measuring works of architecture with regard to continuity of roughness over a specific scale-range (coherence of scales)' (Lorenz 2009: 703). However, architectural researchers, like the scientists and mathematicians before them, have also noted that the method has some weaknesses and have identified several specific factors which can dramatically affect the accuracy of the calculation (Bovill 1996; Benguigui et al. 2000; Ostwald et al. 2008; Lorenz 2012). Despite this, it is only in the last few years that solutions to these problems have been identified and their impacts determined (Ostwald 2013; Ostwald and Vaughan 2013b; 2013c).

Using this stable computational version of the method, which is described in detail in the present dissertation, it is now possible to measure the fractal dimensions of the plans and elevations of a wide range of buildings. The data points extracted from these views can then be synthesised into sets of values that are in turn compiled in various ways to produce a series of composite results describing the fractal dimension of a complete building. Once this process is complete the data may be coded with additional information producing a set of mathematical results that describe the properties of a design, or a set of buildings, or changing formal and spatial patterns over time.

The particular version of the box-counting approach that has typically been used in almost all architectural and urban analysis is known by scientists and mathematicians as the 'basic' or 'naïve' version, because it uses the base mathematical process without any optimisation or refinement (Huang et al. 1994). This version commences with, for example, an architectural image, say an elevation of a facade. A grid is then placed over that image and each square in the grid is analysed to see if are any of the lines (often called 'information' in the scientific applications) of that elevation drawing are present. The number of boxes with lines in them is then recorded, often by cross-hatching the cell and then counting the number of cells which have been marked in this way. Then a grid of reduced size is overlaid on the same image and the process is repeated, now at a different scale, and the number of boxes with lines in them is also recorded. A mathematical comparison is then made of the number of boxes with detail in the first grid ($N_{(s1)}$) and the number of boxes with detail in the second grid ($N_{(s2)}$). Such a comparison is made by plotting a log-log diagram (log[$N_{(s\#)}$] versus log[1/s#]) for each grid size. The slope of the straight line produced by this comparison is called the box-counting dimension (D_b). This value is calculated for a comparison between two grids (# = 1 and # = 2 in this example) as follows:

$$D_b = \frac{[\log(N_{(s2)}) - \log(N_{(s1)})]}{[\log(1/s2) - \log(1/s1)]}$$

Where: $N_{(s\#)}$ = the number of boxes in grid number "#" containing some detail.

1/s# = the number of boxes in grid number "#" at the base of the grid.

When this process is repeated a *sufficient* number of times, for multiple grid overlays on the same image, the average slope can be calculated, producing the fractal dimension (D) of the image. The critical word in this sentence is *sufficient*; the lower the number of grid comparisons the less accurate the result, the higher the number of comparisons the more accurate the result. In essence, the fractal dimension is the mean result for multiple iterations of this process and an average of only two or three results will necessarily be inaccurate. For example, an average of two figures will likely produce a result with only ±25% accuracy; or a potential error of 50%. A comparison of three scales will typically only reduce this to ±22% accuracy. In order to achieve a useful result at least eight and preferably ten or more comparisons are needed, reducing the error rate to around ±1% or less. However, this is a somewhat simplistic explanation, because the error rate is also sensitive to other factors, including the quality of the starting image, the configuration and positioning of successive grids and the scaling coefficient (the degree by which each successive grid is reduced in size).

If all of these other factors are optimized, then the error rate will be reduced to such a level that between eight and ten comparisons will be sufficient to achieve a reasonable result. If none of these factors are optimized, then up to one hundred comparisons may be required to achieve a highly accurate result. Keeping this limitation in mind, the mathematics of the method are demonstrated hereafter in a simple example.

4.4.1 A Worked Example of the *Robie House*

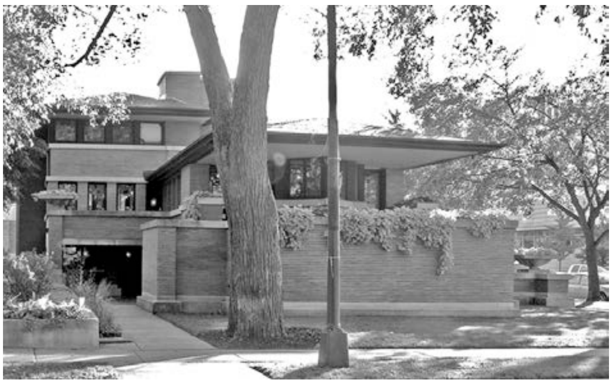


Figure 4.1 View of the western facade of Frank Lloyd Wright's Robie House *(Photograph by the author)*

This worked example is a partial calculation of the fractal dimension of the west elevation of the *Robie House* (figs 4.1 – 4.6). Four grid overlays are provided creating three grid comparisons (1 to 2, 2 to 3 and 3 to 4). Each successive grid is half the dimension of the previous one, normally described as using a scaling coefficient of 2:1. This is the most common and practical scaling coefficient used in architectural analysis, but not, as a later chapter reveals, the most accurate or useful one for generating multiple points for producing a statistically viable result.

i. In the first grid (# = 1), with a 5 x 3 configuration (1/s1 = 5) there are 13 cells ($N_{(s1)}$ = 13) with detail contained in them (fig. 4.3).

ii. In the second grid (# = 2), with a 10 x 6 configuration (1/s2 = 10) there are 29 cells ($N_{(s2)}$ = 29) with lines contained in them (fig. 4.4).

iii. In the next grid (# = 3), with a 20 x 12 configuration (1/s3 = 20) there are 93 cells ($N_{(s3)}$ = 93) with lines contained in them (fig.4.5).

iv. In the final grid in this example (# = 4), with a 40 x 24 configuration (1/s4 = 40) there are 307 cells ($N_{(s4)}$ = 307) with lines contained in them (fig. 4.6).

Figure 4.2 Base image, west elevation

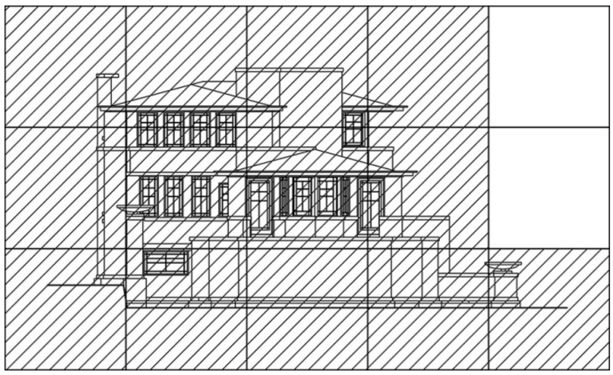


Figure 4.3 Grid 1: 5 x 3 grid; box count 13 or 1/s1 = 5 and $N_{(s1)}$ = 13

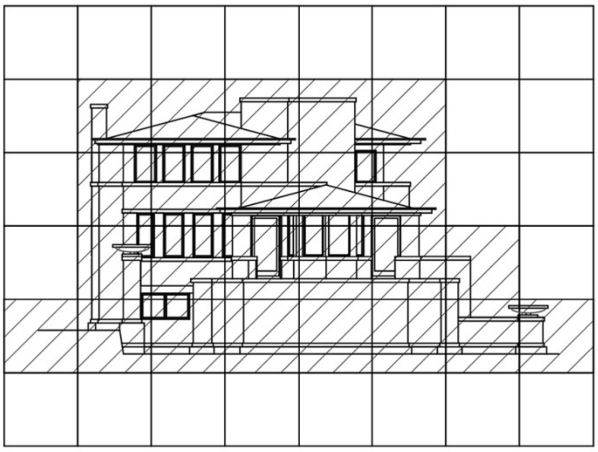


Figure 4.4 Grid 2: 10 x 6 grid; box count 29 or 1/s2 = 10 and $N_{(s2)}$ = 29

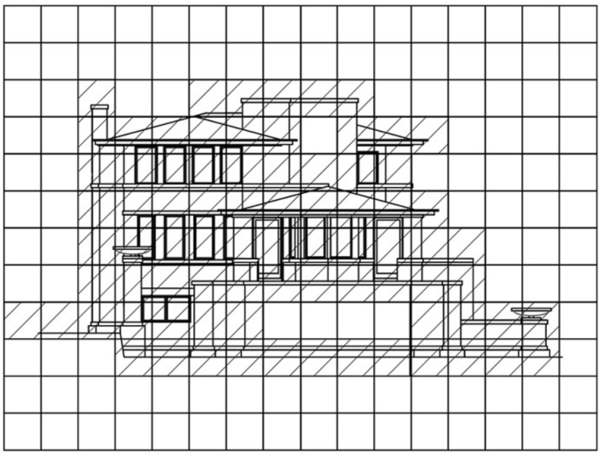


Figure 4.5 Grid 3: 20 x 12 grid; box count 93 or 1/s3 = 20 and $N_{(s3)}$ = 93

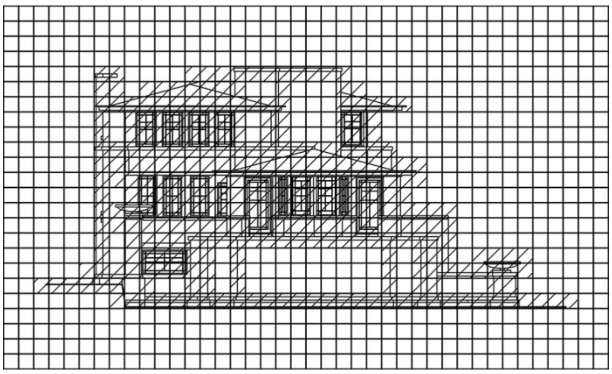


Figure 4.6 Grid 4: 40 x 24 grid; box count 307 or 1/s4 = 40 and $N_{(s4)}$ = 307

Before progressing with the calculations, note that in this section figures are rounded to three decimal places and because the scaling coefficient is 2:1 in all cases, the ultimate denominator is always 0.301.

Using the standard formula and the information developed from the review of the grid overlays, the comparison between grid 1 and grid 2 is constructed mathematically as follows:

$$D_b = \frac{[\log(N_{(s2)}) - \log(N_{(s1)})]}{[\log(1/s2) - \log(1/s1)]}$$

$$D_b = \frac{[\log(29) - \log(13)]}{[\log(10) - \log(5)]}$$

$$D_b = \frac{[1.462 - 1.114]}{[1 - 0.699]}$$

$$D_b = \frac{0.348}{0.301}$$

$$D_b = 1.156$$

Thus, the first box-counting dimension is 1.156.

The second comparison between grid 2 and grid 3 is as follows:

$$D_b = \frac{[\log(93) - \log(29)]}{[\log(20) - \log(10)]}$$

$$D_b = \frac{[1.968 - 1.462]}{[1.301 - 1]}$$

$$D_b = \frac{0.506}{0.301}$$

$$D_b = 1.681$$

The second box-counting dimension is 1.681.

The calculation is repeated to compare grids 3 and 4:

$$D_b = \frac{[\log(307) - \log(93)]}{[\log(40) - \log(20)]}$$

$$D_b = \frac{[2.487 - 1.968]}{[1.602 - 1.301]}$$

$$D_b = \frac{0.509}{0.301}$$

$$D_b = 1.724$$

The last of the three box-counting calculations for the window gives a result of 1.520. The mean for these comparisons—which is an estimate of *D*, or alternatively a *D* calculation with a high error rate as a result of such a limited data set—is therefore:

$$D = \frac{1.156 + 1.681 + 1.724}{3}$$

$$D = 1.520$$

The set of results are then graphed in a log-log graph (that is, both scales are logarithmic), with the box-count (*y* axis) against the box size (*x* axis). In this example, the three comparison results appear relatively close to the mean (fig.4.7).

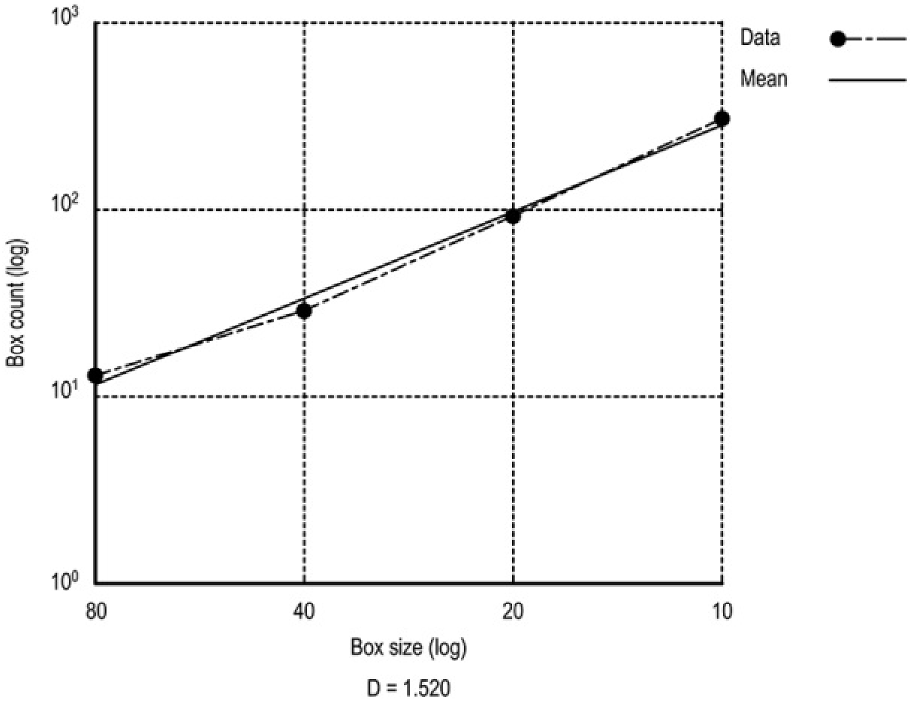


Figure 4.7 Log-log graph for the first three comparisions of the Robie House *elevation*

4.5 Fractal Analysis and the Built Environment

The following section provides an overview of past research that has been undertaken using the box-counting method to measure the fractal dimension of the built environment. The scale of these studies varies from the analysis of city plans (Masucci et al. 2012) to measurements of individual buildings and architectural details (Zarnowiecka 2002). Many of these studies were undertaken using a manual version of the method which, much like the worked examples in the present section, rely on a person physically counting the number of details in various grids, then using formulas to calculate the fractal dimension of an image. The more recent examples tend to use purpose-designed or authored software to undertake much larger and more accurate applications of the method. Despite this difference, the basic approach remains the same. However, as several comments in the present section indicate, not all of the results of this basic variation of the method are useful or accurate. Thus, despite an increase in the application of this method, surprisingly few of these past studies include details about the particular variation they employ, or the settings and raw data they use for their calculations. This means that the results of most of these studies are impossible to replicate. Furthermore, there are some serious methodological flaws in a few of the past applications along with more subtle problems with the way authors have interpreted their results. While a small number of these concerns are noted in the next section, its primary purpose is not to be critical of these works, but to describe the breadth of applications of the method.

This section divides past research using the box-counting approach broadly by application, starting with research that is focussed on urban forms and then considering those that focus on architecture, and then finally on fractal analysis of the architecture of Frank Lloyd Wright. While many of the results of these studies are described in the text, most cannot legitimately be compared with each other because they use different starting points (from photographs to sketches and line drawings) and different data extraction and processing procedures (from manual techniques to software supported ones). Furthermore, several past publications co-authored by the present author are also included in the discussion as they use box-counting to investigate various buildings (Vaughan and Ostwald 2008; 2011; Ostwald and Vaughan 2013a).

4.5.1 Urban Analysis

Studies of cities using fractal analysis range from a consideration of urban morphology to measurements of the plans of streets, transport networks and green spaces. As noted by Lachlan Robertson, fractal analysis 'can potentially be the tool that allows us to describe accurately [...] "organic" urban form' (1995: 13). Observations about the potential fractal dimension of urban forms began to be published in the late 1980s (Yamagishi et al. 1988) and since then a growing number of different approaches to the fractal analysis of urban plans have been proposed (Oku 1990; Mizuno and Kakei 1990; Rodin and Rodina 2000; Ben-Hamouche 2009). However, the earliest research to specifically use the box-counting method in urban analysis can be traced to Michael Batty and Paul Longley (1994) who employed a variation of the method, which they called 'cell-counting', to examine changes in the growth and form of urban boundaries. Following their work, fractal analysis continued to be used to measure changing urban forms including studies of Tel Aviv (Benguigui et al. 2000) and London (Masucci et al. 2012), along with shifting settlement patterns in Mayan cities (Brown and Witschey 2003). The application of the box-counting method to the analysis of urban form has also been undertaken by Mauro Barros-Filho and Fabiano Sobreira (2005), who examined, amongst other areas, slums in Brazil. The box-counting method has since been used to compare the fractal dimension of street patterns in more than twenty cities (Cardillo et al. 2006) and a worldwide urban classification system using fractal dimensions has been proposed (Encarnação et al. 2012).

In a variation of these urban approaches, the box-counting method has also been used to analyse transportation networks and their impact on settlement patterns, including a comparison between Seoul and Paris (Kim et al. 2003). Yongmei Lu and Junmei Tang (2004) used the method to analyse the connection between city size and transportation networks in Texas, while Isabelle Thomas and Pierre Frankhauser (2013) compared the dimensions of developed spaces and roadways in Belgium. At a smaller scale Ron Eglash (1999) examined plans of part of a Mofou settlement in Cameroon and the urban core of the Turkish city of Amasya, the latter of which has been the subject of several studies about the relationship between the fractal dimension of traditional urban centres and of their surrounding natural context (Bovill 1996; Lorenz 2003; Vaughan and Ostwald 2009a; Bourchtein et al. 2014). Green spaces, typically urban parks, have also been measured using box-counting to develop a model for sustainable development (Wang et al. 2011) and to compare the porosity of parks in the USA, China and Argentina (Liang et al. 2013). Jon Cooper has led a series of detailed studies of streetscape quality in Oxford (Cooper and Oskrochi 2008; Cooper et al. 2010) and Taipei (Cooper et al. 2013) using the box-counting method. Distant views of city skylines have also been analysed by Stamps (2002) and the visual qualities of city skylines in Amsterdam, Sydney and Suzhou have been measured and compared (Chalup et al. 2008).

In the majority of these examples of urban dimensional analysis, the box-counting method has been used to quantify the characteristic complexity of a city, including its growth patterns, road and rail networks, open spaces and skylines. Several of the studies (Benguigui et al. 2000; Stamps 2002; Bourchtein et al. 2014) also display an awareness that fractal dimensions are more informative when used for comparative purposes, or for classifying different types of patterns against a standard value or measure.

4.5.2 Architectural Analysis

The earliest serious attempt to calculate the fractal dimension of architecture using the box-counting method is found in the work of Carl Bovill, whose publication *Fractal Geometry in Architecture and Design* (1996) provided the first major exploration of the relationship between fractal geometry and art, music, design and architecture. In that work Bovill not only demonstrated the box-counting method in detail, he also used it to measure the fractal properties of plans and elevations of several canonical buildings, including the south elevation of Wright's *Robie House* and the west elevation of Le Corbusier's *Villa Savoye*. Bovill concluded from this analysis that the *Robie House* elevation is in the order of 10% more visually complex than the *Villa Savoye* elevation. This comparison seems to confirm the intuitive interpretation that architects have historically offered, that Wright's design, with its elaborate windows, modelling and raked rooflines, has greater and more consistent levels of visual complexity than Le Corbusier's white, geometric facade.

More controversially, Bovill also used the box-counting method to compare architecture and its surrounding context by calculating the fractal dimensions of a row of houses and their mountainous setting. He suggests that the 14% difference in characteristic visual complexity between these two sets of results demonstrates that 'the indigenous builders somehow applied the rhythms of nature to their housing site layout and elevation design' (1996: 145)—this claim will be further explored in Chapter 6. While the efficacy of such claims have been examined and criticised (Vaughan and Ostwald 2009a), Bovill's clear and detailed explanation of the method paved the way for many scholars to use this method for measuring architecture. The remainder of this section reviews the application of the box-counting method to both historic and more contemporary buildings.

Clifford Brown et al. argue that the box-counting method is useful for archaeologists because 'it is always important to identify, describe, and quantify variation in material culture' (2005: 54). These concerns are of similar significance for architectural historians who, like archaeologists, are often interested in both the form of a cultural artefact and symbolic meaning. However, applications of the box-counting method to historic buildings also contain a high proportion of arguments which seem to confuse fractal dimensions with fractal geometry, as well as those which try to conflate measured dimensions with mystical or symbolic properties. Within papers which otherwise contain rigorous mathematical analysis (Oleschko et al. 2000; Burkle-Elizondo and Valdez-Cepeda 2001) , an unexpected range of misleading conclusions are recorded, including several which are not supported by the method or its results.

The most common historic buildings that have been the subject of fractal analysis are temples and pyramids. In the latter category, a team led by Klaudia Oleschko analysed three major Teotihuacan pyramids and six ancient complexes (100 BC–700 AD), as well as four recent buildings in modern day Teotihuacan. The computational analysis was based on digitized black and white aerial photographs of these buildings. The results grouped the images in three fractal dimension ranges, with pyramids $1.8876 < D < 1.8993$, complexes $1.8755 < D < 1.883$ and modern buildings $1.7805 < D < 1.8243$ (Oleschko et al. 2000). Despite the fact that these results only determine fractal dimensions, and not necessarily that the buildings have any fractal geometric qualities, Oleschko's team claims that 'this technique, […] confirms the supposition that Teotihuacan was laid out according to a master plan, where each small building may be considered to be a replica of the whole complex' (Oleschko et al. 2000: 1015). Notwithstanding the serious methodological problems inherent in extracting data from aerial photographs (where countless additional features artificially raise the D result), a common range of dimensions does not necessarily mean that all of the buildings in a given set were designed in accordance with a similar formal schema; there are other more plausible explanations. For instance, a large number of Gothic church elevations have similar fractal dimensions but this does not mean that the architects responsible for them were all involved in a cult to replicate this form across Europe (Samper and Herrera 2014). Instead, common crafting techniques, materials and details, along with similar technology and iconography, means that a level of consistency would naturally exist.

Two studies of Mesoamerican pyramids and temples (Burkle-Elizondo 2001; Burkle-Elizondo and Valdez-Cepeda 2001) feature interpretations that, like the Teotihuacan case, may be debatable. These studies use the box-counting method to measure the dimension of scanned images of elevations of Mayan, Aztec and Toltec monuments (300 BC–1110 AD). These results superficially suggest that these monuments are ornate, visually complex structures with an average *D* of 1.92. However, before considering Gerardo Burkle-Elizondo's conclusion, it is worth noting that a *D* of 1.92 would be amongst the highest dimensions ever recorded in architecture, being comparable with the dimension of an intricate vascular network or dense tree structure, but in this case it is only for a set of stepped pyramids and some decorative panels. A close review of the images used for the analysis reveals that they are scanned, grey-scale images, which when converted into line drawings, generate a large amount of visual 'noise', including a large number of features which are not actually present in the architecture. Thus, the *D* results are exaggerated by the nature of the starting images. Regardless of the results, Burkle-Elizondo's conclusion, which echoes that of Oleschko, is that, based on the results, 'we think that there undoubtedly existed a mathematical system and a deep geometrical development in Mesoamerican art and architecture, and that they used patterns and 'golden units' (2001: 212). Because the Golden Mean is actually a 'primitive' or 'trivial' fractal, it has a 'known' fractal dimension which is far less than *D* = 1.92. Furthermore, that a culture promulgates a recurring set of geometric patterns is not unexpected, but this is not necessarily a reflection of any deeper level of understanding or significance. These two facts mean that the spirit of Burkle-Elizondo's conclusion may be correct, but the fractal dimension results are insufficient, in and of themselves, to support this position.

Iasef Rian et al. (2007) consider both fractal geometry and fractal dimensions as two distinct and separate aspects of the *Kandariya Mahadev*, an eleventh-century Hindu temple in Northern India. They use the box-counting method to confirm the characteristic complexity of plans, elevations and details of the temple, and a separate diagrammatic analysis provides a breakdown of the monument's fractal-like geometric construction. Their research also reports important information regarding the method used, the results of which identify a close range of high dimensions (1.7 < *D* <1.8) in the plans, elevations, details and ceiling panels of the ancient temple.

Both Wolfgang Lorenz and Daniele Capo have used the box-counting method to analyse classical Greek and Roman orders. Lorenz (2003) investigated a set of line drawings of the entry elevations of four ancient Grecian temples and found that of the set, the *Treasury of Athens* (c. 490 BC) in Delphi had the lowest fractal dimension (*D* = 1.494) and the *Erechtheion* (c. 400 BC) in Athens had the highest (*D* = 1.710). Lorenz concluded that the dimensions confirmed an intuitive visual reading of the complexity of the different building elements of the temples. Capo (2004) used a modified version of the box-counting method (described as the 'information dimension') to compare the Doric, Corinthian and Composite orders of architecture (600 BC–100 BC). Capo did not publish the resulting dimensions, but concluded that they 'showed a fundamental coherence' (2004: 35).

Architecture of the sixteenth-century Ottoman period in Turkey has been the subject of fractal analysis by several authors. For example, William Bechoefer and Carl Bovill analysed a set of Ottoman houses in the ancient city of Amasya which were an example 'of the most important remaining assemblage of waterfront houses in Anatolia' (1994: 5). They used a limited, manual version of the box-counting method to measure the elevation of the group of five houses, producing a result of *D* = 1.717. This same strip of housing was re-analysed using the manual method by Lorenz in 2003 with a different result (*D* = 1.546) and a third result (*D* = 1.505) has also been calculated using a computational version of the method (Vaughan and Ostwald 2010). The houses were further analysed by Bourchtein et al. in 2014 using a different computational method and with error correction filtering applied and they found the row of houses had a *D* value of 1.58. The geometric properties of another group of eight traditional Ottoman houses were measured by Gulen Cagdas, Gaye Gozubuyuk and Özgür Ediz (2005). Three different facets of these houses, in the Chora district of Istanbul, were considered. First, their combined roof plans (*D* = 1.7) then their building outline (*D* = 1.2) and finally their street elevation (*D* = 1.2).

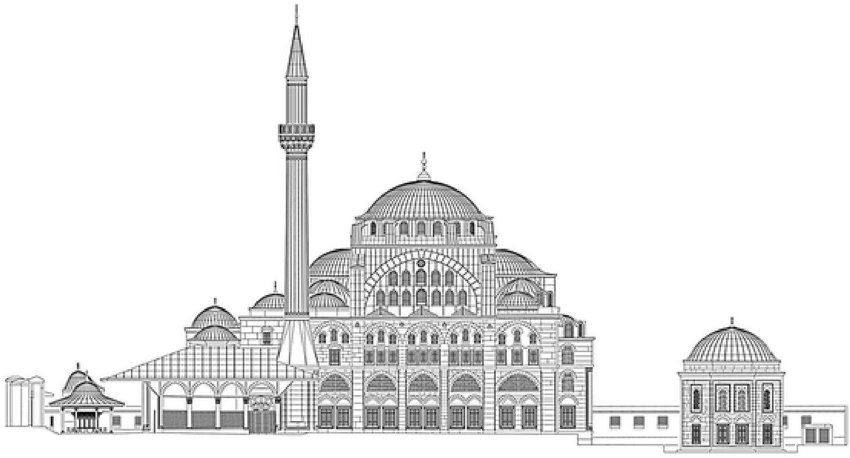


Figure 4.8 Image of the Kılıç Ali Paşa Mosque *analysed by Ostwald and Ediz (2015: 14)*

In a large and technically advanced application of the method, Ediz and Ostwald analysed the elevations of Mimar Sinan’s sixteenth-century *Süleymaniye Mosque* (2012) and the *Kılıç Ali Paşa Mosque* (Ostwald and Ediz 2015), both in Istanbul. Ediz and Ostwald used box-counting to provide quantitative data to interpret scholarly arguments about the importance of visual layering in these culturally significant buildings (fig. 4.8). Consistent and accurate line drawings of elevations of the two mosques were measured with three different levels of detail: the form of the elevations, the form and major ornament of the elevations and the form, plus ornament and with all the material joints expressed. For the *Süleymaniye Mosque*, the results for these three different representations were, respectively: $1.598 < D < 1.688$; $1.638 < D < 1.702$; and $1.790 < D < 1.807$. Notably, these mosques are amongst the most richly textured buildings ever constructed, with dense layers of ornament and material joints, and their highest D result is in the order of 1.807. For this reason, any non-integer dimensional measure for architecture that is higher than this should be carefully and critically reviewed.

As well as being an important example of an architectural era, the houses analysed from the Ottoman period could also be thought of as examples of vernacular or traditional architecture. Another type of traditional housing that has been analysed using this method is from Northeast Poland. Jadwiga Zarnowiecka (2002) found that a traditional Polish cottage had a fractal dimension of $D = 1.514$. When Zarnowiecka expanded her use of the method to determine the effect on the visual complexity of a traditional cottage after being ‘modernised’, the result changed from *D* = 1.386 to *D* = 1.536. In a similar way Laurent Debailleux (2010) analysed thirty-six elevations of vernacular timber-framed structures in rural Belgium. Debailleux extracted line drawings from a set of photographs for the analysis. The complete results were not reported in the paper, but Debailleux concluded that the fractal dimensions were consistent with the different frame types, and the average value for all of the structures was *D* = 1.38. Lorenz (2003), in one of the more extensive studies of traditional architecture using this method, analysed line drawings of sixty-one elevations of vernacular farmhouses in the Italian Dolomite Mountains. He employed a rigorous computational methodology, reporting most of the parameters used, and noted several significant challenges with the process. He concluded that the houses could be grouped into nine characteristic sets with similar fractal dimensions ranging from $1.20 < D < 1.66$.

Bovill (1996) chose two iconic houses for his initial excursion into fractal analysis, Wright’s *Robie House* (*D* = 1.520) and Le Corbusier’s *Villa Savoye* (*D* = 1.3775). Modernist architecture was also the focus of the first recorded application of the box-counting method in architecture: William Bechhoefer and Carl Bovill’s (1994) analysis of an elevation of a hypothetical two-storey Modernist apartment block (*D* = 1.37). Since Bovill’s original assessment of the *Villa Savoye*, it has become a regular test subject for attempts to refine the method. Lorenz (2003) used a manual variation of the method to analyse Bovill’s drawing of the north elevation of the *Villa Savoye*, producing an overall result of *D* = 1.306. This low result led Lorenz to agree with Bovill’s claim that Modern architecture lacks ‘textural progression’ (Bovill 1996: 6). Furthermore, Lorenz suggests that the *Villa Savoye* ‘is missing …natural, structural depth’ (2003: 41). Another analysis of the same drawing using a computational method produced a result of *D* = 1.544; higher than Lorenz’s and Bovill’s, but still lower than the calculated results for the *Robie House* (Vaughan and Ostwald 2010). A composite result for the entire villa was also determined, which averaged the fractal dimension of all of the elevations of the building (*D* = 1.480) (Ostwald et al. 2008). In contrast, Kuo-Chung Wen and Yu-Neng Kao (2005) studied the ground floor plan of the *Villa Savoye* using a computational variation of the method (*D* = 1.789). Most recently, Lorenz returned to measure Bovill's original image using an improved computational method and found difficulties analysing the elevation, observing that if the analysis was of the distant view of the entire elevation, the *D* value was higher (1.66), compared to an analysis of a specific part of the building where the value was lower (*D* = 1.25). This led Lorenz (2012) to conclude that the 'result underlines the tendency of modern architecture towards a clear expression with details on small scales being reduced to a minimum: after higher complexity at the beginning, the data curve quickly flattens, but remains constant' (2012: 511).

Eight other Modernist residential designs by Le Corbusier have also been studied using fractal analysis. Wen and Kao (2005) examined plans of five houses by Le Corbusier spanning five decades (1914–1956). The spread of fractal dimensions for the houses was between *D* = 1.576 (*Villa Shodan a Ahmedabad*) and *D* = 1.789 (*Villa Savoye*) and, despite a range of 21%, the authors concluded that the results were consistent. Michael J. Ostwald, Josephine Vaughan and Christopher Tucker measured the fractal dimensions of all elevations of five of Le Corbusier's Modern houses (1922 – 1928) using two different computational variations of the method (Benoit and ArchImage) and the results ranged between *D* = 1.420 (*Villa Weissenhof-Siedlung 13*) and *D* = 1.515 (*Villa Stein-De Monzie*) and the average for the set was *D* = 1.481 (2008). A further study analysed elevations from a set of five of Le Corbusier's more ornate, Swiss-chalet style homes (1905–1912) from his pre-Modernist period, using two computational methods (Vaughan and Ostwald 2009b). That analysis identified a range between *D* = 1.458 (*Villa Jaquemet*) and *D* = 1.584 (*Villa Favre-Jacot*).

Possibly due to Bovill's bold statement that 'some modern architecture […] is too flat' (1996: 6), several other iconic architectural designs from the Modernist era have been examined using fractal analysis. For example, five houses by Ludwig Mies van der Rohe (1907–1952) were measured by Wen and Kao (2005) with the results ranging between *D* = 1.4281 (*Alois Riehl House*) and *D* = 2.561 (*Edith*

Farnsworth House). This last result must be considered extremely controversial, and most likely totally incorrect, because, it will be remembered that the *D* of a two-dimensional image 'must' be within the range between 1.0 and 2.0. Anything outside this range is almost certainly an experimental error. A result of 2.5 suggests a serious flaw in the method and is most likely a by-product of using a colour or greyscale image that the software has incorrectly processed.

Another major Modernist architect whose work has been examined using this method is Eileen Gray, five of whose designs (1926–1934) were investigated using a computational method (Ostwald and Vaughan 2008). The results for the houses were between *D* = 1.289 (*House for an Engineer*) and *D* = 1.464 (*E.1027*). Two additional works of Modernist architecture, Gerrit Rietveld's 1924 *Schröder House* (*D* = 1.52) and Peter Behrens's 1910 industrial Modernist *Turbine Factory* (*D* = 1.66), were also examined by Lorenz. Lorenz found that, unlike his results for Le Corbusier's *Villa Savoye*, the results for both Rietveld and Behrens were consistent for the entire box-counting process, suggesting that 'even at first sight smooth modern architecture may offer complexity for smaller scales' (2012: 511).

There have been very few applications of the box-counting method to more recent architecture. The lower practical limits of fractal dimensions for architecture were examined the work of late twentieth-century Japanese Minimalist architect, Kazuyo Sejima (Vaughan and Ostwald 2008; Ostwald et al. 2009). Of a set of five of her houses built between 1996 and 2003, the fractal dimensions we developed using an early variation of this method range from *D* = 1.192 (*S-House*) to *D* = 1.450 (*Small House*). Minimalism, with its monochromatic finishes and unadorned surfaces would be expected to have a low *D* value and the significantly lower fractal dimension of Kazuyo Sejima's architecture supports this assumption. Some famously abstract, post-representational designs that had been criticised as lacking human scale were considered in a study of the architecture of John Hejduk and Peter Eisenman (Ostwald and Vaughan 2009b; 2013a). The results for Eisenman's famous House series elevations ranged from *D* = 1.344 (*House I*) to D = 1.533 (*House III*), with an average for the set *D* = 1.419. Five of John Hejduk's designs were also analysed, with the elevation results ranging from D = 1.406 (*House 4*) to D = 1.519 (*House 7*) with an average of D = 1.472. These results demonstrated that fractal dimensions are measures of characteristic complexity, regardless of any symbolic, semiotic or emotional cues present in a design.

4.6 Box-counting Analysis of Wright's Architecture

Perhaps because Bovill also demonstrated the box-counting approach to fractal analysis using the work of Frank Lloyd Wright, Wright's architecture in particular has remained a common focus of this approach (Sala 2000; Lorenz 2003, Wen and Kao 2005). Bovill acknowledged that the 'idea that Wright's designs have a progression of detail from large to small scale is not new' and he further proposes that 'fractal analysis provides a quantifiable measure of [this] detail' (1996: 127). Bovill undertakes a manual method of fractal analysis on the *Robie House* (D = 1.520) and on one of its patterned windows (D = 1.673). It was in the same study in 1996 that Bovill calculated the fractal dimension for the *Villa Savoye* as D = 1.377. This result is lower than his result for the *Robie House*, leading him to suggest that such a variation occurs because 'Wright's organic architecture called for materials to be used in a way that captured nature's complexity and order. Le Corbusier's purism called for materials to be used in a more industrial way' (1996: 143). Bovill's initial fractal analysis of the south elevation of Wright's *Robie House* has since generated a detailed response from other scholars (Sala 2000; Lorenz 2003, Ostwald et al. 2008; Ostwald 2013) and this one facade is probably the most frequently analysed of any example, with at least seven separate box-counting studies published. The results of these studies are discussed in more detail in Chapter 5 but they typically range from D = 1.520 (Bovill 1996) to D = 1.689 (Vaughan and Ostwald 2010).

Including the *Robie House*, a total of twenty of Wright's houses have been measured using the box-counting method. Wen and Kao (2005) applied a computational version of the method to plans of five houses by Wright spanning from 1890 to 1937. The houses studied were the *Frank Lloyd Wright House* (*D* = 1.436), the *Harley Brandley House* (*D* = 1.626) the *Avery Coonley House* (*D* = 1.589), the *Sherman M. Booth house* (*D* = 1.609) and the *Herbert Jacobs house* (*D* = 1.477). The elevations of five of Wright's Prairie Houses (1901–1910) have also been examined using two different computational variations of the box-counting method (Ostwald et al. 2008). The range of fractal dimensions which were recorded is between *D* = 1.505 (*Zeigler House*) and *D* = 1.580 (*Evans House*). Past research has also examined Wright's Usonian houses and Textile-block houses (Vaughan and Ostwald 2011). While these results are revised and refined later in this dissertation, the original range for the Usonian houses was between *D* = 1.350 (*Fawcett House*) and *D* = 1.486 (*Palmer House*) and the average for the set was *D* = 1.425. The fractal dimensions for the Textile-block houses were between *D* = 1.506 (*Freeman House*) and *D* = 1.614 (*La Miniatura*) and the average for the set was *D* = 1.538.

The *Unity Temple* (1905) in Chicago is the only non-domestic building designed by Wright which has been analysed using this method. The fractal dimension of the north elevation of the *Unity Temple* has been the subject of three separate studies. In his 1996 publication, Bovill undertook fractal analysis on several features of the north elevation of the *Unity Temple*, believing this particular building 'should help explain Wright's ability to grasp the underlying structure of a natural form and translate it into a building form' (128). Bovill proposes the *Unity Temple* as a demonstration because he considered Wright's admiration of the effect of light in a forest to be translated into a building which Bovill considers to be—in its levels of visual complexity—akin to the forest itself (128). Bovill explains that 'The forest displays a form that is complex at the ground plane, simpler in the zone of the tree trunks, and complex again in the branching structure of the tree canopy' (128). Bovill found that the results from this manual fractal analysis were 'as expected for a design with forest imagery as a base idea. The upper part (*D* = 1.415) and base (*D* = 1.678) of the building have higher fractal dimensions than the middle (*D* = 1.223) of the building' (132). Bovill's overall results for the facade of the *Unity Temple* (*D* = 1.550) have been retested using the same image by others including Lorenz who also used a manual method, *D* = 1.513 (2003) and with a computational variation, producing a relatively similar measure, *D* = 1.574 (Vaughan and Ostwald 2010).

Conclusion

As demonstrated in this chapter, the box-counting method is deceptively simple to apply, and this is why there are a growing number of examples of its application in urban and architectural analysis. Conversely though, the method has multiple complicating factors that have undermined the usefulness and validity of many early studies. These problems are readily apparent in the review of past results, where multiple applications of the method to the same facades have produced often-divergent results, and where a large number of completely counter-intuitive outcomes have been published (Oleschko et al. 2000; Burkle-Elizondo and Valdez-Cepeda 2001; Wen and Kao 2005). The three major concerns facing those seeking to use the method are about image representation standards, data pre-processing standards and methodological considerations.

The first of these concerns arises from the fact that the box-counting method measures information contained in an image. Obviously, if this image is a photograph, then the information contained in it will be very different from the information in a line drawing. Shadows, textures and perspective are all part of the way in which we experience the world, but they also complicate and undermine the process of measurement to such a degree that they are typically removed from any consideration of questions of form. For example, unless a person was specifically interested in the visual impact of plants, trees or shadows, all of these features will completely dominate any analysis of visual complexity in a building facade. Furthermore, when studying a building, the question must be asked, what data is relevant? That is, which lines in a plan or elevation should be measured and why? These questions are addressed over the following chapters.

Chapter 5

Variables in the Box-counting Method

In the last two decades a growing body of research has been published which uses the box-counting method to measure the fractal dimensions of architectural or urban forms. However, much of this research displays only a low level of awareness of the sensitivities or limits of the method. As a consequence, often widely varying results have been produced using the same mathematical approach and, in some cases, exactly the same images. It is only recently that these limitations have been determined and a range of optimal standards and settings to overcome many of these limitations have been proposed and accepted (Ostwald and Vaughan 2012; Ostwald 2013; Ostwald and Vaughan 2013; 2016).

The challenges associated with the accuracy and accountability of the box-counting method are threefold. The first challenge, which is associated with image representation, is to determine, in a consistent and reasoned manner, the lines in an image which are significant for analysis. Inconsistent representational standards will render the results of most studies meaningless, and this chapter begins by describing a uniform approach to the presentation of images to be analysed. If a consistent rationale for the correct starting image information and representation is applied, then the second challenge is to determine the correct way to present or prepare that data prior to mathematical or computational analysis. For example, how large should the starting image be, what line weights should architecture be depicted in, and how much space should be left around the image for a reasonable starting grid to be drawn. The third challenge is found once the image is being analysed, when it is necessary to ensure that all of the computational variables are set to an optimal standard. These methodological standards include the ratio by which successive grids are reduced in size—the ‘scaling coefficient’—and the position from which these grids are generated—the ‘grid disposition’. This chapter describes these three areas of limitation in detail, and considers the range of settings and options available for all of these variables with reference to the latest information and suitability of these options.

Based on the results of this past experimental research—some of which was co-written by the present author—the optimal settings or variables for the method are determined and then applied to the south elevation of the *Robie House*, the standard test subject of multiple previous studies. Finally, a summary of the ideal settings and standards selected for fractal analysis of images in this dissertation will then be presented.

5.1 Representation Challenges: Measuring

All of the main computational methods of formal and spatial analysis used in architecture rely on measured representations of buildings or spaces. Thus, they derive data from orthographic projections (plans, elevations and sections), CAD models and photographic surveys. For two of the most established computational methods the rationale describing which part of a building plan to analyse and how the analysis is undertaken is relatively straightforward. Space Syntax research typically analyses habitable space, being rigorous in its geometric mapping of lines of sight, visually defined space or permeability (access) in a plan (Hillier and Hanson 1984; Hillier 1996). Shape grammar researchers have a different but similarly meticulous way of extracting geometric and topological properties from a building plan before any analysis is undertaken (Stiny 1975; Knight 1992). While the logic underlying these approaches to measurement continues to be debated, there are accepted standards in each field.

Like architectural analysis using Zipf's law or Van der Laan septaves and pixel counts, fractal analysis provides a measure of the distribution of information (lines or details) in an object across multiple scales (Stamps 1999; Crompton and Brown 2008; Crompton 2012). Unlike Space syntax and Shape Grammar, there is no standardised guideline to identify which parts of a building facade or plan should be the subject of fractal analysis measurement. Despite early attempts to clarify which parts of a building should be analysed (Bovill 1996), researchers have repeatedly noted that there is a lack of consistency in the field (Lorenz 2003; Ostwald et al. 2008). Moreover, it has been demonstrated that different measures can be derived from an analysis of the same elevation of a building, depending on which lines are chosen for consideration (Zarnowiecka 2002; Vaughan and Ostwald 2009b). Consider the example of Frank Lloyd Wright's *Robie House*, a design which has been the subject of seven separate applications of fractal analysis (Bovill 1996; Sala 2000; Lorenz 2003; Ostwald et al. 2008; Vaughan and Ostwald 2011; Ostwald 2013; Lorenz 2013). Across these studies, the variation in the measurements recorded is in the order of 17%. This is because these studies have multiple mathematical and methodological differences.

The most obvious explanation for the 17% anomaly is simply that computational methods like fractal analysis do not measure buildings; rather, they extract measures from representations of buildings. The primary representational media used for architectural analysis is the orthographic drawing and there are many variations in how a building can be represented in such a drawing (Hewitt 1985; Leupen et al. 1997) For example, in Bovill's original (1996) study of the south elevation of the *Robie House* (fig. 5.1), he chose to analyse an image in which only major changes in form were delineated. Using a limited range of graphic standards, Bovill predominantly represented the geometrical forms of the architecture. For example, the line-work in the elevation is highly simplified, with the elevation reduced to a collection of Euclidian shapes, lacking in the architectural details that exist in the actual building, including guttering and window mullions. Architects understand that such graphic conventions are representative of a form; they are not meant to be taken literally. In contrast, the 2008 analysis of the same facade by Ostwald et al. is derived from a tracing of a similar drawing, wherein a greater level of detail is included (fig. 5.2). In this study, guttering is shown, the glazing panels are shown in detail, with mullions depicted; however, the full amount of detail in the ornately glazed windows is not shown. On the walls, the concrete coping and other relief is represented in greater detail, but not to extent of individual bricks being depicted. Whereas Bovill's level of representation is suited to an analysis of form, the representation for the 2008 study depicts the level of detail required for studying architecture for inhabitation or function. The difference between Bovill's (1996) and Ostwald et al's (2008) representations of the *Robie House* at least partially explains the 17% anomaly; they were measuring different lines on a drawing of the same building. But which lines, if any, are right?

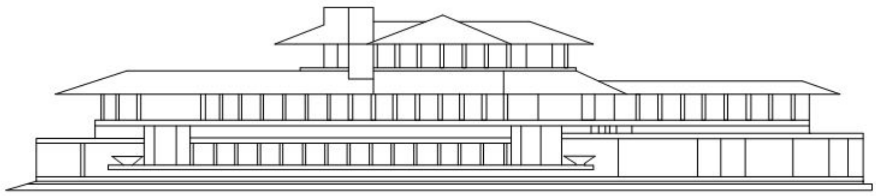


Figure 5.1 Wright's Robie House *as drawn for analysis by Bovill, derived from Bovill 1996: 120*

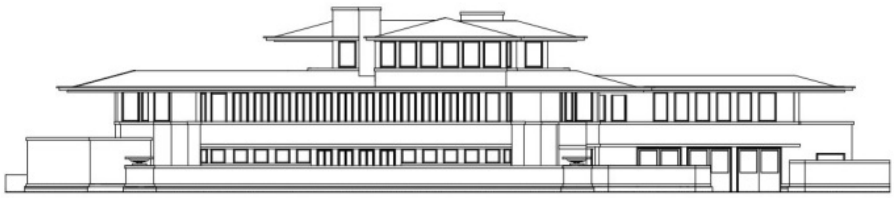


Figure 5.2 Wright's Robie House *as drawn for analysis by Ostwald et al., 2008*

Past research in fractal analysis notes that without some consistent and reasoned rationale for selecting the particular lines in a building to analyse, the measurements extracted from that building are likely to be meaningless for any comparative purpose (Zarnowiecka 2002; Lorenz 2003; Ostwald et al. 2008; Lorenz 2009). The initial requirement then for fractal analysis, like any method of building measurement, is to determine which lines in a plan, section or elevation should be measured, and why. This requirement can be considered by breaking it down into three seemingly simple questions about measuring architecture generally. *Why* is this object being analysed, *how* will its form be measured and *what* parts of it will be measured? All three of these issues are interconnected and the answers must be well aligned to each other for the result to be meaningful. For example, for a practising architect or surveyor, the answer to the second question is seemingly straightforward; there are many standard ways of measuring the length, height and depth of a wall using rulers, tape measures or lasers (Watt and Swallow 1996; Swallow et al. 2004). However, for the scholar or researcher, the issue is more contentious, as these methods may not meet the needs of the first question (why) (De Jonge and Van Balen 2002; Stuart and Revett 2007).

The often unstated assumption in architectural research is that the more accurate the measure, the better the result. However, as several researchers have demonstrated, this can provide a poor basis for testing a hypothesis (Frascari and Ghirardini 1998; Eiteljorg 2002). Thus, the 'how' question cannot be answered without first considering the 'why'. The third question is even more complex: what parts of the building should be measured? Because architecture operates across a range of scales—from the macro-scale of the city and the piazza, to the micro-scale of the doorjamb or the pattern on a wall tile—there is no simple answer to this question. Arthur Stamps, when considering this problem, notes that a building facade 'may be described in terms of its overall outline, or major mass partitions, or arrays of openings, or rhythms of textures' (1999: 85). He goes on to ask; '[w]hich of these many possible orderings should be used to describe' a building (1999: 85)?

Before progressing, three points need to be made about the content of this chapter. First, in this chapter the word 'measuring' is taken to include any process which extracts numerical or geometric information from a building or representation of a building, whether drawings, models or photographs. In computational analysis it is common to talk about the processes of abstracting or translating information derived from the built environment into a graph or map; these are both types of measuring. Second, while parts of the philosophical discussion hereafter are relevant to all types of measuring, the majority of the chapter is more explicitly about the measurement of form.

5.1.1 Image Delineation: 'Texture'

A legitimate system of inquiry for investigating the formal properties of buildings must have a clearly aligned method of measurement and research purpose. Thus, the research question or hypothesis must be one for which measurements can provide useful evidence. While this may seem obvious, it is less common to observe that the particular architectural features being measured must also be appropriate for the research purpose. In computational analysis this is a question of representation or delineation. For example, it is possible to delineate the facade of a building, in a drawing or model, using many different combinations of lines or textures. However, in all of these cases the act of measuring is reliant on the conventions of representation. This is because, regardless of whether field dimensions are taken using a laser scanner or tape measure, the dimensions have to be transcribed into a representational system, be it a drawing, CAD or BIM model, for it to be analysed.

The particular question of how much texture to include when measuring a facade or plan is one of the more controversial ones in fractal analysis. When considering an image, the 'texture' is considered as the amount of detail depicted. Bovill (1996) argues that the geometric patterns produced by repetitive materials (like the horizontal lines of floorboards) should not be measured; this would increase the amount of visible texture. However, Joye (2011) has at least partially rejected the proposal to discard this level of image texture. Jadwiga Zarnowiecka in particular offers a balanced account of this issue. She originally disagreed with Bovill's proposition that, for example, the horizontal lines in a facade made by timber siding should be ignored. Zarnowiecka notes that if this is the case, then 'one must make a decision if a decorated top roof boarding is still a siding or a detail. Should this decision depend on the width of the planks being used in boarding?' (2002: 343). However, after measuring the difference between the elevation with planks, and without, she realised that the 'concentration of the lines on the facade' changes the measured result even though they are not an important feature (2002: 344). When considering a simple regional house in Poland, Zarnowiecka notes that the addition of window mullions 'change[s] the results of the measurement, even though aesthetically they are quite meaningless' (2002: 344). Zarnowiecka's problem may be traced to the fact that measuring texture (to use the terminology of the current chapter) skews the results of the analysis, effectively making it unusable. The lack of a consistent set of guidelines for what level of information, or linear texture to include in an image for testing, may affect the results of the analysis. It has been found that—on an analysis of the same building—the fractal dimension increases with each additional layer of information included in the representation (Ostwald and Vaughan 2013c).

In order to accommodate this need, a framework of five cumulative levels of representation have been defined and mapped against comparable research purposes (Ostwald and Vaughan 2013c). This framework shows that, for instance, it is not reasonable to study the impact of material texture on a building when only the footprint of a plan is measured. Conversely, if the impact of planning decisions regarding site amalgamation is to be studied, then measuring the geometry of material textures in a facade will be counter-productive. This framework, aligning level of representation with research intent, is also inherently cumulative. That is, it relies on the fact that the building outline is required as a precursor to defining primary forms. Thereafter, secondary forms can only be added if the boundaries of the primary forms are already present, and so on. Thus, the framework is described in terms of what is added with each level of representation, as shown in Table 5.1

Table 5.1 Levels of representation mapped against research purpose

Level	Representation	Research Focus	Purpose
1	Outline	Building skyline or footprint	To consider major social, cultural or planning trends or issues which might be reflected in large scale patterns of growth and change in the built environment.
2	+ Primary form	Building massing	To consider issues of building massing and permeability which might be a reflection of social structure, hierarchy, responsiveness (orientation) and wayfinding (occlusion).
3	+ Secondary form	Building design	To consider general design issues, where 'design' is taken to encompass decisions about form and materiality, but to not extend to concerns with applied ornament, fine decoration or surface texture.
4	+ Tertiary form	Detail design	To consider both general and detail design issues, or where 'design' is taken to include not only decisions about form and materiality but also movable or tertiary forms and fixed furniture which directly support inhabitation.
5	+ Texture	Surface finish and ornament	To consider issues associated with the distribution or zoning of texture within a design, or the degree to which texture is integral to design.

The five levels of representation are described in the following sections. Both plans and elevations are used in the descriptions, as an elevation can be considered to provide a measure of the geometric complexity of the building as measured from the exterior and the plan provides a measure of the complexity of the design as it is inhabited (Ostwald 2011).

Level One: Outline

The silhouette of a building—its elevation and associated ground plane—when drawn as one simple continuous line, is often referred to as a 'skyline' drawing. The analysis of skyline characteristics is common in urban design and town planning and there are many examples of this approach to considering the visual complexity of urban or architectural landscapes (Heath et al. 2000) including several applications of fractal analysis (Stamps 2002; Cooper 2003; Chalup et al. 2008). Less commonly, the plan form of a building can also be represented in this way, as a figure of the footprint of a building or as an outline of the roof plan (Brown and Witschey 2003; Frankhauser 2008), for the analysis of the structure of large urban neighbourhoods. In both cases, the consideration of silhouettes and footprints, the purpose is typically to examine the way in which particular types of construction create distinctive patterns, which in turn are thought to reflect the individual social and cultural characteristics of a region. This strategy is used where the large-scale patterns found in the built environment are thought to be a reflection of distinct differences between regions or groups (Brown and Witschey 2003). If this approach is taken, the silhouette retains much of the character of the aggregate geometry of the design, with the roof outline, showing and details such as hips, gables and chimneys. Features such as the windows, through which the sky cannot be seen, are not shown.

Level Two: Outline + Primary form

The second level of detail that could be considered for analysis is the formal massing of the building as a whole; what might be termed its primary form. This level is focussed on major formal gestures, not secondary forms, detail or ornament. The building is represented by the outline but now with the addition of massing elements, including openings. Smaller scale formal changes within these elements, such as individual stair treads or brick corbels, would not be included. All windows and doors are shown as portals but with no indication of fenestration or detail. Window openings of all sizes can be included at this stage as they represent a significant impact on the three-dimensional form of the building. In elevation specifically, gross changes in form, such as protruding walls, significantly advancing and receding elements (which measure greater than 250 mm) and the roof planes, are also delineated. Likewise in plan, the walls and major changes in floor level are shown. This level of representation was selected by Bovill (1996), for a fractal analysis of Frank Lloyd Wright's *Robie House* to gain a sense of the geometry of the major formal gestures in the plan.

Level Three: Outline + Primary form + Secondary form

In combination, the elements which make up the overall massing in a design along with major changes in materials could be considered secondary forms. By including secondary forms—in addition to the information previously provided by the outline and massing of the building—the primary geometric gestures that make up a design become measurable. In both plan and elevation, a single line separating surfaces should represent any changes in material. Basic mullions in doors and windows, stair treads and other elemental projections of a similar scale should be included in plan and elevation. Formal changes included in the drawing are more refined at this level and include any building elements which produce a change in surface level of greater than 25 mm. For example, the gutter and a fascia would be represented, but not the top lip of the gutter. These representational standards are very similar to those which have been used for the fractal analysis of Le Corbusier's *Villa Savoye* (Bovill 1996) and of an urban district in Istanbul (Cagdas et al. 2005).

Level Four: Outline + Primary form + Secondary form + Tertiary form

Once the form of a building has been defined (along with any secondary elements or changes in material needed to support that form) then various additional features must be added to more directly support the building's users. These tertiary forms, including doors, window panes and built-in furniture, are all critical to the inhabitation of a building, but are often simply assumed to be part of a design process. For example, windows are obviously represented in design analysis but what about the glass that is so integral to the window's function. Kitchens and bathrooms have built-in furniture and fittings which are often forgotten in architectural formal analysis. If a broad definition of design is being considered — that is, one that takes into account basic physical needs — then this level of detail is required. This level of detail has commonly been used in the analysis of regional and traditional housing (Bechoefer and Bovill 1994; Zarnowiecka 1998) and of architect designed housing (Ostwald and Vaughan, 2010; 2016; Vaughan and Ostwald 2011). It could be argued that this level represents design decisions that have clear consequences for inhabitation.

Level Five: Outline + Primary form + Secondary form + Tertiary form + Texture

The final level of representation includes surface or pattern. This level includes the repetitive surface geometry of a material (the grid marked by floor tiles, the parallel lines of floor boards or the distinctive wavy lines made by rows of roof tiles) or the patterns in ornamental tiles, wall-paper or applied decorations. In theory it could even include some level of representation of the grain in wood or marbling in polished stone. But it might be acknowledged that it is rare for an architect to 'design' the pattern or geometry in a surface; more often a material is specified, and the grain chosen is indicative, rather than particular. Moreover, many of these textures are effectively invisible from a distance, or require very close observation to become apparent. This is why this last level of detail, while able to be represented, adds a new level of abstraction or artificiality to the process. It could even be argued that the major geometry of a design is complete before the materials, fabrics and colours are chosen. This does not mean that these surface or textural decisions are unrelated to the design process, but rather that they are no longer such clearly measurable geometric ones. Moreover, at the level of surface textures, the capacity to produce consistent results is diminished by a growing number of peculiarities and singularities in the design and construction process.

Because fractal analysis operates across multiple scales of observation, this has led various researchers to include a high level of textural or ornamental information in some examples of Mayan architecture (Burkle-Elizondo 2001), Hindu Temples (Rian et al. 2007) and Islamic Mosques (Ediz and Ostwald 2012; Ostwald and Ediz 2015). In these studies, any ornamental textures or painted patterns are included as part of the geometry of the design, along with representations of materials of the walls and roof in elevation, and the floors in plan. Joye has even argued that this level of information in an elevation is critical to its fractal dimension, claiming that '[s]urface finishes and textures' are an 'important aspect of the visual richness of the architectural structure, which also influences perceived complexity' (2011: 822).

5.1.2 Selecting the Appropriate Level of Representation

When considering the level of representation to be employed when delineating an image for fractal analysis, factors contributing to the decision include the appropriateness for the purpose, success of past applications, amount of relevant comparative information available for this level of representation and availability of information for the image.

Previous testing (Ostwald and Vaughan 2013c; Ostwald and Vaughan 2016) of the impact of image texture shows that the representational differences between levels 1 and 2, and levels 4 and 5, are responsible for the biggest variations in fractal dimensions. In contrast, there is a more stable zone in the results—for both plans and elevations—around the representational levels 3 and 4 (Ostwald and Vaughan 2013a; 2016).

When delineating an image for analysis, the information required from the source must be available to match the level of representation. For example, if the analysis source was a satellite image of a settlement, it would be impossible to analyse anything over level 2, as the details required for inclusion would not be available. *Fallingwater*, however, is an extremely well-represented and accessible building, not only is it open for public visits, photographs and plans are also available in many publications. Therefore, there is no innate restriction for the present dissertation about which representational level could be used. It must just be the most appropriate for the research question.

5.2 Methodological Variables

In the years after the mathematician Richard Voss (1986; 1988) first demonstrated the use of the box-counting method, a growing number of scientific, engineering and medical researchers began to observe problems with both its accuracy and repeatability. In terms of its accuracy, Asvestas, Matsopoulos and Nikita (2000) found that for complex images, where D > 1.8, the box-counting method loses veracity and its results become both inconsistent and understated. In terms of the reliability of the method, Buczkowski et al. (1998) argue that the central problem with the box-counting method is that 'no step-by-step general procedure to use [it] has ever been written' (412). Multiple studies have confirmed that, for such a seemingly simple method, problems of accuracy and repeatability have plagued its application from the start (Xie and Xie 1997; Yu et al. 2005). Moreover, a lack of understanding of the role played by several methodological variables has exacerbated this situation (Camastra 2003; Jelinek et al. 2005).

Of the two major problems identified, repeatability is regarded as the most straightforward; it is solvable by clearly stating all of the parameters used in an application (Buczkowski et al. 1998). The more complex problem is accuracy. Computer scientists argue that four critical methodological variables – scale range, grid shifting, orientation of the grid and error characterisation – should be analysed and tested in every field where the method is applied to determine its limits (Da Silva et al. 2006). A similar point has been made in architectural applications of the method which identify five key problematic variables (Lorenz 2003; Cooper and Oskrochi 2008; Ostwald et al. 2008). If all of these lists of factors are combined they reveal that there are eleven common variables that can be broadly divided into three categories – image pre-processing, processing and post-processing (Table 5.2). These variables will be explained in detail in the next section.

Table 5.2 Variables in the box-counting method.

Category	Sub-Category	Variable	Description
Image Pre-Processing	Field Properties	White space	The proportions and dimensions of the field containing the image being analysed determine how much of the surrounding 'white space' is included in each calculation.
	Field Properties	Image position	The location of the image relative to the field has been theorised as having an impact on the calculated result.
	Image Properties	Line weight	More relevant for architectural analysis than for the consideration of data extracted from photographs, the thickness of the lines or points being analysed has been demonstrated as shaping the calculated result.
	Image Properties	Image resolution	The depth (dpi) of the source image is an indicator (along with the image size) of the potential quantity of information in the starting image. The less information present in an image (that is, the less the dpi) the less accurate the calculation is likely to be.
Data Processing	Grid Properties	Scaling Coefficient (*SC*)	The ratio by which successive grids are reduced in size. The scaling coefficient determines how many grid comparisons are able to be used in the calculation of *D*, but it also determines how much extraneous white space is added with each set of comparisons.
	Grid Properties	Grid Disposition (*GD*)	The location from which successive grids are generated. Are successive grids positioned such that they share a common corner, edge, or centroid?
	Grid Properties	Starting Grid Size	The dimensions of the largest cell in the starting grid. This effectively determines the upper limit (or largest scale) of the data being collected.
	Grid Properties	Starting Grid Proportion	The number of cells on each axis (x x y) which make up the first grid. This variable shapes the usefulness of the data derived from the opening grid; if too few or too many cells are filled, the opening calculation is unlikely to be statistically close to the mean.
	Grid Properties	Closing Grid Size	The dimensions of the smallest cell in the closing or last grid analysed. This effectively determines the lower limit (or smallest scale) of the data being collected. This can be either pre-determined as part of the method, or it can be 'corrected' in the data post-processing stage.
Post-Processing	Statistical Properties	Statistical Divergence (*SD*)	A means of moderating or managing the impact of two types of methodological biases (opening and closing divergence) which the central *D* calculation in the box-counting method can be overly sensitive to.
	Statistical Properties	Error Characterisation	Instead of managing statistical divergence, an alternative approach is to record and explain the character of the data. Often presented in the form or a correlation coefficient (r) or coefficient of determination (r^2) of the complete data set, this is useful for supporting interpretation, but it does not respond to or correct the explicit flaws in the method.

5.3 Image Challenges: Pre-processing Settings

While the statistical validity of the fractal analysis method is largely reliant on the later data processing variables, image pre-processing factors also have the potential to cause substantial errors. For example, these variables could cause four seemingly identical elevations, all derived from the same CAD file, to produce different results, due to the way they have each been saved or positioned.

Four types of image pre-processing properties are significant for understanding the limits of the box-counting method. The first pair, white space and image position, are associated with the field on which the starting image is positioned and the relationship between the field and the image being analysed. The second pair of factors, line weight and image resolution, are properties of the image itself, being literally the lines which make up the image being analysed and the size and sharpness of the image.

5.3.1 Image Pre-processing: Field Properties

The background on which the image being analysed is placed is called the field. Two initially important properties of the field are its size and proportion. Size is measured in pixels (the length and breadth of the image) to accommodate different image densities. The field size is the first determinant of the practical limits of the analytical process. Ideally, the larger the field and image, the more grid comparisons may be constructed and the better the result. The proportion of the field is important because it determines the field's capacity to be neatly divided by grids. As the box-counting method uses regular grids, it is obvious, but almost never stated, that the dimensions of the field should be multiples of the same figure. Thus, a 1000 pixel high by 2000 pixel wide field will accommodate several ideal starting grid configurations including a 500p grid (2 x 4 cells), a 250p grid (4 x 8 cells) and a 200p grid (5 x 10 cells). However, Foroutan-Pour, Dutilleul and Smith (1999) have demonstrated that the ideal starting proportion for the grid is a multiple of four on the shortest side. This starting configuration limits the volume of white space included in the first calculation and in doing so, reduces the need for post-processing corrections (see the discussion of statistical divergence in section 5.4.2 of this chapter). If the field does not have an ideal proportion, then it must be cropped or enlarged to achieve such a configuration.

The field comprises three components: white space, image space and empty space. The descriptor ‘white space’ refers to the region surrounding the image; ‘image space’ refers to the lines that make up the image itself; and ‘empty space’ is any region enclosed by the lines (fig. 5.3). The image space and the empty space are effectively fixed quantities, but the initial amount of white space is determined when the image is positioned or cropped on the ‘canvas’ prior to analysis. Why is this seemingly trivial feature so significant? Because, hypothetically, the more white space there is around an image the more the results of the calculation will be skewed by factors that are not intrinsic to the elevation or plan being analysed. Alternatively, if there is almost no white space (that is, the image is tightly cropped), then the first few grid comparisons may be statistically biased because every cell may have information in it. Results from previous testing on the effect of white space suggest that the best image pre-processing setting was to have either 40% or 50% of the image size added around the image as white space (Ostwald and Vaughan 2013b).

Just as the area of white space surrounding the image has an impact on the result, so too does the location of the white space relative to the image space (the image position). If, for example, the field is twice as large as the image on it, then the image could be positioned in a range of alternative locations on that field. If it was placed to the left side of the field, a large amount of white space will appear to the right. However, if the image space is primarily on the top right of the field, the white space on the lower left will be counted in a different iteration of the box-counting process, with both architectural images essentially the same but possibly resulting in different fractal dimensions. Previous studies found image position to be the least consistent of any of the four pre-processing variables examined

(Ostwald and Vaughan 2013b). With no clear pattern, the centre-centre position, identified as the most stable, is adopted for the target value for this study.

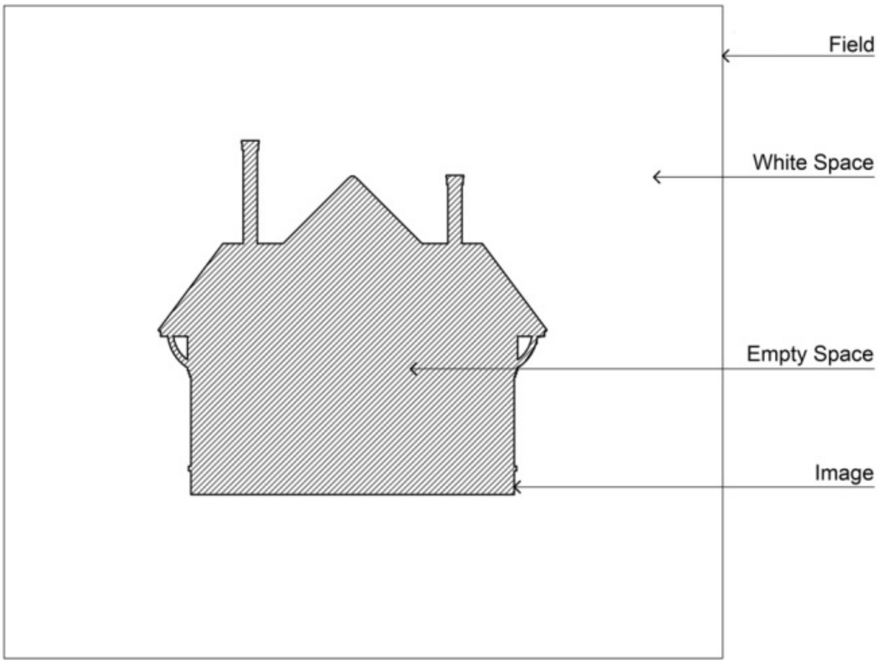


Figure 5.3 Defining the parts of the image

5.3.2 Image Pre-processing: Image Properties

Starting images for analysis may potentially be in colour (32 bit), greyscale (16 bit) or black and white (2 bit), but the analytical method only handles black and white lines or points. Data is either present in a grid cell (black) and can be unequivocally counted, or it is not (white). Without exception, every application of the box-counting method in architectural or urban analysis which uses photographs has relied on the application of multiple additional filters (often hidden in the software being used and possibly not even obvious to the researchers) to reduce greyscale and colour gradients to simple black and white lines and points. This factor also explains many of the false or grossly exaggerated results that have been reported in the past. To the human eye, a greyscale photographic image may seem to clearly represent a building form, but by the time the greyscale has been converted to a two-bit image, it has lost resemblance to the original.

One of the critical image variables for architectural analysis, the line weight or thickness factor, relates to the width of the lines in the image being analysed. The box-counting method will incorrectly calculate the dimension of solid black sections of images and even thickened lines will be artificially counted twice, with each reduction in grid scale, leading to high error rates (Taylor and Taylor 1991; Chen et al. 2010). The standard solution to this problem is that all images must be pre-processed with edge detection software to convert them into one-pixel-wide lines (Chalup et al. 2009). Alternatively, it has been suggested that all images should be pre-processed in a CAD program to choose the finest practical line that the software can produce. Previous testing on line weight shows that as the line weight increases, so too does the calculated result (Ostwald and Vaughan 2013b; 2016). The line weight to be used for this dissertation was therefore the thinnest, 1pt, as this cannot be counted multiple times in an analysis of the same box-counting grid; a 1pt line is either emphatically inside or outside a 1pt grid-shifted line, whereas a 20pt thickness line can be partially inside (say, 8pts) and partially outside (12pts) a grid line which means that it will be counted twice at that scale.

Too often in architectural computational analysis the size of the image being analysed is given as a metric measure; for example, ‘200mm x 100mm’. This description is often meaningless because it is the resolution of the image—its ‘dots per inch’ or ‘dpi’—and its size in pixels that is relevant, not its physical size. The same image, printed at the same physical size, will be very blurry at 75dpi but very sharp at 500dpi. Thus, the field size of a digital image must be understood as its length and breadth measured in pixels. The field size is important because it is the first determinant of the practical limits of the analytical process. The larger the field, the more grid comparisons may be constructed and the more accurate the result. However, increasing the image size multiplies the computer processing power needed and there are practical limits to all current software, and previous studies have shown has a clear practical upper and lower limit beyond which a result often simply cannot be produced (Ostwald and Vaughan 2013b). The scale of the image on the drawing is irrelevant (1:100, 1:500 etc.) because the method calculates the visual complexity of the representation of the building, regardless of its size.

Previous testing (Ostwald and Vaughan 2013b; Ostwald and Vaughan 2016) on the effect of the image resolution on the results shows that the higher the resolution the more convergent the results, however some higher resolution images produce a file too data rich for the computational program to process, thus 175dpi is a preferred maximum standard with an optimal level of 125dpi. The latter is adopted in this dissertation.

5.4 Methodological Challenges: Processing Settings

5.4.1 Data Processing: Grid Properties

Of the five common *data processing* variables in Table 5.2 – that is, those methodological settings which shape the way the procedure is undertaken – several have either been convincingly optimised in the past or rely on relatively straightforward decisions or parameters. All of these factors are associated with the grids chosen for the analysis, either with the relationship between successive grids, or their proportionality or limits. For example, the ideal starting grid proportion (its $X \times Y$ number of cells) has been determined both intuitively and mathematically (Bovill 1996; Foroutan-Pour et al. 1999). Various ‘rules of thumb’ have also been proposed and tested for selecting the ideal size of the first and the last grid cells used in a set of calculations (Koch 1993; Cooper and Oskrochi 2008). Ostwald (2013) provided the first demonstration of the optimal scaling coefficient and grid disposition variables for architectural analysis.

The grid disposition variable describes the point of origin from which successive grids are generated. This in turn determines where white space is added to the calculation and, in combination with the scaling coefficient, how much white space is added. The two most common variations of grid disposition are edge-growth and centre-growth. The former typically generates the first grid from a corner point of the field, say the top left-hand corner, and white space is then successively ‘grown’ or ‘cropped’ to the right and base of the field to form a suitable starting proportion. Depending on the degree to which each successive grid is reduced, further white space may be added to, or removed from, the right edge and base of the field for each comparison. The centre-growth version uses the centroid of the image as the point of origin for each successive grid. The practical difference between the edge-growth and centre-growth variations is that the latter draws or crops white space equally from around all four sides of the field. A variation of this second version uses the centroid as a point of origin, but rotates the grid with each scale reduction; a process that past research suggests has negligible impact on accuracy (Da Silva et al. 2006). Past research (Ostwald and Vaughan 2013b; 2016) confirms that the edge-growth setting is superior.

Architectural and urban applications of the box-counting method conventionally present it as starting with the largest grid and gradually reducing its size for each subsequent comparison. The ratio between one grid and the next grid is called the scaling coefficient (*SC*). For example, Bovill (1996) describes halving each successive grid, which is a scaling coefficient of 2:1 because the larger grid is double the size of the smaller. The scaling coefficient has a direct impact on two factors: the number of possible mathematical comparisons that can be made of detail in an image, and the amount of white space around the image that is included in each comparative calculation. The lower the scaling coefficient the larger the number of comparisons that can be constructed and, by implication, the more accurate the result (Roy et al. 2007; PourNejatian and Nayebi 2010). However, the lower the scaling coefficient, the more variable the white space included with each comparison, undermining the accuracy of the result.

Consider the examples of Bovill (1996) and Sala (2002), who each use a scaling coefficient of 2:1, effectively the only practical value that does not add any white space to the calculation. This is because successive iterations of the grid have the same external dimension and therefore include exactly the same quantity of white space. However, the 2:1 ratio only allows them to produce around three scale grids for comparison before the cells become too small. The difficulty with this is that it potentially takes at least five comparative scales for the error rate to be reduced to ±25% (Chen et al. 1993). To achieve a result of ±5% accuracy for the same image, Meisel and Johnson (1997) suggest that between 15 and 20 comparative scales may be required, and to achieve a ±0.5% error rate anything between 50 and 125 comparative scales is potentially necessary. Thus, the choice of scaling coefficient is a balance between maximising the number of grid comparisons available and minimising the variable growth of white space included in each calculation (Roy et al. 2007). One solution to the scaling coefficient variable is to use a ratio of √2:1 (approximately 1.4142:1) which increases the number of grid comparisons while moderating the variable amount of white space to a tight zone. Scaling coefficients of less than 1.4 will produce more comparative results, but will cyclically vary the amount of white space included in each calculation. Previous testing of this variable (Ostwald and Vaughan 2013; 2016) identified the scaling coefficient of 1.4142: 1 (√2:1) as the optimal setting for that variable.

5.4.2 Post-processing

There are also two post-processing issues which need to considered, these are statistical divergence (*SD*) and error characterisation (r^2). Each of these factors are described hereafter.

When the log-log chart is plotted, the slope of the line, its fractal dimension, is determined by the data points generated by the mathematical comparison between detail in cells at different scales. The slope of the line is the average of the set of points, but like any average, not all points in the set will be close to that value (fig. 5.4).

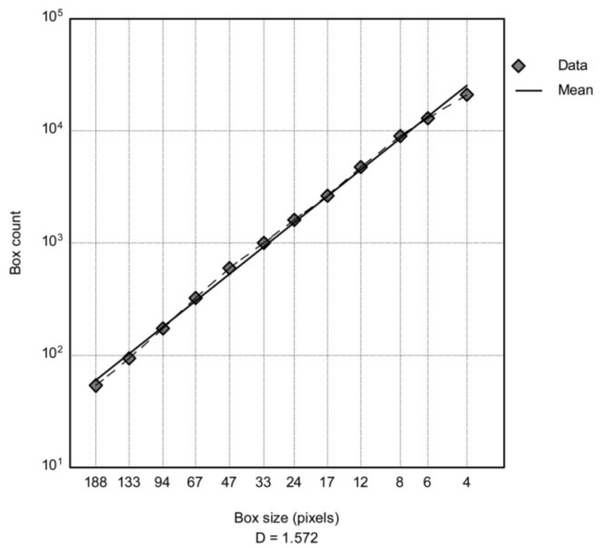


Figure 5.4 Example of a Log-Log chart with a high degree of correlation between data and mean

Statistical divergence (*SD*) refers to the degree to which certain data points do not fit neatly in a set but still participate in its mean calculation. There are three types of statistical divergence in the box-counting method, which is why past researchers have tended not to immediately resort to calculating *r* (correlation coefficients) or r^2 (coefficient of determination) values to examine the validity of a trend line. There is no consistency in how these three are named, but in this chapter we will call them 'opening', 'central' and 'closing' divergence (fig. 5.5)

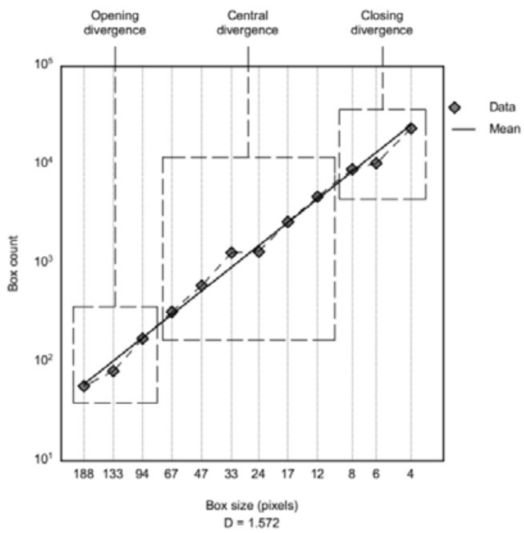


Figure 5.5 Example of a Log-Log chart identifying the three zones of potential statistical divergence

Opening divergence occurs in the first few grid comparisons for one of three common reasons. First, because the proportionality of the opening grid is poor; second, because excessive white space surrounds the image; finally, because the image fills the entire first grid. All of these problems are associated with poor starting field and image settings. Central divergence occurs in the ‘stable’, middle part of the graph and it represents an inconsistent shift in detail in the image itself (meaning that the image is a multi-fractal). Such a shift is not an anomaly; it is an important property of the image. Closing divergence occurs when the analytical grids have become so small that they are mostly counting empty space within the image (Chen et al. 1993). The first and the third types are flaws which can be minimised or controlled in various ways. The second type is a quality of the image itself, representing the scale at which the characteristic irregularity begins to break down. Some software allows for the tactical removal of particular points in the ‘central’ range, but such a process alters the measured character of the object, so it should be avoided unless the user has a clear reason for making such a decision.

While central divergence is critical for the calculation, opening and closing divergence can be controlled. For example, past research suggests that an ideal proportion for the opening field and associated first or largest grid cell is $0.25l$, where l is the length of the shortest side (Foroutan-Pour et al. 1999). Conversely, the smallest grid that should be considered has a cell size of $0.03l$ (Koch 1993; Cooper and Oskrochi 2008).

Another way to approach this problem is to post-process the results to control the extent to which divergence is allowed. For example, to limit the impact of opening divergence, the overall result for all grid comparisons is first calculated and then the first data point is removed and the result recalculated. If the difference between the original and the revised result is greater than a particular threshold level (called the *SD* value), then the first point is removed. Then the process is repeated for the second point and potentially for the third, if a large enough data set is available. The same process also occurs with the last point or two in the line, to limit the impact of closing diversity.

The ideal *SD* value is relative to two factors: the accuracy of the other variables in the method and the purpose of the analysis. In the first instance, there is no need to choose an *SD* of 0.5% (a value which will remove data points which deviate from the average by more than ±0.25% relative to the log-log result), if the accuracy of data produced by the scaling coefficient is at best ±5%. In the second instance, for example in architecture, the human eye will readily differentiate between dimensions with around 4% difference (Stamps 2002; Ostwald and Vaughan 2010; Vaughan and Ostwald 2010), so for some limited purposes, an *SD* of less than ±2.0% may be unnecessary. However, Westheimer's (1991) research into the capacity of the human eye to differentiate between different types of fractal lines (mathematical 'random walks') finds that a less than 1% variation is readily perceived by the human mind for similar objects. Thus, if there are two similar forms (say two different elevations of the *Villa Savoye*), the human eye is likely to be able to detect which one is more visually complex, even if the difference is only in the order of 1%. However, if the images are stylistically dissimilar (say an elevation of the *Villa Savoye* and one of the *Robie House*), then the human eye will readily identify the more complex image, but have a much lower ability to determine how much more complex it is. For this reason, and the results of previous testing (Ostwald and Vaughan 2013b; 2016), for architectural analysis, a ±1% *SD* value is potentially sufficient for most analyses, although for some specific purposes higher or lower values might be more appropriate.

5.5 Revisiting the *Robie House*

The *Robie House* (figs 5.1 and 5.2) is one of the canonical works of twentieth century architecture that Bovill (1996) chose an elevation of to demonstrate that the box-counting approach could be used in architectural studies. Lorenz (2003) and Ostwald (et al. 2008; Ostwald 2013) have repeated variations of this analysis, however none of these studies were undertaken using the standard and settings proposed in this chapter.

In his original study, Bovill (1996) undertook three comparative calculations (over four scales with *SC* = 2.0) for the south elevation, recording *D* results of 1.645, 1.485 and 1.441; average *D* = 1.520. Lorenz (2003) used the same image over the same range of scales and the same *SC* value but produced an overall calculation of *D* = 1.57. Ostwald, Vaughan and Tucker (2008) undertook eleven comparative calculations over twelve scales of grid with *SC* = 1.41 and using image pre-processing to convert all lines to one-pixel-width; the result was *D* = 1.62. Ostwald's (2013) result of *D* = 1.572 was produced using an *SC* of 1.4142:1, and the same elevation image, with a base width of 2900p wide, centred in a 3000 x 1500p field, with edge-growth grid disposition and a 50% Sobel-gradient. *SD* was also used with a ±1.5% threshold.

If the south elevation if the *Robie House* is retested, using all of the optimal settings identified in this chapter for both data processing and pre-processing, a new result is produced, *D* = 1.5708. When the percentage difference between the past results and the new results is calculated, a maximum difference is found of 5.08%, reducing down to the more recent result difference of 0.12%. In effect, this process could be viewed as a record of the growing accuracy and accountability of the method.

Conclusion

Previous attempts to refine the box-counting method have noted that it is both more subtle and complex than most users realise. This chapter highlights the groups of variables which need to be addressed for consistent analysis of images using the box-counting method. These variables need to be considered in a particular order according to their impact on the process. The first variable comes into play prior to analysis—when the amount of information (texture) is selected for inclusion in an image which is to be analysed. The possible outcomes of this variable are acknowledged in this chapter by providing a classification of levels of texture and corresponding meaning, and a suggested approach to representing an image in the selected level is provided. Next, there is a set of methodological variables—similar to the texture representation issue, the methodological variables also involve image presentation, in this case it is the impact of an image positioned on the 'page' and any settings used for a digitised drawing. To provide consistent analysis, these aspects must match between images, and this chapter presents a range of optimal image settings to be used in box-counting analysis. The next set of variables described in this chapter relate to the computational process, and again, consistent settings across the data analysed in required. The box-counting calculations for this dissertation are calculated with the computational program *ArchImage*, which allows for these settings to be entered prior to the calculations being undertaken. The Final variable is considered after the analysis, and this is the effect of statistical properties or error characterisation.

The methodological settings used in the present dissertation are set out in Table 5.3.

Table 5.3 Optimal variables and settings (for an image size of between 2MB and 3MB at 125dpi)

Category	**Variable**	**Optimal Setting From Past Research**	**Used for this dissertation**	**Notes**
Pre-Processing	White space	40-50% increase	50%	40-50% white space around a starting image produces the most consistent result although the potential for errors is also reduced across the 30-60% white space spectrum.
	Image position	Centre-Centre	Centre-Centre	The more centred the image, the more consistent the set of results. Both Centre-Centre and Centre-Base are appropriate positions.
	Line weight	1 pt	1 pt	The thinner the line, the better the result. In practice, all images should be converted into lines of 1 pixel width using either Sobel or Prewitt edge detection algorithms (with a 50/50 black/white threshold, leading to 100% contrast) as a precursor to analysis.
	Image resolution	125-175 dpi	125 dpi	In principle, the higher the resolution and the larger the field, the better the result. However, within the limits of current computing power, 125 dpi consistently produced high quality results, while lower resolutions gradually lost accuracy.
Processing	Scaling Coefficient (*SC*)	1.4142: 1	1.4142: 1	√2:1 or 1.4142: 1 produced the best balance between varying levels of white space being included in the calculations while generating enough grids for comparison to achieve a statistically viable data set.
	Grid Disposition (*GD*)	Top Left	Top Left	Edge-growth (top left-hand corner as point of origin) is the optimal setting although the centre-growth variable generates results with a similar level of accuracy.
	Starting Grid Size	0.25*l*	0.25*l*	The short side (*l*) of the field should be divisible by four (0.25*l*) to generate the starting grid proportion and cell size. If using statistical divergence correction techniques this setting may be less useful because the algorithm will determine the usefulness of starting and closing grid permutations.
	Starting Grid Proportion	4 x *X*	4 x *X*	The shortest side of the field should be divisible by four for the starting grid. It is also suggested that the image, on the field, should be sized in such a way that it has detail in more than half of the cells in the starting grid but ideally not all of the cells in the starting grid.
	Closing Grid Size	0.03*l*	NA	If using error characterisation reporting, then the lowest grid cell size should be 0.03*l* where *l* is the length of the shortest side of the field. If using statistical divergence correction techniques the closing grid size is determined by the spread of results, not an artificial limit.
Post-Processing	Statistical Divergence (*Sd*)	±1%	±0.5%	Generally use either Statistical Divergence or Error Characterisation not both. For architectural analysis, a ±1% *Sd* value is potentially sufficient for most analyses, although for some specific purposes higher or lower values might be more appropriate.
	Error Character	r^2	NA	Generally use either Statistical Divergence or Error Characterisation not both.

Chapter 6

Comparing Architecture and Nature

According to Anthony Antoniades, '[n]ature is everywhere […] it touches everything, giving the blow of life and shaping the prerequisites for the existence and the growth of things' (1992: 233). An enduring interest in nature's influence upon architectural design and theory has resulted in many projects and publications, some of which claim a connection between architecture and nature using only the most whimsical of logic and circular of arguments. Thus, connections between nature and architecture are common, but the rationales for these connections, and the manner in which they are presented or actualised, are highly variable and often unconvincing.

This chapter commences with a brief overview of the application of fractal analysis to nature, and then a review of past cases where the fractal dimensions of architectural and natural forms have been compared. The problems or challenges raised by these past applications of the method are then examined. The second half of the chapter seeks to solve the problem—of a lack of a logical basis for comparing architecture and nature—by categorising methodological examples from both natural and architectural fractal analysis approaches. Specifically, the type of image delineation and the level of information contained in it are compared and ranked for their usefulness. Through this process, the chapter provides a critical overview of the past application of fractal analysis to images of nature and architecture, and provides a framework for developing a methodology for comparing the built and natural environments of Frank Lloyd Wright's *Fallingwater*.

6.1 Relationships Between Nature and Architecture

It would be difficult to argue that any architecture can be produced without some recognition of nature. As buildings are created of the earth's resources, and are subject to the effects of its weathering, Philip Jodidio (2006) argues that all architects must be subject to the influence of nature. According to Antoniades, architects are well-placed to accommodate nature into their work, as

> nobody sees nature in more dynamic ways than architects, because they are looking at it from so many more points of view. They care about the ways and laws of the construction of the various natural elements, and they care equally about […] the dynamism of natural phenomenon (1992: 241).

Furthermore, beyond the general presence of the natural environment in architects' lives, there have been several aesthetic styles or movements which have been inspired by nature, along with philosophers and designers who have cited nature as a direct influence on their work.

Throughout the early human history of the need for shelter, vernacular built forms have been influenced by familiarity with natural elements and forces, and a need to build by hand, using locally sourced materials. While such examples are inevitably closely influenced by nature, it is only in more recent history that architectural movements have specifically claimed a connection to 'nature', whether this is through concepts, forms, materials or climate. For example, around the mid-eighteenth century, the Arts and Crafts movement (c 1860-1915)—influenced by the thinking of John Ruskin and William Morris—rejected the early impact of the mechanised age and proposed a shift away from industrialisation and back to hand crafting and natural materials. In the late 1800's, the Art Nouveau style (c 1890-1910) of architecture emerged, the curling, curving tendrils of its ornamentation reflecting the forms of nature. In this era, within the more industrial Chicago Style, Louis Sullivan also used natural motifs in a decorative manner in his buildings. Sullivan promoted an 'architecture which shall speak with cleanness, with eloquence, and with warmth, of the fullness, the completeness of man's intercourse with nature' (Sullivan 1979: 200).

Some designers and scholars, including James Wines, argue that 'the Arts and Crafts Movement and Art Nouveau became the last architectural styles to celebrate the building arts and natural forms' (2000:22). After this time, the emergence of Functional and later International Modernism more generally, and some would say famously, ignored the natural environment. Wines laments that at that time, 'the battle was lost—Modern Design swept the slate clean with its persuasive arguments about the relevance of industrial imagery' (Wines 2000: 22). However, despite Wines' lamentation, many architects of the Modern style were fascinated and inspired by nature. As discussed previously in Chapter 2, Frank Lloyd Wright followed Sullivan's teachings to create a Modern style that produced buildings which did not necessarily replicate the 'look' of nature, but whose forms emerged from a design language that respected the rules of nature. Another Modernist architect, Richard Neutra, 'felt a fundamental obligation to build houses and their surroundings in close harmony with the landscape […] without resorting to naturalistic mannerism' (Sack 1992: 21). Louis Kahn was also awed by the processes of nature and said that '[i]t must be considered nothing short of a human miracle to have thought of a building which doesn't in any way resemble what is in nature and which could not have been done if nature hadn't approved its making' (Kahn and Wurman 1986: 1).

Wentworth D'arcy Thompson's *On Growth and Form* (1917), presented elements of nature in the context of biomathematics (mathematical and theoretical biology), inspiring many thinkers of the day, including architects, who looked to the forms of nature as a structural guide. In more recent times, Philip Steadman (2008) examined and criticised the use of nature as an analogy for the way natural structures might describe architecture (Groat and Wang 2002). The study of the shapes and forms of nature has led several architects to pursue a type of bio-morphic architecture, where the designer employ shapes which metaphorically reflect or evoke nature, as seen in the late nineteenth century in the work of

Antoni Gaudí. While Wright did not always directly reflect the forms of nature in his designs, many who were influenced by his work extended his Organic Modernism to become a Biomorphic style, typically involving designs with flowing, naturalistic forms. This type of Organic architecture continued throughout the late twentieth century to the present day, with Bruce Goff, Bart Prince, Helena Arahuette and Gregory Burgess having produced designs in this style. A further variation of these themes is found in the Critical Regionalist movement, which considers the natural environment in terms of site and materials.

A broad spectrum of current design activity considers the natural environment as part of the desire to produce Sustainable architecture. This approach 'combine[s] environmental responsibility with formal ambition' (Genevro 2000: 4). While there are no consistent formal or aesthetic responses found in Sustainable or Eco-Architecture, there is a consideration of nature in the design process of most buildings that are called 'sustainable'. This consideration might manifest in a building through a response to embodied energy, climatic control or ecological sensitivity. It might also be expressed through a visual connection, or geometric similarity, between the appearance of a building and nature (Makhzoumi and Pungetti 1999; Hagan 2001; Williams 2007).

6.2 Finding the Similarities Between Nature and Architecture

Qualitative connections between architecture and nature are typically made using visual simile or metaphor, symbolism or semiotics. Such methods consciously or subconsciously evoke—through the poetry of form, the use of materials, or the icons and messages embedded in a design—connections to nature. While such qualitative methods have been used to argue for the visual similarities, or differences, between architecture and nature, there are a limited number of quantitative approaches to this issue. Fractal analysis provides one of very few methods available to analyse and compare the characteristic complexity of diverse objects. Euclidean geometry is unable to measure, with any accuracy, any dimensions such as lengths of these non-linear forms. However, fractal geometry, by iterating measurements over progressive scales, can be applied to determine the characteristic visual complexity of both natural and synthetic forms. Fractal dimensions are ideal for exploring the complex, and seemingly random forms found in the natural world. Fractal geometry and dimensions can be used to demonstrate that within many chaotic systems a deeper rhythm of similar patterns is measurable (Mandelbrot 1982; Barnsley 1988; Feder 1988).

Fractal analysis has been used previously as a mathematical method for measuring and comparing visual complexity and it has been employed—in a limited way—to compare visual complexity in buildings and landscapes (Bovill 1996; Bechhoefer and Appleby 1997). However, such past attempts to compare nature and architecture using fractal analysis have not been entirely convincing (Vaughan and Ostwald 2009a). The disparity of the methodological variables employed in each approach has been cited as the primary reason that fractal data derived from nature cannot be easily compared with equivalent data derived from architecture. In particular, representational approaches to the images that are analysed in this way are disparate and uncategorised. For example, when comparing two very different subjects—natural objects and those designed and constructed—the disparity between the subjects and the essential purpose of the comparison comes into question. For example, how can we obtain data from static, constructed, designed forms, such as those that comprise the synthetic built environment, and meaningfully compare this information with data sourced from the dynamic, seemingly more random forms of nature? This chapter develops a possible answer to this question by examining the compatibility of data sources first by determining the types of data—both natural and synthetic—that have been previously analysed, and then finding a common ground between these data sources, to provide a framework as a basis for comparison.

6.3 Fractal Analysis of Nature

In his 1982 book *The Fractal Geometry of Nature*, Benoit Mandelbrot explains, develops and refines the application of fractal geometry, exploring the fractal qualities of nature. Mandelbrot's book famously describes methods for producing visual images of nature's forms from algorithms; plotting mathematical 'forgeries' of nature. However, for scholars with an interest in representing the complexities of nature in a clear and comparable manner, Mandelbrot provides an explanation of several methods which can be used to calculate the fractal dimensions of natural forms. He states that '[s]cientists will (I am sure) be surprised and delighted to find that not a few shapes they had to call *grainy, hydralike, in between, pimply, pocky, ramified, seaweedy, strange, tangled, torturous, wiggly, wispy, wrinkled,* and the like, can henceforth be approached in rigorous and vigorous quantitative fashion' (Mandelbrot 1982:5). This includes calculations for measuring lengths and irregularity of rivers, lakes, trees and national boundaries as well as the fractal dimension of the sky, clouds and galaxies. In particular Mandelbrot examines the length of coastlines in some depth providing a famous explanation of fractals. He commences by noting that 'coastline length turns out to be an elusive notion that slips between the fingers of one who wants to grasp it' (Mandelbrot 1982: 25). He then goes on to prove mathematically that a fractal dimension can be calculated for any coastline, and demonstrates the usefulness of this geometry by calculating and comparing the coastlines of several nations.

Mandelbrot's work has been adopted by many others as a method for providing a quantitative understanding of the natural world. Richard Voss (1988) argues that fractal geometry is particularly 'appropriate for natural shapes' (26) and that at 'large scales, natural boundaries, geological topography, acid rain, cloud, rain and ecosystem boundaries, seismic faults, and the clustering of galaxies are all susceptible to fractal analysis' (36). Shaun Lovejoy has analysed clouds, measuring their fractal dimension, which he describes as 'wiggliness' or 'degree of contortion of the perimeter' (1981: 196). Fractals have been utilised for large scale analysis including P. J. E. Peebles' (1989) research on galaxy distribution.

At a much finer level, Chi-Wei Lung and Shou-Zhu Zhang (1990) are amongst many scholars who use fractal geometry to measure and predict the growth of cracks in physical surfaces. Using fractal geometry to measure vegetation growth or decline is now a common method in botanical studies. For example, Morse et al. (1985) calculate the fractal dimension of the outlines of certain plants and then consider how the insects living on them might be affected by the lower or higher dimensions of the plant. Others have added to the existing data of measured coastlines with calculations of Norway (Feder 1988), Britain and California (Bovill 1996). Jala Makhzoumi and Gloria Pungetti (1999) use fractal analysis to interpret and understand the ecological landscape. Recently, the fractal dimension of several Australian landscapes have been tested and the conclusion reached that 'different landscape types can be calculated by their mean fractal dimension' (Perry et al. 2008: 15). The characteristic complexity of green spaces, typically urban parks, have also been measured using box-counting to develop models for sustainable development (Wang et al. 2011; Liang et al. 2013). Fractal geometry has also been used to analyse preferences for the visual complexity of natural landscapes (Keller et al. 1987; Stamps 2002; Hagerhall et al. 2004).

These past cases represent some of the wide range of natural data sources analysed using the box-counting method. While fractal analysis is often applied to natural sources, and as shown in Chapter 4, and it is also used to measure the built environment, examples where box-counting is used to measure both nature and architecture in the same study are rare. The following section examines the few cases that have been published.

6.4 Comparing Natural and Built Forms

William Bechhoefer and Carl Bovill published fractal dimension calculations comparing architecture and landscape in 1994. Bechhoefer's and Bovill's paper utilises the box-counting method to undertake a comparative study of the fractal dimensions of natural and built forms. Working on the general assumption that there might be a visual ‘fit’ between the local landscape and a building’s appearance, Bechhoefer and Bovill used fractal dimensions to measure indigenous buildings and a natural land form in Amasya, Turkey. They concluded that each of these subjects had similar fractal dimensions and thus, the topography must have either influenced the design of the buildings, or alternatively all of these features were shaped by larger environmental conditions. Bovill’s (1996) book, *Fractal Geometry in Architecture and Design*, repeated the results of the analysis of Amasya and the conclusion that the natural conditions in some way influence the architectural design. In addition to the case of Amasya, Bovill also offers three further examples where he believes a clear connection can be made between a natural setting and a building (see the following section). At around the same time, Lachlan Robertson (1995) also proposes the use of box-counting to calculate the fractal dimensions of urban landscapes in order to compare them with other urban areas, or to integrate them into wider natural regions.

Following from Bovill’s (1996) arguments, Bechhoefer and Appleby (1998) propose that because ‘the fractal dimension of vernacular housing is very similar to that found in nature’ (3) then perhaps new buildings in historic settings should be designed to match similar levels of visual complexity and thus provide a better contextual fit. They then use fractal geometry—paradoxically aided by the musical patterns in a Brahms waltz—to generate the form and fenestration of a building design for the historical city of Aksehir in Turkey. This might seem a reasonable thing to do, to produce a new building which is sensitive to its historic setting, but their proposal borders on pastiche (and is unnecessarily confounded by the inclusion of Brahms), leading to other researchers rejecting such simplistic responses. For example, Stamps (2002) questions the desirability of achieving a similar level of visual complexity for architecture and its natural setting. As part of his research, which investigates fractal dimensions of the built environment, Stamps produced computer-generated images of mountains and cityscapes with deliberately matching fractal dimensions, and tested peoples’ preferences for each. He concluded that his test subjects did not necessarily prefer the fractal dimension of the buildings to match the natural environment and that 'urban design decisions regarding skylines should not assume that matching [fractal dimensions] of skylines and landscapes is a good idea' (Stamps 2002: 170). Richard Taylor—in his study of preferences for fractal dimension ranges—was relieved by Stamps' findings, interpreting them to mean that 'the fractal skyline does not have to be matched to fractal cloud patterns, thus excluding the highly unfeasible prospect of having to match the fractal designs of buildings to prevalent weather conditions' (Taylor 2006: 250). Nevertheless, interest in the relationship between buildings and landscapes continues in this field.

In 2003, Lorenz reiterated Bovill's conclusions agreeing that 'the measured fractal dimensions of the environment, elevation and detail will be similar' (47). Andrei Bourchtein et al. compared streetscapes and landscapes in Brazil, concluding that 'the relationship between the visual complexity of built and natural landscapes is confirmed for the considered Brazilian settings' (2014: 11). Other research connecting architecture and nature by way of fractal dimensions is limited in its presentation and use of quantitative data. For example, Burkle-Elizondo and Valdéz-Cepeda, in their studies on the fractal dimensions of Mesoamerican pyramids, suggest that 'it is possible to identify' similarities between the pyramids and 'particular mountains in the landscape' (2006: 118). Yet, although they provide calculations for the pyramids, they do not undertake calculations of the surrounding mountains to provide any evidence for their claims.

6.5 Testing Comparisons Between Architecture and Ecology

As the previous section revealed, Bovill (1996) uses fractal analysis to compare nature and architecture in four locations. The first of these involves comparing traditional housing, a mountain view and a town plan in the ancient town of Amasya, Turkey. The next is a comparison between the design of Alvar Aalto's *Home and Office* in Helsinki and the tree spacing of the forest surrounding it. The third is between the highly irregular coastline and geology of Sea Ranch, California, and Moore, Lyndon, Turnbull and Whitaker's *Sea Ranch Condominium* complex. The final case Bovill examines, compares the 'relatively smooth' coastline of Nantucket and the 'simple, basic shapes' of the houses which are found there (1996: 181). To support these cases, Bovill offers mathematical data for both the buildings and mountains in Amasya, and a calculation of the fractal dimensions of the coastline of Sea Ranch, but he does not analyse Sea Ranch Condominium. No data is presented for his analysis of Alto's work nor the architecture or topography of Nantucket. Thus, despite proposing four cases where architecture and nature can be usefully measured, demonstrating dimensional correlations, he provides comparative data for only one of these.

Bovill's (1996) proposition has fascinated a number of scholars and it has been repeated in arguments about environmentally sustainable design and regional architecture (Zarnowieka 1998; Boldt 2002; Nakib 2010). However, the data supporting his findings has been questioned by others (Lorenz 2003; Bourchtein et al. 2014) and the first full assessment of his argument was undertaken by the present author (Vaughan and Ostwald 2010). This assessment is the basis for the following section, which undertakes a close review of Bovill's approach to comparing natural and constructed systems using fractal dimensions. This analysis provides a foundation for the development of a methodological approach to comparing Wright's buildings with their natural settings. The computational fractal analysis method is applied to both Amasya and Sea Ranch in the next section and a comparative analysis of the original results and the new results is undertaken.

6.5.1 Application of a Fractal Methodology to Amasya

The city of Amasya, Turkey, has been settled for over 2000 years. Members of the ruling royal family and important leaders were based there during the Ottoman period, when the city became established as a significant centre for creativity and the base for 'many important court architects, artists, artisans and poets'

(Bechhoefer 1998: 25). The area of Amasya analysed by Bechhoefer and Bovill is Hatuniye Mahallesi, which is 'the historic neighbourhood on the north bank of the Yesilirmak River [and] is the clearest embodiment of Amasya's history. […] The riverfront houses are among the most important assemblages of traditional residential construction in Anatolia' (Bechhoefer 1998: 28). These buildings maintain much of their history and are set in a significant geographical location. Looming above the strip of old houses of Hatuniye Mahallesi is a large craggy hill, appearing as one massive peak. To compare the fractal dimensions of the architecture and the local landscape, Bechhoefer and Bovill undertook a box-counting analysis of three images; a line drawing of the hill (fig. 6.1), the elevation of five connected historical houses along the river front (fig. 6.2), and the urban plan of Hatuniye Mahallesi (fig. 6.3).

Figure 6.1 Reproduction of Bovill's image of the hill at Amasya

Figure 6.2 Reproduction of Bovill's image of the elevation of the row of houses

Figure 6.3 Reproduction of Bovill's image of the urban plan of Hatuniye Mahallesi

Bovill uses a manual method to produce a range of results for these three images (hill, elevation and urban plan) at Amasya and concludes that the fractal dimension for the ‘traditional housing is very close to that of the hill, which is the dominant visual feature of the city of Amasya. This suggests that the indigenous builders somehow applied the rhythms of nature to their housing site layout and elevation design’ (1996: 145). In this context, what does ‘very close’ mean?

Bovill’s calculations for the fractal dimension of the three Amasya images range between a high of $D = 1.717$ for the elevations, to a low of $D = 1.432$, for the urban plan. This is a range of $D = 0.285$ which can be expressed as a percentage of the maximum possible range of D for an image ($1.0 < D < 2.0$). The gap represents a 28.5% range between the visual complexity of the three images as calculated by Bovill. Lorenz used an early version of the Benoit software to repeat Bovill’s calculations in 2003. Lorenz’s results recorded a high of $D = 1.546$ (for the elevations) and a low of $D = 1.357$ (for the hill). The range was $D = 0.189$ and the gap, expressed as a percentage, was 18.9%. This seems to strengthen Bovill’s conclusions. When the computational fractal analysis method outlined previously in this dissertation is applied to the three images the highest result is $D = 1.585$ (for the urban plan) and the lowest is $D = 1.495$ (for the hill) (Vaughan and Ostwald 2010). This is a gap of $D = 0.080$ or 8% (see Table 6.1). Across the three data sets, the more recent and accurate the methodological application, the closer the three results are, seemingly supporting Bovill’s conclusion. However, we still do not know what exactly constitutes a close result in Bovill’s terms, although a large study of 85 architectural designs determined that an 8% difference in D, could at best be described as ‘similar’ (Ostwald and Vaughan 2016: 152). The difference in visual complexity between the *Robie House* and the *Villa Savoye* has also, as the previous chapter reveals, been calculated as between 8-14%, depending on the variation of the method used. Yet, these would normally be regarded as dissimilar buildings.

Table 6.1 Comparison of fractal dimensions calculated for Amasya

Results	$D_{(elevations)}$	$D_{(hill)}$	$D_{(urban\ plan)}$	$D_{(range)}$	**%gap**
Bovill (1996)	1.717	1.566	1.432	0.285	28.5%
Lorenz (2003)	1.546	1.357	1.485	0.189	18.9%
Vaughan and Ostwald (2010)	1.505	1.495	1.585	0.080	8%

6.5.2 Application of a Fractal Methodology to Sea Ranch

Bovill's second proposal, concerning the alignment between natural and built forms that are responsive to the environment, is focused on Sea Ranch, California. This exposed coastal region, north of San Francisco, was developed in the 1960's into a township which set out to model regionalist and ecological principles of design. Its planning aim was 'to link the character of natural form to the character of built form' (Halprin 2002: 12). For this reason alone, the mathematical analysis of the relationship between the landscape and the buildings is of interest.

The highly irregular natural coastline and topography of Sea Ranch has been described by Canty as possessing a

> wild beauty and intimidating power, more challenging than comforting: hillsides thick with fir and redwoods; grassy meadows mowed and mauled by sheep […] cypress hedgerows [and] finally, the blue-green sea, surging against huge sculpted rock formations and steep bluffs, carving irregular inlets (Canty 2004: 23).

Bovill suggests that the formal properties of this landscape are echoed in Moore, Lyndon, Turnbull and Whitaker's *Condominium One*, the first large building in the new Sea Ranch development. It is easy to understand Bovill's proposition, because descriptions of the building regularly emphasise visual connections to the local context. For example, Lyndon and Alinder argue that the walls of *Condominium One*

> drop like cliffs from its irregular edges, themselves further modulated by bays, projections, and hollows as they reach to the ground. The volume they make is like a large, rectilinear landform, a wooden escarpment with edges

> that move back and forth like the boundaries of a cove (Lyndon and Alinder 2004: 39).

Despite such conceptual and poetic links between the visual and formal qualities of *Condominium One* and the landscape of Sea Ranch, the only data provided by Bovill to support his argument are calculations of the fractal dimension of the coastline at Sea Ranch. In order to investigate any connection between the visual complexity of the landscape and of the building, new data has to be produced. For the present research, the computational fractal analysis method was used to recalculate the *D* of the coastline image provided by Bovill (fig. 6.4). Then, for comparative purposes, the *D* of the single image Bovill provides of *Condominium One* is also produced and measured (fig. 6.5).

Figure 6.4 Reproduction of Bovill's image of the coastline at Sea Ranch (D = 1.3215)

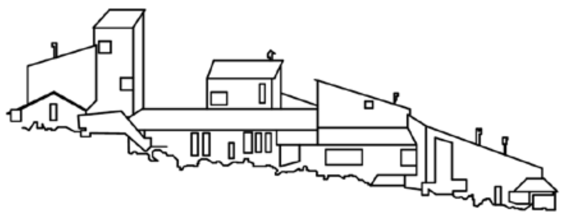


Figure 6.5 Reproduction of Bovill's image of Condominium One *at Sea Ranch (D = 1.426)*

In addition, the coastline immediately beside *Condominium One* was redrawn from the site plan (Lyndon and Alinder 2004) (fig. 6.6) and finally, four new elevations of *Condominium One* were redrawn for the present research based on original drawings by Moore and Turnbull (Johnson 1986) (fig. 6.7), and an average fractal dimension calculated.

Figure 6.6 Reproduction of Lyndon and Alinder's site plan of the coastline at Sea Ranch (D = 1.249)

Figure 6.7 Reproduction of Moore and Turnbull's north elevation of Condominium One *(D = 1.381)*

Table 6.2 Comparison of average fractal dimensions calculated for Sea Ranch

Results	$D_{(coastline, Bovill 96)}$	$D_{(Con.1, Bovill 96)}$	$D_{(range)}$	**%gap (Coastline to Elevation)**	$D_{(Coastline, Lyndon \& Alinder)}$	$D_{(Con.1, original, average)}$	$D_{(range)}$	**%gap (Coastline to Elevation)**
Bovill (1996)	1.329	-	-	-	-	-	-	-
Vaughan and Ostwald (2010)	1.215	1.426	0.211	21.1%	1.249	1.382	0.1325	13.2%

Rather than supporting Bovill's case for a relationship between architecture and its surroundings, the results for Bovill's original images of Sea Ranch suggest a significant difference between the fractal dimensions of the images (21% gap). The new results provided in this study, of an additional elevation and the associated coastline, are marginally more supportive of Bovill's proposition but still not convincing (13% gap, suggesting a dissimilar relationship).

6.5.3 Outcomes of Re-testing Bovill's Work

The task of re-testing the results for Amasya and Sea Ranch reveals several weaknesses in the various versions of the box-counting method. In the first instance, Bovill's original results were produced by hand, using tracing paper and pencil. The number of scales (or grids) over which his analysis was undertaken, was limited for this reason and his results are variable in quality (for him, using a manual method, 14% is a close result). Lorenz used a more accurate software-based method that relied on a greater number of grids (scales of analysis) but with the same original drawings. Lorenz's research produced a more realistic gap (9.45%) but as discussed in Chapter 5, one of the known problems with the box-counting method is that thick lines in the original image can produce anomalous readings. These differences or inconsistencies in the method and its application explain the reason why the similarity between the natural and built forms in Amasya can vary between 14% and 4% using the same analytical method.

What does this say about Bovill's (1996) conclusion for Amasya; that 'the indigenous builders somehow applied the rhythms of nature to their housing site layout and elevation design' (145). From the point of view of quantifiable data, and with the results of the computational method as a benchmark, the human eye can readily detect visual similarities between objects with a *D* range of less than 4%. For example, the visual difference between one of Le Corbusier's Modernist elevations, and one of Wright's Prairie House elevations is potentially around 10% (Ostwald et al. 2008; Ostwald and Vaughan 2016). This means that the visual similarities between the images of Amasya are not especially striking (~8%) and for Sea Ranch even less so (~ 13–21%). In mathematical terms, a *D* range of 1% seems to suggest a very high degree of similarity and a *D* range of around 17% is a very low degree of similarity for comparisons between buildings. However, despite these results which might seem critical of Bovill, the purpose of this section is twofold. First to demonstrate that comparisons between nature and architecture can not only be constructed using fractal dimensions, but they have been done in the past. Second, as these examples demonstrate, the challenge is not so much ‘can we compare nature and architecture using fractal dimensions’, but ‘how can a valid (useful, consistent and logical) comparison be undertaken’?

Bovill’s results were limited by the number of images he tested, the selection of images he chose and the manual version of the analytical method he used. He didn’t provide any clear rationale or guidelines for the data source or type required to make such a comparison. This problem can be traced to the often-overlooked fact that computational methods, like fractal analysis, do not measure ‘nature’ or ‘architecture’ per se, rather they extract measures from representations of natural objects, landscapes or buildings. Images such as geological landform drawings and architectural elevation drawings are ‘secondary representations of artefacts’ (Hewitt 1985: 3), and there exists a vast range of typical representation options and standards available for scholars analysing such subjects (Leupen et al. 1997). Rather than rejecting the whole concept outright, it is proposed that the potential validity of a computational comparison of the complexity of nature and architecture could be further developed if a more rigorous methodology could be applied to the data selected for analysis. This idea, which follows from the various precedents outlined in the present chapter, is developed in the following section.

6.6 Image Requirements for Comparing Fractal Dimensions

As discussed in Chapters 4 and 5, the fractal analysis method has many variables and failing to apply them in a consistent manner can mean that results are difficult to compare between different studies. Previous research has identified optimal settings for fractal analysis which ensure consistent, repeatable results (Koch 1993; Buczkowski et al. 1998; Foroutan-pour et al. 1999; Cooper and Oskrochi 2008; Ostwald 2013; Ostwald and Vaughan 2013b). As Chapter 5 reveals, the usefulness of any data is also reliant on the two-dimensional representation which is subject to analysis (Vaughan and Ostwald 2010; Ostwald and Vaughan 2012). However, while the framework presented in Chapter 5 can be used to select the right level of representation for various architectural research topics or questions, what happens when we want to compare two very different subjects, say a building and a landform?

When fractal analysis is used to make comparisons, for example, in biological sciences to establish a difference in complexity between two forest types, this could be considered a legitimate or reasonable comparison of natural data (Zeide and Pfeifer 1991). Or in the built environment, to compare the changes in design complexity during an architect's career, this could be considered a legitimate or reasonable comparison using synthetic data (Vaughan and Ostwald 2009b). While each of these separate cases are potentially reasonable (such as the correlation between multiple natural forms and between different buildings), when the data from two different sources—the natural and the synthetic—is compared, this raises questions regarding the basis for such a comparison. This section develops an approach to images as a type of data that represent (in several different ways) an object in reality.

Mark Hewitt emphasises the importance of distinguishing and categorising aspects of an image noting that for analysis of images we need to 'consider drawings, models, and other representational devices both as works […] and as ideas' (1985:6). To approach the comparison of images of nature and images of architecture in a consistent and useful way, four practical elements, or categorising groups, are proposed to be considered.

- First, the images need to be similar in the *topic* they depict; what might be called the theme of the research. This doesn't necessarily imply that only identical subjects may be compared, but rather that there needs to be a reasoned approach to comparing subjects. For example, if it has been argued that the silhouette of a mountain range inspired local architects to create elevations which reflected its geometry, then both the geometry of the mountain's silhouette, and that of the local architecture, may reasonably be considered part of the same theme or topic.

- Second, knowing the *attributes* of the subject will clarify the practical capacity to compare subjects by acknowledging their difference and finding a common ground between different data sources. In this study, the attributes are considered to be either *synthetic* (static, constructed, designed forms, such as those that comprise the built environment) or *natural* (the dynamic, natural, seemingly random forms found in nature).
- Third, not only do the images need a cohesive topic, they must have a similar *representation* method; that is, the physical presentation, be it a photograph or a line drawing for example. In art terms, this would be called the 'medium' (Lucie-Smith 2003: 136). When undertaking a fractal analysis, comparing line drawings of nature or architecture is more likely to produce a viable result than comparing photographs of one with line drawings of the other.
- Fourth, they need to be homogeneous in their data *type*. This refers to the many typical modes of presentation of a particular set of information used in the attribute's field, whether it be an architectural elevation, or a geographic strata map. Having a homogeneous type means that it is reasonable to—for example—compare site plans or compare perspective drawings, but that comparing site drawings with perspective drawings will not provide a valid basis for comparison.

Figure 6.8 provides an example of what these four terms or concepts might mean in practice. For the purposes of the table, the topic could be the comparison of a house and its setting. The data is divided into two columns, synthetic and natural. The image is then defined for its representation (method of presentation) and its type (mode of presentation).

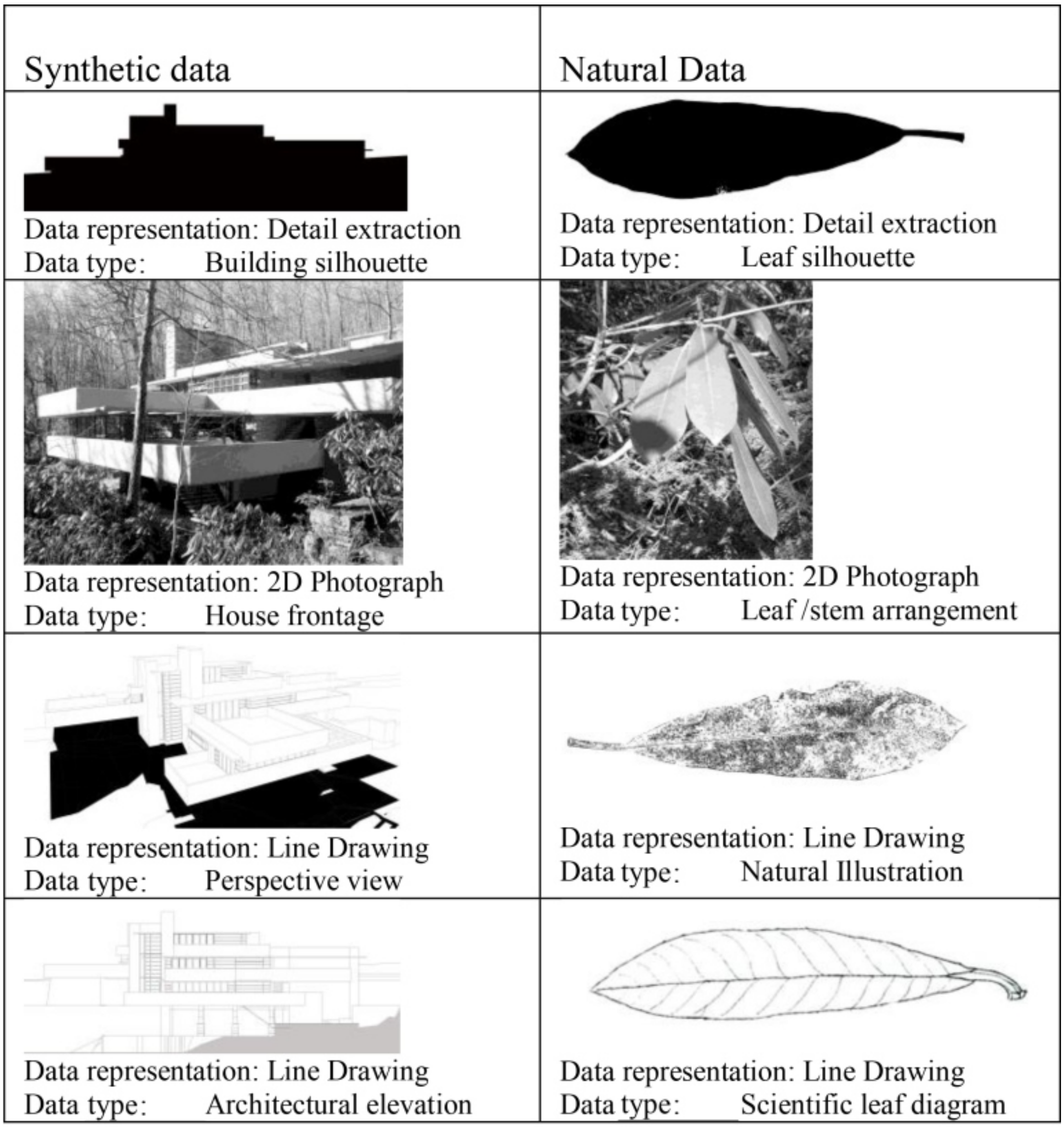


Figure 6.8 Examples of representations and types of synthetic and natural data

These four considerations are important because knowing the *topic*, *attribute*, *representation* and *type* means that we can approach a comparative method in a logical manner. For example, within a fractal dimension study of one subject, say a study of house facades on a street, the images being compared need to relate to each other. Thus, for an analysis of housing in this street (being the 'topic'), the data could be a collection of photographs ('representation') of house frontages ('types'). In this case, the fractal analysis would be based on synthetic images ('attribute'). The data from the study would be compatible as the topic, attributes, representation and type would all be similar, at least in terms of the hypothesis being tested. A different fractal study might be based on a tree species ('topic').

The *D* values for which could be found from a set of line-drawn tracings ('representation') of natural ('attribute') leaves ('type') from particular trees. Again, the data will correlate for a meaningful outcome. However, if we wished to compare the trees on the street with the houses on that same street, we need to approach the relationship between the topics (houses/trees), their attributes (synthetic/natural), the method of representation (photograph/line drawing) and their type (house frontages/leaf tracings). Given the disparity of these image variables, the results of two studies would be difficult to meaningfully compare unless some of the variables were somehow made analogous. While we may not want to change the natural/synthetic attributes in the example study, we could change the topic to the study of a particular streetscape. The method would then require an appropriate representation and type for all of the images being analysed. The next section develops a guideline for making such a comparison.

6.7 A Data Selection Methodology

While there are multiple image variations commonly used for various box-counting applications, no guidelines exist for matching the representation and type of images for analysis (Vaughan and Ostwald 2010). Thus, the following sections of this chapter describe an approach to achieving homogeneity of representation and type in the data selection process. First, existing cases of *representation* and *type* which are found in box-counting analyses of nature, and then the built environment, are explored and tabulated (Tables 6.3 and 6.4). Thereafter, the idea that these images might have different data gradients—depending on what they depict and how they display it—is introduced and an approach for matching data gradients to increase the likelihood of a more realistic or useful quantitative comparison is proposed. Next, a discussion of the reasoning behind the selection of data considers data grouping of previous fractal analysis data sets, forming a framework of criteria for data section. Finally, these criteria are applied to the possible data available from sources relating to *Fallingwater* and a set of potential data is described in terms of its type and representation, which will be developed in the following chapter into a set of final data ready for analysis and comparison.

6.7.1 Reviewing Natural Data Representation and Type

The standard box-counting method of fractal dimension analysis, used for both natural and synthetic objects, utilises base data in several standard forms. Despite concerns that ‘no single photograph can represent the diversity readily seen from a particular viewpoint’ (Palmer and Hoffman 2001: 159), black and white binary photographs have been used to calculate the fractal dimension of top down, close-up views of plants (Morse et al. 1985) and pebbles (Yang and Juo 2001), and the box-counting fractal dimension has been calculated from photographs framing abstract views for a range of plants, landforms and celestial bodies (Spehar et al. 2003). However, photographs generally produce a high fractal dimension due to the large amount of data in the image, a factor that is complicated by shadows, reflections, textures and depth of field. In contrast, a silhouette extracted from a photograph using edge-detection reduces this volume of extraneous ‘noise’ making the image processing more consistent and the process more repeatable (Chalup et al. 2008; Chen et al. 2010), partially due to the fact that silhouette extraction by software doesn’t require personal judgement (Hagerhall et al. 2004). James Keller et al. (1987) initiated much of the methodology used for silhouette detection for fractal analysis, and the results of their research demonstrate that fractal dimension ranges of silhouettes can be used to distinguish between different elements in nature. Edge-detected photographic silhouettes have been used as raw data for the box counting-method for studies of vista outlooks and natural landscapes (Hagerhall et al. 2004; Chen et al. 2010; Wang and Ogawa 2015), top down views of outlines of leaf collections (Tucek et al. 2011) and aerial views of natural landscapes (Wang and Ogawa 2015). Osmond (2010) presents a novel approach by using a fisheye lens to photograph overhead landscapes, using edge detection to produce a hemispheric skyline for analysis. Other linear plan type images used for box-counting analysis include line drawings of landscape plans (Perry 2012) and vegetation cover (Ingegnoli 2013). Nautical charts (Simon and Simon 1995) and geographic maps (Wahl et al. 1994;

Bovill 1996) are also examples of sources for line drawings of the natural forms analysed using box-counting. Other nature-based image data used for quantitative analysis include (but are not limited to) line drawings of landscape views, botanical illustrations and contour plans.

Table 6.3 Summary of natural data- representation and type

Attribute: Natural		
Representation	Type	Selected scholars
Raw photographs	Landform and botanical views Celestial maps	Spehar et al. 2003
Binary photographs	Geological plans Vegetation maps	Morse et al. 1985 Yang and Juo 2001
Edge-detected photographs	Landscape, landform and botanical views Vegetation maps Skylines	Seto et al. 1996 Hagerhall et al. 2004 Chen et al. 2010 Osmond 2010 Tucek et al. 2011 Wang and Ogawa 2015
Line drawings	Vegetation maps	Perry 2012 Ingegnoli 2013
Line drawings	Nautical charts Geographic maps	Simon and Simon 1995 Wahl 1994 Bovill 1996

6.7.2 Reviewing Built Environment Data Representation and Type

Akin to the fractal analysis of nature, various representations of the built environment have been used for the box-counting method. In everyday architectural use, the primary raw data used for architectural representation is the orthographic drawing, which lends itself to fractal analysis. Orthographic drawings (or orthogonal projections) represent the three dimensional world in two dimensions, providing direct, planar representations of an object, without including any representation of the depth of the object as if the observer is 'viewing it centrally from infinity' (Leupen et al. 1997:204). The simple line drawings found in plans, elevations and sections are examples of orthographic drawings. These images are usually already binary and are ideal sources for edge detection processing. Elevations and plans are relevant subjects for analysis, as an elevation can be considered to provide a measure of the geometric complexity of the building as viewed from the exterior and the plan provides a measure of the complexity of the design as it is inhabited (Ostwald 2011). In the past, box-counting has been applied to line drawings of building plans (Rian et al. 2007; Wen and Kao 2005; Vaughan and Ostwald 2011; Ostwald and Vaughan 2016), simple line elevations of houses (Bovill 1996; Cagdas et al. 2005; Vaughan and Ostwald 2013; Ostwald and Vaughan 2016) and detailed linear elevations (Zarnowiecka 2002; Ediz and Ostwald 2012). Single line, digitised tracings of site plans showing the outlines of buildings have been taken from maps of both ancient (Brown and Witschey 2003) and contemporary cases (Benguigui et al. 2000).

Orthographic views provide a solution to creating a specific, repeatable approach to preparing architectural drawings, and this drawing representation is particularly suited to comparing stylistic or formal qualities in sets of architectural images using fractal analysis. However, there are a small number of phenomenological studies—that investigate the experience of a building—which have calculated the fractal dimensions of digitally drawn, pre-processed perspective images of built forms, as the perspective images are potentially more suited to the 'perceptual' research subject than orthographic images (Hewitt 1985: 6). A study of the suggestion of depth in the facades of Glenn Murcutt's buildings tested twelve perspectival images of the *Marie Short House* (Vaughan and Ostwald 2014a) and a study of spatio-visual experience was also carried out using a set of 52 computer generated perspective views charting the progress into and though Frank Lloyd Wright's *Robie House* (Vaughan and Ostwald 2014b).

Like the studies of *D* values of natural landscapes, edge-detected outlines from photographs are also have been converted to binary images and used to study the fractal dimension of buildings. For example, Klaudia Oleschko et al. (2000) used edge-detected photographs to calculate the *D* of aerial, top-down views of ancient buildings. Frankhauser used this image representation method for studies of European housing layouts (2008), and others have used the approach for frontal views, as extracted elevations from photographs of vernacular housing (Debailleux 2010) and in building skyline studies (Chalup et al. 2008).

Table 6.4 Summary of synthetic data - representation and type

Attribute: Synthetic		
Representation	**Type**	**Selected scholars**
Binary photographs	Building Layout diagrams	Oleschko et al. 2000
Edge-detected photographs	Building Layout diagrams Building skylines Facade views	Frankhauser 2008 Chalup et al. 2008 Debailleux 2010
Line drawings	Plans	Wen and Kao 2005 Rian et al. 2007 Ostwald and Vaughan 2016
Line drawings	Elevations	Bovill 1996 Zarnowiecka 2001 Cagdas et al. 2005 Ediz and Ostwald 2012 Ostwald and Vaughan 2016
Line drawings	Perspectives	Vaughan and Ostwald 2014a Vaughan and Ostwald 2014b
Line drawing	Building Layout diagrams	Benguigui 2000 Brown and Witschey 2003

From these examples it can be seen that both natural and synthetic sources of information have shared data formats – photographs, edge-detected photographs and line drawings. Other sources, for both examples, could include 3D laser scanning and stereo photography. In a further alternative, as outlined previously in this chapter, Stamps (2002) produced computer-generated images of imagined mountains and cityscapes to test peoples' preferences for which should match (Stamps, 2002: 170). Stamps' use of computer-generated images is indicative of the need for consistent parameters for constructing such a comparison. Computer generated images can be set at a similar scale, with a similar level of detail and produced using an identical method. The data produced in this way is consistent and straightforward to analyse. However, images produced entirely by computer generation do not solve the problem of extracting data for the comparison of real locations; buildings and their site features.

6.7.3 Data Gradients of Realism and Quantitative Potential

The methodology proposed in this section seeks to determine which of the cases of natural and synthetic images result in compatible sources of raw data. This process begins by categorising the different raw data sources with regard to the way in which they represent reality. The examples of previously analysed, extracted synthetic and natural data provide a breakdown of not only *how*—via a particular representation method (say, a line drawing or photograph)—the subject is presented, but also *what*—via the decision on type (say, a plan or a skyline)—is expressed in the image. This data can be further classified in two ways – the level of realism perceived in the image, and the amount of potentially quantifiable information found in the image.

The first of these two classifications, the *realism*, is based on the notion that images 'give only a limited picture of what they represent; they are an abstraction of reality' (Leupen et al. 1997: 204). This categorisation ranks the 'quality' of information present in the image, relative to the realism of the image or data, a criterion which relates to our worldview. The level of realism indicates how much the image looks like the actual object being represented (Table 6.5 column a).

- A 'high' level of quality is the closest level to visual reality; for example, a high resolution, 3D colour laser scan might fulfil this criteria. The purpose of depicting objects or places as images in this way is often to reproduce a visual image as close as possible to that which is seen by the observer.
- A 'Medium' level of quality relates to images which are broadly connected to the visual properties of their originals, such as a silhouette extracted from a photograph.
- 'Low' quality images do not strongly correspond to forms as we perceive them. For example, we do not view a hillside as being covered in lines at regular intervals, despite what a contour plan suggests. Stan Allen describes this effect whereby a plan drawing can 'describe' a building very effectively, but when one is in the building, these plans 'vanish' (Allen 2009: 46).

Whereas the category of realism may show an object as it appears to the eye, there are many additional ways we might gain an understanding of an object via its representation (Foucault 1970). The next data classification considers what else an image might convey, so that '[i]nstead of tangible objects floating in measureless space, space itself can be measured and precisely represented' (Allen 2009: 12). Many image types used in architectural drawings and natural analysis serve a purpose to transmit information to the viewer and different images provide different levels of information. The next classification of the data here grades the *quantitative potential* of the data, by categorising the degree of accuracy to which the data in a representation reflects the original object (Table 6.5, column b).

- A 'high' level of quantity or accuracy might be found in a 3D laser scan or a site plan, such as a contour plan, both of which are metrically accurate, but the former has a high level of 'realism[, and the latter a low level. Nevertheless, while a site plan has a 'low' level of realism of representation—as we rarely perceive our surroundings as abstracted plan views—they can provide a high quantity of information when analysed, due to the amount of extractable data, and the relationship between information and the actual site. This is a case where, '[p]aradoxically, the dry, dispassionate form of notation, which makes no attempt to approach reality through resemblance, is better able to anticipate the experience of the real' (Allen 2009: 45). Topographical maps are examples of technical, convention-based drawings, which have a general standard of representation (you would expect to see single curved lines for contours, dots or small circles for tree trunks), making them more data rich, yet less realistic (Leupen et al. 1997).
- A 'medium' level of quantity or accuracy is found in images that, when compared to the previous examples, have a less specific amount of information, but can provide quantitative data nonetheless. Perspective drawings would have a medium degree of accuracy, particularly the mechanical projection method of setting-out a perspective. Arthur Drexler emphasis that 'this laborious process ensures that a building be represented in its true proportions', this method being a more accurate transmission of

the data as the draftsperson 'is discouraged from those distortions of perspective that suggest a building is much larger or longer or higher than it really is' (1965: 9).

- A 'low' level of quantity or accuracy might be found in a hand drawn landscape illustration. Such an image might convey an artist's impression of a view, and it may capture some of the realistic qualities of that view, but it will not offer much analysable information. It has thus, a relatively low level of quantity or accuracy in these terms.

These twin categories of realism and quantitative potential are applied to the representations found in previous studies for natural images and images of the built environment (Table 6.5). Table 6.6 then correlates the image types according to the data gradients outlined in Table 6.5, providing a framework to determine suitable images for comparison using fractal analysis.

Table 6.5 Data Gradient: degree of realism and quantitative detail

Attribute: Synthetic			
Representation	**Type**	**(a) Realism**	**(b) Quantitative potential**
Binary photographs	Building Layout diagrams	Medium-high	medium
Edge-detected photographs	Facade views	medium	medium
Edge-detected photographs	Building Layout diagrams Building skylines	low	medium
Line drawings	Plans	low	high
Line drawings	Elevations	low	high
Line drawings	Perspectives	medium	medium
Line drawing	Building Layout diagrams	low	medium
Attribute: Natural			
Raw photographs	Landform and botanical views Celestial maps	high	high
Binary photographs	Geological plans Vegetation maps	Medium-high	medium
Edge-detected photographs	Landscape, landform and botanical views Vegetation maps Skylines	medium	medium
Line drawings	Vegetation maps	low	high
Line drawings	Nautical charts, Geographic maps	low	high

Table 6.6 Framework to determine correlating data

Examples	Data Gradient: Realism of representation	Quantitative potential
	High	High
Natural	Raw photographs: Landform and botanical views, celestial maps	
Synthetic	-	
	Medium-High	Medium
Natural	Binary photographs: Geological plans, vegetation maps	
Synthetic	Binary photographs: Building layout diagrams	
	Medium	Medium
Natural	Edge-detected photographic silhouettes: Landscape, landform and botanical views, vegetation maps, skylines	
Synthetic	Line drawings: Perspectives Edge-detected photographic silhouettes: Facade views	
	Low	High
Natural	Line drawings: Vegetation maps, nautical charts, geographic maps	
Synthetic	Line drawings: Plans, elevations	
	Low	Medium
Natural	-	
Synthetic	Line drawing: Building layout diagrams, building skylines	

The data correlation (Table 6.6) shows several sets of natural and synthetic data representations that could reasonably be compared. Binary photographs of both natural and synthetic attributes have both a medium-high level of reality and a medium quantitative potential. Edge-detected photographs of nature and building facades, and perspective line drawings of buildings share medium reality and also medium quantitative potential. Line drawings of maps and charts of natural places share similar data gradients with line drawings of synthetic plans and elevations. The chart also finds no available correlation for a nature/synthetic comparison (based on past scholarly studies) for the two extremes—a high realism /high quantitative potential, nor for a low realism/medium quantitative potential—which effectively removes these image types from the guidelines.

6.7.4 Testing the Data Comparison Framework

If the hypothetical study of trees and houses in a streetscape—posed previously in section 6.6 of this chapter—is examined in the context of the data comparison framework, it would provide a method to review the original approach for constructing a comparison between the data (Table 6.7).

Table 6.7 Non-correlating data

Topic	House/tree study	
	Subject #1	**Subject #2**
	Houses	Trees
Attribute	Synthetic	Natural
Data Representation	Binary Photograph	Line Drawing
Data Type	House frontages	Vegetation map
Realism	Medium-high	Low
Quantitative potential	Medium	High

As only a few of these properties correlate, this does not provide a 'reasonable' comparison between the synthetic and natural data types. Not only is the quantitative potential dissimilar, the level of realism does not match. Referring back to the options for correlation presented in Table 6.6, changing the data for the houses from a set of photographs to a set of line drawn elevations, the two subjects would match their data levels in all aspects as shown in Table 6.8.

Table 6.8 Correlating data

Topic	Streetscape study	
	Subject #1	**Subject #2**
	Houses	Trees
Attribute	Synthetic	Natural
Data Representation	Line Drawing	Line Drawing
Data Type	Elevations	Vegetation map
Realism	Low	Low
Quantitative potential	High	High

6.8 Selecting Data for *Fallingwater* and its Natural Setting

This final part of the chapter considers the types of synthetic and natural data that could be obtained for the comparative analysis of *Fallingwater* and its natural setting. The strategies identified at the end of Chapter 2, as connecting elements between *Fallingwater* and its surrounding natural landscape, will be considered in combination with the framework developed in the present chapter. Potential data sources are then tested with the suggested framework to determine if they provide a reasonable basis for comparison.

6.8.1 Data Selection

Section 6.6 of this chapter sets out the criteria to be identified in order to identify correlating data for analysis. These criteria are; the topic, the subjects and their attributes, the data representation, data type, and data gradients (both realism and quantitative). This section applies that criteria to determine the images required for a comparative study between architecture and nature for *Fallingwater*.

Topic, Subjects, Attributes

The topic of the study is provided by the second hypothesis: a comparison of the formal and visual qualities of *Fallingwater* and its natural setting. Next, the subjects and their attributes need to be identified. We already know that the attributes will be either natural or synthetic. The sole synthetic subject is already identified as Frank Lloyd Wright's *Fallingwater*. The counterpoint of this analysis—the landscape surrounding *Fallingwater*—is broken down into four natural subjects; these are the 'site characteristics' of *Fallingwater's* surroundings, identified in Chapter 2 as four main features of the landscape, which many scholars claim are directly reflected in the built form of *Fallingwater*. The four natural subjects are: the Pottsville sandstone outcrop, the Mesophytic forest, the gully setting and Bear Run stream. Having determined the topic, subjects and their attributes, the representation and type of the data must be next considered for analysis and comparison in Part III of this dissertation.

Data Type and Representation

In answering the first hypothesis, the formal properties of houses analysed (including *Fallingwater*) are found in architectural drawings of their elevations and plans. It would make sense to analyse *Fallingwater* for the second hypothesis from the same sorts of viewpoints as the first hypothesis, from a top-down, plan type view and from a frontal view, perpendicular to the dominant geometry of the ground plane. Would it then be suitable to re-use the fractal dimensions calculated for the *Fallingwater* plans and elevations from the architecture-architecture hypothesis and compare them to the natural elements? This can be answered by considering the framework for correlating data (Table 6.6). Starting with the idea of comparing plans; the framework shows the only natural/synthetic correspondence for plans to be architectural line drawing plans of a building compared to line drawing plan-based views of vegetation, geology and water systems. These image representations and types of both subjects share low levels of realism and high levels of quantitative data. This suits the data sources and will be the approach for comparing natural and synthetic plans of *Fallingwater* and its surrounding landscape.

When the proposal to compare *Fallingwater's* synthetic elevations to natural views is applied to the framework, the 'view' is considered to be a formal expression of a building or natural element, which is visible from points which are external to the structure and are largely perpendicular to the dominant geometry of the ground plane. When looking at the synthetic elevation view, in the low/high category which it belongs, there is no corresponding natural image view. The natural view representations and types all depict a greater sense of the 'real world' than architectural elevations. A line drawing of the elevation of a building has only a low level of realism in this sense – it is only with great difficulty that we could ever see a building that looks exactly as it does in elevation. However, an elevation is full of information about a building, which means it has high quantitative potential. In both respects, the elevation differs from one of the most widely used natural image types—a line image extracted from a photograph of nature—as line drawings extracted from photographs appear more alike to the original object depicted (medium level of realism) but at the same time, they have less quantitative potential than an elevation. For this reason, it is not possible to extract as much useful data or information from line detected photograph of nature as we could from an elevation.

Thus, it is not appropriate to compare architectural elevations of *Fallingwater* with natural analogue views. The framework shows instead two options, both falling in the medium realism/medium quantitative category. These are the comparison of edge-detected photographs of natural elements with either edge-detected photographs of building facades or with line drawings of architectural perspectives. The option to use edge-detected photographs of *Fallingwater,* while valid, does have some sourcing issues. This study is focused on the original design of *Fallingwater,* as it was first built, and photographs from that era of full facades of the house from all angles are limited, not only by small primary source collections but also by the siting of *Fallingwater* – its position 'anchored […] in the wooded hillside above stream and waterfall' (Hoesli 2005: 214) makes it very difficult to obtain frontal photographs of facades. Additionally, photographs of the house would inevitably include trees in front of the building, however the fractal analysis method—as outlined in Chapter 5—does not include trees and other plants in the image used for architectural analysis.

Perspective drawings of *Fallingwater*, on the other hand, have several supportive reasons to be included in this analysis. The comparison for the second hypothesis is at least partially based on the understanding that Wright spent time at the Kaufmann's Bear Run property, observed the landscape (Kaufmann 1986) and then made his design for *Fallingwater* based on his own visual observations, as well as interpretations provided from technical drawings (Cleary 1999). In this case images derived from a visual experience need to be included in the analysis. Orthographic images for example, do not perceptually relate to visual experience, as it is impossible to actually experience an elevation in the same way that it is drawn, because while an elevation or plan is drawn in parallax, the human eye read the world through a type of perspective lens, and cannot see the 'real world' in parallax: we never see two lines as parallel, we see them as converging. Thus, while plans and elevations are universal modes of representation and this is why they are useful for fractal analysis comparisons between buildings, they do not replicate the way we view the world.

The analysis for the second hypothesis is not concerned with a comparison between buildings, but interested in the way a specific object or building is visually experienced from different positions in space. Carl Bovill alludes to the measuring of changing fractal dimensions in response to the viewer's experience (1996). He effectively asks: why don't we measure the fractal dimensions of perspective views of buildings? Bovill proposes that architecture is necessarily produced through the manipulation of rhythmic forms. He expands this idea to argue that fractal geometry allows the development of a 'quantifiable measure of the mixture of order and surprise' (1996: 3) in architecture and, moreover, that this measure reveals an essence of a building's formal composition. For Bovill, '[a]rchitectural composition is concerned with the progressions of interesting forms from the distant view of the facade to the intimate details' (1996: 3). Bovill suggests a method of measuring fractal dimensions in response to the shifting position of the viewer. If we wanted to measure the visual experience of Wright as he imagined a building in three dimensions, then perspective drawings are an accepted method for representing a building, generally to convey an impression to the viewer of how the building will actually appear (Leupen et al. 1997; Vaughan and Ostwald 2014b).

According to Arthur Drexler, Wright's 'drawings are valuable beyond their intrinsic beauty; they are a clue to the process of this thought' (1965: 9). It is known that Wright typically designed buildings in his mind before committing his thoughts to paper (Kaufmann 1986; MacCormac 2005). It was Wright's advice that one should '[c]onceive the building in the imagination, not on paper but in the mind, thoroughly - before touching paper (Wright 1928: 49). It is also known that Wright had strong three-dimensional visualisation skills and used perspectives as a design tool. In 1925, before beginning the design of *Fallingwater,* Wright emphasised that in practice, 'schemes are conceived in three dimensions as organic entities' (Wright 1992:18) and to achieve this, Wright and 'his office staff designed almost from the start using perspective drawings as study sketches' (Hewitt 1985:3). Drexler observes that 'Wright's [perspective] drawings were very much part of the day to day process of design. This fact is revealed not only by the preliminary sketches for perspective drawings that are now famous, […] and by certain unpublished perspective studies' (1965: 9). In the design and presentation process for *Fallingwater,* Wright used perspective drawings, some from different directions and some variations on one viewpoint. These perspectives can be used to set the angles for digital line drawing perspectives of *Fallingwater*, suitable for analysis.

Considering the options for representing *Fallingwater* and its surrounding landscape for this dissertation's second hypothesis, the most suitable images for the plan comparisons will be line drawings of plans of both the house and the four features of the landscape. For the views of the house and its surroundings, perspective line drawings of *Fallingwater* will be compared with line drawings extracted from edge-detected photographs of the four natural elements. Table 6.9 summarises the approach to the plan data and Table 6.10 the view data for this analysis.

Table 6.9 Plans; correlating data

Topic	Comparing plans of nature and architecture at *Fallingwater*				
	Subject #1	**Subject #2**	**Subject #3**	**Subject #4**	**Subject #5**
	House	Valley	Trees	Rock	Water
Attribute	Synthetic	Natural	Natural	Natural	Natural
Data Representation	Line Drawing	Line Drawing	Line Drawing	Line Drawing	Line Drawing
Data Type	Architectural floor and roof plans	Contour plan	Vegetation map	Geological plan	Nautical chart
Realism	Low	Low	Low	Low	Low
Quantitative potential	High	High	High	High	High

Table 6.10 Views; correlating data

Topic	Comparing views of nature and architecture at *Fallingwater*				
	Subject #1	**Subject #2**	**Subject #3**	**Subject #4**	**Subject #5**
	House	Valley	Trees	Rock	Water
Attribute	Synthetic	Natural	Natural	Natural	Natural
Data Representation	Line Drawing	Line drawings extracted from edge-detected photographs	Line drawings extracted from edge-detected photographs	Line drawings extracted from edge-detected photographs	Line drawings extracted from edge-detected photographs
Data Type	Architectural perspective	Landscape view	Botanical view	Geological view	Landform view
Realism	Medium	Medium	Medium	Medium	Medium
Quantitative potential	High	High	High	High	High

Conclusion

The second hypothesis in this dissertation requires a comparison between the forms of nature and architecture in *Fallingwater,* carried out using the box-counting method of fractal dimension analysis. The first part of this chapter examines a sample of existing cases of box-counting analysis of nature, and of architecture, and the handful of comparative studies of nature and architecture. An overview of the data types and presentation opportunities available is then extrapolated from the past examples. A set of methodological frameworks to determine which of these data types exactly could be compared in order to answer the second hypothesis are then provided and tested.

Reviewing the many data presentation methods and types available through the framework finally provides the analysis of *Fallingwater* and nature with a rationale of suitable data for analysis. The synthetic subject, the *Fallingwater* house, is already known. The natural data subjects are the valley, the forest, the watercourse and the stone outcrops. Knowing the data subject, the first step to select the representation method is to consider the background information, suitability for purpose and greatest data validity. The present chapter ends with the suggestion of data selected for comparison to be represented in two main ways, outlines of natural views to be compared with architectural perspective line drawings and architectural plans to be compared with site plans.

Chapter 7

Methodology

This chapter describes the method used in this dissertation to examine the two hypotheses and the rationale, limitations and scope of the method. The chapter includes a detailed discussion of the stages in the research process and the use of calculated and derived measures to characterise and compare the properties of individual designs, sets of designs and natural analogues.

It should now be clear that a different approach is required for the images used to test the two hypotheses. The data analysed in Chapter 8 provides results for the first hypothesis, which is focused on an architecture-architecture comparison. This follows the standard protocols used for architectural image analysis. In contrast, Chapter 9 tests the second hypothesis; an architecture-nature comparison. The requirements for the latter analysis have been developed exclusively for this study and—as shown in the previous sections—those requirements are different to those used for the former analysis. While acknowledging that all of the drawings analysed are artificially abstracted views, the aim of every decision taken in the re-drawing and re-representation of the subjects being analysed is to limit the impact of artificial graphic conventions and to standardise representational systems such that reasonable comparisons can be made between them.

The two-dimensional variation of the box-counting method can be used to measure the fractal dimension of a wide range of objects, as represented in images, including such diverse forms as arterial networks (Thomas and Frankhauser 2013), forest perimeters (Zeide and Pfeifer 1991), cityscapes (Chalup et al. 2008) and star clusters in galaxies (Peebles 1989). For every application of the method there are two different aspects of the experimental design that must be considered and described. The first, the optimisation of factors that are innate to the mathematical basis of the approach, is described in Chapter 5. The second, a considered approach to using that method to interrogate, interpret and understand Wright's architecture and its natural analogues, is contained in the present chapter. The first step in this approach builds on material presented in previous chapters and involves setting the rationale for selecting the data source, image texture levels and data settings. A comprehensive list of all of the designs that are analysed in Part III is also provided in this chapter, as are the representational standards employed to prepare the data for analysis. In the second part of this chapter, the stages of the research method are described. The last stages include deriving comparative indicators of the consistency of the data (or lack thereof).

7.1 Research Description

This dissertation uses fractal dimensions to examine two hypotheses about Frank Lloyd Wright's *Fallingwater.* A fractal dimension provides a measure of the characteristic visual complexity of a subject. Because fractal dimension data is numerical, it can be rigorously compared, provided the original subjects are all selected and prepared for analysis in a consistent manner.

The first hypothesis investigates if *Fallingwater* looks similar to Wright's other architectural designs, or if it is unique in its appearance in comparison to them. Wright's stylistic consistency, throughout various defined periods of his architectural career, has been previously demonstrated using multiple computational methods including syntactical analysis (Dawes and Ostwald 2014; 2015; Behbahani et al. 2016), shape grammars (Koning and Eizenberg 1981) and justified graph grammars (Lee et al. 2017). Fractal dimensions have also been used to mathematically differentiate the properties of Wright's three great stylistic periods; the Prairie, Textile-block and Usonian works (Vaughan and Ostwald 2011). The results of these computational studies demonstrate that Wright's architecture can be mathematically categorised into different styles, and it can be applied to analyse and differentiate the character of both plans and elevations. In the present context, by comparing the fractal dimensions of plans and elevations of *Fallingwater* with those of fifteen houses selected from three of Wright's well known architectural periods, encompassing a timeframe that includes *Fallingwater's* construction, any differences in visual complexity between *Fallingwater* and the other houses should be uncovered in the numerical results of the fractal analysis. The method using this process is described in the present chapter and the results of the analysis of these sixteen houses are presented in Chapter 8.

The second hypothesis uses fractal dimensions to compare the characteristic complexity of eight line drawings of *Fallingwater* with twenty line drawings of its natural setting. As Chapter 6 reveals, fractal analysis has been successfully used to analyse and compare natural forms in many past research projects, however the comparison of landscape (natural data) and architecture (synthetic data) is relatively untested. The natural data sets for this second study, the results of which are presented in Chapter 9, comprise of plans and views of the valley, the trees, rocks and water extracted from the landscape surrounding *Fallingwater*. The synthetic sets are made of plans and perspectives of *Fallingwater*. This chapter will provide details of how the method will be applied for this comparison of nature and architecture.

The methodology presented in this chapter first looks at the selection, scope, interpretation, representation and processing used for the data selected for the first hypothesis, then the respective data for the second hypothesis is provided. All of the results in Part III of this book were produced using software to undertake both the box-counting procedure and the calculation of fractal dimensions. That software, called *ArchImage* (Version 1.16) is used for all of the fractal dimension calculations undertaken for this dissertation.

7.2 Data Selection and Scope

7.2.1 Architecture

The argument that *Fallingwater* is distinctly different from any other works in Wright's oeuvre could be tested by comparing the house to *any* of his buildings; public or domestic. A study of commercial, urban or religious designs is possible using fractal dimensions, however, none of these building types have the same potential for producing consistent and, within reason, statistically valid results for comparisons with other designs. Houses are an ideal subject for an application of fractal analysis because, as a type, they possess similar scale, program and materiality. Thus, three sets of domestic designs by Wright have been selected for comparison with *Fallingwater* in this dissertation. Famous houses have been chosen because, by definition, they have been extensively researched in the past and thereby offer an opportunity for comparing the quantitative results derived from the present study with past qualitative interpretations. Indeed, in the analysis provided in Part III, the measured results are tested against specific arguments about these houses that have been suggested by historians, theorists and critics.

To maintain a level of consistency across each set of houses several guiding parameters have been chosen. The first of these is the general goal that no more than ten years should separate the earliest design in a set from the last design. Another consideration in grouping the entire fifteen houses into sets based on a time period means that the sets can be drawn from the three distinct stylistic shifts that occurred in Wright career (spanning, 1901 to 1910, 1923 to 1929 and 1950 to 1956) (Koning and Eizenberg 1981; MacCormac 2005; Dawes and Ostwald 2014; Behbahani et al. 2016; Lee et al. 2017). By using these defined styles, which both historians and computational researchers have previously validated, it is possible to use existing scholarly discourse on these periods to frame and interpret the results. A second parameter shaping the selection process is that single houses (rather than pavilions or estates) were chosen, to limit the impact of dramatically divergent scale projects. The third parameter is that completed works rather than unbuilt projects were chosen, in an attempt to ensure a similar level of design development. The fourth parameter is that houses were selected with a relatively tight geographic distribution, to limit the impact of climate on the form of the house.

Architectural Data Sets

Historians have defined three distinct stylistic periods in Wright's early and mid-career housing; the Prairie style (generally the first decade of the 20th century), the Textile-block era (the 1920s) and the Usonian era (the 1930s to the 1950s). For a qualitative comparison with *Fallingwater*, fifteen houses were identified using the four parameters, and divided into three sets based on the three stylistic periods, with five designs from each period. The years in which these houses were constructed, their locations and the number of plans or elevations available for analysis in Chapter 8 are recorded in Table 7.1.

*Table 7.1 Data scope: Houses/*Fallingwater

Set	Source	Year	Location	Elevations	Plans
Prairie Style	*Henderson*	1901	Illinois, USA	4	4
	Tomek	1907	Illinois, USA	4	4
	Evans	1908	Illinois, USA	4	3
	Zeigler	1910	Kentucky, USA	4	3
	Robie	1910	Illinois, USA	4	4
Textile-block	*La Miniatura (Millard)*	1923	California, USA	4	4
	Storer	1923	California, USA	4	4
	Freeman	1923	California, USA	4	3
	Ennis	1923	California, USA	4	2
	Lloyd-Jones	1929	Oklahoma, USA	4	4
	Fallingwater	1937	Pennsylvania,USA	4	4
Usonian	*Palmer*	1950	Michigan, USA	4	2
	Reisley	1951	New York, USA	4	3
	Chahroudi	1951	New York, USA	3	2
	Dobkins	1953	Ohio, USA	4	2
	Fawcett	1955	California, USA	3	2
	16			62	50

7.2.2 Nature

The possible natural data available to construct a visual comparison between a building and its site is extensive, particularly because the comparison between nature and architecture using fractal analysis has rarely been undertaken in the past, and no rigorous selection methodologies have been published. Previously, in Chapter 2, one of Wright's design strategies was identified that offered clear potential for a comparative analysis between *Fallingwater* and its surrounding landscape. This strategy, 'site characteristics', was further developed in Chapter 6, and now supplies the first of three parameters for selecting natural data which is appropriate for such a comparison. This first parameter is that the natural data must be sourced from one of four features, previously identified; the Pottsville sandstone, the Mesophytic forest, the steep gully and Bear Run stream. The second parameter defines the location of the source, being that these elements must come from the site. For example, one data source could be a Pottsville sandstone boulder near—or in—*Fallingwater*, rather than from a section of Pottsville exposure elsewhere in the country. The final parameter is based on the representation of the house, which will be examined as the whole visible object, rather than in part. Thus, the whole natural element, which is visible from a particular viewpoint, serves as the data source. For example, if a rhododendron tree on the site is selected, it will be the entire tree, rather than a leaf or branch (being just a component), and the root system will not be included (being invisible).

Natural Data Sets

For the four natural subjects selected for a qualitative comparison with *Fallingwater*, four views and one plan of each are produced for analysis. *Fallingwater* itself is represented by four perspective views and four plans – the three floor plans plus the roof plan. Table 7.2 records the details of the scope of natural data.

*Table 7.2 Data scope: Nature/*Fallingwater

Set	Source	Views	Plans
Natural element	Rocks	4	1
	Valley	4	1
	Forest	4	1
	Water	4	1
House	*Fallingwater*	4	4
		20	8

7.3 Data Source, Data Settings and Image Texture

All of the images analysed in this dissertation are based on specific primary sources relevant to the study. The parameters and limitation for selection of these sources are discussed for all data sets in this section. Once the sources are selected, the images being for analysis are derived from these sources following the pre-processing standards described in Chapter 5. The specific pre-processing standards for all images—summarised in Table 5.3—including image position, line weight, white space and image depth are all standardised using *Photoshop* (Adobe) prior to importing the files into *ArchImage* for analysis.

Chapter 5 also describes the framework for the levels of image texture/information to be included in the representation of the source (Table 5.1). Applying the research focus and purpose to that framework determines the level of information to be included in the images for analysis. A comparison between fractal analysis studies is difficult to achieve when the studies compared are conducted by different scholars. This is due to the range of variables, whereas having other studies in a similar representation type provides a rough guide for judging similarities or differences. The two hypotheses presented in this dissertation do not necessarily have the same research focus. Hypothesis 1 compares sets of buildings while Hypothesis 2 compares natural and built elements, and the levels of texture to be included in each approach are determined in this section.

7.3.1 Comparing Architecture with Architecture (Hypothesis 1)

The most productive images to use for measuring the fractal dimensions of an architectural design are line drawings of orthogonal plans and elevations (Ostwald and Vaughan 2016). Although elevations and plans are less realistic, they offer a universal system of representation that can be independently validated and used to construct reasonable comparisons between buildings (Leupen et al. 1997). The majority of all computational techniques for investigating architecture rely on plans and elevations, and this includes almost all past applications of fractal analysis listed in Chapter 4. Therefore, for the purposes of this research, the basic formal properties of these sixteen buildings are assumed to be sufficiently encapsulated in their 62 elevations and 50 plans.

Data Source

The first step in the house comparison process is to source an authoritative set of working drawings (or measured drawings if the former are not available) for each building being analysed. All the sources for Wright's architecture used in this thesis were predominantly reconstructed from his original working drawings reproduced by Storrer (2006) and Futagawa and Pfeiffer (1984, 1985a, 1985b, 1985c, 1986, 1987a, 1987b, 1987c) All of the elevations and plans are scanned and traced using *ArchiCAD* (Graphisoft) software. Provided the plans and elevations match, and overall dimensions are consistent, these documents are accepted as the primary data. If there are inconsistencies, the dimensions on the drawings or surveys are used to reconcile the views and then the design drawings and photographs are employed as a final means of interpreting and correcting any discrepancies. If any sets of drawings are incomplete, missing views are reconstructed using information from other sources (including sections or axonometrics) along with any photographs of the houses. In some situations where the design has since been altered—as is the case with several of Wright's houses—it is the original design that is analysed, not any later alterations.

For most designs analysed four elevations are typically produced; however, in the case of the Usonian houses, due to their triangular planning, three elevations are more practical. Whether there are four or three elevations, they are regarded as collectively constituting what might be called the ‘perimeter’ or ‘boundary’ facades of the building, that is, the formal expression of the building which is visible from points which are external to the structure and are largely perpendicular to the dominant geometry of the plan. In addition, some building plans are sufficiently complex that small facade surfaces may not be visible on any elevation or may be distorted. Such hidden elevations are also excluded from the analysis.

House plans used for analysis include the ground floor and any upper, habitable levels (which may include functional spaces in an attic level) and the roof plan. Basements are only drawn and analysed if they were clearly designed to contain habitable floor space. This means that plant or boiler rooms and wood storage spaces, which are on a separate floor plan and serve no other habitable function, are excluded from the analysis.

Image Texture

When producing the images for analysis, the level of ‘texture’ in the image delineation must be considered in accordance with the levels of representation in Table 5.1. For all the plans and elevations for every building analysed in Chapter 8, the building outline and primary, secondary and tertiary forms are digitally traced, but any material representation is excluded. This follows the guidelines for level 4 of the levels of representation framework in Chapter 5. In practice, this means that all tracing is undertaken using single lines, with no textures or infills. All changes in form and between materials are depicted using a single line separating the surfaces. As the delineated images represent a ‘real’ view of the building, dotted lines indicating hidden surfaces and forms are not shown. Typically included in the traced representation are any building elements that would produce a change in the surface level of more than 1 cm. Thus, a gutter and a fascia would be drawn, but not the top lip of the gutter. In plans, any change in floor material with a single line to divide them is traced, but, as in the elevations, the material is not indicated. Any built-in furniture, such as bathroom items and built-in benches are delineated with a simple outline of the furniture item. For the representation of doors and windows in elevations, the main frame, plus any secondary sash details or mullions are included, but not secondary leadlight or ornate moulds and joinery. Glass is depicted as opaque unless otherwise stated. In plan, doors are all drawn open at 90°, while all windows are depicted closed. No 'swings' are shown on doors or windows.

There are many architectural graphic conventions for representing voids, stair runs and roofs in plan but none of these could be used for the present analysis. To assist in the decision of how to represent the form of a plan, the building is imagined with its upper part sliced off, just below each ceiling line, and the view is drawn as if looking down into it. In a multi-level house this is especially significant because all stair treads up to the top of the level or floor being depicted in a plan are drawn. Again, no hidden detail lines for forms that are not visible are shown. However, any details that would be seen through void spaces and on the roof plan any features (such as lower roof levels) that would be seen below the roof, are all shown. Using a similar logic, it should be obvious that dotted 'roof-lines above' on a plan, or landscape contour lines, paths or paving are not depicted. The edge of a building is the limit of the drawing, with engaged steps and the balconies included, but not site works. If in elevation, the garden walls are a clear extension of the building form, and are integral to the visual appearance of a house, they are retained. Any internal construction details which would not be visible when built are not depicted. No vegetation, shadows or other entourage elements or textures are included in the analysis of the architecture.

7.3.2 Comparing Architecture with Nature (Hypothesis 2)

As described in the previous chapter, the most suitable images of nature are those that will provide correlating data with synthetic subjects (Keller et al. 1987; Chalup et al. 2008; Chen et al. 2010). For the view analyses in this study, the images for the natural subjects are simple linear representations, derived from edge-detected photographs (linear detail extraction), and the matching images for views of *Fallingwater* are simple line drawings of architectural perspectives. In plan view, the natural subjects are represented by scientifically specific—yet not overly detailed—line drawn plans (technical site drawings), and *Fallingwater* is represented by a line drawn architectural plans.

Data Source

The primary sources for the perspective images of *Fallingwater* are sourced from reproductions of Wright's original perspective drawings found in Drexler (1965) and Futagawa and Pfeiffer (1987c). These images were first scanned and then using *ArchiCAD* (Graphisoft) software, the original images were used to set the location and viewing cone to generate new the digital perspective drawings generated from a CAD model of *Fallingwater.* The CAD model was reconstructed from Wright's original working drawings reproduced by Storrer (2006) and Futagawa and Pfeiffer (1986). The plan images for *Fallingwater* are derived in the same way as those in section 7.3.1.

The source for views of three of the elements of the natural landscape (the trees, rocks and water) are from photographs taken by the author when visiting *Fallingwater* to undertake fieldwork for this dissertation in 2012. The photographs were scanned into *Photoshop* (Adobe) and the relevant natural element was extracted by converting it into a single line drawing using the edge detection function. Just as buildings are shown in their entirety—without nearby objects included in the analysed images—this process is applied to the natural elements. In extracting the elements from the source there may be parts of the object that are hidden from view because they have something in front of them in the photograph, but if you could walk into and around the scene you could see the part obscured in the photograph. Thus, in this case, the hidden part is reconstructed based on other evidence from other photographs or videos. For example, a boulder might have a tree branch partially obscuring it in an original photograph, and in its representation for analysis, this branch is removed and the missing section of the boulder is reconstructed. A different scenario is presented when parts of an element are hidden in the photograph because they can never be seen by a viewer, even if in the actual landscape. For example, the roots of a tree are hidden by the earth and the base of a boulder may also be completely hidden by the earth. In such cases, the part of the object which is never visible is ignored in the analysis.

Photographs capturing the views of the valley are problematic for analysis due to the thick forest and the house obscuring the essential information required for the analysis. To resolve this issue, the source for the valley images were selected from 2D still shots of 3D *Google Earth* views, which were then edge detected and converted to line drawings.

The source for the plan views of the natural elements is a combination of the original site plan produced for the Kaufmanns and the site plan produced by Wright's apprentices. These plans were scanned into *Photoshop* (Adobe) and line detection function used to isolate the four elements in plan form, generating four line drawings of the plans.

Image Texture

The approach to the level of texture included in past examples of image representation for fractal analysis of natural objects is typically equivalent to level three. A further consideration about the data presentation method used in this dissertation is based on the results of the previous comparative fractal studies between nature and architecture; being Bovill's (1996) analysis of Amasya, and his proposals for analyses at Sea Ranch, Nantucket and Helsinki. In these studies, he used linear, minimally detailed images, also equivalent to level three in the gradients of texture representation provided in Chapter 5. This level of representation is appropriate for general design issues, where ‘design’ is taken to encompass decisions about form and materiality, these being the main elements scholars use to describe *Fallingwater*. Typically, the house and its surroundings are described in terms of overall shape, form and aspect—such as the primary geometric gestures that make up the landscape and the building design—criteria that all fit under the notion of ‘site characteristics’. In this way, it is proposed that the analysis in this study is of line-based imagery, using level three representation for the nature-architecture study.

The architectural perspectives and plans, edge-detected views of the natural elements and plans of the natural landscape, are all depicted with the image outline and primary and secondary forms, but any tertiary form or material representation is excluded, in accordance with the level 3 framework. This is an important consideration because typically, some architecturally-rendered perspective images can be highly detailed. In this case, much of that fine detail will not be considered. In practice, this means that all tracing is undertaken using single lines, with no textures or infills. In plan, perspective and line-detected images, all changes in form and between materials are depicted using a single line separating the surfaces. Typically included in the traced representation are any elements that would produce a change in surface level of greater than 25 mm. For example, when depicting a tree on the site, if it had small changes at the base of the tree, with less than 30 mm of modulation where the roots descend into the earth, these lesser details are not depicted. However, if the tree had a deeply buttressed trunk, then these changes in form are shown.

Apart from the level of texture depicted in the architectural images, most of the other considerations for representing architecture listed in the previous section apply to the representation of *Fallingwater* in this second approach. This includes not representing shadows, vegetation or other transient of unbuilt details around the building. For example, while the waterfall is a key element in the house, it is not included in the perspective images, as it will be included as a stand-alone element and its individual fractal dimension calculated for comparison *with* the house. As in previous section, typical drawing conventions, such as door swings, dotted lines etc., will not be included in the depictions for testing the second hypothesis.

7.4 Dissertation Research Method

There are six stages to the standard research method used, each of which are described in detail over the following sections. These stages are:

i. Identifying and coding data (source images).
ii. Box-counting fractal analysis of each building or natural feature in isolation to determine *D* values and derive mean values and a 'composite' mean for the entire item.
iii. For the comparative sets, analysis of each set to determine mean results as well as an 'aggregate' result for the entire set.
iv. Comparative analysis of all results.
v. Presentation of results.

In the context of this research, the 'set' of buildings is a group of five houses designed by Wright and defined by a particular style. The two sets for *Fallingwater* comprise the plans and elevations reproduced at level 4 for Hypothesis 1, and the plans and perspectives reproduced at level 3 for Hypothesis 2.

7.5 Definitions and Coding Method

The terminology and coding procedure for all the raw data analysed in Part III of the dissertation is described in the following two sections, each relating to the particular hypothesis it is focussed on, and the particular data which serves the test. The first section describes the terminology and coding method for the approach taken to the data in Chapter 8, first explaining how it is applied for individual buildings and then specifically the approach to the building sets (Prairie, Textile-block and Usonian). The second section describes the definitions and coding method to derive data for Chapter 9, the views and plans of *Fallingwater* and the natural elements

7.5.1 Definitions and Coding Method: Hypothesis 1

i. The elevations of each house are either numbered ($E_{1\text{-}4}$) in accordance with the conventions used in past research.
ii. The ground floor plan is numbered zero (P_0) and any floors above ground level are numbered consecutively from 1 (P_1, P_2 ,...). If one or more basement levels, are present in a design, they are designated with negative integers (P_{-1}, P_{-2} ,...).
iii. The roof is separately labelled (P_R) although it is grouped with the plan set for determining mean values.

Analysis of Each Building (15 houses + Fallingwater*)*

Fractal dimension measures are calculated for each view of a particular house, along with some derived measures from this raw data (Table 7.3). The following steps describe the way a series of fractal dimension results for elevations and plans are determined and then combined to create a 'composite' value for a building.

i. Each elevation is measured using *ArchImage* software to determine its fractal dimension ($D_{E1\text{-}4}$).
ii. The mean D_E value for the house is determined (μ_E). This value is a measure of the typical level of visual complexity observable in the exterior of the house.
iii. Each plan is measured using *ArchImage* software to determine its fractal dimension ($D_{P\#}$ or D_{PR}).

iv. The mean of the $D_{P\#}$ and D_{PR} results for the house is determined (μ_P). This value is a measure of the typical level of formal complexity present in the spatial arrangement of the plan and its corresponding exterior expression in the roof.

v. The $D_{E1\text{-}4}$ and $D_{P\#\text{-}PR}$ results for the house are combined into a mean for the entire house (μ_{E+P}). This is a composite measure of the typical level of characteristic complexity present in the building.

Table 7.3 Summary of definitions relating to the analysis of an individual house

Abbreviation	Meaning	Explanation
D	Fractal Dimension	Fractal dimension (*D*) is a measure of the formal complexity of a design and the consistency with which it is distributed across all scales of a design. For an image, *D* is a value between 1.0 and 2.0. The fractal dimension of an architectural elevation is D_E. The fractal dimension of an architectural plan is D_P.
D_E	*D* for a specific *elevation*.	
D_P	*D* for a specific *plan*.	
μ_E	Mean *D* for the visible *elevations* of a building.	A 'mean' is the average of a set of values (the sum of the values divided by their number). It is expressed here as a 'population' mean (μ) because the findings of this research are generally not extrapolated to comment on anything other than the actual houses being analysed. The mean *D* for all of the elevations of a single building is μ_E. This value reflects the typical level of characteristic formal complexity visible in the exterior of a design. The mean *D* for all of the plans of a single building is μ_P. This value reflects the typical level of characteristic complexity present in the spatial and formal properties of the interior and the expression of its roof. The 'composite' result, μ_{E+P}, is the mean for the plans and elevations of a single building.
μ_P	Mean *D* result for the habitable *plans* of a building.	
μ_{E+P}.	Mean *D* result for all of the plans and elevations of a building.	

Analysis of a Set of Buildings (5 houses of one style)

The group of five houses in each of Wright's stylistic periods—the Prairie, Textile-block and Usonian—can each be called a set of houses that provide a point of comparison for the results of *Fallingwater*. Thus the five Prairie style houses can be grouped together and considered as the Prairie set etc. The results of sets are signified in this research by the presence of curly brackets {…}. The following steps describe the process for combining a series of fractal dimension measures derived from five individual houses to develop results for the set. Table 7.4 shows the summary of definitions used regarding these sets.

i. The five μ_E results in the set are averaged together to create an aggregate result for the set ($\mu_{\{E\}}$) which is a measure of the typical level of characteristic visual complexity present across all facades in the set.

ii. The median fractal dimension for all elevations in the set is calculated for comparative purposes ($M_{\{E\}}$).

iii. The standard deviation of the elevations in the set is determined ($std_{\{E\}}$).

iv. The five μ_P results are combined to create an aggregate result $\mu_{\{P\}}$ which is a measure of the typical level of formal complexity present in, and experienced throughout the interior of, the set of the architect's works.

v. The median fractal dimension for all plans in the set is calculated for comparative purposes ($M_{\{P\}}$).

vi. The standard deviation of the plans in the set is determined ($std_{\{P\}}$).

vii. The five μ_E and μ_P results are combined to create an aggregate value ($\mu_{\{E+P\}}$). This value measures the typical level of characteristic complexity present across the entire set of plans and elevations.

Table 7.4 Summary of definitions relating to the analysis of a set of houses.

Abbreviation	Meaning	Explanation
$\mu_{\{E\}}$	Mean *D* for a set of *elevations*.	The mean *D* result for all of the elevations in a set of buildings is $\mu_{\{E\}}$. This value is a measure of the typical level of characteristic formal complexity visible across the exterior of a set of designs.
$\mu_{\{P\}}$	Mean *D* for a set of *plans*.	The mean *D* result for all of the plans of a single building is $\mu_{\{P\}}$. This value is a measure of the typical level of characteristic complexity present in the spatial and formal properties of the interiors of a set of buildings.
$\mu_{\{E+P\}}$	Mean *D* for a set of *elevations* and *plans*.	The mean *D* result for all of the plans and elevations of a set of buildings is $\mu_{\{E+P\}}$.
$M_{\{E\}}$	Median *D* for a set of *elevations*.	In some sets of data, outliers skew the results in a particular way. A comparison between the mean *D* result for the set ($\mu_{\{E\}}$ or $\mu_{\{P\}}$) and the median *D* result for the same set ($M_{\{E\}}$ or $M_{\{P\}}$) allows for the detection of statistical outliers and identification of the direction of skew in the data. This combination is useful for being able to identify if a particular building, or group of elevations or plans, have unduly influenced the final result.
$M_{\{P\}}$	Median *D* for a set of *plans*.	
$std_{\{E\}}$	Standard Deviation for a set of *elevations*.	The standard deviation of a set is a measure of its distribution or dispersion relative to the mean. The higher the standard distribution, the more divergent the results.
$std_{\{P\}}$	Standard Deviation for a set of *plans*.	The standard deviation of a set of buildings is calculated for both elevations ($std_{\{E\}}$) and plans ($std_{\{P\}}$).

7.5.2 Definitions and Coding Method: Hypothesis 2

The naming and coding process for the raw data of the second hypothesis used in Chapter 9 is broadly similar to the first, with some differences due to the different image sources. The perspective views of *Fallingwater* form another composite measure of the Kaufmann house, in this case a result that reflects more of the building's actual visual appearance and less of its architectural details. This section first describes the definitions and coding method applied to the natural elements and then describes those used for

Fallingwater. As both share the same terminology, table 7.5 summarises all the definitions at the end if the section.

Table 7.5 Summary of definitions relating to the analysis of an individual house

<table>
<tr><th>Abbreviation</th><th>Meaning</th><th>Explanation</th></tr>
<tr><td>D</td><td>Fractal Dimension</td><td rowspan="3">Fractal dimension (D) is a measure of the formal complexity of a design and the consistency with which it is distributed across all scales of a design. For an image, D is a value between 1.0 and 2.0. The fractal dimension of the view of an object is D_V. The fractal dimension of a plan is D_P.</td></tr>
<tr><td>D_V</td><td>D for a specific view.</td></tr>
<tr><td>D_P</td><td>D for a specific plan.</td></tr>
<tr><td>Set</td><td>Collection of related values</td><td>All of the images for one natural element are considered a ‘set’ while all the Fallingwater images are another ‘set’</td></tr>
<tr><td>μ_V</td><td>Mean D for the views of a set.</td><td rowspan="2">A ‘mean’ is the average of a set of values (the sum of the values divided by their number). It is expressed here as a ‘population’ mean (μ) because the findings of this research are generally not extrapolated to comment on anything other than the actual images being analysed.
The mean D for all of the views is μ_V. This value reflects the typical level of characteristic formal complexity visible.
The mean D for all of the plans of Fallingwater is μ_P. This value reflects the typical level of characteristic complexity present in the spatial and formal properties of the interior and the expression of its roof. There is only one plan for each natural element so the mean D is not calculated for these.</td></tr>
<tr><td>μ_P</td><td>Mean D result for the habitable plans of a building.</td></tr>
</table>

Identifying and Coding Data (Natural Elements)

i. Four edge detected frontal views for each natural element are numbered (V_{1-4}) in accordance with the conventions used in past research.

ii. Technical plans used for natural elements are typically only of one layer. For this reason, only one plan for each of the natural elements is used. This plan is not numbered but simply labelled (P).

Analysis of Each Natural Element

Results are directly calculated for each natural element, along with some derived measures from this raw data (Table 7.5). The following steps describe the way a series of fractal dimension results for views and plans are determined.

i. Each natural view is measured using *ArchImage* software to determine its fractal dimension (D_{V1-4}).

ii. The mean D_V value for each natural element is determined (μ_V). This value is a measure of the typical level of visual complexity observable in the element.

iii. Each plan is measured using *ArchImage* software to determine its fractal dimension (D_P).

*Identifying and Coding Data (*Fallingwater*)*

i. Four perspective views of *Fallingwater* are numbered ($V_{1\text{-}4}$) in accordance with the conventions used in past research.
ii. The ground floor plan is numbered zero (P_0) and the floors above ground level are numbered consecutively from 1 (P_1, P_2)
iii. The roof is separately labelled (P_R) although it is grouped with the plan set for determining mean values.

Analysis of Fallingwater

Results are directly calculated for *Fallingwater,* along with some derived measures from this raw data (Table 7.5). The following steps describe the way a series of fractal dimension results for views and plans are determined.

i. Each perspective view is measured using *ArchImage* software to determine its fractal dimension ($D_{V1\text{-}4}$).
ii. The mean D_V value for *Fallingwater* is determined (μ_V). This value is a measure of the typical level of visual complexity observable from the viewpoints suggested by Wright.
iii. Each plan is measured using *ArchImage* software to determine its fractal dimension ($D_{P\#}$ or D_{PR}).
iv. The mean of the $D_{P\#}$ and D_{PR} results for *Fallingwater* are determined (μ_P). This value is a measure of the typical level of formal complexity present in the spatial arrangement of the plan and its corresponding exterior expression in the roof.

7.6 Comparative Analysis

The difference between two fractal dimensions is defined as the *Range* (R) and it can be expressed in two ways. First, the difference can be measured in terms of absolute fractal dimensions (R_D) where the subtraction of one D result from another determines the positive or negative difference in terms of D. Alternatively, because the fractal dimension of an image is necessarily between 1.00 and 2.00, the difference between two dimensions can also be expressed as a percentage ($R_{\%}$). Importantly, while both expressions are useful for the analysis of results, $R_{\%}$ is simply R_D with the decimal point moved two places to the right. In general $R_{\%}$ is more useful for considering large sets of results, whereas R_D is more commonly used for individual comparisons (Table 7.7). Range is handled as follows.

i. The range between the highest and the lowest D_{E} result in an individual house is calculated ($R_{\mathrm{E}\ (D \text{ or } \%)}$).

ii. The range between the highest and the lowest D_{E} results in a set of houses is calculated ($R_{\{\mathrm{E}\}\ (D \text{ or } \%)}$).

iii. The range between the highest and the lowest D_{P} result in an individual house or natural element is calculated ($R_{\mathrm{P}\ (D \text{ or } \%)}$).

iv. The range between the highest and the lowest D_{P} results in a set of houses or the set of natural elements is calculated ($R_{\{\mathrm{P}\}\ (D \text{ or } \%)}$).

v. The range between the highest $\mu_{\mathrm{E+P}}$ and the lowest $\mu_{\mathrm{E+P}}$ result in a set is calculated ($R_{\{\mu\mathrm{E+P}\}\ +\ (D \text{ or } \%)}$). This measure reflects the degree of diversity within the $\mu_{\{\mathrm{E+P}\}}$ result.

vi. The range between the μ_{E} of *Fallingwater* and the $\mu_{\{\mathrm{E}\}}$ of a stylistic set of houses ($R_{\mu\mathrm{E}\ (D \text{ or } \%)}$) reflecting the diversity between elevations of *Fallingwater* and elevations of Wright's other houses of distinctive stylistic periods.

vii. The range between the μ_{P} of *Fallingwater* and the $\mu_{\{\mathrm{P}\}}$ of a set ($R_{\mu\mathrm{P}\ (D \text{ or } \%)}$) reflecting the diversity between *Fallingwater* and any set of plans studied.

viii. The range between the μ_{E+P} of *Fallingwater* and the $\mu_{\{E+P\}}$ result of a set is calculated ($R_{\mu E+P + (D \text{ or } \%)}$). When comparing this result to a $R_{\{\mu E+P\}}$ result, the measure reflects the degree of diversity the diversity between *Fallingwater* and other sets of houses.

ix. The range between the highest and the lowest D_V result in an individual natural element or the *Fallingwater* perspectives is calculated ($R_{V (D \text{ or } \%)}$).

x. The range between the μ_V of *Fallingwater* and the μ_V of a set of natural elements ($R_{\mu V (D \text{ or } \%)}$) is calculated.

xi. The range between the μ_P of *Fallingwater* and the D_P of a natural element ($R_{\mu P (D \text{ or } \%)}$) is calculated.

Table 7.7 Summary of definitions of data used for comparative purposes

Abbreviation	Meaning	Explanation
R_D	Range between the highest and lowest results expressed as a value of *D*.	The difference between two sets of *D* results is the range (*R*). Because the maximum *D* value for an image is 2.0 and the minimum practical value is 1.0, *R* can be expressed as either an absolute value of *D*, or as a percentage (% = 100 x R); this is signalled in the subscript annotation of *R*.
$R_\%$	Range between the highest and lowest results expressed as a percentage.	
$R_{E (D \text{ or } \%)}$	Range between the highest and lowest D_E results in a single building.	A low R_E, R_V or R_P value implies that each of the images representing a single building or subject have a high degree of formal similarity. Conversely, a high R_E, R_V or R_P value suggests that at least one of the items, in terms of formal similarity, diverges from the others.
$R_{V (D \text{ or } \%)}$	Range between the highest and lowest D_V results in a single subject.	
$R_{P (D \text{ or } \%)}$	Range between the highest and lowest D_P results in a single building.	
$R_{\{E\} (D \text{ or } \%)}$	Range between the highest and lowest D_E results in a set of buildings.	The range between sets of results is significant for interpreting the relationship between elevations or plans across the complete set of buildings, or the views in the entire set of natural elements.
$R_{\{P\} (D \text{ or } \%)}$	Range between the highest and lowest D_P results in a set of buildings or in the set of natural elements.	The mean for the combined plans and elevations of a building may be compared across the set.
$R_{\{\mu E+P\} (D \text{ or } \%)}$	Range between the highest and lowest μ_{E+P} results in the set of buildings.	
$R_{\mu E (D \text{ or } \%)}$	Range between the μ_E of *Fallingwater* and the $\mu_{\{E\}}$ of a set of houses.	The range between mean elevations and mean plans of *Fallingwater* and the mean elevations and mean plans of the sets of Prairie, Usonian and Textile-block houses will provide data to answer Hypothesis 1.
$R_{\mu P (D \text{ or } \%)}$	Range between the μ_P of *Fallingwater* and the $\mu_{\{P\}}$ of a set of houses.	
$R_{\mu V (D \text{ or } \%)}$	Range between the μ_V of *Fallingwater* and the μ_V for the sets of natural elements.	The range between the views, and plans of *Fallingwater* and the sets for the landscape surrounding the house provide data towards an answer for Hypothesis 2.
$R_{\mu E+P + (D \text{ or } \%)}$.	Range between the μ_{E+P} of *Fallingwater* and the $\mu_{\{E+P\}}$ result of a set.	

7.7 Interpretation of Results

While developing a mathematical measure of complexity has been previously explained, it can be useful to develop a more unintuitive understanding of what particular measures or ranges imply. For example, if you imagine that you have a set of images laid out before you, how similar might they appear in terms of their relative visual complexity and how would you describe this verbally to someone else? Past research has presented indicative qualitative descriptors (summarised in Table 7.9) for the purpose of more intuitively relating the comparative results to various theorized relationships between buildings or architects works (Ostwald and Vaughan 2016). This practice is purely qualitative, and while the descriptors have been used previously purely for architectural analysis, their application to comparing natural elements should be similar and these descriptors will be consistently in the discussion for Part III.

Table 7.9 Qualitative descriptors used for ranges

Range (%)	**Qualitative Descriptors**
$x < 2.0$	'Indistinguishable'
$2.0 \leq x < 6$	'Very similar'
$6 \leq x < 11$	'Similar'
$11 \leq x < 20$	'Comparable'
≥ 21	'Unrelated'

Conclusion

The methodology for sourcing and preparing the final versions of images selected for analysis in this dissertation is covered in this chapter, as well as the approach to presenting and analysing the numerical data produced by the fractal analysis of all 144 images tested.

The large number of measures presented in this chapter might seem complex at first, but there are really only two basic things being measured in all cases: the first is the difference between *Fallingwater* and the other houses, via the fractal dimensions of elevations and plans; and the second is the difference between *Fallingwater* and its surrounding landscape, via the fractal dimensions of views and plans. To compare the various measures derived in this way, the difference or range between the results is determined. If the range is relatively small, then the images are visually similar. If the range is large, then they are dissimilar. Ultimately, in most cases, a small range implies a degree of consistency in the way a designer works, even though various site and program-specific differences might occasionally confound the data.

PART III Results

Chapter 8

Comparing *Fallingwater* with Wright's Architecture

To answer the first hypothesis of this dissertation, the present chapter uses fractal dimensions to analyse the characteristic complexity of *Fallingwater* and of fifteen other houses by Frank Lloyd Wright, focusing on how they relate to each other. It commences by treating architecture as a special type of dimensional data, which can be measured in individual designs, and then compared. However, it is not productive to examine architecture solely using numbers. Buildings serve human functions, they enable critical social structures and they embody cultural values. Architecture is not just space and form divorced from purpose, geography or human aspiration. Therefore, previous chapters have provided a social and historical context for *Fallingwater*, and this chapter also provides a brief background to the fifteen additional houses, prior to undertaking a mathematical analysis of each. Once the analysis is complete, the resultant data is then interpreted in terms of both simple statistical patterns and accepted historical and theoretical readings. In this way the chapter shifts between qualitative and quantitative approaches, using the former to ground or frame the research and the latter to give it a unique lens through which to study the claim that *Fallingwater* is different to other houses by Wright.

The chapter commences by using fractal dimensions to analyse four plans and four elevations of *Fallingwater*. The results for the house are then critically assessed, demonstrating the way such information can be used to test a more traditional interpretation of the building. The houses used as a point of comparison with *Fallingwater* were identified in the previous chapter, being five houses each from Wright's Prairie, Textile-block and Usonian styles. The next section of the present chapter calculates the fractal dimensions of the plans and elevations of each of the houses in each stylistic set, and these results are also presented in the context of an overall stylistic interpretation of the houses and these key design periods. Finally, the results for *Fallingwater* are compared with the fifteen houses, in terms of levels of complexity measured in the sets and in individual houses, to determine mathematically, how similar or different they are to *Fallingwater*. This process provides an answer for Hypothesis 1.

8.1 Interpreting the Data

The data representing the immediate results is presented in two types of tables, and at least one type of chart, firstly to assist with understanding the results in relation to each house or set of houses, and also to highlight any indication of visual complexity differences or similarities between *Fallingwater* and Wright's other houses. The data is first presented in results tables that display the *D* values for every elevation and plan of each house, along with mean results for each house's elevations and plans (Tables 8.1, 8.3, 8.5 and 8.7). For the three stylistic sets, the table additionally records mean, median and standard deviation results for the overall set. At the base of all tables, composite results for each house are recorded (being the mean of both elevations and plans), and for the stylistic sets, the aggregate results for the overall set are also included.

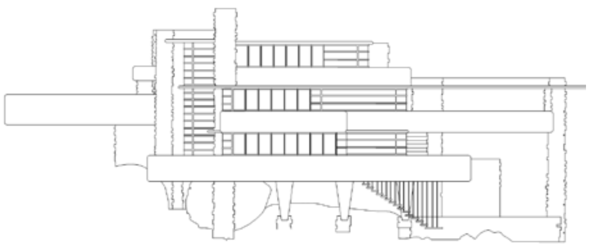
The numerical values contained in the results table are then charted in a combined line and bar graph (figs 8.2, 8.4, 8.6, 8.8). The vertical *y*-axis of this chart is the fractal dimension (*D*), while the horizontal *x*-axis is the set of houses. The name of each house has a vertical bar graph above it indicating the range of *D* values for both plans and elevations ($D_{\text{E1-4}}$ and $D_{\text{P\#-PR}}$). For the sets of houses, an overlaid line graph connects the mean results for both elevations (μ_{E}) and plans (μ_{P}), and a horizontal line records the mean value for the sets of both elevations ($\mu_{\{\text{E}\}}$) and plans ($\mu_{\{\text{P}\}}$) and the associated medians ($M_{\{\text{E}\}}$ and $M_{\{\text{P}\}}$). The *D* value for the roof in each case is indicated on the vertical bar with a triangle.

The difference between two fractal dimensions is defined as the range (*R*). The range of the plans and elevations can be read visually from the graphed results, and the second table of data associated with each set of results contains these comparative values, expressed as either a range of *D* or as a percentage difference (Tables 8.2, 8.4, 8.6, 8.8). For individual houses, the range within both plans and elevations is shown. For the stylistic sets, the range across the overall set is recorded and at the base of the comparative results table, the range between the highest and lowest composite results (combined plans and elevations for each house) are reported for the overall set.

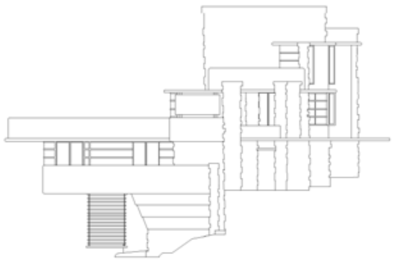
The range (*R*) values are particularly useful for showing differences or similarities between results, particularly when a set of guidelines are used for interpreting how similar the images might appear in terms of their relative visual complexity and how these could be described. For the purpose of more intuitively relating the comparative results to various theorized relationships between buildings, Table 7.9 in Chapter 7 connects the mathematical results to some indicative qualitative descriptors. This practice is purely qualitative, but these descriptors have been used previously in similar studies and have been compiled for use in architecture (Ostwald and Vaughan 2016). They are used consistently in the discussion sections over the following chapters. The range values are used in comparing *Fallingwater* and the other houses, in a Table (8.9) and the qualitative descriptors interpret these ranges graphically (figs 8.15 - 8.17). Importantly, these descriptors have been used to characterise variations between very different styles (say, between Minimalism and Postmodernism, or between Modernism and the Arts and Crafts movement) and as such, it might be expected that Wright’s architecture should fall in the “similar” or “very similar” range.

8.2 Analysis of *Fallingwater*

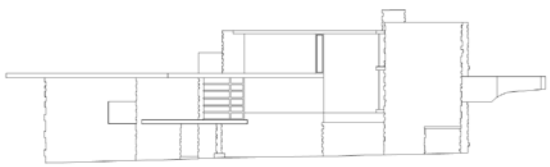
This section first presents the images of *Fallingwater* that were analysed using the box-counting method. The first table and chart show the results for the level of characteristic complexity (*D*) in the elevations and plans, and the mean calculations of these (Table 8.2). The comparative values table shows the range between the results (Table 8.3). All of these results are then interpreted in the overall discussion that follows, on the complete set of fractal dimension measures for *Fallingwater*.



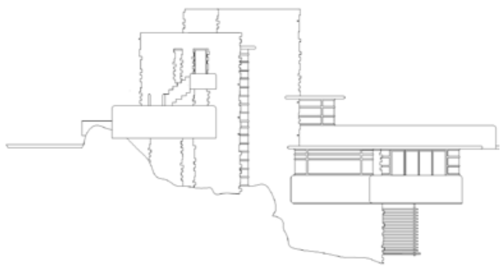
a. South Elevation



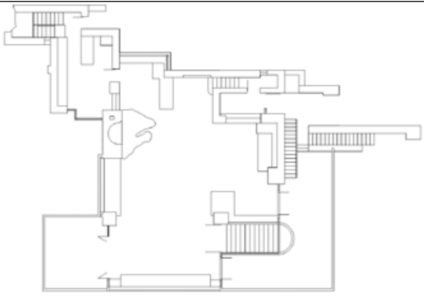
b. East Elevation



c. North Elevation

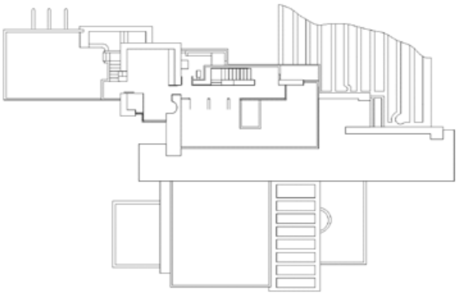


d. West Elevation

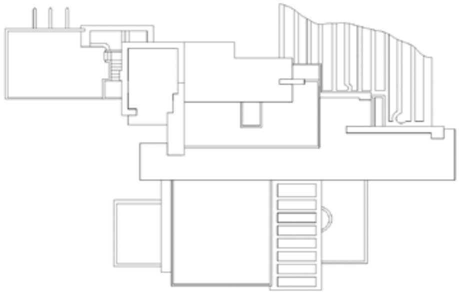


e. Ground Floor Plan

f. First Floor Plan



g. Second Floor Plan



h. Roof Plan

Figure 8.1a – h Images of Fallingwater *analysed – not shown at a uniform scale*

Table 8.1 Fallingwater, *results*

Elevations	D_{E1}	1.3321
	D_{E2}	1.4628
	D_{E3}	1.4341
	D_{E4}	1.3786
	μ_E	1.4019
Plans	D_{P0}	1.3897
	D_{P1}	1.4439
	D_{P2}	1.4133
	D_{PR}	1.3870
	μ_P	1.4085
Composite	μ_{E+P}	1.4052

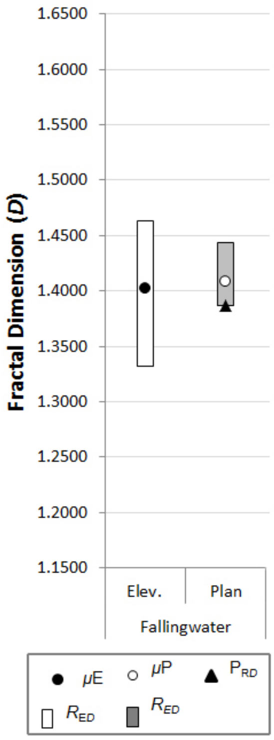


Figure 8.2 Fallingwater, *graphed results*

Table 8.2 Fallingwater, *comparative values*

Elevations	R_{ED}	0.1307
	$R_{E\%}$	13.07
Plans	R_{PD}	0.0569
	$R_{P\%}$	5.69

Measuring the characteristic visual complexity of a building such as *Fallingwater* produces a series of numerical values (Table 8.1). These numerical outputs do not necessarily express much until they are interpreted in context of the building as an architectural form. Starting with the elevations, the fractal analysis reflects the level of detail or formal information that is typically visible across all scales of observation of the facade. This measure could also be considered a reflection of the functional or habitable qualities of its interior because the location of windows and doors, along with the modulation of walls, roofs and balconies, are all potentially expressions of function.

The fractal dimension results for the *Fallingwater* elevations indicate that the facade with the lowest result—or least amount of visible characteristic complexity—is the north (D_{E1} = 1.3321). This is the side facing the cliff and hill, without much outlook. In the northern hemisphere, the northern side gets no direct sun, and as Wright designed houses to address the sun (Hoppen 1998; Hess and Weintraub 2012) it is no surprise that this elevation has less fenestration than the other facades, and correspondingly, less visual complexity. On the opposite side of the house is the south elevation, the features of which are prominent in photographs commonly used as the cover of many publications on Wright or *Fallingwater* (Kauffmann 1986; Hoffmann 1993; Fell 2009; Menocal 2000). This south elevation is parallel to the Bear Run stream and it reflects or expresses much of the program of the house, with its layered balconies, their projecting roof overhangs, and the windows and doors that vary according to location and purpose. These details add up to a visually complex elevation and the results show it is the most geometrically expressive facade of the house (D_{E2} = 1.4628). The east elevation is the second most visually complex (D_{E3} = 1.4341) with the end view of the many stacked stone walls contributing to the visual complexity. Overall, these results contribute to the mean outcome for the elevations of the overall house (μ_E = 1.4019).

Plan analysis requires a different interpretation of the meaning of the fractal dimension of architecture. The fractal analysis of a building plan measures the formal and spatial complexity of a design, not as it can be seen in its totality, but as it can be experienced through movement or inhabitation (Ostwald 2011a). While an elevation is potentially close to the experience of viewing a facade (albeit through a telephoto lens and using perspective correction), the plan view assumes that part of the building has been completely removed to reveal a more abstract spatial relationship within, one which is never really seen in this way, but is experienced. Hillier and Hanson have demonstrated that this experience of space and form, as a reflection of the social structure implicit in a building, is a significant property (Hillier and Hanson 1984; Hillier 1996).

The floor plans of *Fallingwater* show a mean value of μ_P = 1.4085. Perhaps surprisingly, the ground floor plan—which contains the entry and living room and includes visually complex items such as the existing boulder retained as the hearth for the fire and several stairways—has the lowest value (P_0 = 1.3897). The greatest amount of formal information can be found on the first floor (P_1 = 1.4439). In comparison to the open planning of the ground floor, this next level up features a veritable warren of rooms and passageways. This planning reflects the era, wealth and lifestyle of the Kaufmann family, with bedroom arrangements that appear unusual today. This floor has one room each for Edgar and Liliane, each with a person bathroom, and a guest bedroom and another bathroom. The combination of all these small rooms, several staircases in different directions and more outdoor terraces, creates increased formal complexity in this plan.

In architectural research, the roof plan poses a different dilemma for interpretation, as it is shaped by both the facade expression of a building and its interior planning. In theory, it is neither clearly separate from the set of elevations and plans nor does it fit with either set perfectly. Nevertheless, it is notable that with a few exceptions, relatively few roof plans resemble their elevations so much as they resemble their internal plans (Leupen 1997; Ostwald and Vaughan 2016). This is because roof plans are typically either a product of expediency (weather-proofing the form of the plan) or a by-product of other decisions about massing and expression. Therefore, despite the roof-scape being described in various architectural primers as the ‘fifth facade’ of a building, in this case it is treated as a special type of plan.

While the roof plan of *Fallingwate*r has the lowest complexity of all the plans (P_R = 1.3870) this is only slightly less complex than the second floor, in the order of 0.3%, an extremely small variation. Unlike many houses that have a simple roof covering the entire house—and a correspondingly low P_R—*Fallingwater’s* cantilevering terraces, overhangs and outdoor staircases all add greatly to the complexity of its aerial view. In particular many of the living spaces of

Fallingwater are outdoors, and these are captured in the roof plan, which shows all parts of the building down to the ground.

Comparing all four elevations of *Fallingwater* to each other produces a range of $R_{E\%}$ = 13.07. According to the gradients provided in Table 7.9, the elevations only show some correspondence to each other visually, but are not as similar to each other as the plans are. The plans of *Fallingwater* could be considered to be very similar to each other $R_{P\%}$ = 5.69. The mean result of all the plans and elevations provides a composite result for the house (μ_{E+P} = 1.4052). While this result describes the overall house, in order to derive some meaning from it, it needs to be compared with other house values. The next section analyses fifteen other houses by Wright from which a comparison can be made.

8.3 House Sets for Comparison with *Fallingwater*

During his lengthy career Wright pioneered many architectural design strategies for housing. The houses selected for analysis in this chapter are drawn from the three most distinct periods, marking significant early, mid and late eras in Wright's domestic architecture. The first five of Wright's early house designs analysed in this chapter were completed between 1901 and 1910 and are from his Prairie style period, the next set of houses analysed are from his mid-career Textile-block period (1922 -1932) and the last set are from Wright's Usonian period (1950 - 1955).

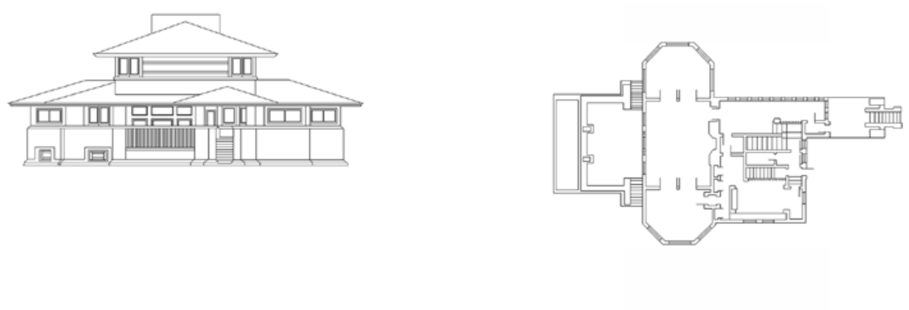
8.3.1 Prairie Style Houses

Wright's Prairie Style is an approach inspired by the long flat reaches of the American prairie plains and the houses he designed during this period likewise have strong horizontal lines, dramatically wide eaves and low-pitched roofs. Hess and Weintraub describe the style as 'a fully formulated Modern architecture rooted in the American Midwest' (2006: 12). In these houses, 'a vocabulary of forms was used to translate or express the grid at all points - the solid rather than pierced balconies, planters, bases of flower urns, clustered piers, even built in seats were evocations of the underlying structure of a house' (Sergeant 2005: 192).

The five Prairie style houses by Wright were constructed between 1901 and 1910. Four of the five are in the state of Illinois and the fifth is in the neighboring state of Kentucky. All the houses display the characteristics of Wright's Prairie style. Importantly, the five houses span the period between the first publication of Wright's Prairie Style, in the *Ladies Home Journal* in 1901, and what is widely regarded as the ultimate example of this approach, the *Robie House* (fig. 8.3e).

The first Prairie style design analysed in this chapter is the *Henderson House* in Elmhurst, Illinois which was completed in 1901 (fig. 8.3a). The house is a timber, two-storey structure with plaster rendered elevations. A range of additions were made to the house in the years following its completion until, in 1975, the house was restored to its original form. The *Tomek House*, completed in 1907, in Riverside, Illinois, is also a two-storey house although it possesses a basement and is sited on a large city lot (fig 8.3b). This house is finished with pale, rendered brickwork, dark timber trim and a red tile roof. Storrer notes that, in response to the Tomek family's needs, Wright later allowed posts to be placed beneath the cantilevered roof to heighten the sense of support and enclosure (Storrer 1993: 128). As the posts were not required for structural reasons, and Wright found them personally unnecessary, they have been omitted from the analysis. The *Evans House* (fig 8.3c), completed in Chicago, Illinois in 1908, features a formal diagram wherein the 'basic square' found in earlier Prairie style houses is 'extended into a cruciform plan' (Thomson 1999: 100). The house is set on a sloping site and possesses a plan similar to the one Wright proposed in 1907 for a 'fireproof house for $5000'. The *Evans House* was later altered to enclose the porch area and the stucco finish on the facade was also cement rendered. The *Zeigler House* in Frankfort, Kentucky was constructed in 1910 and has a similar plan to the *Evans House*. Designed as a home for a Presbyterian minister, this two-storey house is sited on a small, city lot and it was constructed while Wright was in Europe (fig 8.3d). After a decade of development and refinement, the quintessential example of the Prairie Style—the *Robie House*—was constructed in Chicago, Illinois in 1910. Designed as a family home, the three storey structure fills most of its corner site. Unlike many of Wright's other houses of the era, the *Robie House* features a facade of exposed Roman bricks with horizontal raked joints and is described by Alofsin as 'a startling image of sliding parallel horizontal masses hugging the ground' (1994: 36).

a. Henderson House



b. Tomek House

c. Evans House

d. Zeigler House

e. Robie House

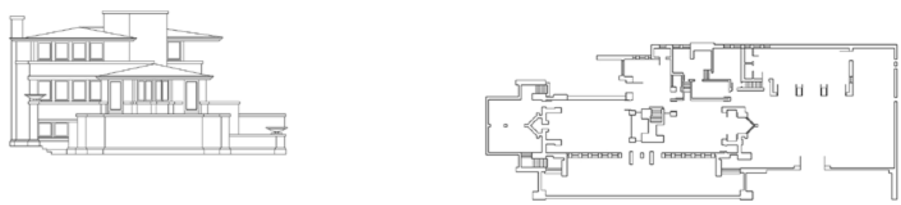


Figure 8.3 a-e Prairie set, entry elevations and ground floor plans (not drawn to scale)

Table 8.3 Prairie set results

Houses		*Henderson*	*Tomek*	*Evans*	*Zeigler*	*Robie*	Set {…}
Elevations	D_{E1}	1.5255	1.5103	1.5592	1.4442	1.5174	
	D_{E2}	1.5177	1.4885	1.5709	1.4542	1.5708	
	D_{E3}	1.4910	1.4342	1.5254	1.4385	1.4785	
	D_{E4}	1.5072	1.4799	1.5337	1.4424	1.4677	
	μ_E	1.5104	1.4782	1.5473	1.4448	1.5086	
	$\mu_{\{E\}}$						1.4979
	$M_{\{E\}}$						1.4991
	$std_{\{E\}}$						0.0432
Plans	D_{P-1}	1.3001	1.4448				
	D_{P0}	1.4499	1.3902	1.4307	1.4170	1.3385	
	D_{P1}	1.3763	1.3721	1.3817	1.3802	1.4220	
	D_{P2}	-	-	-	-	1.3984	
	D_{PR}	1.1817	1.3077	1.3147	1.2295	1.3066	
	μ_P	1.3270	1.3787	1.3757	1.3422	1.3664	
	$\mu_{\{P\}}$						1.3579
	$M_{\{P\}}$						1.3783
	$std_{\{P\}}$						0.0734
Composite	μ_{E+P}	1.4187	1.4285	1.4738	1.4009	1.4375	
Aggregate	$\mu_{\{E+P\}}$						1.4318

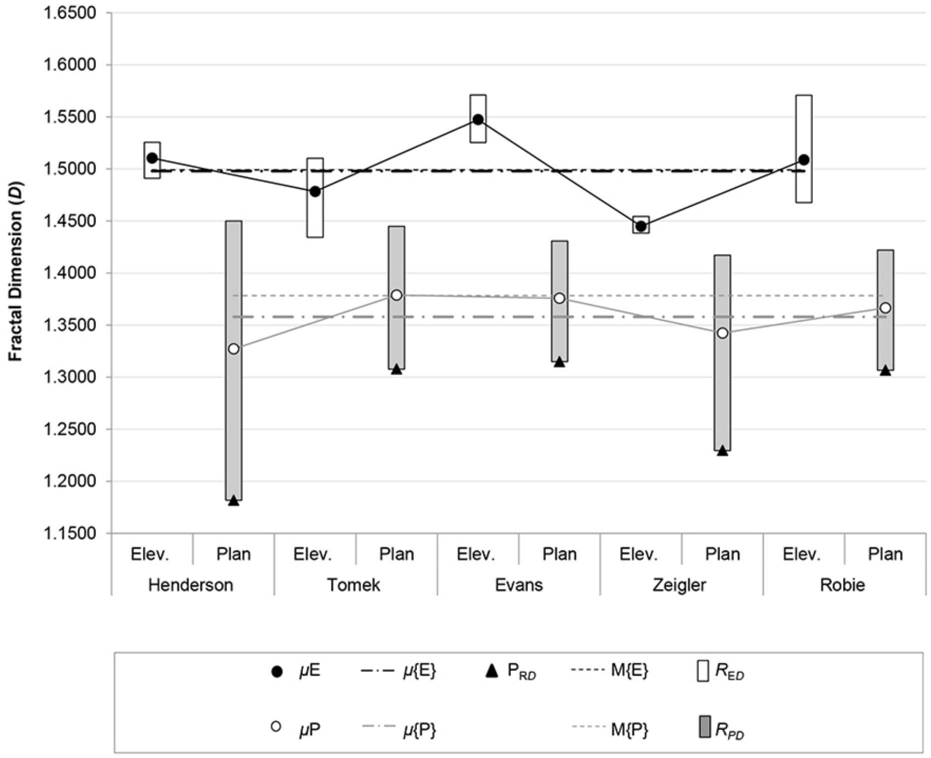


Figure 8.4 Prairie set, graphed results

Table 8.4 Wright, Prairie set, comparative values.

Houses		*Henderson*	*Tomek*	*Evans*	*Zeigler*	*Robie*	Set {…}
Elevations	R_{ED}	0.0345	0.0761	0.0455	0.0157	0.1031	
	$R_{E\%}$	3.45	7.6100	4.55	1.57	10.31	
	$R_{\{ED\}}$						0.1367
	$R_{\{E\%\}}$						13.67
Plans	R_{PD}	0.2682	0.1371	0.1160	0.1875	0.1154	
	$R_{P\%}$	26.82	13.71	11.60	18.75	11.54	
	$R_{\{PD\}}$						0.2682
	$R_{\{P\%\}}$						26.82
Composite	$R_{\{\mu E+PD\}}$						0.0729
	$R_{\{\mu E+P\%\}}$						7.29

In the set of Wright's Prairie works, the *Zeigler House* has the lowest average elevation result (μ_E = 1.4448) and the highest is found in the *Evans House* (μ_E = 1.5473). The median elevation result is 1.4991, the mean 1.4979 and the standard deviation is 0.0432. Results for the plan means show the lowest is the *Henderson House* (μ_P = 1.3270) while the *Tomek House* has the highest (μ_P = 1.3787). The median for the set of plan results is 1.3783, the mean is 1.3579 and the standard deviation is 0.0734 (Table 8.3, fig.8.4).

The entire set of five prairie houses have a close, comparable range of complexity across all twenty elevations ($R_{\{E\%\}}$ = 13.67), and while the degree of complexity of all thirteen plans could still be considered related ($R_{\{P\%\}}$ = 26.82), there is no clear visual correspondence between them. This situation is further amplified when the individual house results are observed. The *Zeigler House* has a remarkably tight range of fractal dimensions in elevation ($R_{E\%}$ = 1.57) which suggests the four elevations for this house are identical in their level of visual complexity. The range of complexity for the plans of the *Zeigler House* however ($R_{P\%}$ = 18.75), while offering more visual correspondence than the range for the group of five Prairie houses, are only comparable rather than indistinguishable (Table 8.4, fig. 8.4).

The graphed results show the *Henderson House* to be diverse in planning, but alike in facade treatment. The set of fractal dimensions for the elevations ($1.4910 < D_E < 1.5255$) corresponds with the even distribution of detail on the exterior of the house, where each elevation has around fifteen windows and similar wall detailing. The plans have a different purpose on each level, with the most complex of the plans being the ground floor (D_{P0} = 1.4499) which includes flexible living spaces and outdoor terracing. The roof plan being the least complex (D_{PR} = 1.1817), reflects the fundamental simplicity of the layout of the *Henderson House*.

The *Tomek House* is the only house in the set of prairie houses to have an overlapping level of detailing found in the plans and elevations. This only occurs in the least complex east elevation (D_{E3} = 1.3432) and the most complex plan (D_{P-1} = 1.4448). The east facade is smaller and dominated by a typical Prairie style, externally expressed, wide chimney and has less remaining space for fenestration or any other typical details found in the other three elevations. The most complex plan is that of the entry level and includes the additional details of the stonework mouldings which Wright used in many of his Prairie houses to anchor them to the ground.

The *Evans House* and the *Robie House* share a similar pattern of results, both with highly complex elevations and a very similar set of results for their plans. The *Evans House* has a more similar set of elevations, in terms of complexity ($R_{E\%}$ = 4.5) than the *Robie House* ($R_{E\%}$ =10.3), and the *Evans House* results for elevations all fall within those of the *Robie House* (1.4677 < D_E < 1.5708). Likewise, the *Evans House* maximum plan dimension is very similar to that of the *Robie House* (D_{P0} = 1.4307 and D_{P1} = 1.4220 respectively) and the minimum plan value is also similar for the *Evans House* (D_{PR} = 1.3147) and *Robie House*, (D_{PR} = 1.3066).

Overall, the results from the analysis show the elevations of Wright's Prairie houses to be generally more complex than the plans. Furthermore, the Median and the Mean of all elevations are almost identical.

8.3.2 Textile-block Houses

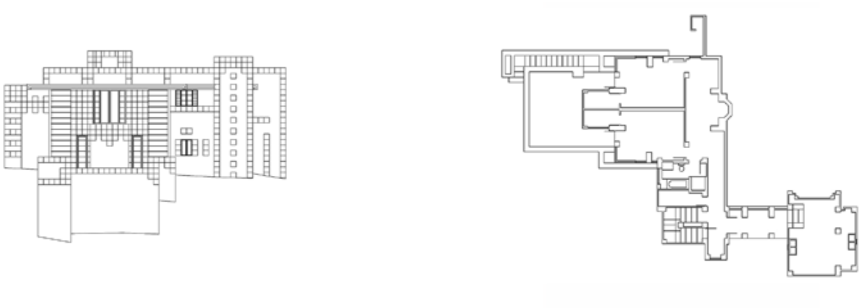
Wright expanded his practice into Los Angeles in the early 1920's and during the following decade he designed many buildings, although only five houses were built. These five houses, which share some of the character of Wright's famous *Hollyhock House*, have since become known as the Textile-block houses. Appearing as imposing, ageless structures, these houses were typically constructed from a double skin of pre-cast patterned and plain exposed concrete blocks held together by Wright's patented system of steel rods and concrete grout. Ornamented blocks generally punctuate the plain square blocks of the houses and for each house a different pattern is employed. Despite the difference in appearance to the Prairie Style houses, Hess states that ‘every aspect of the LA homes followed organic principles’ (Hess and Weintraub 2006: 38).

The first of the set, the *Millard House* or “*La Miniatura*” was completed in Pasadena, California, in 1923 (fig 8.5a). This house is the only one of the Textile-block works not to feature a secondary structure of steel rods. Reflecting on *La Miniatura*, Wright wrote that in this project he ‘would take that despised outcast of the building industry – the concrete block – out from underfoot or from the gutter – find a hitherto unsuspected soul in it – make it live as a thing of beauty textured like the trees’ (Wright 1960: 216-217). The second of the Textile-block houses, the *Storer House,* was completed in Hollywood, California, in 1923 (fig 8.5b). It is a three-storey residence with views across Los Angeles. The *Freeman House* in Los Angeles, California, was also completed in 1923 (fig 8.5c). It is regarded as the third Textile-block house and the first to use mitred glass in the corner windows of the house; all the previous works in this style have solid corners. It is a two-storey, compact, flat roofed house made from both patterned and plain textile-block and with eucalyptus timber detailing. The fourth Textile-block house, the *Ennis House*, is probably the most famous of Wright’s works of this era (fig 8.5d). Also completed in 1923 and overlooking Los Angeles, it is regarded as the ‘most monumental’ (Storrer 1974: 222) of the houses of this era. It has been described as ‘looking more like a Mayan temple than any other Wright building except [the] *Hollyhock House*’ (222). The *Ennis House* is conspicuously sited and is made of neutral coloured blocks with teak detailing. Some of the windows feature art glass designed by Wright in an abstraction of wisteria plants. The final design in this sequence, the *Lloyd-Jones House*, is in Tulsa, Oaklahoma. Completed in 1929, it is the only non-Californian Textile-block house (fig 8.5e). Designed for Wright’s cousin, it is a large house with extensive entertaining areas and a four-car garage. The *Lloyd-Jones House* is notably less ornamental than the others in the sequence with Wright rejecting richly decorated blocks ‘in favor of an alternating pattern of piers and slots’ (Frampton 2005: 170).

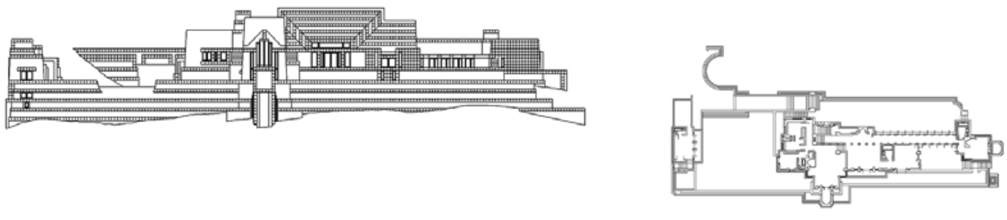
a. Millard House

b. Storer House

c. Freeman House



d. Ennis House



e. Lloyd-Jones House

Figure 8.5a-e Textile-block set, entry elevations and ground floor plans (not drawn to scale)

Table 8.5 Textile-block set results

Houses		*Millard*	*Storer*	*Freeman*	*Ennis*	*Lloyd-Jones*	Set{…}
Elevations	D_{E1}	1.4420	1.5389	1.3603	1.6130	1.5947	
	D_{E2}	1.4786	1.5543	1.5125	1.6390	1.5589	
	D_{E3}	1.3434	1.5111	1.4666	1.4900	1.6105	
	D_{E4}	1.3128	1.4395	1.4868	1.4417	1.5983	
	μ_{E}	1.3942	1.5110	1.4566	1.5459	1.5906	
	$\mu_{\{E\}}$						1.4996
	$M_{\{E\}}$						1.5006
	$std_{\{E\}}$						0.0925
	D_{P0}	1.4078	1.4497	1.3964	1.4955	1.4465	
Plans	D_{P1}	1.3801	1.4330	1.3799	-	1.4228	
	D_{P2}	1.2826	1.4311	-	-	1.4158	
	D_{PR}	1.2809	1.4024	1.3901	1.4664	1.4127	
	μ_{P}	1.3379	1.4291	1.3888	1.4810	1.4245	
	$\mu_{\{P\}}$						1.4055
	$M_{\{P\}}$						1.4127
	$std_{\{P\}}$						0.0557
Composite	μ_{E+P}	1.3660	1.4700	1.4275	1.5243	1.5075	
Aggregate	$\mu_{\{E+P\}}$						1.4591

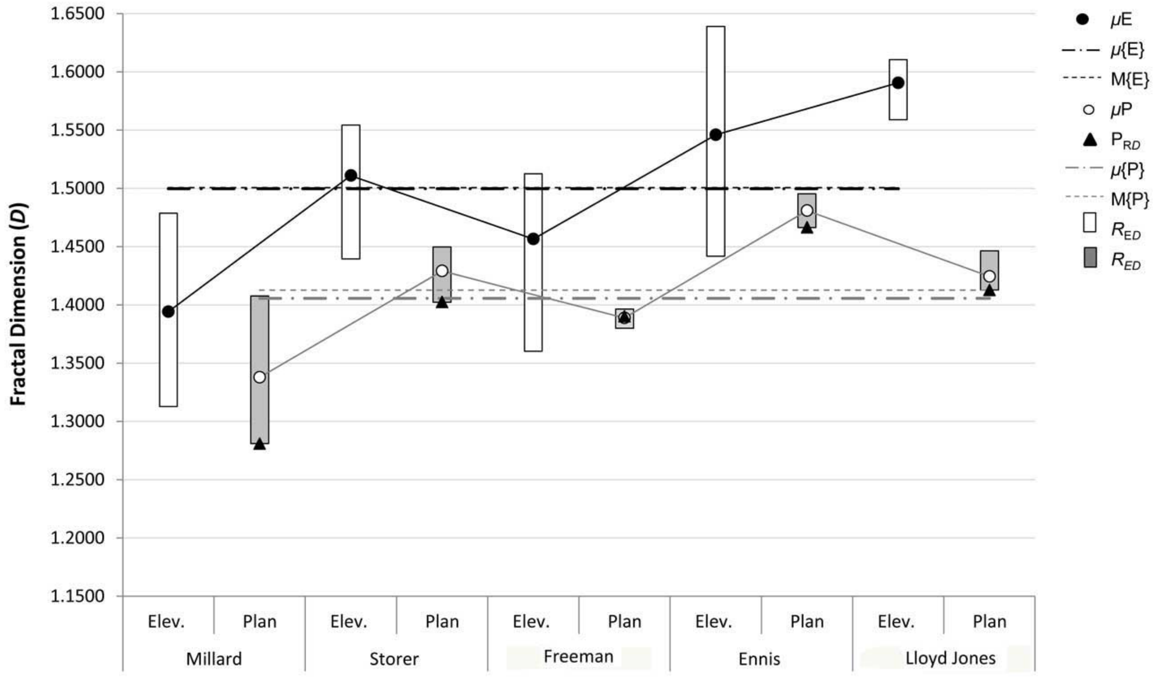


Figure 8.6 Textile-block set, graphed results

Table 8.6 Textile-block set, comparative values

Houses		*Millard*	*Storer*	*Freeman*	*Ennis*	*Lloyd-Jones*	Set{…}
Elevations	R_{ED}	0.1658	0.1148	0.1522	0.1973	0.0516	
	$R_{\text{E\%}}$	16.58	11.4800	15.22	19.73	5.16	
	$R_{\{\text{ED}\}}$						0.3262
	$R_{\{\text{E\%}\}}$						32.62
Plans	R_{PD}	0.1269	0.0473	0.0165	0.0291	0.0338	
	$R_{\text{P\%}}$	12.69	4.73	1.65	2.91	3.38	
	$R_{\{\text{PD}\}}$						0.2146
	$R_{\{\text{P\%}\}}$						21.46
Composite	$R_{\{\mu\text{E+PD}\}}$						0.1582
	$R_{\{\mu\text{E+P\%}\}}$						15.82

In the set of Wright's Textile-block houses, the first house in the set, the *Millard House,* has the lowest average elevation result (μ_E = 1.3942) and the highest is found in the *Lloyd-Jones House,* the last house of the set (μ_E = 1.5006). The mean elevation result is 1.4996 and median elevation result 1.5006, with the standard deviation 0.0925. Thus, there is very little skew in the results, although the deviation in the data is higher than it was for the Prairie style works. Results for the plans show the lowest average is also from the *Millard House* (μ_P = 1.3379) while the *Ennis House* has the highest (μ_P = 1.4810). The mean for the set of plans is 1.4055, the median is 1.4127 and the standard deviation is 0.0557 (Table 8.5, fig. 8.6).

The entire set of results of the seventeen Textile-block house plans have a familial relationship, however the results are not closely enough related that they can be considered "comparable" ($R_{\{P\%\}}$ = 21.46). The range of complexity across all twenty elevations ($R_{\{E\%\}}$ = 32.62) is even wider and when presented with a view of all elevations in this set, the complexity between each view is dissimilar and unrelated (Table 8.5, fig. 8.6).

The *Millard House* results are lower than expected, with all results for the elevation and most results for the plans falling below their respective averages. The textured, ornamental blocks covering this house all have the same pattern and this texture is treated as one surface in the representation of the elevations for analysis, lowering the expected result. This approach does not affect the planning however, and the *Millard House* results do generally show a simple type of plan.

The *Storer House* fits neatly into the overall results, with the overall median and average for all the Textile-block houses set falling within the results for both plans and elevations of the *Storer House*. As expected, most roof plans provide the lowest result for each house in the Textile-block houses set, however for the *Freeman House* it is the first floor which has the least visual complexity (D_{P1} = 1.3799). As a house designed with terraced levels, the view of the roof includes a roof garden and a view of the collection of roofs below, increasing the visual complexity of this roof plan (D_{PR} = 1.3901).

The *Ennis House* could be considered as the most complex house in the Textile-block houses set with the highest results for all plans (D_{P0} = 1.4955 and D_R = 1.4664), and its north (D_{E1} = 1.6130) and south Elevations (D_{E2} = 1.6390) being the most visually complex of the Textile-block houses set. However, the average elevation result for the *Lloyd-Jones House* is the highest overall (μ_E = 1.5906). The elevations for this house have a high fractal dimension due to the window framing used by Wright in this building, where each panel of glass is framed to match the blockwork. This house has an unusual result for its plans and elevations, which are distinctly different, where the elevations are far more complex than the plans (μ_P = 1.4245). All other houses in this set however, have some overlap in complexity for the plan and elevations of the houses.

The results for the Textile-block houses set overall suggest a set of visually complex dwellings in elevation and particularly in planning, with a broad relationship between the complexity of the plan and elevations. Furthermore, over the six-year period from the first to the last, the complexity of the house designs increased. This result partially confirms the typical descriptions of these houses provided by historians, who argue that Wright's architecture became more visually complex, heavy and ornate throughout this time, largely as a property of the decoration embedded in the blocks. However, some historians disagree with this, suggesting that in the *Lloyd-Jones House* Wright moved away from the 'primitivism' or 'Mayan-revivalism' found in the first four to produce a much simpler formal expression. For example, Alofsin (1994) argues that as Wright 'responded to the incipient International Style he simplified his surface patterns, a shift that marked the end of his primitivist phase' (42). Yet, the total level of formal complexity in the work did not fall; instead, the level of ornamental detail fell in the final house, whereas the formal modelling reached its most attenuated expression. This interpretation of the data supports the views of those critics and historians who see the *Lloyd-Jones House* as triggering a shift from vertical to horizontal modelling, rather than being less ornamental in its expression (Sweeney 1994).

8.3.3 Usonian Houses

More than twenty years were to pass before Wright developed his third major sequence of domestic works; the Usonian houses. Wright explains that the Usonian house is intended to be ‘integral to the life of the inhabitants’, be truthful in its material expression (‘glass is used as glass, stone as stone, wood as wood’) and embrace the elements of nature (1954: 353). Hoffman describes the Usonian house as ‘a simplified and somewhat diluted prairie house characterized by the absence of leaded glass and the presence of […] very thin wall screens with a striated effect from wide boards spaced by recessed battens’ (Hoffmann 1995: 80). While there were multiple variations on the Usonian house, the five works featured in the present chapter are all based on an underlying equilateral triangular grid and were constructed between 1950 and 1956.

The first of the triangle-plan Usonian Houses, the *Palmer House* is located in Ann Arbour, Michigan and was completed in 1950 (fig 8.7a). The house is a two-storey brick structure, set into a sloping site, with wide, timber-lined eaves, giving the viewer an impression of a low, single level house. The brick walls include bands of patterned, perforated blocks, in the same colour as the brickwork. The repeatedly scaled triangle motif in the Palmer house has made it the subject of fractal studies by others (Eaton 1998; Joye 2006; Harris 2007).

The second house, the *Riesley House*, was the last of Wright’s Usonian houses built in Pleasantville, New York; it was completed in 1951 (fig 8.7b). This single level home with a small basement is constructed from local stone with timber panelling and is set on a hillside site. In contrast, in the same year the *Chahroudi House* was built on an island in Lake Mahopac, New York, and constructed using Wright’s desert masonry rubblestone technique with some timber cladding and detailing (fig 8.7c). Wright originally designed the cottage as the guest quarters for the Chahroudi family home; however, only the cottage was built and subsequently used as the primary residence.

The *Dobkins House* was built in 1953 for Dr John and Syd Dobkins in Canton, Ohio. This small house is constructed from brick with deeply raked mortar joints. However, unlike the *Robie House*, the mortar colour contrasts with the bricks in the vertical as well as the horizontal joints (fig 8.7d). Finally, the *Fawcett House*, completed in 1955, had an unusual brief for Wright to design a home for a farming family. The house is set on the large flat expanse of the Fawcett's walnut farm in Los Banos, California. The single storey house is constructed primarily of grey concrete block with a red gravel roof (fig 8.7e).

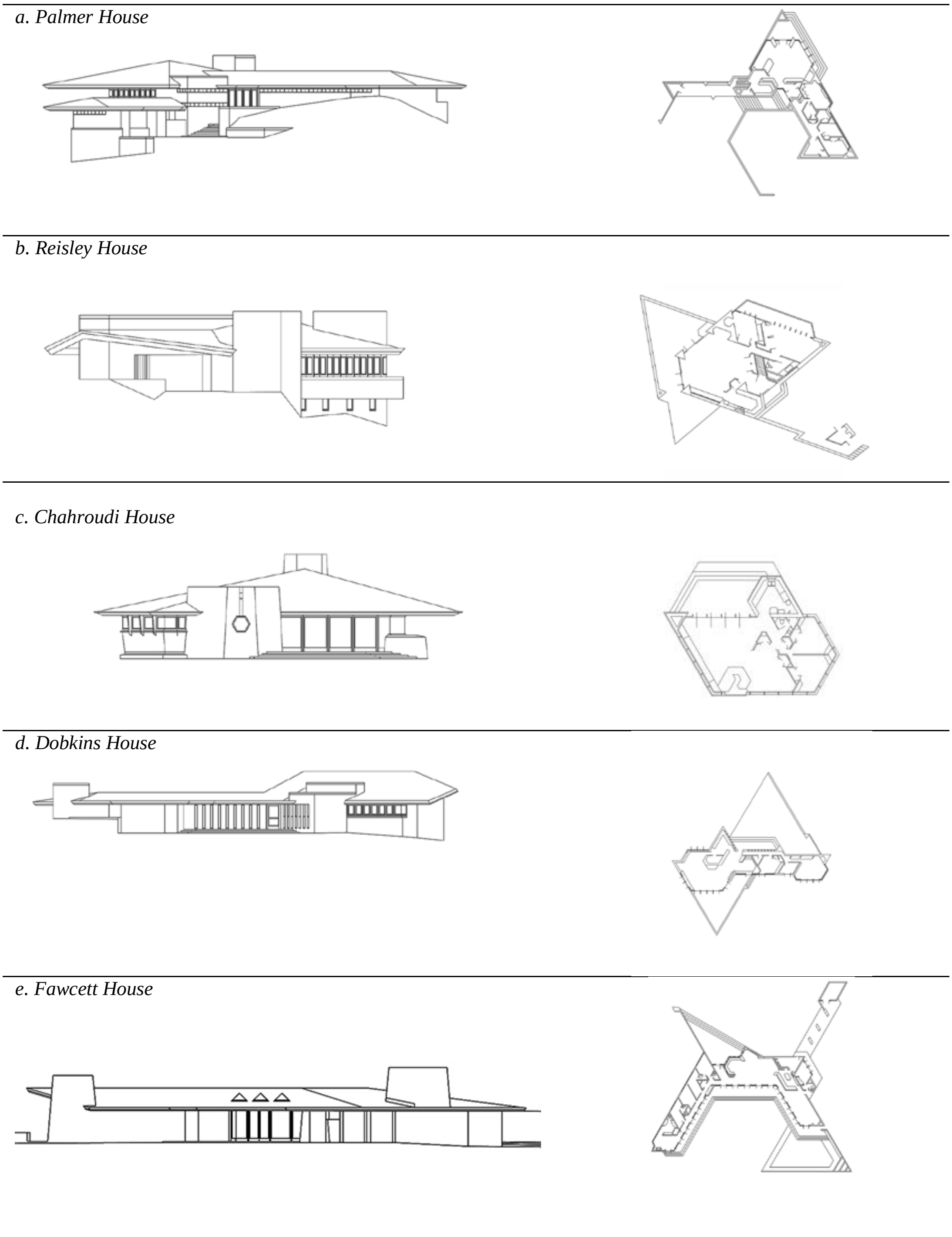


Figure 8.7a-e Usonian set, entry elevations and ground floor plans (not drawn to scale)

Table 8.7 Usonian set, results

Houses		Palmer	Reisley	Chahroudi	Dobkins	Fawcett	Set {…}
Elevations	D_{E1}	1.4802	1.3865	1.4328	1.4596	1.3991	
	D_{E2}	1.4461	1.3710	1.4529	1.3375	1.5575	
	D_{E3}	1.4642	1.4086	-	1.5359	-	
	D_{E4}	1.4018	1.4265	1.4045	1.3745	1.4591	
	μ_E	1.4481	1.3982	1.4301	1.4269	1.4719	
	$\mu_{\{E\}}$						1.4350
	$M_{\{E\}}$						1.4297
	$std_{\{E\}}$						0.0560
Plans	$D_{P\text{-}1}$	-	1.2968	-	-	-	
	D_{P0}	1.4412	1.3687	1.3973	1.3810	1.4155	
	D_{PR}	1.2875	1.3256	1.2908	1.2400	1.3839	
	μ_P	1.3644	1.3304	1.3441	1.3105	1.3997	
	$\mu_{\{P\}}$						1.3480
	$M_{\{P\}}$						1.3687
	$std_{\{P\}}$						0.0634
Composite	μ_{E+P}	1.4202	1.3691	1.3957	1.3881	1.4430	
Aggregate	$\mu_{\{E+P\}}$						1.4032

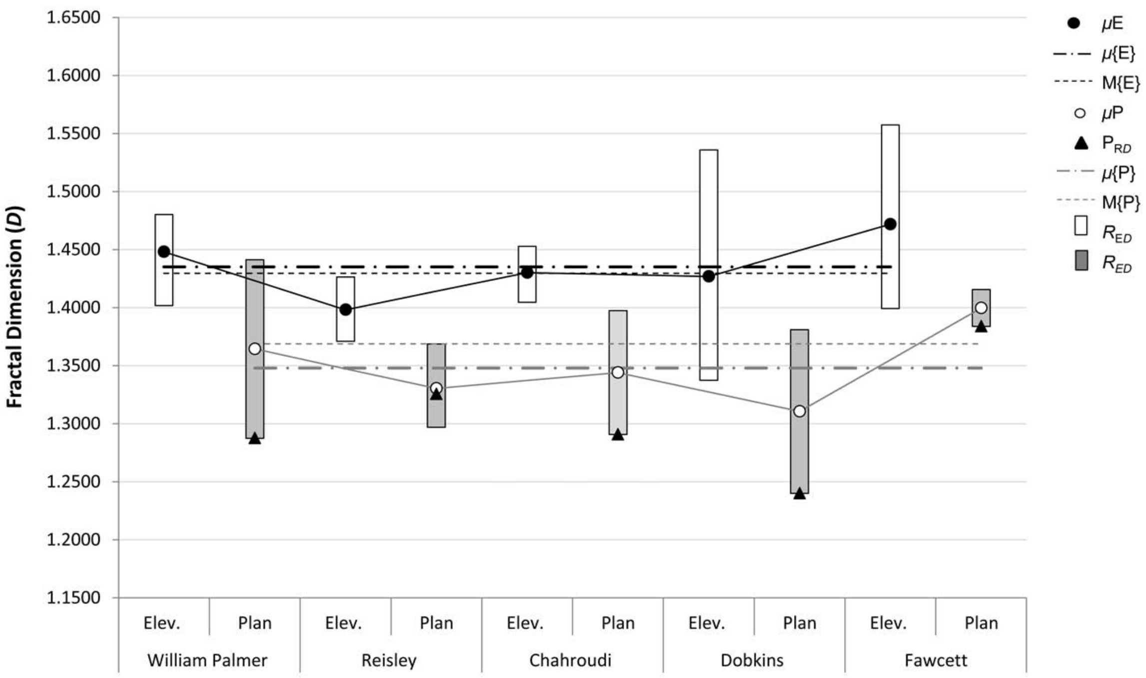


Figure 8.8 Usonian set, graphed results

Table 8.8 Usonian set, comparative values

Houses		Palmer	Reisley	Chahroudi	Dobkins	Fawcett	Set {…}
Elevations	R_{ED}	0.0784	0.0555	0.0484	0.1984	0.1584	
	$R_{E\%}$	7.84	5.5500	4.84	19.84	15.84	
	$R_{\{ED\}}$						0.2200
	$R_{\{E\%\}}$						22.00
Plans	R_{PD}	0.1537	0.0719	0.1065	0.1410	0.0316	
	$R_{P\%}$	15.37	7.19	10.65	14.10	3.16	
	$R_{\{PD\}}$						0.2012
	$R_{\{P\%\}}$						20.12
Composite	$R_{\{\mu E+PD\}}$						0.0739
	$R_{\{\mu E+P\%\}}$						7.39

The results indicate that a typical house of the Usonian period is a simple dwelling, without a great degree of complexity in elevation. The fractal dimensions of all five of Wright's Usonian houses show that the lowest mean elevation is found in the *Reisley House* (μ_E = 1.3982) and the highest in the *Fawcett House* (μ_E = 1.4719). The highest individual elevation result is also from the *Fawcett House* (D_{E2} = 1.5575), the complete set of results from this house suggesting it is highly complex in both plan and elevation. The median for all elevations in the Usonian set is 1.4297, the mean 1.4350, and the standard deviation 0.0560. The highest plan average is also from the *Reisley House* (μ_P = 1.3997), however the highest individual plan was the ground floor of the *Palmer House* (D_{P1} = 1.4412) and the lowest plan average is from the *Dobkins House* (μ_P = 1.3105). The range of all the plans ($R_{\{P\%\}}$ = 20.12) was in a close percentile to that of the elevations ($R_{\{E\%\}}$ = 22.00). The median for all plans is 1.3687, the mean 1.3480, and the standard deviation 0.0634. The aggregate result for all plans and elevations is $\mu_{\{E+P\}}$ = 1.4032 and the composite range is $R_{\{\mu E+P\%\}}$ = 7.39 (Tables 8.7 and 8.8, fig. 8.8).

The ground floor plan of the *Palmer House* (D_{P0} = 1.4412) is higher than the mean of all the elevations in the set ($\mu_{\{E\}}$ = 1.4350), and in the *Fawcett House* all plan results ($1.3839 < D_P < 1.4155$) are higher than the mean of the other plans of the Usonian set ($\mu_{\{P\}}$ = 1.3480). These two houses and the *Dobkins House* all have ground floor plans which share corresponding levels of visual complexity with at least one of their elevations. The other two houses in the Usonian set, the *Reisley House* and the *Chahroudi House*, present a ground floor fractal dimension which is very close to, but not as complex, as the least complex of their elevations.

Due to the triangular planning system that Wright employed with these houses, the *Chahroudi House* and the *Fawcett House* have only three elevations in representational form. This lesser number of data points however does not appear to affect the results, as the two houses still appear typical when compared with the others. Indeed, the *Chaharoudi House* provides balanced results with the extent of the *D* values falling neatly above and below the mean average in the case of both the plan and elevations.

8.3.4 Wright's Stylistic Continuity

When architectural historians review the career of Frank Lloyd Wright they generally agree that throughout his life, his buildings display a consistent set of design principles even though his works have varied in appearance across several distinct stylistic periods (Hoffmann 1995; McCarter 1999; Frampton 2005). Historians tend to acknowledge such obvious visual and stylistic differences while focusing on similarities in the underlying tactics and theories which shape Wright's work. For example, Robert Sweeny concedes that Wright's ability to 'renew himself repeatedly throughout his career' (1994: 1) is a characteristic of his approach, but argues that it does not change his underlying values. David De Long supports this view when he proposes that over time, Wright 'was able to retain allegiance to earlier principles while arriving at markedly different conclusions' (1994: xii). Kenneth Frampton similarly maintains that there is a constant thread throughout Wright's work which is related to a modular system of planning and construction that 'varied according to local circumstance' (2005: 178). Frampton defines this continuous thread as a 'plaited approach to architectonic space' that 'prevailed throughout Wright's long career' (2005: 178). Robert McCarter, who claims that Wright's Usonian houses are derivations of his Prairie house ideals, argues that Wright's 'architectural designs were a continuous reinvention or rediscovery of the same fundamental principles' (1999: 249). Finally, Donald Hoffmann supports this argument confirming that 'the language of Wright's buildings continued to change, but the logic did not; once he grasped the principles, his work no longer evolved' (1995: 52). To support this assertion Hoffman quotes Wright stating that 'I am pleased by the thread of structural consistency I see inspiring the complete texture of the work revealed in my designs and plans, […] from the beginning, 1893, to this time, 1957' (qtd. in Hoffman1995: 52).

While the preceding quotes provide interpretations of the reasons why Wright's architecture remained so consistent over his various stylistic periods, when looking at the data for Wright's Prairie, Textile-block houses and Usonian periods, the scholarly view is generally supported. By comparing the average complexity for the elevations of Wright's houses over these three periods, the largest variation is 6.4%, between the Usonian and Prairie elevations. Starting with the first of Wright's stylistic periods analysed, the Prairie houses have an average fractal dimension for all elevations of $\mu_{\{E\}}$ = 1.4979. This level of complexity remains virtually unchanged in Wright's Textile-block houses period ($\mu_{\{E\}}$ = 1.4996) before decreasing slightly in the Usonian period ($\mu_{\{E\}}$ = 1.4350). In plan form, Wright appears to have gone full circle in complexity starting from the Prairie style ($\mu_{\{P\}}$ = 1.3579) then increasing in the Textile-block houses ($\mu_{\{P\}}$ = 1.4055), before returning to the lower levels in the Usonian houses ($\mu_{\{P\}}$ = 1.3480). Comparing the aggregate results of the three periods of Wright's architecture, the Textile-block buildings are generally the most complex ($\mu_{\{E+P\}}$ = 1.4591), the Usonians are the least ($\mu_{\{E+P\}}$ = 1. 4032) and the Prairie houses are midway between the two ($\mu_{\{E+P\}}$ = 1. 4318) (Tables 8.3, 8.5, 8.7).

Comparing sets of fractal dimensions is one method of assessing similarities between the elevations and plans of a building. Another is to use the Range to determine the level of correspondence between the visual complexity of the elevations and of the plans. The composite, or overall ranges for each set show that the Prarie ($R_{\{\mu E+P\%\}}$ = 7.29) and Usonian ($R_{\{\mu E+P\%\}}$ = 7.39) have a similar level of complexity across all plans and elevations for the sets. However, the range is higher ($R_{\{\mu E+P\%\}}$ = 15.82) for the Textile-block houses set, which suggests the representations of these buildings have only some visual correspondence, and could not be described as similar (Tables 8.4, 8.6, 8.8).

8.4 The Visual Complexity of *Fallingwater* Compared

The consistency in the appearance of Wright's stylistic periods, especially the Usonian and Prairie styles—as proposed academically and verified by the fractal dimension study—implies that an unusual house such as *Fallingwater* might stand out amongst the others. As discussed in Chapter 1, the proposal that this 'revolutionary' (Fell 2009: 91) building was formally 'unexpected and unique in the work of Wright' (Hoesli 2005: 204) is supported by many histories and scholarly critiques (Lind 1996; Kaufmann 1986; Futagawa and Pfeiffer 2003; Hoesli 2005; Fell 2009). Yet other scholars claim there are formal elements in *Fallingwater* which recall his previous designs, and which seem to prefigure his later Usonian works (McCarter 1999; Smith 2000; Lesau and Tice 2000). As such, claims that *Fallingwater* is unique in Wright's oeuvre are contestable.

This section compares the level of characteristic visual complexity of *Fallingwater* with the other fifteen houses analysed. The analysis is first approached in stylistic groups and then individual houses are also considered. Figures 8.9 - 8.11 demonstrate with linear trendlines for each period which describe how Wright's works evolved over the course of five projects. For example, just considering elevations, visual complexity is relatively constant across the works of Wright's Prairie and Usonian houses, while it rises more noticeably over time in his Textile-block houses. For the plans of the sets of houses, the same pattern occurs, with the Prairie and Usonian houses remaining similar in their complexity and the Textile-blocks increasing over time. Finally, when elevations and plans are combined, these trends are confirmed, with the Prairie houses remaining extremely stable, the Usonian houses increase in complexity slightly over time and there is a dramatic increase in the results for the Textile-block houses. Along with these linear indicators, a triangle is included with each graph, representing the mean fractal dimension of *Fallingwater's* plans, elevation and the composite of the plans and elevations.

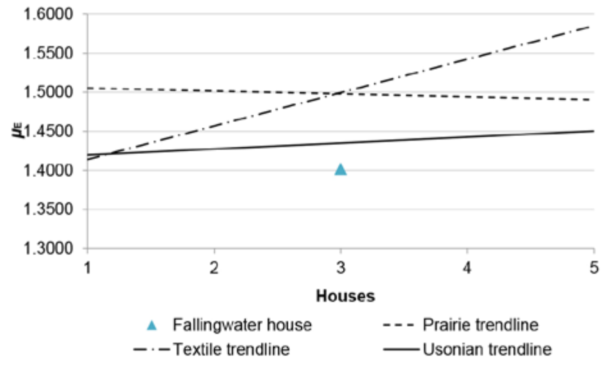


Figure 8.9 Linear trendline data for elevations of the stylistic periods, compared with Fallingwater

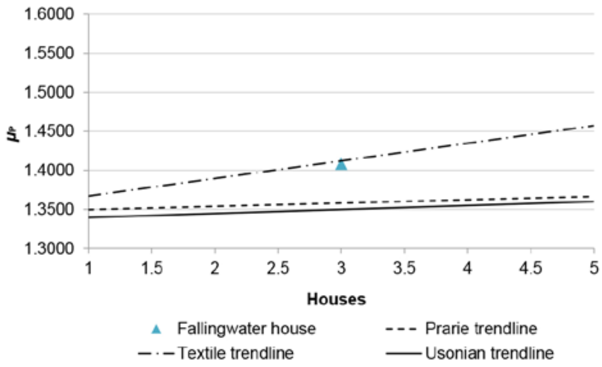


Figure 8.10 Linear trendline data for plans of the stylistic periods, compared with Fallingwater

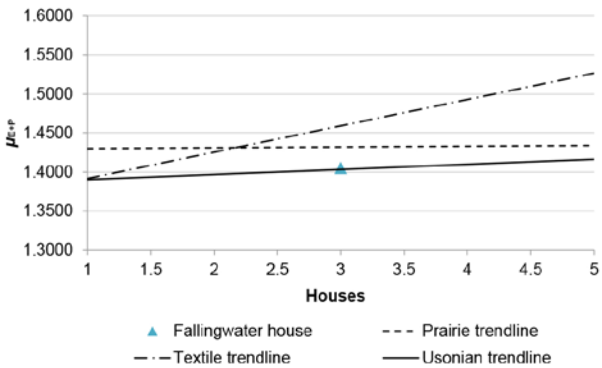


Figure 8.11 Linear trendline data for composite values of the stylistic periods, compared with Fallingwater

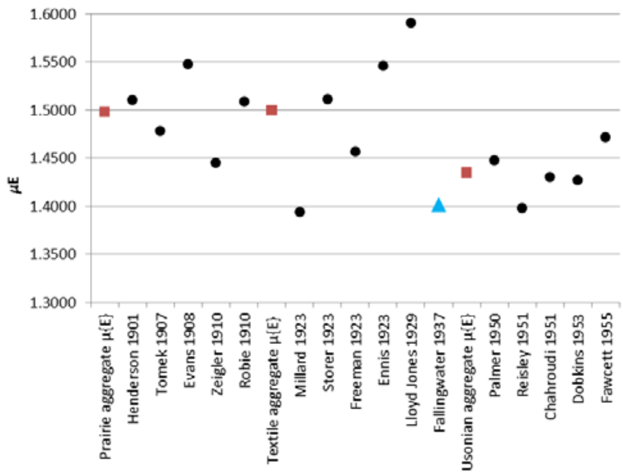


Figure 8.12 Mean and aggregate elevations compared

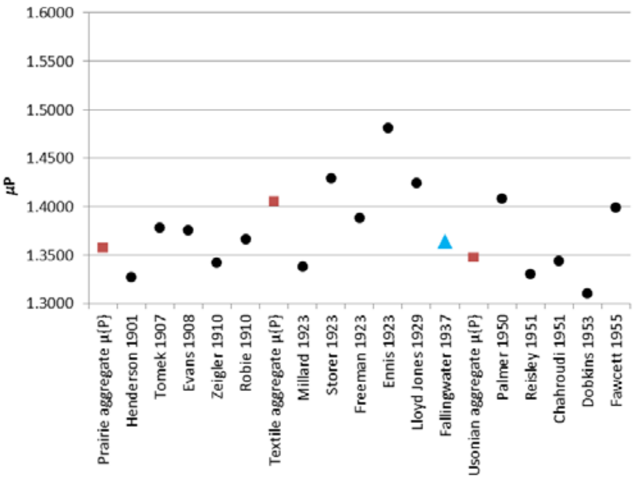


Figure 8.13 Mean and aggregate plans compared

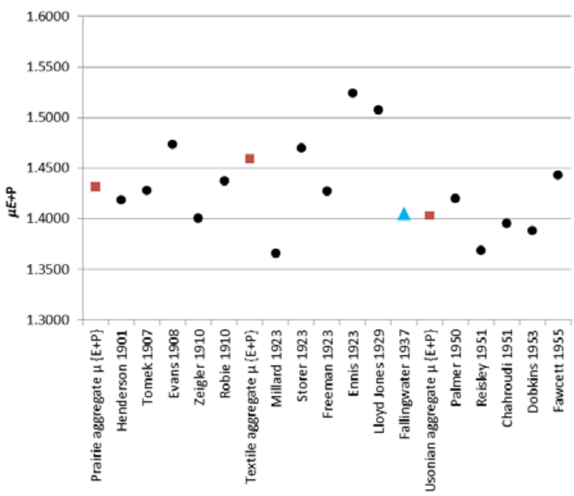


Figure 8.14 Mean and aggregate elevation and plan composites compared

Individually, the graphed results show *Fallingwater* to generally have lower formal complexity than most of the other houses measured, but it is never the least visually complex (figs 8.12 - 8.14). Comparing the mean elevations of *Fallingwater* (μ_E = 1.4019), only two of the houses have a lower overall visual complexity in elevation; the Textile-block *Millard House* (μ_E = 1.3942) and the Usonian *Reisley House* (μ_E = 1.3982). The aggregate values for the elevations of each set ($\mu_{\{E\}}$) show that compared to the stylistic periods, *Fallingwater* has the least complex elevations, followed by the Usonian houses, then the Prairie style, which is only slightly less complex than the Textile-block houses elevations. In plan form, *Fallingwater's* mean dimension (μ_P = 1.4085) is not so outstanding, with just over one third of the houses with lower complexity than *Fallingwater* in plan form. Again, this includes the *Millard House* and the *Reisley House*, and two other Prairie and two other Usonian style houses. In the aggregates of the stylistic sets, compared with the mean values for *Fallingwater*, the plans ($\mu_{\{P\}}$) for the Usonian and Prairie styles are only just less complex than *Fallingwater*, while the Textile-block plans have higher fractal dimensions.

The graphical representations of the trendlines of the three sets show that the elevations of *Fallingwater* fall for the Usonian style, confirming that *Fallingwater* has a similar level of characteristic complexity in its elevations to those Usonian houses studied, and less complexity than the houses of the Prairie and Textile-block (fig. 8.9). Looking at the trendlines for the plans, *Fallingwater* appears more complex than the Usonian works studied, and its plans have a higher fractal dimension than those of the Prairie style works (fig. 8.10). While the Textile-block houses do not have such a horizontal (or constant) trendline as the other stylistic sets, the plans for *Fallingwater* do rest on the trendline for the Textile-block houses at a point, meaning that on the planning level, *Fallingwater* is most likely formally closer to the Textile-block houses than any of the others studied. However, the individual results confirm that four of the five Textile-block houses have greater complexity in plan than *Fallingwater*. The composite trendlines confirm the overall positioning of *Fallingwater* among the complexity levels of the stylistic sets. In this combined value—of plans and elevations—*Fallingwater* displays a similar level of complexity to the Usonian houses studied (fig. 8.11).

These results suggest that contrary to the proposals of scholars—such as Lind, Pfeiffer and Hoesli—*Fallingwater* actually has a level of visual detail akin to Wright's other architectural styles. However, the trendlines only provide an overall view of the level of complexity for each stylistic set over time. Individual houses will fall above or below the trendline and in the next section, these individual results and their precise values are compared with *Fallingwater*.

8.5 The Similarity of *Fallingwater* to Wright's Other Houses

Individually, the mean results for all houses studied are compared in Table 8.9. The Range values in the table are set using *Fallingwater* as a target value, and the $R_{\%}$ values provided are the difference between the μ value for the house and the μ value for *Fallingwater*. Thus, the R_{μ} indicates the percentage by which the houses differ from *Fallingwater*, in elevation ($R_{\mu E\%}$), plan ($R_{\mu P\%}$), and their composite value ($R_{\mu E+P\%}$).

Table 8.9 Comparison of mean results for all houses

Period	Houses				Range Compared to *Fallingwater*		
		μ_E	μ_P	μ_{E+P}	$R_{\mu E\%}$	$R_{\mu P\%}$	$R_{\mu E+P\%}$
Prairie 1907-1910	*Henderson*	1.5104	1.3270	1.4187	10.8450	8.1500	1.3475
	Tomek	1.4782	1.3787	1.4285	7.6325	2.9800	2.3263
	Evans	1.5473	1.3757	1.4738	14.5400	3.2800	6.8557
	Zeigler	1.4448	1.3422	1.4009	4.2925	6.6267	0.4343
	Robie	1.5086	1.3664	1.4375	10.6700	4.2125	3.2288
Prairie style set		1.4979	1.3579	1.4318	9.6	2.9	2.6
Textile-block 1923-1929	*Millard*	1.3942	1.3379	1.3660	0.7700	7.0650	3.9175
	Storer	1.5110	1.4291	1.4700	10.9050	2.0550	6.4800
	Freeman	1.4566	1.3888	1.4275	5.4650	1.9700	2.2314
	Ennis	1.5459	1.4810	1.5243	14.4025	7.2450	11.9067
	Lloyd-Jones	1.5906	1.4245	1.5075	18.8700	1.5950	10.2325
Textile-block style set		1.4996	1.4055	1.4591	9.7	0.3	5.4
1937	*Fallingwater*	1.4019	1.4085	1.4052	0.0000	0.0000	0.0000
Usonian 1950-1955	*Palmer*	1.4481	1.3644	1.4202	4.6175	4.4150	1.4967
	Reisley	1.3982	1.3304	1.3691	0.3750	7.8133	3.6100
	Chahroudi	1.4301	1.3441	1.3957	2.8167	6.4450	0.9540
	Dobkins	1.4269	1.3105	1.3881	2.4975	9.8000	1.7117
	Fawcett	1.4719	1.3997	1.4430	7.0000	0.8800	3.7820
Usonian style set		1.4350	1.3480	1.4032	3.3	6.0	0.2

Figures 8.15, 8.16 and 8.17 provide a visual reference to compare the difference of the houses to *Fallingwater*, using a qualitative interpretation of results. These figures are an assessment of the data in elevation (μ_E), plan (μ_P), and in combination (μ_{E+P}), where the *x*-axis is generated with reference to Table 7.9 (presented in Chapter 7). The terms in the *x*-axis describe how similar or different individual houses are to *Fallingwater,* and the columns increase in the *y*-axis depending on the number of houses with that level of visual similarity. To clarify that these terms are derived from the table, they are mentioned in the descriptions that follow the chats in inverted commas.

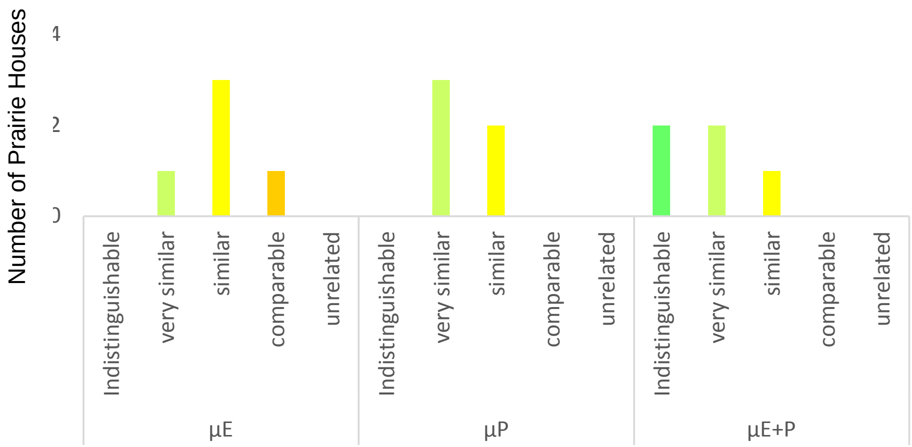


Figure 8.15 Interpretive description of Prairie houses when compared to Fallingwater

Overall, the five Prairie style houses are typically "similar", or "very similar" to *Fallingwater* in plan and elevation, and while the composite means of two of the Prairie houses are "indistinguishable", no aspects of the houses are "unrelated" to *Fallingwater*. The composite of the elevation and plans for the *Zeigler House* could be considered "indistinguishable" in comparison to *Fallingwater* ($R_{\mu E+P\%}$ = 0.4343), and this is the lowest composite $R_{\mu E+P\%}$ for all 15 houses. Within the Prairie style set, the *Zeigler House* is the closest set in elevation to *Fallingwater* ($R_{\mu E\%}$ = 4.2925) and the *Tomek House* has the closest set of plans ($R_{\mu P\%}$ = 2.9800), but is less like *Fallingwater* in elevation ($R_{\mu E\%}$ = 7.3625).

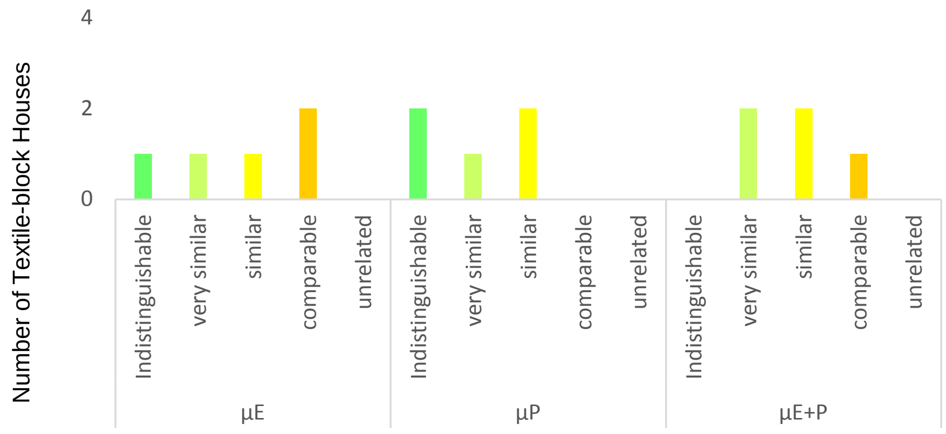


Figure 8.16 Interpretive description of Textile-block houses when compared to Fallingwater

Like the trendline results for the complexity of the Textile-block houses set (Tables 8.9 - 8.11), there is no clear relationship or clustering of the results in terms of how close the appearance of the Textile-block houses are to those of *Fallingwater*. While the *Millard House* is the only house "indistiguishable" from *Fallingwater* in elevation ($R_{\mu E\%}$ = 0.7700), and the *Lloyd-Jones House* ($R_{\mu P\%}$ = 1.5950) and the *Freeman House* ($R_{\mu P\%}$ = 1.9700) are "indistinguishable" in plan , none of these similar results coincide to suggest a house that is so alike when the composite values are considered. Overall, the results suggest that it is the plans of the Textile-block houses style that are the most comparable to *Fallingwater*, although none of the Textile-block houses are completely "unrelated" to the character of *Fallingwater*.

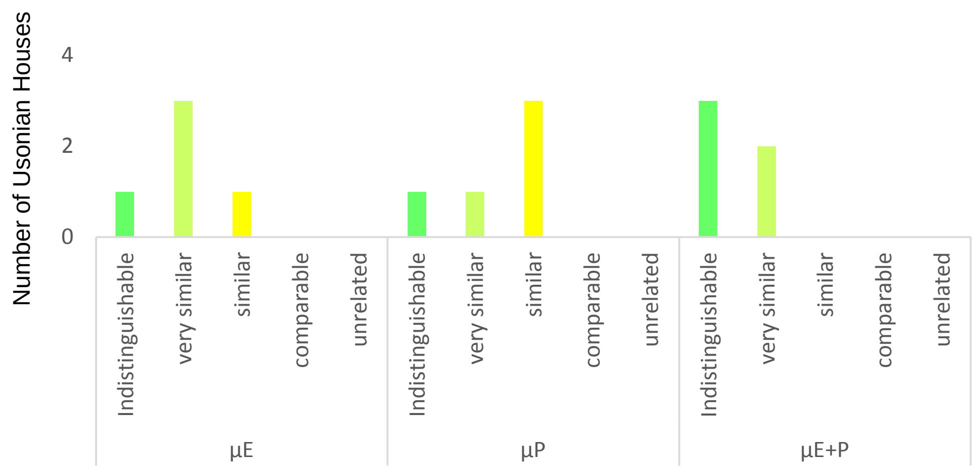


Figure 8.17 Interpretive description of Usonian houses when compared to Fallingwater

The Usonian set are the most related to *Fallingwater* in terms of their visual complexity. Unlike the other two periods, none of the houses in this set are so different that they could be considered only “comparable” or “unrelated” to *Fallingwater*. Three of the houses are effectively “indistinguishable” in their composite result, the *Chahroudi House* being the closest to *Fallingwater* for this set ($R_{\mu\text{E+P\%}}$ = 0.9540). Two of the Usonian houses have the least difference to *Fallingwater* of all the fifteen houses tested; the *Reisley House* elevations are “indistinguishable” to those of *Fallingwater* ($R_{\mu\text{E\%}}$ = 0.3750) and the *Fawcett House* is “very similar” in plan ($R_{\mu\text{P\%}}$ = 0.8800), more so than any of the other 14 houses.

Conclusion

Frank Lloyd Wright’s architecture is conventionally divided into several stylistic periods, some of which, including his Prairie and Usonian works, were refined over more than one hundred constructed works. Historians and critics regard both of these styles as exhibiting a high degree of consistency and, for the five Prairie style works examined in this chapter, the results strongly support the conventional interpretation as the plans and elevations in the set do exhibit a degree of uniformity in their mean, median and range results. Similarly, the Usonian houses have more closely related plans and elevations across the set of five works. In contrast, the Textile-block houses works are more distinctive and diverse, being only five houses from a short-lived, almost experimental style. While the trendlines for plans and elevations in the Prairie and Usonian Styles were almost flat, for the Textile-block houses both rose over time. Thus, Wright’s Textile-block houses works suggest an evolving experiment in design and construction, rather than the steady-state results for the other two styles that had been refined over longer periods or more extensive examples.

After determining the fractal dimensions for *Fallingwater* and placing this result in the context of the other houses, two measures are determined in this chapter. The first is the level of characteristic complexity of all of the houses—including *Fallingwater*—and accompanying this information is a clarification of which houses and styles have lower or higher fractal dimensions in elevation, plan and composite aspects. The second comparison describes the level of visual similarity between Wright's stylistic periods and *Fallingwater*.

From these approaches to the data, a profile of *Fallingwater* in comparison to the other houses studied is generated (fig. 8.18). This profile shows the complexity of the styles and *Fallingwater* ranked according to *D* on the *y*–axis and then a bar indicating the difference of each style from *Fallingwater* along the *x*–axis. This bar graph is determined by loading the occasions of "indistinguishable" to "unrelated" (extracted from Table 8.9) with numerical weight from 0 – 4. With "indistinguishable" suggesting no difference from *Fallingwater* (0), the lower the result, the shorter the bar, and the more similar the style could be described as being to *Fallingwater*.

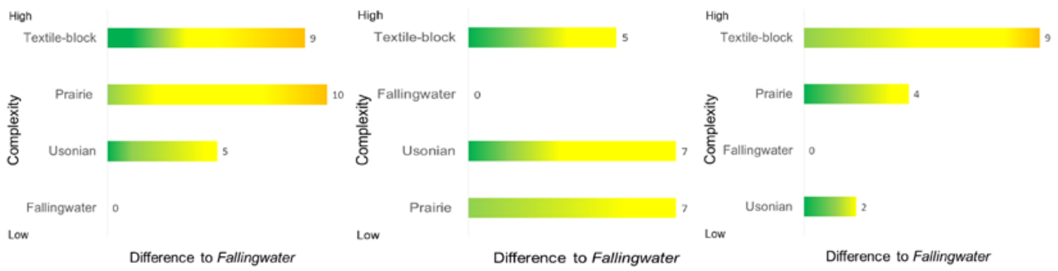


Figure 8.18 a-c Fallingwater *profiles: a. elevation b. plan c. Elevation+plan*

The profiles and information in this chapter show that the visual complexity of *Fallingwater* is fairly typical of the Prairie, Textile-block and Usonian houses, in varying degrees. In its elevations, *Fallingwater* is the least complex overall, and the closest style to it is the Usonian style. In plan, *Fallingwater* is more complex than the Usonian and Prairie styles, but less so than the Textile-block houses, to which it has the closest visual similarity of the three styles. When these results are combined as a composite of plan and elevation, only the Usonian style is less complex than *Fallingwater*, it is also the most similar.

In addition to building on the scholarly information available on *Fallingwater*, the information in this chapter provides a response to hypothesis 1, which is: that the formal and visual qualities of Frank Lloyd Wright's *Fallingwater* are atypical of his early and mid-career housing (1901-1955). This chapter shows this hypothesis to be false.

Chapter 9

Comparing *Fallingwater* with its Natural Setting

To examine the second hypothesis outlined at the start of this dissertation, the present chapter uses the box-counting method to measure and compare the characteristic complexity of *Fallingwater* and four natural elements within its surrounding landscape. Chapters 2 and 6 provide the background to the analytical method and the testing rationale required to decide which images are analysed in this chapter. The specific images of *Fallingwater* which are measured in the present chapter are four perspective views and four plan views of the house. These eight measures are compared with those derived from sixteen line drawn views and four site plans of four different natural subjects, collectively encapsulating one possible reading of the geometric complexity of *Fallingwater's* setting.

The methodological approach used in the previous chapter has been extensively tested, refined and validated in the past (Ostwald and Vaughan 2016). In contrast, the methodological approach used for the present chapter is largely untested and as such, the results of its comparison between architecture and nature could be regarded as akin to a pilot study or preliminary examination. Indeed, the data presented in this chapter may serve more to provide an indicator that the method might (or might not) work, rather than simply providing evidence that *Fallingwater* does (or does not) have a connection to its setting. Thus, while this chapter aims to determine if there is a correlation in terms of characteristic complexity between Wright's architecture and its natural setting, the results cannot be taken as a definitive proof.

The images used for fractal analysis in this chapter are taken from the following sources. The perspective drawings which are analysed in this chapter are based on

Wright's original drawings reproduced by Drexler (1965) and Futagawa and Pfeiffer (1987c; 2003). The plans for *Fallingwater* are traced from those published by Storrer (2006) and Futagawa and Pfeiffer (1986). Except for the views of the valley, the views of the natural elements are edge-detected line drawings extracted from photographs taken by the present Author of the landscape surrounding *Fallingwater* on a field trip in 2012. The views of the valley are taken from 2D still images of the site generated using Google Earth. The plans for the natural elements are all derived from a combination of two primary sources, the site plan prepared for the Kaufmanns in March 1935 (McCarter 2002: 5) and the map traced over this site plan by Wright's apprentices, as reproduced by Kaufmann (1986: 39). The results developed in this chapter are presented and analysed in the same way as those in Chapter 8, using the terminology defined in Chapter 7.

9.1 Scholarly Approaches to *Fallingwater* and its Natural Setting

The broad range of scholarly views that traditionally provide insight into *Fallingwater's* strong connection to its natural setting are presented in Chapter 2, where it is shown that this house is generally regarded by architectural scholars as being 'part of the enveloping woodland' (Fell 2009: 88). Chapter 2 also demonstrates that for Wright, the intent for a house like *Fallingwater* is that 'the building with landscape and site became inevitably one' (Wright 1955: 84). Architectural scholars have repeatedly identified the particular strategies used by Wright in the design of *Fallingwater* to connect it to the site. These include: cantilevering the house into the landscape from a stone firmament (Mumford 1938; Wright 1938; Frazier 1995; Hoesli 2005; Storrer 2006); an interplay of internal and external space (Wright 1938; Laseau and Tice 1992; Andropogon

1997; Sergeant 2005; Fell 2009); retaining natural elements in the house (Wright 1938; Cleary 1999; Levine 1996, 2000; Smith 2000); apertures to the natural landscape (Mumford 1938; Meehan 1984; Kaufmann 1986; Levine 2000; Fell 2009); and the approach to materials (Wright 1938; Alofsin 1994; Lind 1995; Cronon 1994; MacCarter 2005). Other strategies used by Wright, which have been identified as relating to *Fallingwater* and its natural setting, include: connecting with the character of the site (Hoffmann 1978; Nordland 1988; Simonds 1983); and determining the specific natural characteristics of the site (Riley 1994), including the sandstone geomorphology (Wright in Meehan 1984; Kaufmann 1986; Hoffmann 1986; Levine 2000; Fell 2009), the valley setting (Kaufmann 1986; Andropogon 1997; Wright 1994), the forest (Wright 1938; Levine 2000; Fell 2009), and the water (Wright 1938; Hoffamnn 1986; Cleary 1999; Levine 2000; Smith 2000).

While these scholarly views are well-represented in the literature, alternate arguments about *Fallingwater's* relationship to the landscape have been outlined by others. Such propositions follow a general line of argument, that while Wright had a distinct way of interpreting the natural landscape, he deliberately designed *Fallingwater* to contrast with its setting. For example, Hoffmann feels that '[a]lthough he meant to honor the forest site, Wright also chose to compete with the high drama of the falls and with the insistent asymmetric rhythms of the projecting sandstone ledges and long cantilevered leaves' (1995: 83). While Aguar and Aguar acknowledge that 'Fallingwater evokes a responsive sense-of-place', they also feel that the house is 'an architectural intrusion' that 'contradicts every dictum he ever expressed with respect to site integrity or harmony with nature. Indeed, Fallingwater *overwhelms* nature' (2002: 230). In a similar way, Alofsin considers *Fallingwater* to be a 'metaphorical interpretation of human confrontation with nature' (1994:46) and Spirn argues that Wright left the natural landscape of *Fallingwater* untouched to deliberately create a juxtaposition with the building. For Spirn, this contrast emphasises a *human verses nature* confrontation within which Wright provided an 'elevated prospect' in the cantilevering form of *Fallingwater,* which 'gives one a sense of comfortable control, like lord of the manor, over all one surveys' (Spirn 1996: 144).

In these examples, the tension between divergent interpretations of the relationship between *Fallingwater* and its natural setting is dramatised. To date, all of these arguments and positions have been qualitatively framed, whereas the present chapter offers a quantitative perspective on this issue for the first time.

9.2 Analysis of the *Fallingwater* House

The approach adopted in this chapter to image analysis differs slightly from that used in the previous chapter. As outlined in Chapter 6, four perspective views and four plan views of the house are prepared for this study, using a lesser level of included information (Level 3). The four elevations are generated from a CAD model, with the angles for the perspective views set as close as possible to the vanishing points of four perspective drawings of *Fallingwater* prepared by Wright (fig 9.1 a-d). These images depict the house from three distinct angles with the fourth being a slight variation of Wright's oft-published colour rendered perspective view of the house from below (fig.9.1a). Lacking other means of determining which of the myriad of potential perspective views should be examined to test arguments about nature and *Fallingwater*, Wright's own viewpoints have been chosen as most likely to clarify his intentions. However, it must be acknowledged that these are not necessarily the perfect viewpoints to test some of the claims (see Chapter 2) about the experience of *Fallingwater*.

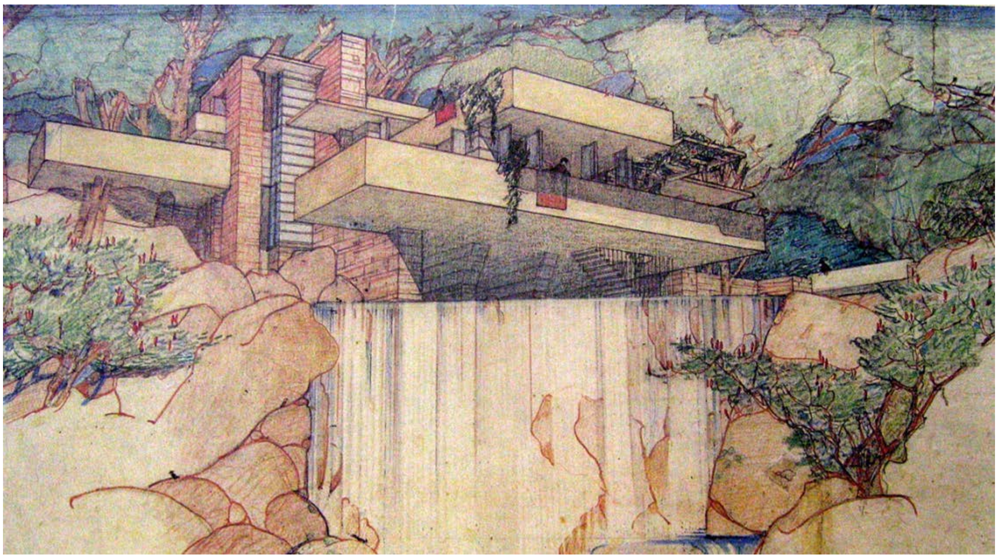


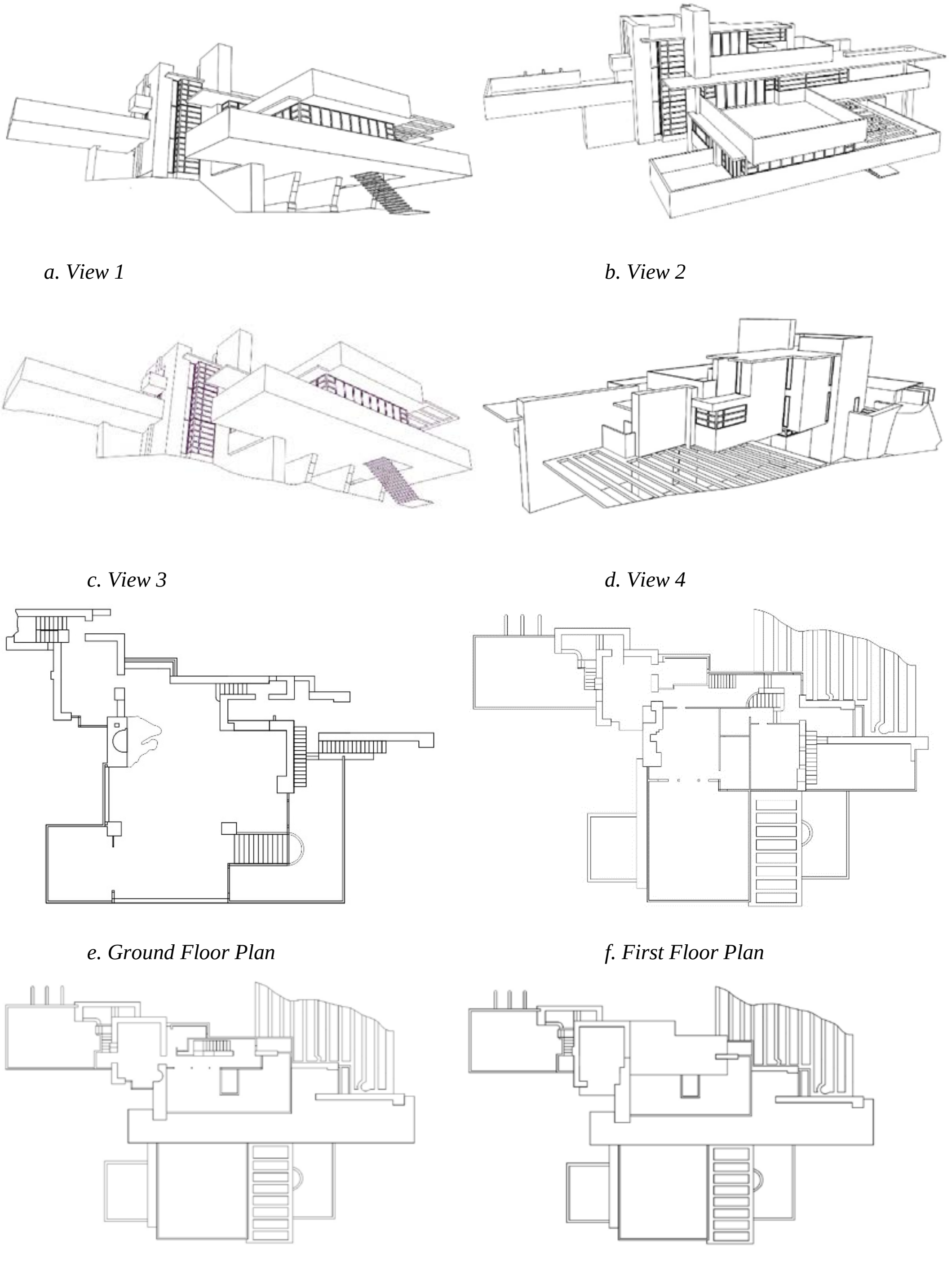
Figure 9.1 a. View 1, perspective of Fallingwater *from below (Futagawa and Pfeiffer 2003: 18-19)*

Figure 9.1 b. View 2, perspective of Fallingwater *from above (Drexler 1965: 137)*

Figure 9.1c. View 3, alternative view from below (Drexler 1965: 140)

Figure 9.1 d. View 4, perspective view from south. (Futagawa and Pfeiffer 1987c: 49)

The plan images of the house used for analysis in this chapter are the same as the ones used in Chapter 8 with one exception. In this chapter, the detail included has been reduced in each drawing from texture Level 4 to Level 3 (see Chapter 5). This means that doors, glazing and built-in furniture are not depicted in the plans that are analysed in this chapter. As *Fallingwater* does contain a considerable amount of built-in furniture, as well as doors and windows, the amount of detail in the images is reduced. The fractal dimension results therefore indicate the difference made by the removal of these details from the images tested in Chapter 8. The effect of reducing the amount of detail included in the linear representations of *Fallingwater* means that instead of looking at the house as an inhabitable architectural design, the results will now describe the primary geometric gestures of the form, and will not include as much detailed information about the purpose or use of the building. Figure 9.2 shows the perspective views and plans of the *Fallingwater* house analysed in this section, followed by the results of their analysis.



a. View 1 *b. View 2*

c. View 3 *d. View 4*

e. Ground Floor Plan *f. First Floor Plan*

g. Second Floor Plan *h. Roof Plan*

Figure 9.2 a – h Images of Fallingwater *analysed – Level 3 representation, not shown at a uniform scale*

Table 9.1 Fallingwater, *results for perspective views (D_V) and Plans (D_P)*

Views	D_{V1}	1.4474
	D_{V2}	1.5140
	D_{V3}	1.4354
	D_{V4}	1.5170
	μ_V	1.4785
Range	R_{VD}	0.0816
	$R_{V\%}$	8.16
Plans	D_{P0}	1.3540
	D_{P1}	1.4291
	D_{P2}	1.4018
	D_{PR}	1.3845
	μ_P	1.3924
Range	R_{PD}	0.0751
	$R_{P\%}$	7.51

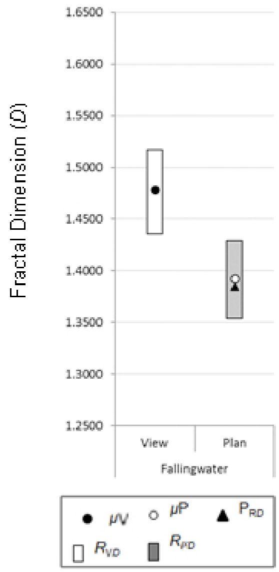


Figure 9.3 Fallingwater, *graphed results for perspective views (D_V) and Plans (D_P)*

The cardinal directions from which the perspective views are predominantly framed are from the south and south-west (looking towards the north and north-east), with only one perspective view from the north (looking south towards the side of the house facing the steep slope behind). Of the elevations analysed in Chapter 8, this northern facade has the lowest level of visual complexity, however in the perspective views studied in this chapter, this northern perspective has the highest fractal dimension result of all the perspective views of the house (D_{V4} = 1.5170). This may be because in elevation, the orthographic view of the house flattens out what is actually a formally complex facade. Compared to the long, cantilevered planes of the southern facade, the northern facade is stepped and notched on both the horizontal and vertical planes, as it responds to the angle of the driveway and to Wright's internal planning. Of the southern perspectives, the treetop view looking down onto the southern balconies from above has the second-highest fractal dimension (D_{V2} = 1.5140), a result which is quite close to that of the northern perspective. The two views looking up from the water of Bear Run at the southern facade of the house vary only slightly in their perspectival construction, and likewise their results are relatively similar (D_{V1} = 1.4474 and

D_{V2} = 1.4354). With a view predominantly of the underside of the outdoor terraces, these two perspectives lack the volume of geometric detail found of the other views and thus have the lowest fractal dimensions. Overall the mean result for the perspective views is μ_V = 1.4785, despite their delineation having a texture of Level 3, the view results are higher than the mean results of the elevations (delineated in Level 4) from the previous chapter (μ_E = 1.4019). Such a result is not unexpected, as past research (Vaughan and Ostwald 2014a) has found that perspective views tend to contain more information than elevations, but also that this depends on the particular geometry of the building and the framing of the view chosen.

The floor plans of *Fallingwater* in this second study all have a lower fractal dimension than the previous chapter, a result that is also expected because—as previously noted—of the reduced volume of detail included in the images being analysed. The most dramatic change is found in the ground floor plan, which now has the lowest fractal dimension of the house plans (D_{P0} = 1.3540). Without the furniture included and particularly without the doors leading to the outside spaces, this floor becomes a shelf-like open space. The first and second floors are still the most complex plans in the house (D_{P1} = 1.4291 and D_{P2} = 1.4018), when depicted with Level 3 representation. Due to the reduction of complexity in the ground floor plan, the roof plan is no longer the least complex (D_{PR} = 1.3845) and is now very close to the mean result of all the plans (μ_P = 1.3923). The terraces, overhangs and outdoor circulation are all clear expressions of the geometry of the building, and are all visible in the roof plan.

The Range of the results for the perspective views is $R_{E\%}$ = 8.16 which, according to the qualitative descriptors in Chapter 7 (Table 7.9), suggests that, compared to each other, the perspective views are visually similar, and indeed are more similar to each other than the elevation views in the previous chapter. For the new plan results, the Range is slightly tighter than the perspective views at $R_{P\%}$ = 7.51, and these could also be described as visually similar to each other. However, the more detailed plans analysed in Chapter 8 had an even greater level of visual similarity ($R_{P\%}$ = 5.69).

9.3 Analysis of the *Fallingwater* Site

The plans and views of the natural elements analysed in this chapter are all derived from the landscape in the immediate surroundings of *Fallingwater*. The area used for the natural elements selection is based on the site plan produced by Wright's apprentices and used by Wright in his design for the house (fig. 9.4a). The selected area used for the present research is based on the area reproduced in Wright's studio image, but it is slightly enlarged for the present study to contain the entirety of some of the elements that are only partially represented in Wright's studio site plan. Wright's studio version of the site plan does contain some errors and omissions that might affect the analysis, including the position of the waterline and the tree canopies, but no attempt has been made to correct these issues for the present research. The claims about *Fallingwater* and nature are largely about Wright's intentions and so it is more important to use the same information available to Wright if possible. The additional area and details added to the site plan used in this study are derived from the original 1935 site plan prepared for the Kaufmanns, upon which the studio drawing is based (fig. 9.4b).

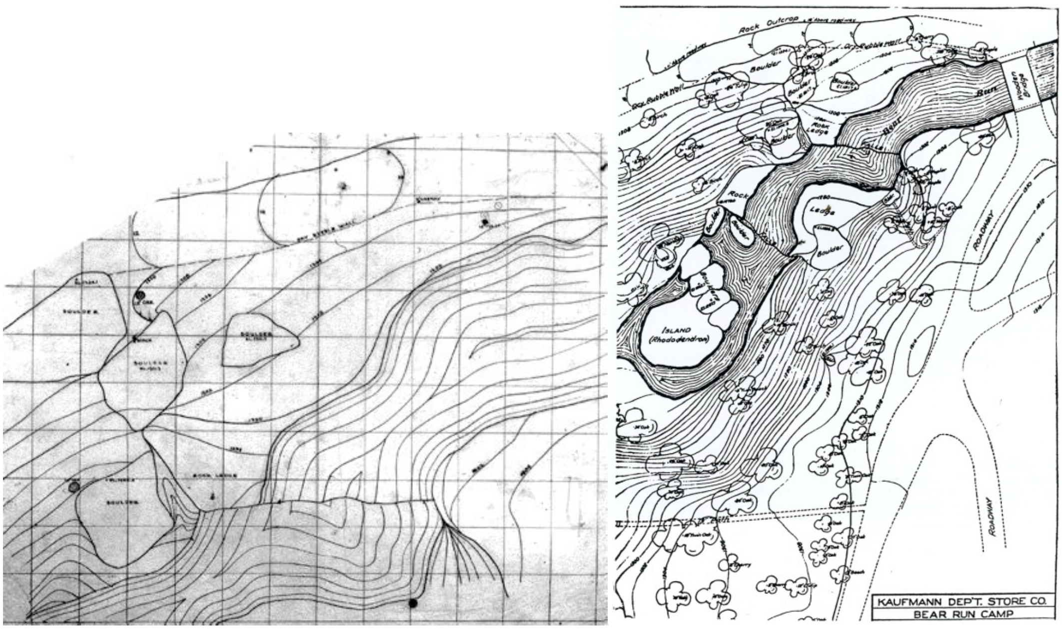


Figure 9.4 a. Studio version of Fallingwater *site plan (Kaufmann 1986: 39) b. Original site plan (McCarter 2002: 5).*

For the present research, the two historic site plans were reproduced and then merged into a new site plan, which has been used as the basis of analysis for the plan drawings of the four natural elements. All of the natural elements analysed in this chapter are located within this site area. For each natural element, four line drawn representations have been made of a unique example of each on the site. Figure 9.5 shows the combined plan with the position of each element selected for representation indicated, and the images of natural views produced for analysis are depicted in Figures 9.6 b-e - 9.9 b-e. This new site plan is then separated into four layers, each only showing the individual element analysed: the rocks, the contours, the watercourse and the tree cover (Figs 9.6a-9.9a). The rationale behind the particular view and framing of each natural element in provided in Chapter 6.

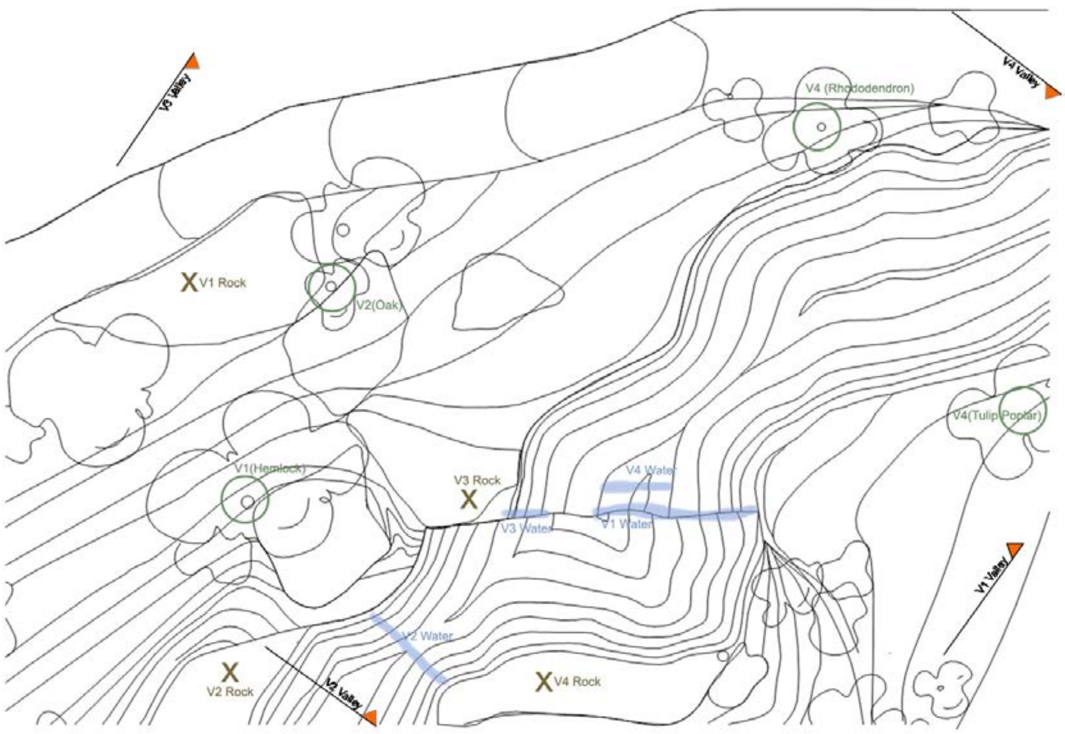
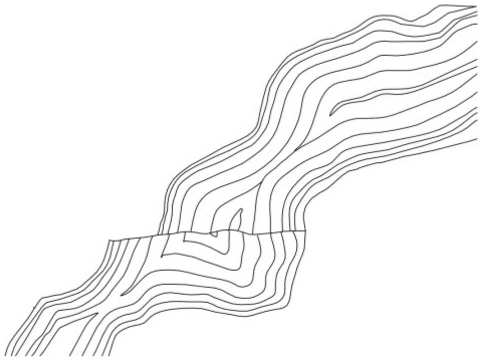
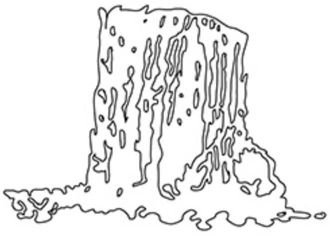


Figure 9.5 Plan showing location of each natural element analysed in view form

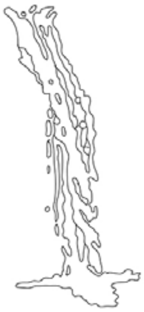


a. Water plan

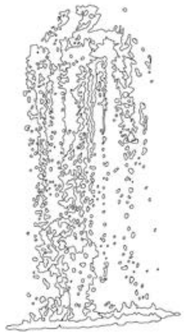
b. Water view 1



c. Water view 2

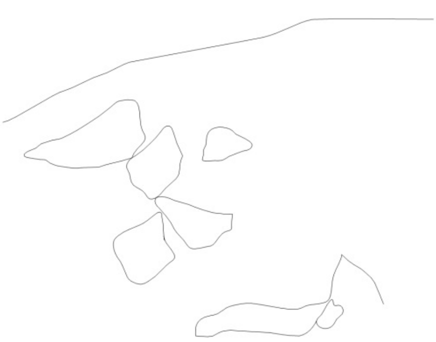


d. Water view 3



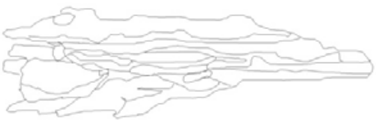
e. Water view 4

Figure 9.6 a-e Images of water analysed – not shown at a uniform scale



a. Rock plan

b. Rock view 1

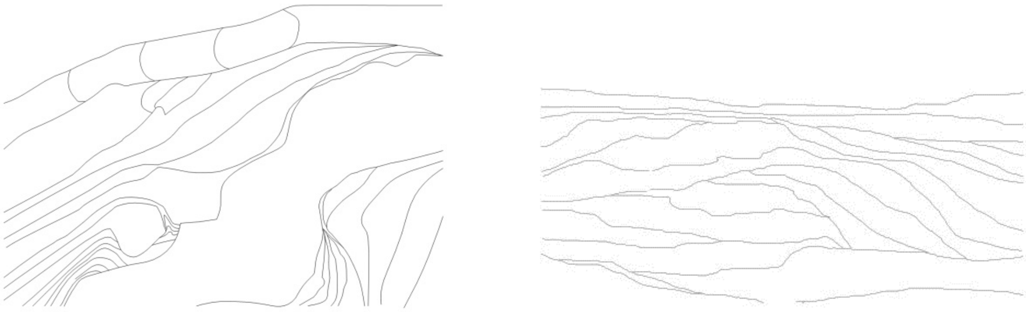


c. Rock view 2

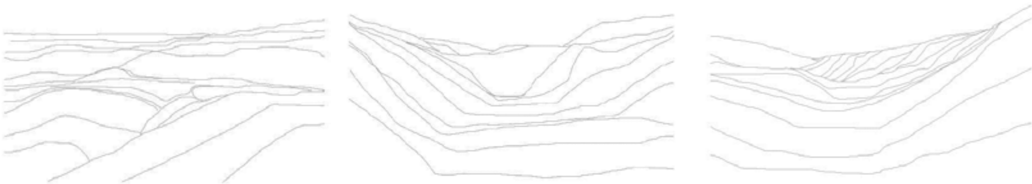
d. Rock view 3

e. Rock view 4

Figure 9.7 a – e Images of rocks analysed – not shown at a uniform scale

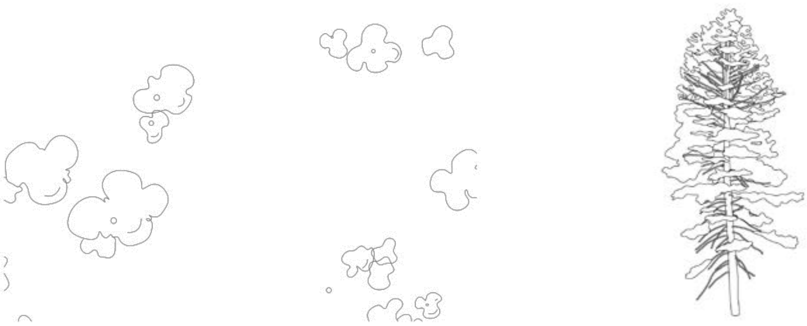


Valley plan *b. Valley view 1 (north)*



a. Valley view 2 (east) *c. Valley view 3 (south)* *d. Valley view 4 (west)*

Figure 9.8 a-e Images of the valley analysed – not shown at a uniform scale



a. Tree plan *b. Tree view 1 (eastern hemlock)*

c. Tree view 2 (scarlet oak) *d. Tree view 3 (tulip poplar)* *e. Tree view 4 (great laurel rhododendron)*

Figure 9.9 Images of the trees analysed – not shown at a uniform scale

Table 9.2 Natural elements, results: SD is the Standard deviation of the view data.

Natural Elements		*Water*	*Rocks*	*Valley*	*Tree*
Views	D_{V1}	1.6532	1.5450	1.3200	1.5699
	D_{V2}	1.5985	1.5450	1.3169	1.4176
	D_{V3}	1.4198	1.4744	1.3180	1.4142
	D_{V4}	1.5840	1.2928	1.3109	1.7316
	μ_V	1.5639	1.5215	1.3165	1.5333
	R_{VD}	0.2334	0.0706	0.0091	0.3174
	$R_{V\%}$	23.34	7.06	0.91	31.74
	SD	0.1005	0.7614	0.0039	0.1508
Plans	D_P	1.4671	1.1630	1.3378	1.1787

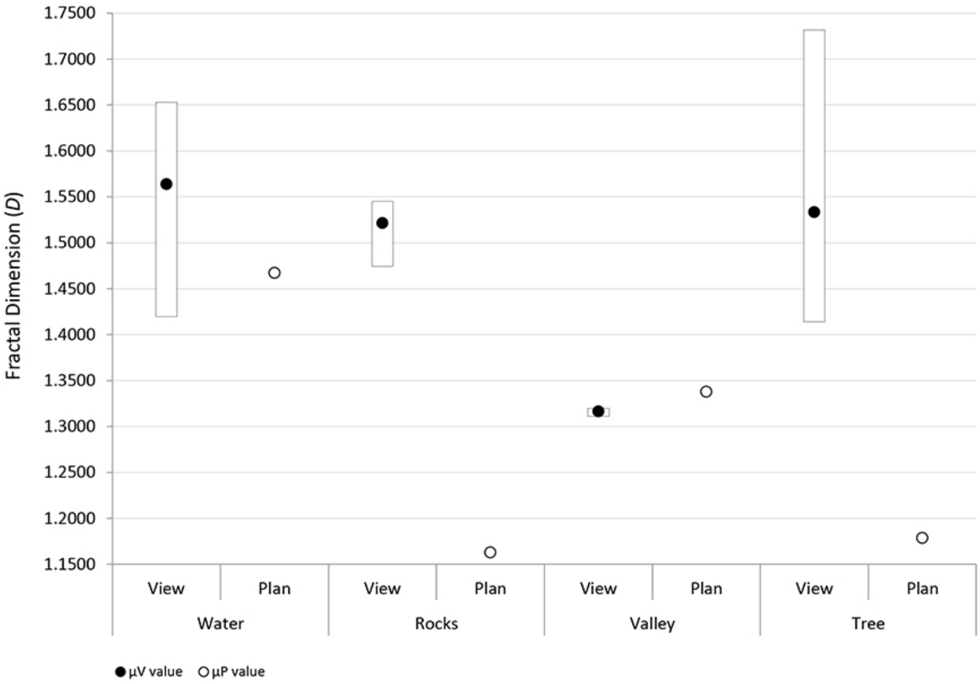


Figure 9.10 All results for natural analogues graphed

The views of the water are taken from four different photographs of the waterfalls created by the stepping down of the rock shelf in the Bear Run stream. Of these, the main drop, during heavy rains or after the snow has melted, creates a wall of falling water, parallel to the southern facade of the house and the image of this fall has the highest visual complexity of all the water images (D_{V1} = 1.6532). The least complex water image is of the same waterfall, but from a line drawing extracted from a photograph taken when there was a lower water level in the Bear Run stream (D_{V3} = 1.4198).

At the time of Wright's first visit to the site of *Fallingwater* in 1934, it was winter and most of the trees would have been bare of leaves except for the evergreen Great Laurel Rhododendrons and the Eastern Hemlocks, both of which grow in abundance around the house site. One each of these evergreens has been reproduced for analysis along with two of the deciduous trees which also grow on the site—the Tulip Poplar and the Scarlet Oak. Of the tree views, the Great Laurel Rhododendron has the highest fractal dimension (D_{V4} = 1.7316) this is also the highest dimension of all of the natural views analysed. The other evergreen tree analysed, the Eastern Hemlock, has the second highest dimension (D_{V1} = 1.5699), this is the expected result, as the leaves add visual detail to the images. The deciduous trees, the Scarlet Oak (D_{V2} = 1.4176) and the Tulip Poplar (D_{V3} = 1.4142) have a similar result to each other, but lower than the evergreens.

The four rocks analysed are all examples of the Pottsville Sandstone found in the Bear Run creek bed or near the house. The results for the first two are interesting because they have exactly the same fractal dimension (D_{V1} = 1.5450; D_{V2} = 1.5450). These two may also be outcrops of the same rockface: the view 1 rock is the large outcrop that supports the western terrace of the house, and the view 2 rock is of the cliffside along part of the stream, below the western terrace. Those two rocks have the highest complexity of the four rocks analysed. The next most complex section of rock is the cliffside underneath the southern terraces of the house (D_{V3} = 1.4744), a result not too dissimilar to the others. The least complex result is for a group of boulders that sit mid-stream, just below the house (D_{V4} = 1.2928). Perhaps because they are subject to continual water erosion they are less fissured than the cliff edges or the boulders above the water level, hence they have a lower fractal dimension.

The views of the valley are the least complex of all the natural elements analysed, and rather than representing just one object such as a tree or a rock, these images are landscape views over a greater distribution of area. While all the results for the valley views are relatively similar, the highest is the view from the north (D_{V1} = 1.3200), which looks across the Bear Run gully to the road used to approach the house. The least complex view is the view from the west (D_{V4} = 1.3109), which is taken from a viewpoint down in the stream which is constrained by the steep gully sides.

Of the plan views, the nautical chart of the water has the highest fractal dimension (D_P = 1.4671) and the rocks have the lowest level of complexity in plan (D_P = 1.1630). The plan of the rocks which was analysed lacks detail and while it provides some qualitative information, as it is an aerial view, many complex aspects of the rock outcrop, such as the cliffline, are represented by a single line, and thus the image is not overly complex or representative. Likewise, the tree plans which have a similar level of representational detail to the rocks, have only a slightly higher fractal dimension (D_P = 1.1787); while the contour drawing used to measure the valley in plan has a higher level of complexity which is closer to those of the waterway (D_P = 1.3378).

Excluding the plans from the mean view results, the water set has the highest fractal dimension (μ_V = 1.5639), followed by the trees (μ_V = 1.5363) and then the rocks (μ_V = 1.5215); while the valley has a noticeably lower level of visual complexity (μ_V = 1.3165). The Range of the results for the four views of the valley show the images to be visually indistinguishable ($R_{V\%}$ = 0.91) and the standard deviation; while only for a very small data sets, confirms this (*SD* = 0.0039). The range for the views of the rocks is similar ($R_{V\%}$ = 7.06, *SD* = 0.7614); in contrast, the views of the water ($R_{V\%}$ = 23.34, *SD* = 0.1005) and the trees ($R_{V\%}$ = 31.74, *SD* = 0.1508) are so different that they affectively unrelated. These last two range results signal several challenges for interpreting the final answer to Hypothesis 2. In essence, there is so much difference between these results that the mean is not necessarily useful for interpreting or comparing some of the data.

9.4 The Visual Complexity of *Fallingwater* House and Site Compared

This section compares the level of characteristic visual complexity in Wright's *Fallingwater* with the four natural elements analysed. The comparison is first approached in view form and then in planar form, with the individual results for each image described before means from the data are considered.

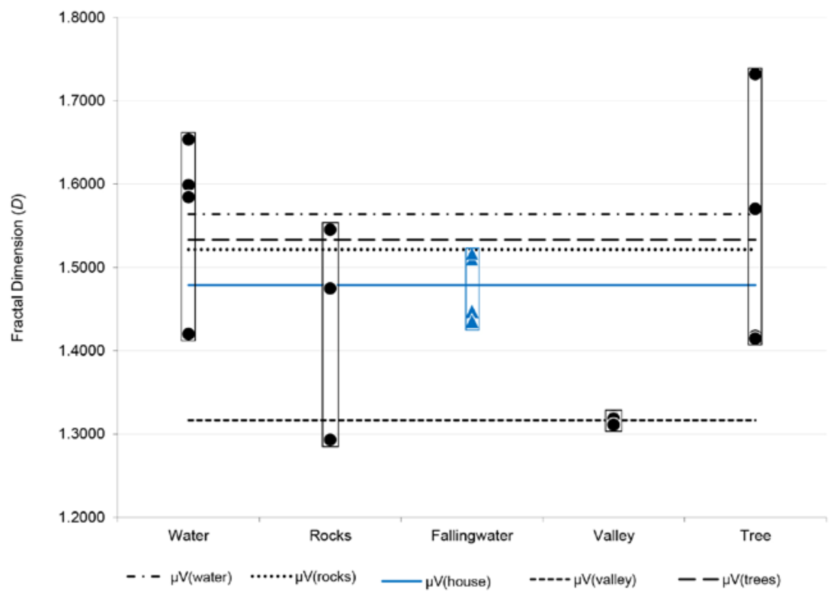


Figure 9.11 Graphed comparison between natural and synthetic views

For the individual view results, half of the results from the natural elements have a higher fractal dimension than the perspective views *Fallingwater* (1.4354 < D_V < 1.5170); and the other half all have a lower fractal dimension. There is only one exception; the image of one of the rocks (D_{V3} = 1.4744) sits within the range of results for perspective views of *Fallingwater.* All the valley views and one representative from each of the other elements are less visually complex than *Fallingwater*. This confirms that generally, most of the results for the rocks, trees and water, are richer in detail than the perspective views of the house, and this can also be confirmed by the positioning of the mean trendlines for the natural elements compared to that of the house. Figure 9.12 helps to visualize difference or similarities between perspective views of *Fallingwater* (results all within the grey band) and the views of the natural elements with a lower value (within the central circle) and the natural elements with greater visual complexity (outer band of results).

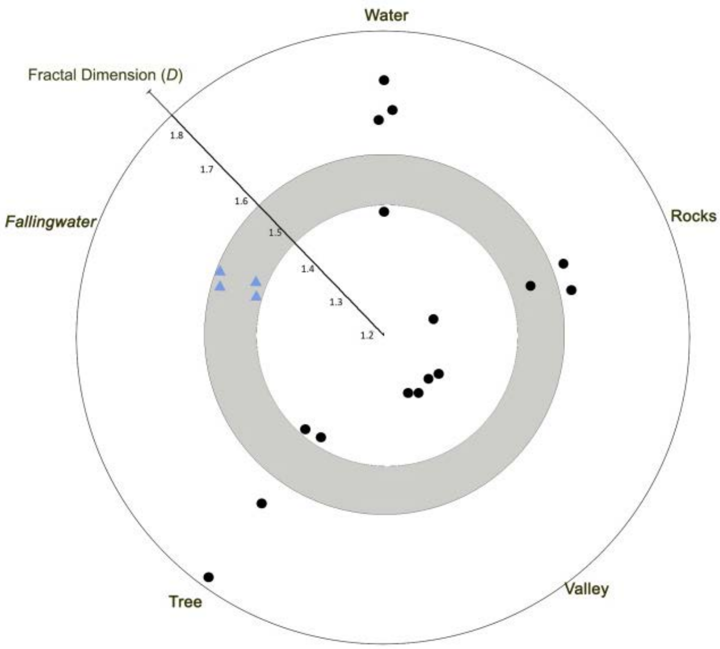


Figure 9.12 Graphic spread of view results data

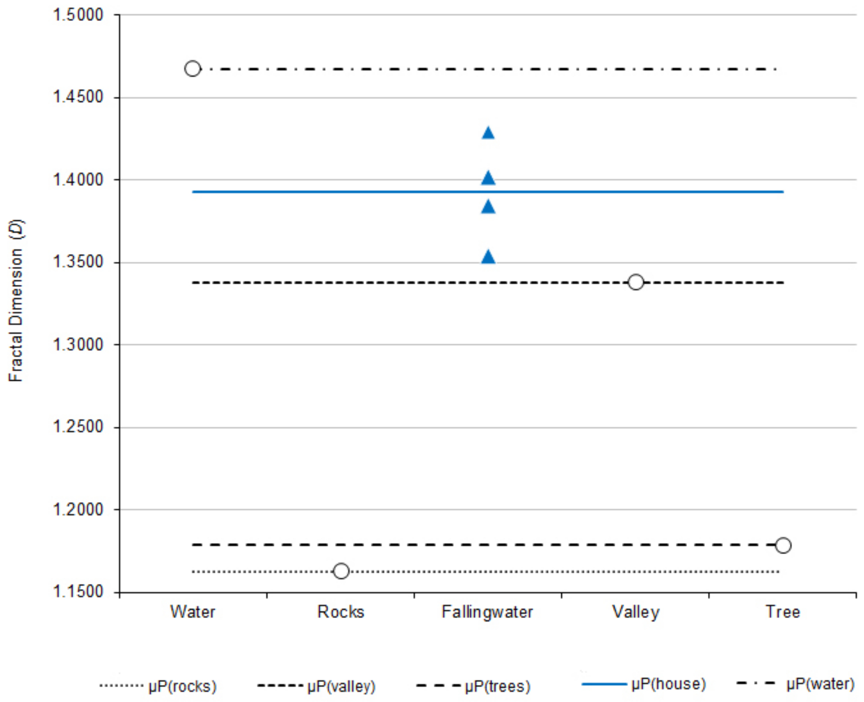


Figure 9.13 Graphed comparison between natural and synthetic plans

The plan results are not as data-rich as the view results, as there is only one plan each of the natural elements. Despite the limited data, Fig. 9.13 shows each as the equivalent of a mean-line to assist with comparison. The plan results show a different pattern to the views. In this case, none of the plans of natural element fall within the range of the *Fallingwater* house plans ($1.3540 < D_P < 1.4291$). Only one of the natural element plans has a higher fractal dimension; the nautical chart used to represent the waterway of Bear Run in plan. The contour plan for the valley ($D_P = 1.3378$) is not much lower than the ground floor plan of the house ($D_{P0} = 1.3540$), however the other plans are all significantly lower. Figure 9.14 helps to visualize difference or similarities between the plans of *Fallingwater* (results all within the grey band) and the plans of the natural elements with a lower value (within the central circle) and the only natural element with greater visual complexity (outer band of results).

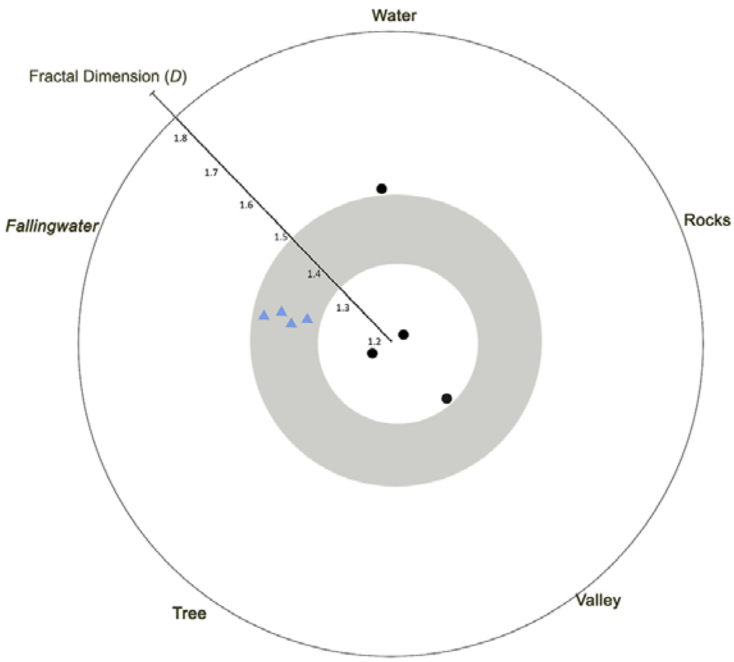


Figure 9.14 Graphic spread of plan results data

To understand the degree of difference between the views and plans of the natural elements and those of *Fallingwater*, a chart of the ranges is presented (Table 9.3). The Range values in the table are set using *Fallingwater* as a target value, and the $R_{\%}$ values provided are the difference between the μ value for the natural element and the μ value for *Fallingwater*. Thus, the R_{μ} indicates the percentage by which the natural elements differ from *Fallingwater*, in view ($R_{\mu V\%}$) and in plan ($R_{\mu P\%}$).

Table 9.3 Comparison of mean results

		μ_V	μ_P	$R_{\mu V\%}$	$R_{\mu P\%}$
Natural element	*Water*	1.5639	1.4671	8.54	7.47
	Rocks	1.5215	1.163	4.30	22.94
	Valley	1.3165	1.3378	16.20	5.46
	Tree	1.5333	1.1787	5.48	21.37
House	*Fallingwater*	1.4785	1.3924	0.00	0.00

Notwithstanding the statistical problem with several of the means discussed previously, if we accept them as reasonable reflections of the data they are developed from, then two of the views and one of the plans of the natural elements could be considered to be "very similar" to those of the house. These are the view sets of the rocks ($R_{\mu V\%}$= 4.30) and the trees ($R_{\mu V\%}$= 5.48), and the contour plan of the valley ($R_{\mu P\%}$ = 5.46). In both view ($R_{\mu V\%}$= 8.54) and plan ($R_{\mu P\%}$ = 7.47), the water can be considered broadly "similar" to *Fallingwater*, which seems fitting considering the name of the house and the significance Wright accorded Bear Run in the design (Wright 1938; Cleary 1999; Levine 2000). The complexity of the valley views are possibly "comparable" to the house views ($R_{\mu V\%}$= 16.20); however the plans of the rocks and trees cannot justifiably be compared to the plans of F*allingwater*, as they are visually "unrelated" ($R_{\mu P\%}$ = 22.94, $R_{\mu P\%}$ = 21.37). However, as very few of the mean results are for data sets with low standard deviations, such an interpretation would be simplistic. Indeed, of the 15 natural analogue views, only one is within the same range as the views of *Fallingwater* and of the four natural plan views, none are within the same range as the plans of *Fallingwater*.

Conclusion

The proposal that the form of *Fallingwater* strongly reflects its natural setting is a claim made by many scholars but it is certainly not universally accepted. Using fractal dimension analysis, this chapter measures the visual complexity of *Fallingwater* and of several parts of its natural setting, to see if there is evidence for, or against, this famous argument. While this may be the primary goal of the chapter, it is also effectively a test of the method itself, and for this reason, the results cannot be used to emphatically provide an end to this debate.

This chapter adapts the method used previously in Chapter 8 by determining the fractal dimension of perspectives and modified plans of *Fallingwater* and comparing them to fractal dimensions of views and plans of four natural elements found in the landscape at *Fallingwater* (rocks, trees, water and the valley). This is not the first time that architecture has been compared with nature in a fractal analysis study. The most recent, detailed study on the effectiveness of comparisons made between architecture and nature (Vaughan and Ostwald 2010) measured the difference between the highest and lowest values of three supposedly similar images identified by Bovill: one set of elevations, one site plan and one image of a mountain. The resulting 'gap', of 28.5% was identified by Bovill (1996) as indicating a degree of similarity between natural and synthetic forms. However, the later analysis of Bovill's claims (Vaughan and Ostwald 2010) found that this 'gap' (from highest to lowest result) not only implies a dissimilar relationship but that a comparison of the range between mean values, for a larger data set, would be more meaningful. Indeed, if we adopt Bovill's approach to calculating the nature-to-architecture gap for the entire set of data used in the present chapter, it would be 56%. While this figure seems to completely quash any argument that the forms of *Fallingwater* are visually similar to those of its natural setting, a comparison constructed solely around outliers in a set of data (the highest and lowest values) ignores most of the properties of the complete set. Furthermore, Bovill's (1996) gap approach to comparing nature and architecture using fractal dimensions was always presented as a suggestion, which should be tested and developed, to illustrate potential uses of the box-counting method in architecture.

This present chapter is the first to develop Bovill's original suggestions about comparing nature and architecture, using a more rigorous (although still imperfect) approach. This chapter uses more examples (of nature and architecture) leading to more data and the capacity to use some basic statistical approaches. A more detailed and consistent rationale is also used for the selection process for identifying appropriate images (for testing specific claims about Wright and *Fallingwater*). However, despite the larger volume of data, and the more carefully chosen sets, a perfect result was never anticipated. Thus, when the data is examined and compared in methodologically corresponding sets—as the present chapter does—a better measure of difference is produced, but it is still not compelling. Certainly, when the methods derived from this thesis are applied to specific sets of images for correlation studies, the % range between the building and nature is reduced to between $5.46\% < R < 22.94\%$, which is an improvement over earlier approaches, although it can still not offer a definitive proof of either of the conflicting positions taken by Wright scholars to the relationship between *Fallingwater* and its setting. Nevertheless, within the limits of the method and the images chosen, this chapter shows a varying degree of visual correlation between *Fallingwater* and its natural setting. However, given the many scholars who are adamant that *Fallingwater* is inextricably entwined with its landscape, it would be expected that the results of this study would show that the house was predominantly "indistinguishable" or at least "very similar" to the natural setting. As such the hypothesis, as it is framed for testing using fractal dimensions, could potentially be considered disproved.

Chapter 10

Conclusion

Typical approaches in the architectural scholarship of the last few decades include interpretation, analysis and assessment of the architecture of Frank Lloyd Wright, and these are equally pivotal to the present dissertation. While such approaches have been used in the past to understand Wright's architecture—many of which are discussed herein—this dissertation takes a slightly different path, which offers a new opportunity to interpret the architecture and philosophy of Frank Lloyd Wright. New approaches of this type are especially significant, as Donald Hoffmann observes, because '[t]o begin afresh with Wright is to reject the accumulated burden of received opinion, all the academic theories that pretend to explain his architecture from presumed methods and sources' (1995: 85). For example, Wright's architecture could be examined through the lens of the Arts and Crafts movement, or in terms of the manipulation of geometric grids, shape grammars and three-dimensional Froebel blocks. Interpretations of Wright's architecture in terms of 'archetypal memories or sophomoric Freudian symbols, arcane literary illusions or even dreamlike condensations of motifs' (Hoffmann 1995: 85) are also common. But to perpetuate these existing ideas, rather than to pursue new approaches, is unlikely to break new ground or resolve existing disagreements in Wrightian scholarship. As Hoffman argues, to 'respond to each of these theories would only compound the pedantry beyond which Wright never fails to soar' (1995: 85). Thus, the present dissertation does not propose new theories for explaining Wright's architecture, or generates forms which are akin to Wright's. Instead, it applies a unique system of measuring to Wright's most famous house, and uses this to test several conflicting views about its properties. This house is *Fallingwater*—the remarkable structure Wright designed over a rocky waterfall in a deeply forested valley of the Pennsylvanian wilderness. It has been the subject of wide-reaching scholarly interest for the 80 years of its existence, but of the many different interpretations of this house, there are two proposals that are of interest for this dissertation. The first is the proposition that *Fallingwater* is a unique design amongst Wright's architecture, being unlike his three major housing styles - Prairie, Textile-block and Usonian. The second is that *Fallingwater* is a house that strongly reflects its natural setting.

In this dissertation these two propositions are examined on the basis of new evidence which is developed using fractal dimensions. Fractal dimensional analysis is a repeatable, quantitative method for measuring the characteristic visual complexity of a subject. In this case, the subjects are the physical forms and the visual details of buildings and natural objects. Because fractal dimensions of *(a) Fallingwater's* natural setting, *(b) Fallingwater* itself and *(c)* Wright's domestic architecture, can be separately determined and compared in any configuration, fractal analysis has been selected as the computational method which is most likely to contribute to resolving, or at least illuminating, the two propositions.

These two propositions, raised by architectural critics, historians and theorists, are reframed as hypotheses for the present dissertation.

- **Hypothesis 1:** That the formal and visual properties of Frank Lloyd Wright's *Fallingwater* are atypical of his early and mid-career housing (1901-1955).
- **Hypothesis 2:** That the formal and visual properties of Frank Lloyd Wright's *Fallingwater* strongly reflect its natural setting.

The data and associated analysis for Hypothesis 1 are contained in Chapter 8, while Chapter 9 covers Hypothesis 2. However, before summarising the key findings of this research, it is important to reiterate the limitations of the method and the approaches used.

Fractal analysis is a rigorous method which is accepted throughout the sciences, but it can only provide information about the subject being analysed and even then, its primary use is typically for constructing comparisons. A fractal dimension is a statistical approximation of the spread of detail or geometric information across an image. Fractal dimensions do not provide information about any other visual properties such as proportion, composition or color.

The fractal analysis method has several known limitations which can affect the accuracy of results. For example, as a method that uses mathematical algorithms to analyse images, its outcomes can be greatly affected by the quality and consistency of the data input sources. A consistent method for selecting images, determining which data to include (levels of representation) and how to process this data is therefore a necessity. Furthermore, there are inconsistencies in the mathematical and statistical aspects of the box-counting method which are described in detail in Chapter 5. These methodological limitations have been addressed where possible through careful decisions about data sources and processing methods. However they still do have an occasional impact on the results, and where this occurs it is noted in the text. Furthermore, like any study that interprets numerical data, the volume of data available shapes the accuracy of the outcome, and this study was limited by the number of sources available. A larger number of data sets (source images) for this study would have provided greater surety in the results, and may have assisted in interpretation of results as additional data points might display clustering patterns more clearly.

10.1 Results for Hypothesis 1

The fractal analysis method for architecture has been progressively developed and refined over more than two decades (Bovill 1996). Significantly, this method—while very recently used for the analysis of Frank Lloyd Wright's architecture (Ostwald and Vaughan 2016)—has never been used to calculate the visual complexity of *Fallingwater*, 'the most celebrated [building] of his entire career' (Hoffmann 1995: 83). Using the fractal analysis method it is possible to construct a numerical comparison between different periods in Wright's domestic designs and thereby test the first hypothesis.

To test Hypothesis 1, the characteristic complexity of all four elevations and four plans of *Fallingwater* are measured. Then the same method is applied to plans and elevations of 15 of Wright's other houses, built between 1901 and 1955, producing results for 58 elevations and 46 plans. These 15 houses include five representatives each from three of Wright's key stylistic periods, the Prairie, Textile-block and Usonian periods. The results were sorted and tabulated into different options for comparison—numerical comparisons using individual results, mean dimensions and comparative ranges—between the 112 major and over 1000 minor measures produced. This numerical information is then interpreted in combination with past scholarly arguments about Wright's work, combining the quantitative and qualitative to produce a nuanced assessment of the data.

The results for the first hypothesis show that, when compared to elevations of other houses by Wright, *Fallingwater's* elevations generally have lower formal complexity than most of the other houses measured. Moreover, *Fallingwater's* mean elevation dimension is less complex than the means of all the other sets. Despite these results, *Fallingwater* is very similar to the Usonian houses in terms of the characteristic complexity of elevations. In plan form, *Fallingwater* typically has a similar level of complexity to the majority of the other houses. For the mean plan results, *Fallingwater* has higher complexity than the Usonian and Prairie houses, and shares a similar level of complexity to the Textile-block homes. Thus, within the limits of the method, the results indicate that the visual complexity of *Fallingwater* is largely typical of Wright's Prairie, Textile-block and Usonian houses and indeed, that in terms of formal expression, it is broadly similar to the latter group. Collectively these results suggest that Hypothesis 1 is false, demonstrating that—within the parameters of this dissertation— *Fallingwater* is visually similar to Wright's Prairie, Textile-block and Usonian houses.

The indicators of a positive, neutral or negative result for the hypothesis are described in Chapter 1. A positive result for Hypothesis 1 would be justified if the compared sets have a high degree of difference. This would be indicated by the mean elevation and plan values of *Fallingwater* and of each of the other stylistic sets, having a higher range than 10% ($x \geq 11.0$ %) when compared. However, none of the mean values of any of the stylistic sets have a percentage difference from *Fallingwater* that is over 10%, suggesting that Hypothesis 1 is false (Table 8.9). However, as outlined in Chapter 1, the answers to the hypotheses are not necessarily a straightforward true/false dichotomy and we can further investigate the data for indicators of a neutral or positive outcome. The indicator of an intermediate or neutral result would be a range that is 10% or less ($x < 11.0$%), but greater than 5% ($x \geq 6.0$ %). For the mean elevation results, the Prairie and Textile-block houses all have a percentage difference from *Fallingwater's* mean elevations that match this neutral outcome, while the Usonian meets this result in plan. The rest of the results—the Prairie and Textile-block house plans and the Usonian elevations—are all so similar to Fallingwater ($x < 6.0$%) that they emphatically show that Hypothesis 1 is false.

10.2 Results for Hypothesis 2

While the box-counting method of fractal analysis has been widely used to measure architecture, and separately to analyse natural elements and systems, the use of fractal analysis to compare architecture and nature has only rarely been attempted (Bovill 1996; Lorenz 2003; Vaughan and Ostwald 2010; Bourchestein et al 2014). However, to determine if the form of *Fallingwater* is similar to that of its surrounding natural setting—and thus provide an answer to the second hypothesis—a variation to the architectural approach has been created. This methodological variation relies on a rationale or framework for selecting images for comparison. Thus, prior to testing Hypothesis 2, a literature review of Wright's philosophy of nature and architecture was carried out, and possible source images were investigated, until finally sixteen edge-detected drawings of views of natural elements and four plans derived from the original site surveys of the location, and four perspective views and four simplified plans of *Fallingwater* house were identified as appropriate. The views of the natural elements were extracted from photographs of *Fallingwater's* setting, including its rocks, trees, water and the valley itself. Despite the underlying image-selection framework being consistently applied, it must be acknowledged that the final images used represent only a small number of the myriad of potential natural images available for this purpose. As such, they have been chosen to test arguments about the formal relationship between nature and *Fallingwater* and they are not necessarily perfect to test some other claims.

With the images selected and prepared, the second hypothesis was tested by comparing the fractal dimension measures for the sets of images of *Fallingwater* to the measures derived from sets of images of the natural elements. The results were tabled and sorted into different options for comparison—numerical correlations using individual results, mean dimensions and comparative ranges—between the 28 major data points and approximately 300 minor data points. As it was for the first hypothesis, this numerical information was then examined in combination with past scholarly interpretations of Wright's approach to nature and architecture, particularly in the case of *Fallingwater*, combining quantitative and qualitative to produce a meaningful reading of the data.

To determine the outcome for Hypothesis 2, the indicators presented in Chapter 1 are used. A positive result for Hypothesis 2 could be justified if the sets of natural elements—when compared with *Fallingwater*—have a low degree of difference. This would be indicated as a positive result if the mean elevation and plan have lower range values than 5% ($x < 6.0\%$) when compared. A negative outcome would be indicated if the results were higher than 10% ($x \geq 11.0\%$), and a neutral result would be between the two extremities ($6.0\% \leq x < 11.0\%$). The results for the test of the second hypothesis (Table 9.3) are less straightforward than the results for Hypothesis 1. The mean elevations for the rocks and the trees, and the plan of the valley, all have a percentage difference under 6.0%, meaning that Hypothesis 2 could be considered valid in these cases. However contrary to this, the plans of the rocks and trees and the elevations of the valley all have a percentage difference from the *Fallingwater* results by over 10%, so that these sets suggest Hypothesis 2 to be false. Both the results of the elevations and plan for the water lie between these ranges, providing an intermediate, or neutral response to Hypothesis 2 for the comparison between the house and the water.

These results do suggest—within the limits of the method and the images chosen—a level of similarity between the forms of *Fallingwater* and some of those found in its natural setting. However, given the many scholars who are adamant that *Fallingwater* is an example of Wright's aim 'to achieve an indivisible bond' between architecture and landscape (De Long 1996: 120), it would be expected that the results of this study would show that the house was predominantly "indistinguishable" or at least "very similar" to the natural setting, with the hypothesis outcomes being predominantly true, perhaps minimally neutral and with no false response. Instead, the results show a more mixed or neutral result, and as such the second hypothesis, as it is framed for testing using fractal dimensions, could potentially be considered false and indicate that the formal and visual properties of *Fallingwater* do not reflect its natural setting.

10.3 Other Observations Arising from the Research

In addition to testing the two hypotheses, the present dissertation also uncovers some interesting aspects of Wright's approach to design. For example, it can be seen from the literature that there is a consistent thread wherein Wright refers to 'nature', throughout his lifetime. While this is not a new observation, on examining the terminology that Wright uses to describe 'nature', it is clear that he—whether consciously or not—took one particular approach to *nature*, which he regarded in 'almost mystical terms' (Pfeiffer 2004: 12) and another to *landscape*, which he referred to as the physical 'features or pattern' of the natural world (Spirn 2000b: 15). Wright's clear distinction between nature and landscape is rarely mentioned in the scholarship, although it provides a valuable point of departure from which to study Wright's approach to landscape and natural forms—being tangible subjects which can be analysed using fractal analysis—rather than the more spiritual aspects of nature.

A detailed examination of literature describing Wright's own views (and scholarly arguments) about the relationship between design and landscape resulted in further findings. The first of these is the identification of a set of eleven interconnected and recurring strategies that Wright frequently employed to connect his architecture to the landscape. These eleven strategies are composed of five site strategies—site interpretation, locality character, site characteristics, landscape alterations and site intensification—and six design strategies—approach to the ground, the formal mass of the building, the roof, the openings, any intersections with natural features of the location and the material palette. These approaches, which Wright took when integrating a building with its setting, are used in the present research to investigate claims about *Fallingwater*. This application revealed further information about Wright's design process and all but two of the strategies were found to be used in *Fallingwater.* A summary of how these strategies were (or were not) applied by Wright at *Fallingwater* is presented at the end of Chapter 2. In addition to these summaries, the dissertation proposes a reading of how much (or little) each strategy is demonstrated at *Fallingwater*. Significantly, while some examples of strategies that Wright used to connect *Fallingwater* and the landscape can be verified by observation of either the building itself or architectural drawings, the majority are not measurable using *any* means. Only one strategy, 'site characteristics', was found to be measurable using fractal dimensions (or is likely to be measurable using any computational means). Pinpointing this strategy was useful because it identified the natural elements in the landscape surrounding *Fallingwater*, the water, the rocks, trees and the valley, as suitable subjects for comparison with *Fallingwater* in order to test Hypothesis 2.

A further observation was made in Part III, as a result of calculating the fractal dimensions of the 15 other houses by Wright. The mathematical analysis of visual complexity of 15 of Wright’s domestic designs shows that—despite some stylistic differences—there is a notable degree of visual consistency across Wright’s housing designs (the largest variation being 6.4%), an outcome that supports the arguments of a several historians (Hoffman 1995; McCarter 1999; Frampton 2005). For the mean elevation data, the Prairie and Textile-block houses have an almost identical fractal dimension, and the Usonian result is only slightly lower. In plan form, Wright appears to have gone full circle in terms of spatial complexity over time, starting from the Prairie style then increasing in the Textile-block houses, before returning to the lower levels in the Usonian houses. Comparing the aggregate results of the three periods of Wright’s architecture, the Textile-block buildings are generally the most complex, the Usonians are the least and the Prairie houses are midway between the two.

10.4 Future Research

Both hypotheses in this dissertation signal opportunities for further research. Firstly, the mathematical methods presented in this chapter for the first hypothesis, along with the comprehensive data for 16 houses, can be used to assist historians and design scholars to ground their analysis of Wright’s architecture and to promote future, more detailed computational analysis of historic buildings. The second hypothesis also offers new research opportunities. With an increased sample size in a comparative nature-architecture study, more statistically reliable and robust results could be gained. Although, there is no guarantee that including additional cases in the analysis will produce a better outcome, it might allow a higher degree of confidence in the results to be developed.

There are also many potential future research topics which involve comparing natural and architectural forms. Starting with Wright, some of his other houses and their settings could be tested. For example, the *Robie house* could be compared with the Prairie landscape surrounding Chicago in the early 1900's. As well as historic buildings, more recent designs (or unbuilt proposals) could be studied using this method. Environmentally sustainable design theories often involve claims that such buildings should 'fit' within the landscape. Developing this method further might result in a process to assist with determining whether a building is a sympathetic (meaning visually similar) addition to a landscape or offers a point of contrast or juxtaposition.

Conclusion

Hoffman argues that Wright's 'words need to be sifted and weighted with care, sifted again and always tested again against the evidence of the eye' (1995: ix). It is only through the careful application of such a rigorous form of visual examination that researchers 'will help to identify the principles that gave [Wright's] architecture not only its extraordinary vigor of structure and form, expression and meaning, but its surprising continuity' (Hoffmann 1995: x).

Taking Hoffmann's advice, this dissertation has studied the work of Frank Lloyd Wright, applying a combination of approaches, based around the quantitative method of fractal analysis. The limitations of this method mean that the interpretations of the data are neither definitive nor irrefutable. The data, Wright's words, his designs and the arguments of various scholars, can be thought of as a guide. When combined and approached in different ways they offer a new way of interpreting the architecture and theory of Frank Lloyd Wright.

Ultimately, this dissertation provides new information and resources that not only contribute to our understanding of Frank Lloyd Wright's architecture and design theory, but also to the understanding of a unique house. The dissertation summarises the strategies Wright used to connect *Fallingwater* with its setting, providing data on the visual complexity of its plans, elevations and perspectives along with views and plans of its setting. Historical and scholarly inputs suggested that *Fallingwater* would be different from Wright's other houses and be strongly connected to the site, however the outcomes of the hypotheses did not support these expectations. In conclusion, this dissertation echoes Hoffmann's words, that '[t]he house on Bear Run defied every expectation […] In short, Fallingwater flouted all the rules' (Hoffmann 1995: 85).

End Matter

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List of Figures

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Dedication

This work is dedicated to Mother Earth, for her continuous inspiration.

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