Façade Design Pattern Optimisation Workflow Through Visual Spatial Frequency Analysis and Structural Safety Assessment

Martin Ivanov[1*], Jun Sato[1]

* Corresponding author: martin.ivanov359@gmail.com
1 The University of Tokyo, Department of Socio-Cultural Environmental Studies, Japan

Abstract
As the demand for highly efficient yet aesthetically pleasing, complex building envelope structures is rising worldwide, computational analysis and generative design tools are becoming ever so relevant. Previous methods for achieving a natural distribution of structural or shading elements in non-uniform façades are mostly based either on computer-generated pseudo-randomness or a literal biomorphic approach where a naturally occurring pattern is directly projected on the façade surface. As an alternative, this research introduces a novel technique for optimisation that utilises a two-dimensional Power Spectrum Analysis, suitable for numerically assessing the alignment of designed geometry with natural patterns. By integrating this optimisation method into the design process, the façade pattern generation can be automated and optimal design can be selected by evaluating multiple design solutions. Instead of using repetitive geometrical patterns or generated pseudo-randomness, patterns objectively similar to those occurring in nature can be created without directly copying natural structures. The distribution of the structural and shading elements controls the way natural light permeates the building and, considering the data gathered from images of natural scenes, this method can be used to design structures not only with optimal structural and energy performance but also with visual and psychological occupant comfort in mind.

Keywords
Generative Façade Design, 2D Power Spectrum Analysis, Computational Design Tools, Non-uniform Façades, Structural Optimisation, Natural Light Control, Naturalness

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1 INTRODUCTION

The design process of façade structures requires many considerations like structural and energy efficiency, solar gain, visual and thermal comfort. The performance of a façade system regarding most of these aspects can be objectively measured through computer simulations with clear values, which can then be used to improve the façade design through various optimisation algorithms (Huang & Niu, 2016). Computational design tools enable semi-automatic façade design generation, where the designer sets constraints and the algorithm automatically creates and evaluates a large number of potential solutions.s (Heusler & Kadija, 2018). Designing a façade structure algorithmically offers adaptability and easy reconfiguration of the structure and its elements based on the input parameters, and computational analysis tools aid the designer in their decision-making process.

Structural performance can be studied by the Finite Element Method (FEM) with linear and non-linear analysis tools (Sato, 2010), and methods such as daylight analysis and glare analysis are effectively utilised for solar gain and visual comfort (Larson & Shakespeare, 1998). There is a multitude of proposed metrics to measure visual comfort by evaluating daylight levels and distribution, exposure to direct sunlight, and glare intensity (Tabadkani et al., 2021) such as the established Daylight Glare Probability metric (Wienold & Christoffersen, 2006). To assess the window view quality in terms of view content, access, and clarity, there is a proposed framework (Ko et al., 2021), an integral part of which is the analysis of the visual features and aesthetic qualities of the view (Matusiak & Klöckner, 2015).

Quantifying the aesthetic appeal of façade designs with objective metrics presents challenges, often leading architects to draw inspiration from natural forms. In achieving a natural distribution of structural or shading elements within non-uniform façade structures, architects generally adopt one of two main strategies: employing stochastic geometry or generated pseudo-randomness (Verbeeck, 2006) or directly incorporating natural shapes through a biomorphic approach (Vincent, 2009). While the randomness employed in generative art or architecture can foster creativity, it may result in uncontrollable and unpredictable outcomes that necessitate further design evaluations. Conversely, the biomorphic approach, which involves the direct application of natural patterns to structural designs, tends to be labour-intensive and might limit design flexibility by typically producing a single design solution based on a singular reference.

To address these challenges, this research proposes a novel approach: the utilisation of a Power Spectrum Analysis (PSA) technique suitable for implementation within automated and semi-automated structural design generation and optimisation systems. Defining "naturalness" in objective terms is challenging, which is why this research explored the potential of 2D PSA, a proven method to evaluate visual scenes (Oliva et al., 1999; Torralba & Oliva, 2003), their perceived aesthetics (Redies et al., 2007; Spehar et al., 2003) and visual comfort (Juricevic et al., 2010; O'Hare & Hibbard, 2011). PSA has seen successful application in evolutionary art systems as a tool to derive a mathematical value conducive to optimisation (Gircys & Ross, 2019). The principal goal of this study is to determine the feasibility of incorporating PSA into a generative design process, specifically for enhancing façade designs by ensuring their spectral alignment with a selected natural pattern. Within a generative design framework, the proposed analysis technique, when paired with optimisation algorithms, enables the automated generation and evaluation of diverse design solutions.

This method can reference either a single natural image or an entire image category, offering a novel alternative to the conventional biomorphic approach. Unlike direct mimicry of natural phenomena, this method employs statistical analysis to evaluate the designed geometry, offering a numeric assessment of how closely a design's pattern aligns with those observed in nature.

The proposed methodology was assessed through two generative design experiments. The initial experiment focused on a double-skin glazed curtain wall system, targeting the singular objective of achieving spectral similarity to a predetermined natural pattern over successive generations through model-based and metaheuristic optimisation solvers. The subsequent experiment demonstrated the utility of incorporating the PSA-based method with other structural optimisation techniques in a Multi-Objective Optimisation (MOO) framework, integrating linear structural analysis via the FEM to simultaneously address structural feasibility and safety.

This methodology presents an alternative form-finding strategy for natural-form façade design, diverging from the conventional biomorphic approach that primarily depends on visual similarities. It aims to strike a balance between emulating natural characteristics and maintaining design control, potentially leading to innovative architectural solutions that embody the essence of natural structures while adhering to practical and functional requirements. This endeavour seeks to bridge the gap between human-made and naturally occurring structural forms, fostering the creation of built environments that resonate with the inherent qualities of the natural world.

1.1 PERCEPTION OF THE BUILT AND NATURAL ENVIRONMENTS

Biological perceptual systems have evolved in response to the physical properties of natural environments, adapting to the statistical patterns observed in natural scenes (David et al., 2004; Field, 1987; Olshausen & Field, 1996; Párraga et al., 2000; Simoncelli & Olshausen, 2001). The psychological effect of environmental stimuli precedes cognition. It is well-proven that natural environments are greatly preferred over artificial ones, and scenes with higher visual complexity are mostly preferred over simple ones in both natural and built environments (Kaplan et al., 1972). This preference is often attributed to the fact that humans evolved over a much longer period in natural settings, which predisposes us to react positively to nature as opposed to built content. Apart from the aesthetic preferences of natural environments, it is also proven that, especially in urbanised societies, the connection to natural environments benefits people emotionally and psychologically (Ulrich, 1983).

A defining feature of the natural environment is the presence of flicker or 1/f-noise, which is the most commonly occurring signal in both physical and biological systems (Szendrő et al., 2001; Bak et al., 1988). Contrary to white noise, which is an expression of mathematical randomness, flicker noise has equal energy per octave of frequency. From plants, water, and clouds, this can be observed at any scale from atomic structures to galaxy formations as well (Gisiger, 2001). Flicker noise in nature is scale-invariant and appears multi-dimensionally. Examples of one-dimensional flicker noise in nature include the sound of waves crashing on the shore and the rustling of leaves in the wind. Two-dimensional flicker noise has equal energy per octave in both the horizontal and vertical dimensions – it has more low-frequency energy and less high-frequency energy than white noise in both dimensions. It typically appears to a different degree in any two-dimensional image of a natural scene.

For the human visual cortex, it is easy to distinguish between built and natural scenes and to what extent a natural scene contains artificially built objects. In computer graphics, however, we need a reliable classification method to achieve this task with high accuracy. The information in images can be encoded through various techniques, and one way to study the statistics of natural images is by analysing their frequency composition (Field, 1987). To convert an input signal from its temporal or spatial domain into the frequency domain we can apply the Fast Fourier Transform (FFT), which is a common technique in a large variety of fields in signal processing and analysis (Cooley et al., 1969; Brigham, 1988). The FFT is a highly efficient algorithm that can be performed in multiple dimensions, and in the case of image analysis, a 2D FFT can be performed, which results in the 2D power spectrum of the image. Following the Fourier transformation, the frequency composition of the image can be analysed. Research consistently demonstrates that the frequency composition of a scene has a direct influence on visual perception and is related to aesthetic preference (Spehar & Taylor, 2013; Hagerhall et al., 2004; Spehar et al., 2003) and visual comfort (Fernandez & Wilkins, 2008; Juricevic et al., 2010; O'Hare & Hibbard, 2011. Consequently, analysing the frequency composition is hypothesised to be well-suited for aesthetic computational image generation and has been successfully applied in generative art systems (Gircys & Ross, 2019). This is further detailed in the following section, which discusses the implications for architectural design.

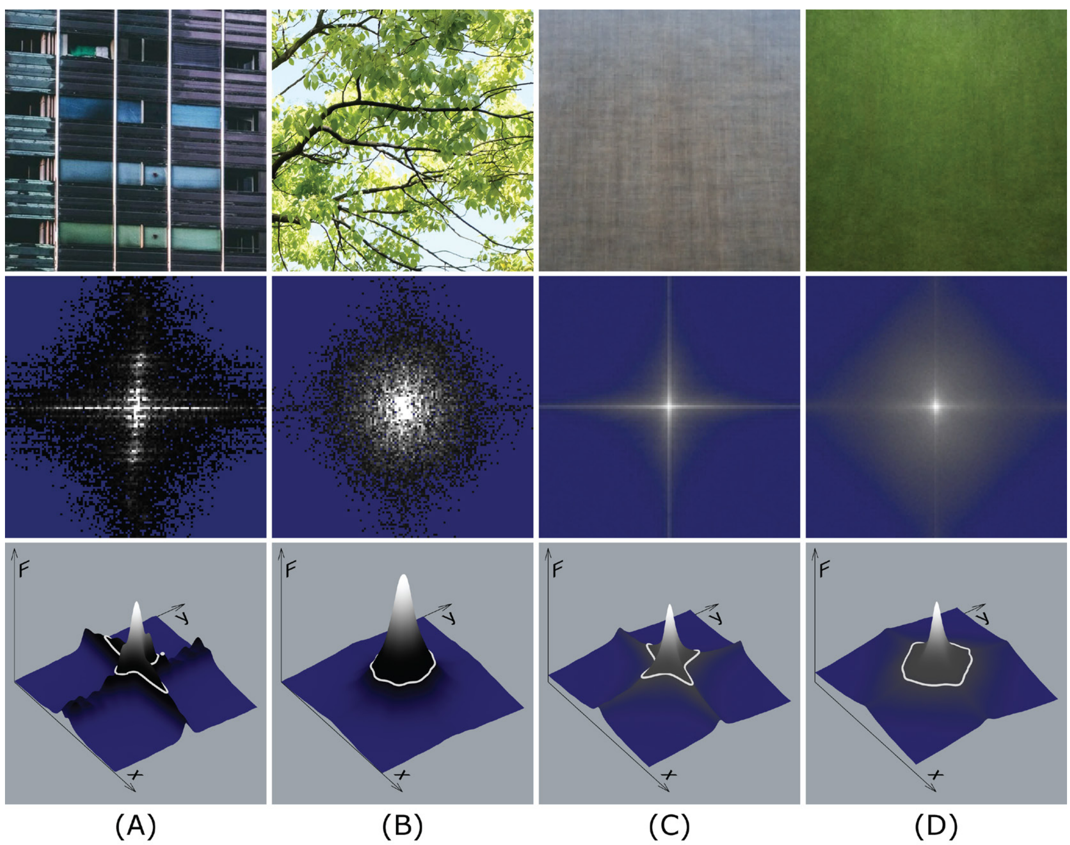

FIG. 1 Comparison of the power spectra of images of built and natural environment scenes (Based on (Torralba & Oliva, 2003)

Analysing the frequency composition of images is a key method for scene evaluation, allowing for the extraction and study of their low-level features. Statistical analysis of thousands of images demonstrates that natural images have a specific output very distinct from images of artificial structures (Ruderman & Bialek, 1994; Oliva et al., 1999; Torralba & Oliva, 2003).

The natural world is distinguished from the one built by humans, for which the term "carpentered world" is often used in literature. Characteristics of the carpentered world, especially in an industrialised society, are straight and parallel lines, right angles, and even planes. Such geometrical features typically lead to scenes whose frequency composition exhibits limited and pronounced directionality, predominantly in horizontal and vertical orientations. On the other hand, for structures occurring in nature, the variability of directionality and, therefore, the uniformity of power distribution is a lot more common. FIG. 1. illustrates these distinct differences in the power spectra of images of natural and built structures. Sets (A) and (B) show the difference in the 2D power spectra of single images of a building and a natural scene. The zero values of the power spectra are recoloured from black to dark blue for a better visual representation of the spectral shape. The power spectra are also plotted on a 3D graph to visualise the magnitude F on the vertical axis. Set (C) of FIG. 1. shows the mean average collected from 100 random pictures from the "Building" category of a public domain image classification database, and the mean average of their power spectra is plotted in 2D and 3D. In the same manner, 100 random images from the "Forest" category were processed in Set (D). This study illustrates the statistically verified spectral disparities between artificial and natural scenes, highlighting 2D PSA's significant utility in distinguishing natural imagery from artificial constructs. Based on these observations, 2D PSA is recognised as a robust technique for assessing the inherent natural qualities in digital images, establishing it as a powerful instrument for scene evaluation.

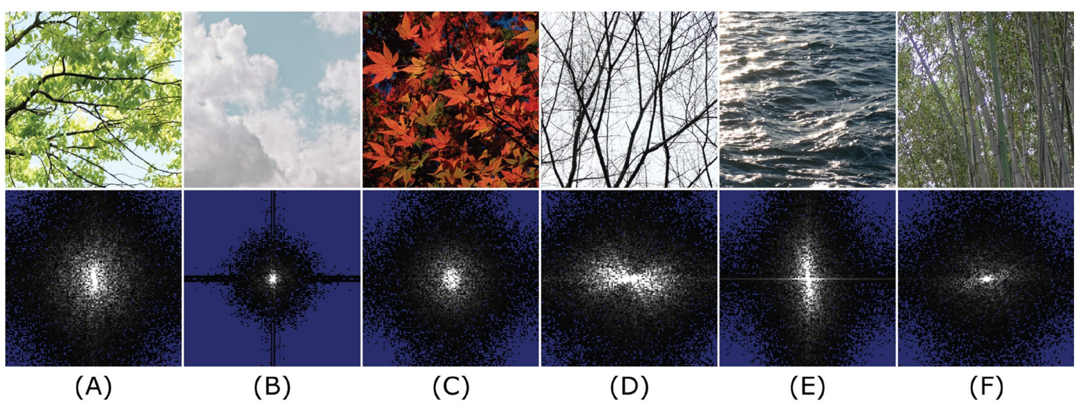

FIG. 2 Catalogue of natural scenes power spectra.

Natural images are also very distinguishable from randomly generated images due to the appearance of specific structures of the flicker noise as opposed to the randomness of white noise (Ruderman, 1994). The power spectra of a variety of naturally occurring structures or phenomena can be studied and used as an inspiration for visual arts and architectural design. FIG 2. presents a part of a custom catalogue of power spectra of different examples of natural scenes, which all contain flicker noise but also display some distinct features. Image set (A) shows a flicker noise distribution observable both in lower and higher frequencies of the power spectrum, while due to its relatively higher uniformity (B) is limited to the lower frequencies of the power spectrum. Image set (C) shows a power spectrum most similar to the pure $1/f^2$ noise. In (D), (E), and (F), we observe some dominant directionality in the power spectra caused by repetitiveness in the directions of some of the natural scene components.

1.2 IMPLICATIONS FOR FAÇADE DESIGN

Structural patterns like those occurring in nature are often considered a suitable reference in architectural design, especially in the design of complex building envelopes. Inspiration from natural structures is implemented in many façade projects using a biomimetic approach, which can prove useful for energy efficiency (Nagy & Osama, 2016). Façade structures act as an environmental filter as they control what permeates in and out of the building, and façade design is directly responsible for the building occupants' experience (Pastore & Andersen, 2022). Aiming to improve the occupants' experience, this study introduces a numerical method to assess and enhance aspects such as aesthetic appeal and visual and psychological comfort by integrating natural environment statistics into a generative design approach.

The visual system of higher mammals is finely tuned to optimally process information from natural stimuli, a capability shaped by evolution, development, and adaptation to the statistical patterns of natural scenes. Studies indicate that humans exhibit a consistent aesthetic preference for images exhibiting scale invariance, regardless of whether these images are derived from natural, human-made, or computer-generated sources (Hagerhall et al., 2004; Spehar et al., 2003. This propensity suggests scale invariance as a possibly universal trait in visual art, with the exception of some modern art forms deviating from aesthetic pursuits to explore alternative artistic tenets (Redies et al., 2007). A variety of aesthetically appealing images, spanning Western and Eastern art to graphic novels, exhibit shared statistical properties in their power spectra, such as the $1/f^2$ characteristic, which aligns with the scale-invariant structure found in complex natural scenes. This parallelism implies that aesthetic images harmonise with the statistical patterns found in nature (Graham & Field, 2007; Field, 1987; Tolhurst et al., 1992). Consequently, it is theorised that artists may instinctively or deliberately align their creations with the mammalian visual system's efficient processing of natural scenes, potentially explaining the universal appeal of certain artistic styles and compositions (Melmer et al., 2013).

Other than the aesthetic appeal, research shows that images closer to the statistical properties of natural scenes are more comfortable, while those that stray from these natural scene statistics may induce visual discomfort (Juricevic et al., 2010; O'Hare & Hibbard, 2011). It is empirically proven through human participant research that discomfort ratings can be predicted by the amplitude of the Fourier spectrum at specific spatial frequencies (Fernandez & Wilkins, 2008). These studies support the notion that the human visual system is optimised for processing natural scenes and can find certain unnatural statistics physiologically stressful. Such insights could help by guiding the selection of images in sensitive settings, such as public art in hospitals, to ensure they are appropriate and comfortable for viewers. Aesthetic preference and visual comfort extend to any visual scene, and as such, the PSA can be considered a suitable tool for evaluating architectural design as well.

For the built environment, the power spectrum was used to analyse structures and patterns as a design consideration. It has already been utilised in the design process of a variety of experimental and commercial projects. A couple of examples in FIG. 3 can serve to explore the power spectra of a transparent glass structure (A), experimentally built during a Stanford University seminar and workshop in 2015 (Choe & Sato, 2016) and a timber façade structure (B), built for a commercial building in Aoyama, Tokyo (Kengo Kuma and Associates, 2013). The power spectra of those structures have visual similarity to the power spectra of natural image scenes such as those occurring in a forest – the Komorebi phenomenon (the permeation of light through the leaves in a forest).

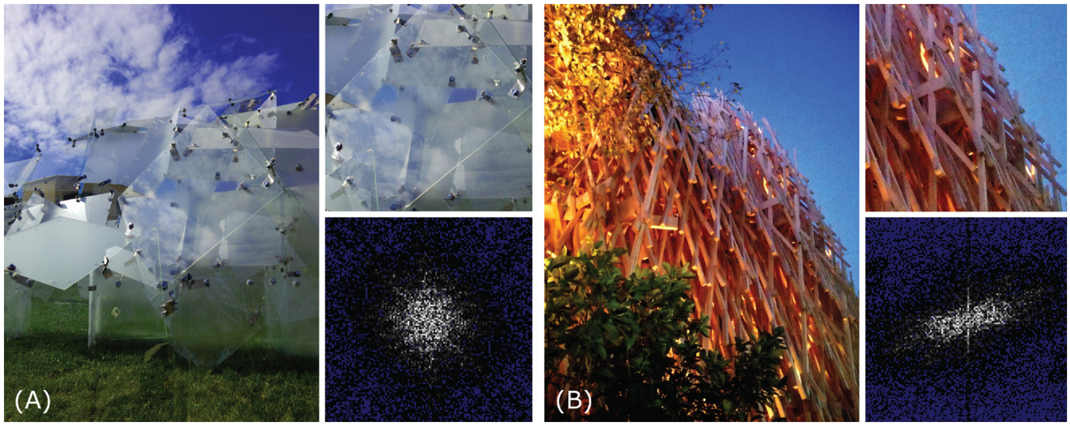

FIG. 3 Examples of experimentally and commercially built structures with their power spectrum analysis: (A) Transparent structure as a perceptual filter, Stanford University workshop project (Choe & Sato, 2016); (B) Sunny Hills Aoyama, commercial building in Tokyo (Kengo Kuma and Associates, 2013).

The validated efficacy of using 2D PSA for assessing aesthetic properties in images suggests its applicability as a fitness measure in generative design systems. By conducting a 2D Fourier analysis on a target image, essential spatial features can be identified and leveraged to guide the development of new images that exhibit similar characteristics. Such a strategy is successfully employed in creating procedural textures and evolutionary art (Gircys & Ross, 2019). Focusing on prominent frequencies and orientations allows evolutionary art systems the flexibility to create variations that resonate visually with the target image without exact replication. Within a genetic programming framework, a fitness metric based on PSA can be applied to evolve images that reflect the spectral qualities of chosen target images or image categories.

The evolutionary generation of images and textures, however, faces significantly fewer limitations when compared with the generative design of architectural structures. Therefore, creating an efficient PSA-based generative design method for building elements necessitates tight control over the geometric and physical properties of the patterns, ensuring the generated structures are both feasible and safe. Consequently, a flexible methodology that can integrate PSA into a broader Multi-Objective Optimisation (MOO) workflow is essential.

2 METHODOLOGY

The goal of the current research was to devise a PSA method suitable for automated and semi-automated structural design optimisation. For this case, computer graphics tools were used to process images and measure spectral similarity to extract a numeric value for the difference between natural input and computer-generated images. This result can be used in the proposed workflow (FIG. 4.), which aims to automate design optimisation based on 2D PSA in combination with other structural analysis methods.

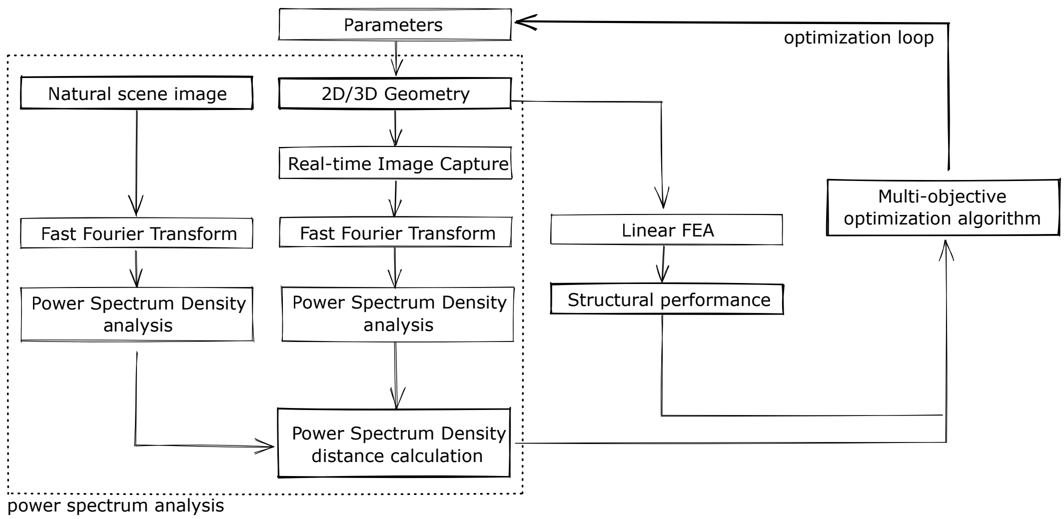

FIG. 4 Proposed optimisation workflow.

The process works with any type of parametrically generated 2D or 3D geometry by capturing 2D bitmaps during each design iteration, transforming the bitmaps with the FFT algorithm, and comparing the result to the power spectrum of an input natural image or image category. This analysis process can be integrated into an automated generative design workflow for design form-finding and optimisation. As such, it can also be combined with other analysis methods to simultaneously improve a structure for multiple objective goals. In the current research, we successfully combined the method with FEM linear structural analysis, which is further discussed in the presented experiments.

2.1 DEVELOPMENT OF THE ANALYSIS METHOD

To solve the problem of real-time PSA for the case of structural design optimisation, a custom software tool was developed with C# programming language. The decision was made to develop the software tool as a plugin for 3D software Rhinoceros and the algorithmic design plugin Grasshopper, chosen for the basic design environment as the most commonly used and versatile software tools for 3D and algorithmic design creation. Their interoperability allows the integration of various plugins and standalone applications, which proved useful for combining the PSA with our C++ FEM software tool for linear structural analysis and automating the whole process through optimisation solvers for single and multi-objective optimisation (MOO).

Different approaches for power spectrum similarity measurement were implemented and their performance was assessed for the specific case. As similarity measurement techniques in image processing and analysis vary by many different methods and approaches, computer image analysers must usually choose the most appropriate option in the context of the actual problem they are trying to solve. One of the most typical similarity measurement approaches in image analysis is the Euclidean distance measurement. It is a fast and simple method by which we can calculate the distance of respective pixel values or equally sized square grid sectors of 2 bitmaps of the same size (FIG.5 (A-B) Euclidean distance). It performs fast, and experiments showed that the results are useful and efficient.

However, in the case of natural scene recognition, we are mostly concerned with the directionality of the power spectrum. To extract the spectral profile of an image useful for scene analysis and classification, a suitable option is to average the power spectrum by orientations (Simoncelli & Olshausen, 2001). The azimuthally averaged power spectrum density (AAPSD) calculator that we devised works by dividing the power spectrum matrix by azimuthal angles into equally sized pie-shaped sectors (FIG. 5 (A-B) AAPSD distance). The number of sectors controls the resolution to which we want to study directionality in the power spectrum. The size of the sectors can be limited between minimum and maximum radii, with the maximum radius being half the width of the 2D spectrum. This allows us to limit the analysed frequencies in the power spectrum, eliminating spectral artefacts occurring at both very low and very high frequencies. The corner regions outside the maximum radius are also excluded from the calculation. The power density in the analysed sectors is then derived by averaging the values inside each of them. The resulting plot shows spectral power (averaged) by radii, which can be used for the final distance calculation.

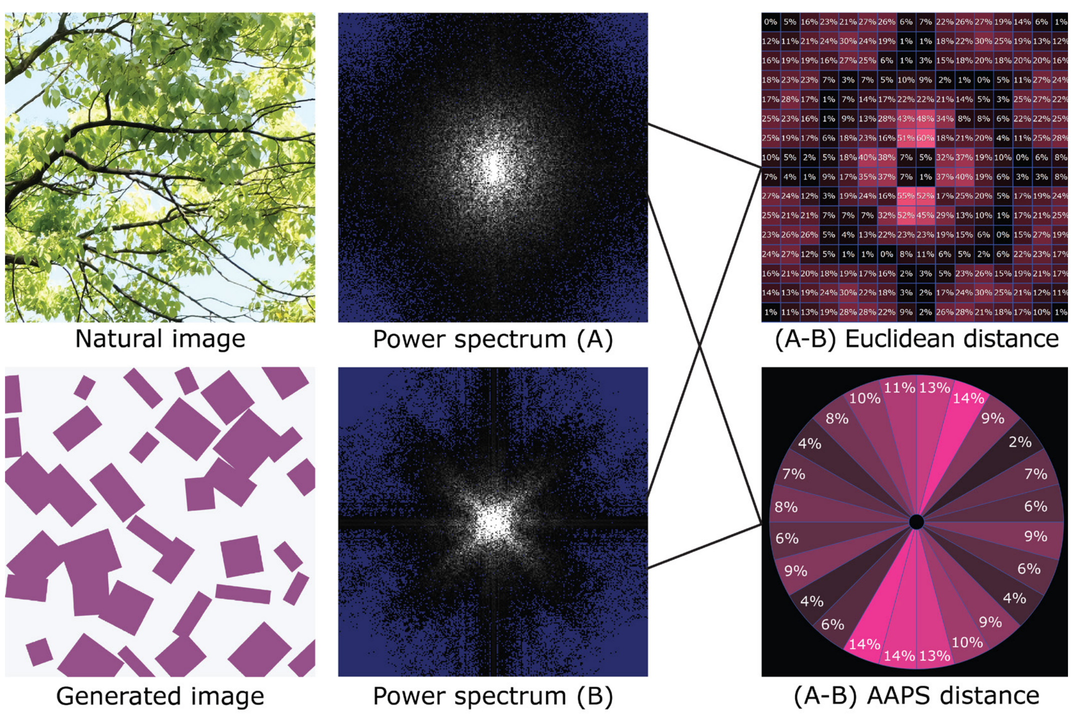

FIG. 5 Power spectrum density distance calculation methods.

Both Euclidean and AAPSD distance calculation methods were tested for the purpose of automatic design optimisation based on power spectrum similarity. FIG. 5. illustrates the difference between the Euclidean distance and the AAPSD distance calculation between two images – one of a natural structure and one of a computer-generated pattern. The AAPSD method can be considered a much more accurate similarity measurement tool in the context of this research, which is why it was applied in the following experiments.

2.2 DEVELOPMENT OF THE OPTIMISATION METHOD

The geometrical optimisation of building envelopes, informed by structural and environmental performance analyses, poses a complex design challenge that can be approached as a black-box problem, where the system's internal workings are not explicitly known or utilised in the optimisation process; rather, only the input parameters and the resulting outputs are considered. This approach allows for flexibility and generality, as the same optimisation techniques can be applied to a wide range of engineering and architectural design problems, facilitating the exploration of complex design spaces and the identification of optimal solutions based on single or multiple, often competing, criteria.

As detailed in the previous section, our integrated analysis tools automatically assess the fitness performance of a computer-generated geometry by calculating an AAPSD distance metric. To successfully integrate this analysis process into an optimisation technique, the proposed methodology necessitates three main steps. First, define the problem phase space by parameterising the façade design and making the numerical parameters accessible to the algorithm. Second, evaluate the fitness function of the design using the proposed PSA tool and, if deemed necessary, integrate FEM analysis to account for structural feasibility and safety, defining a MOO problem. Third, implement an algorithm that iteratively updates the geometry parameters, optimising the design based on the evaluated design performance on the single or multiple objectives.

To test the robustness of the proposed generative design methodology, five distinct optimisation techniques were selected and applied in this research. Initially, for the single-objective optimisation focusing on power spectrum distance minimisation, a general Genetic Algorithm (GA) was used (Rutten, 2013). This popular metaheuristic technique, inspired by biological evolution and relying on mutation and selection, centres on the core idea of heritability, where the algorithm maintains a population of individuals and selectively culls and recombines them to form successive generations. To support the results and ensure repeatability, the analysis method was also tested with four additional optimisation techniques.

A surrogate model-based optimisation method using the Radial Basis Function (RBF) was selected as a second optimisation solver to demonstrate the flexibility of the analysis process and its ability to work with a different class of black-box optimisation algorithms. The RBFOpt (Costa & Nannicini, 2018; Nannicini, 2021) is a powerful derivative-free solver efficient for highly nonconvex, unconstrained mixed-variable problems, which in some cases can outperform GAs, requiring considerably fewer simulation runs (Wortmann & Nannicini, 2016). Another alternative method to evolutionary computations selected for the optimisation methodology is the Particle Swarm Optimisation (PSO) algorithm, based on Swarm Intelligence (SI). Inspired by biological systems like bird flocking, which relies on collective behaviours for optimisation, PSO was chosen for its superior performance in solving single-objective high-dimensional problems compared to some evolutionary algorithms (Cichocka, 2017).

In architectural design and engineering, MOO is often more necessary than single-objective optimisation. Furthermore, most professionals prefer full control over the process, making a human-in-the-loop approach ideal (Cichocka, 2017). Thus, we chose two GAs capable of executing MOO: the Cluster-oriented Genetic Algorithm (COGA) and the Strength-Pareto Evolutionary Algorithm (SPEA). COGA quickly identifies high-performance regions through clustering, allowing focused searches and user interaction to control weighting between objectives (Bonham & Parmee, 2004). An optimisation tool based on the COGA algorithm facilitates the interactive-evolutionary design (Harding & Brandt-Olsen, 2018). SPEA was selected for its efficiency in finding optimal solutions on the Pareto front (Zitzler & Thiele, 1998) and providing higher accuracy than other algorithms (Zitzler, 1999), with Pareto dominance being key for comparing multi-objective solutions. Implemented through a flexible parametric design framework (Vierlinger & Hofmann, 2013), it provided the most favourable results in the following case studies.

3 EXPERIMENTS

During this research, multiple experiments, both for single- and multi-objective optimisation, were conducted using the proposed optimisation workflow FIG.4. Two façade design proposals were chosen for validating the method and illustrating the optimisation process.

3.1 SINGLE-OBJECTIVE OPTIMISATION EXPERIMENT

A double-skin glass façade structure model was selected for a single-objective optimisation experiment. The proposed model consists of a standard curtain wall with glass panels and a second layer of semi-translucent shading elements. These elements are rectangular and come in 5 different size types – 300/300mm, 300/600mm, 600/600mm, and 600/1200mm, and two different levels of opacity – 20% and 60%. Their proposed material is the highly durable glass type Leoflex™ (AGC, 2014), the strength of which was tested through various methods (Oliveira Santos, 2018), and whose light weight and high bending strength make it suitable for the application. Standardised metal spider-type connectors hold the panels tilted at a 5-degree angle, which allows them to be rotated to any degree without interfering with each other. This joint connects the panels to the main façade structure mullions, which makes the location of the panels at fixed points.

The power spectrum of an image of a natural structure was considered one optimisation goal – in this case, the sunlight passing through the leaves of a Japanese maple tree. The scattering of the leaves and their oblique orientations, as well as the different levels of translucency, create a distinct flicker noise pattern typically occurring in natural scenes.

An 8 by 8 meters partial model of the façade with 64 shading panels is studied for the optimisation experiment. The geometry is generated based on three initial parameters – the type of each panel regarding size and proportions (300/300mm, 300/600mm, 600/600mm, or 600/1200mm), the rotation angle defined by the connector element (0 to 360 degrees, with an axis of rotation perpendicular to the façade surface plane), and the opacity of the used material (20% or 60% with 0% being fully transparent and 100% being fully opaque). These parameters are made accessible to the optimisation algorithm and are used to generate the design iterations.

The geometry is visualised using real-time rendering for fast performance. The generative algorithm automatically adjusts the initial parameters, and each newly created geometry triggers the real-time image capturing, saving the image to an external location. Each image is then processed with FFT, which returns its power spectrum. The power spectrum is then azimuthally averaged, and PSD values are compared to the respective input natural image PSD values. The cumulative distance measured in percentage serves as the fitness value, which the optimisation solver uses to adjust the input parameters for subsequent design iterations.

The initial test was performed using the general GA. Starting with a randomly generated set of ten design solutions, the algorithm proceeds to breed them over 20 generations, producing a total of 200 design solutions. Each solution is evaluated to select the one with the lowest PSD distance from the optimisation goal image. Starting from an initial PSD distance of 36.8%, the algorithm achieved a 71.76% improvement, reducing the PSD distance to 10.39%. This result supports the thesis that the devised PSA tool can be effectively integrated within a general optimisation framework.

To assess the validity of the proposed methodology, we expanded the case study by conducting four additional experiments. Using the same geometrical parameters and design conditions, we examined the optimisation of the façade model using the other four techniques detailed in the previous section. All five algorithms were set to produce and evaluate 200 iterations each. In all five cases, the proposed PSA tool successfully informed the optimisation process. Both the RBFOpt and PSO outperformed the GA, introducing significant improvements in the PSD distance and delivering results more quickly. Although primarily designed for MOO, the COGA and SPEA still managed to deliver favourable outcomes in this single-objective optimisation context. The results from the COGA were comparable to those of the general GA, while the SPEA produced the most successful outcomes of the entire case study. TABLE 1 summarises these findings.

TABLE 1 Comparison of the results of the single-objective optimisation experiment achieved by five distinct optimisation algorithms under the same conditions.

Optimization Algorithm	Optimal solution in 200 iterations (AAPSD difference in %)	Improvement from initial state (in %)
GA	10.39	71.76
RBFOpt	9.64	73.81
PSO	7.14	80.6
COGA	10.41	71.71
SPEA	5.99	83.96

The case study produced 1000 different design iterations through five distinct optimisation techniques. The most favourable outcome was located in Generation 19 (out of 20) in the SPEA optimisation and introduced a 6-fold improvement (from 36,8% to 5.99%) from the initial unoptimised geometry. The initial geometry, the optimised geometry projections and the natural goal image, and their respective power spectra are displayed in FIG 6., along with a rendered 3D model of the structure. The design of the structure is automatically optimised to align with the natural phenomenon, not directly in the spatial domain, but through the statistics of the frequency domain, which have proven impact on visual perception and comfort. The algorithm produces many possible design solutions, and each of them is analysed for power spectrum similarity with the natural image. Any of these design solutions could be selected by the objective value but also by the subjective decision of the designer, which maximises the freedom and flexibility of the design process.

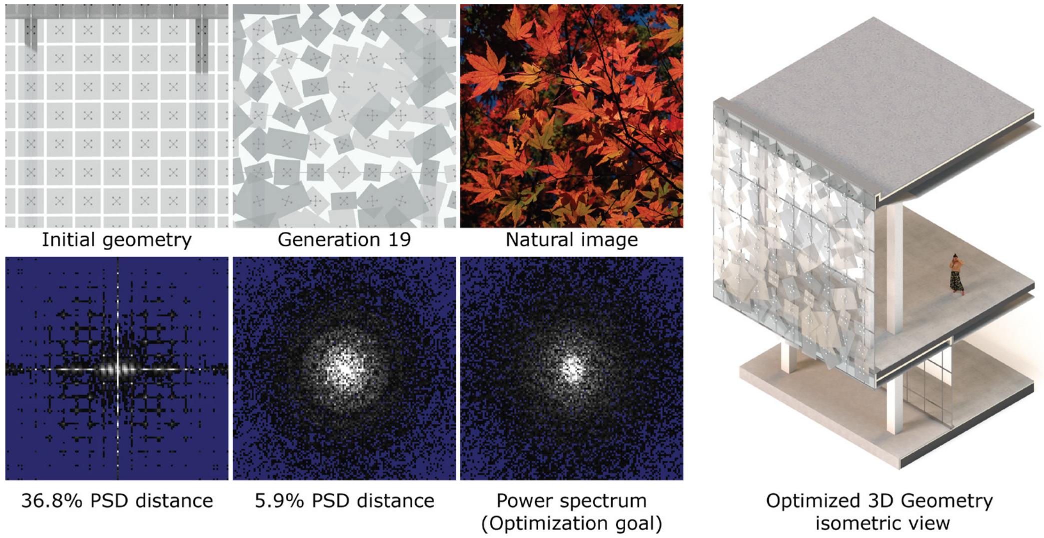

FIG. 6 Single objective optimisation experiment - initial and optimised geometry, optimisation goal - power spectrum analysis results.

3.2 MULTI-OBJECTIVE OPTIMISATION EXPERIMENT

In the second, more complex experiment, the linear structural analysis was implemented to improve structural performance and PSD distance simultaneously. This time, an interlocked timber façade structure model was chosen that could be analysed for PSD difference from a natural image in the same manner as in the first experiment, but also for structural safety based on the finite element method with linear analysis performed by our custom software tool.

An 8 by 8 meters partial model of the façade with 108 linear structural elements is studied for the MOO experiment. The initial geometry features two layers of timber frame structures, spaced 600 mm apart, interconnected by horizontal timber elements that are evenly distributed at a distance of 1300 mm in both directions, forming a 6 by 6 planar array. Optimisation parameters are the locations of the connection points (able to shift from their initial positions by 260 mm in both axes), the length of the timber element in the two layers (from 2500 to 5500 mm), and the angle of their rotation (limited -50 to 20 degrees, with an axis of rotation perpendicular to the façade surface plane, so as to introduce some distinct directionality in the power spectrum of the structure). The minimum and maximum lengths of the linear timber elements are also limited to prevent the generation of excessively long elements prone to buckling. With different lengths and rotations, different intersection points between timber elements occur, so the algorithm automatically divides the elements into their sub-parts. Elements exceeding the 8 by 8 meters bounds of the studied model are automatically trimmed.

The generated line elements are used for the structural analysis of the façade. The supposed structural timber material is Japanese cedar tree. A square cross-section of 160 by 160 mm was determined suitable for the structure and is set for the analysis of all timber elements. Support points are the lower and upper horizontal boundary points of the façade structure. The weight of the elements is measured from their volume and the density of the proposed material. The area of the timber structure is also calculated so that the appropriate wind load can be applied to it. A wind of 34 m/s speed or horizontal load of 100 kgf/m2 is assumed for the sake of the experiment. The calculation happens in each generation and is sent to the structural analysis program through a custom-programmed Grasshopper interface. Each change in the geometry triggers the plugin, which initiates an instance of the software program, which then performs FEM analysis. The analysis results are then sent back to Grasshopper, allowing the optimisation loop to continue running automatically.

Our FEM software tool calculates the safety ratio of each linear element in accordance with the Japanese structural safety code, with values under 1.0 considered safe and any with values over 1.0 considered critical for structural safety. This ratio is then visualised with a colour scale for easier visual understanding. Elements with a safety ratio under 0.2 are blue, 0.2-0.5 – green, 0.5-0.6 yellow, 0.6-0.99 orange, and the critical elements with a value of 1.0 or over are coloured in red. As the optimisation loop runs, the algorithm seeks geometry with both smaller differences in the AAPSD values and a smaller maximal safety ratio value. Any structure with a maximal safety ratio of over 1.0 can be considered unsafe under the supposed wind load and, therefore, unsuitable to build.

To support the validity of the initial results and ensure repeatability, the experiment was again performed using multiple algorithms. The two algorithms selected for MOO – COGA and SPEA – were tasked with generating 1000 solutions each. In both cases, the optimisation managed to find solutions with significant improvements in the PSD while simultaneously meeting the structural safety objective calculated by FEM. The results are summarised in TABLE 2.

TABLE 2 Comparison of the results of the multi-objective optimisation experiment achieved by two distinct optimisation algorithms under the same conditions.

Optimization Algorithm	Pareto front solution in 1000 iteration		Improvement from initial state (in %)
	AAPSD difference in %	Safety ratio	
COGA	9.27	0.92	68.58
SPEA	5.65	0.93	80.85

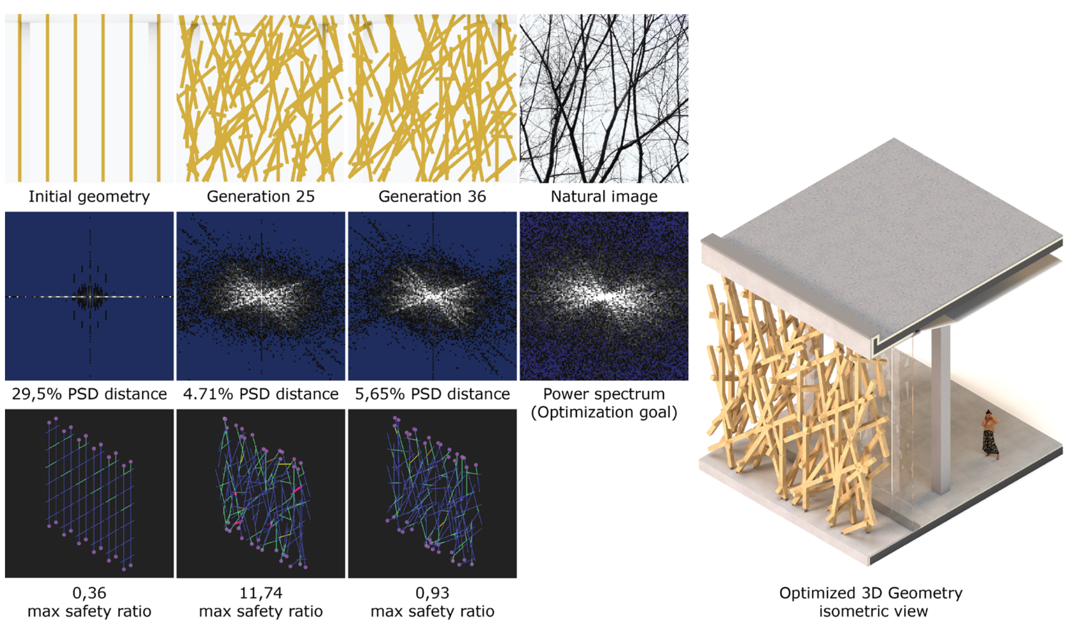

FIG. 7 Multi-objective optimisation experiment - initial and optimised geometry, optimisation goal - power spectrum and structural analysis results.

The most favourable solution in terms of PSD, from the 2000 solutions generated by the two experiments in this case study, was again produced by the SPEA. FIG 7 illustrates key moments of the optimisation process, showcasing the initial geometry of the façade structure, two samples of Generation 25, and Generation 36, and their respective power spectra and safety ratio colours of each of their structural elements calculated by the external FEM tool, as well as the natural goal image (which in this case is an image of multiple tree branches overlapping) and its power spectrum. By Generation 25, we can already observe a significant decrease in the distance between the PSD of the generated geometry and the PSD of the natural goal image (from 29,5% to 4,71%). However, the geometry remains structurally unstable with 15 critical elements and a maximum safety ratio value of 11,74. As the optimisation loop advances with the goal to reduce both values, each consecutive generation is based on the best-performing solutions of the previous one, which is why by Generation 36, a somewhat similar overall geometry can still be observed; however, the number of structurally critical elements is reduced to zero with a maximum safety ratio value of 0,93, which renders the structure safe to build. As expected, the percentage of the PSD difference slightly increased to 5.65%, which is a reasonable trade-off and renders the final solution best considering both optimisation goals.

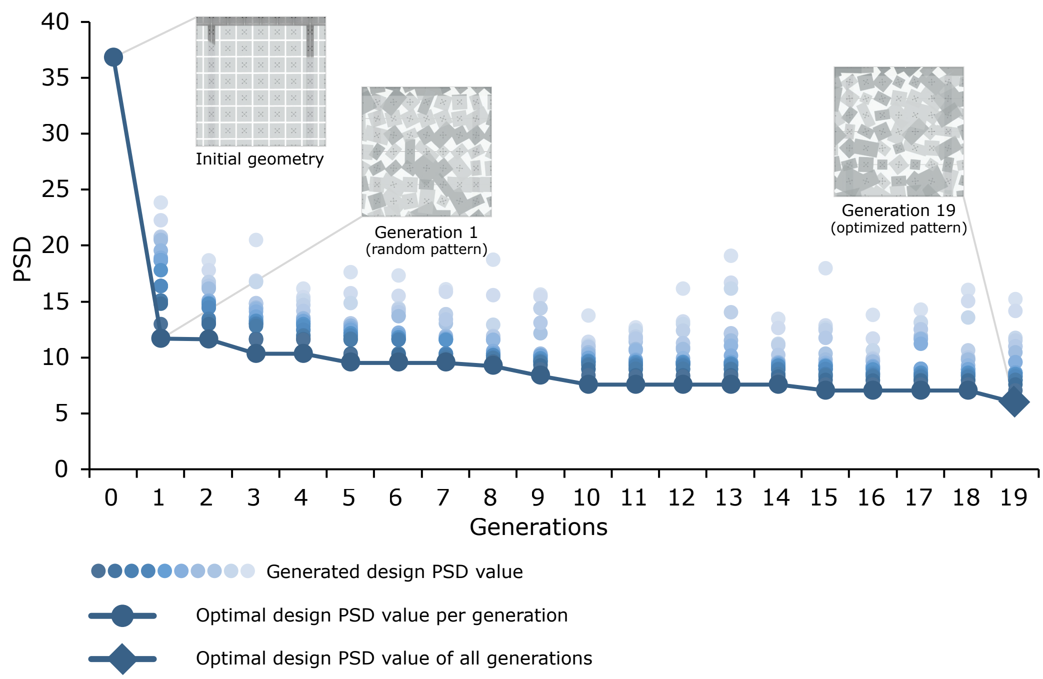

FIG. 8 Single objective optimisation experiment results graph.

4 RESULTS

Considering the data gathered from the presented experiments, we can conclude that PSA can be successfully integrated into façade design optimisation. FIG 8. shows the improvement of the façade structure in the single-objective optimisation experiment from the initial shape to Generation 19.

The generation numbers are plotted on the horizontal axis, and the PSD results from every ten solutions of each generation are plotted on the vertical axis. The line graph connects the lowest distance values, thus illustrating the improvement of the results over each consecutive generation. We can deduct that the mathematical randomness function used for the initial ten solutions in Generation 1 provides results already much closer to those of the natural image goal; however, by continuing the analysis and optimisation loop, a further improvement can be observed to reach a final result of a structure with a PSD distribution of 2 times more similar to the natural input image used as the optimisation goal.

FIG. 9 shows the data from the multi-objective optimisation experiment. Two graphs with the result values for PSD difference and Safety ratio calculation are overlayed with the line graphs representing both values of the optimal solution in the Pareto front in each generation. Fluctuation can be observed in the optimal results through the optimisation process as the algorithm seeks a solution that satisfies both objectives. By Generation 25, the best result of 4.71% in regard to PSD distance was achieved, but the safety ratio value of this solution is 11,74, which renders it unsafe to build. In Generation 39, the optimisation reaches a solution that satisfies the structural safety criterium with a maximum safety ratio of 0.93 while keeping a low PSD distance value of 5,65% from the input natural image set as the optimisation goal.

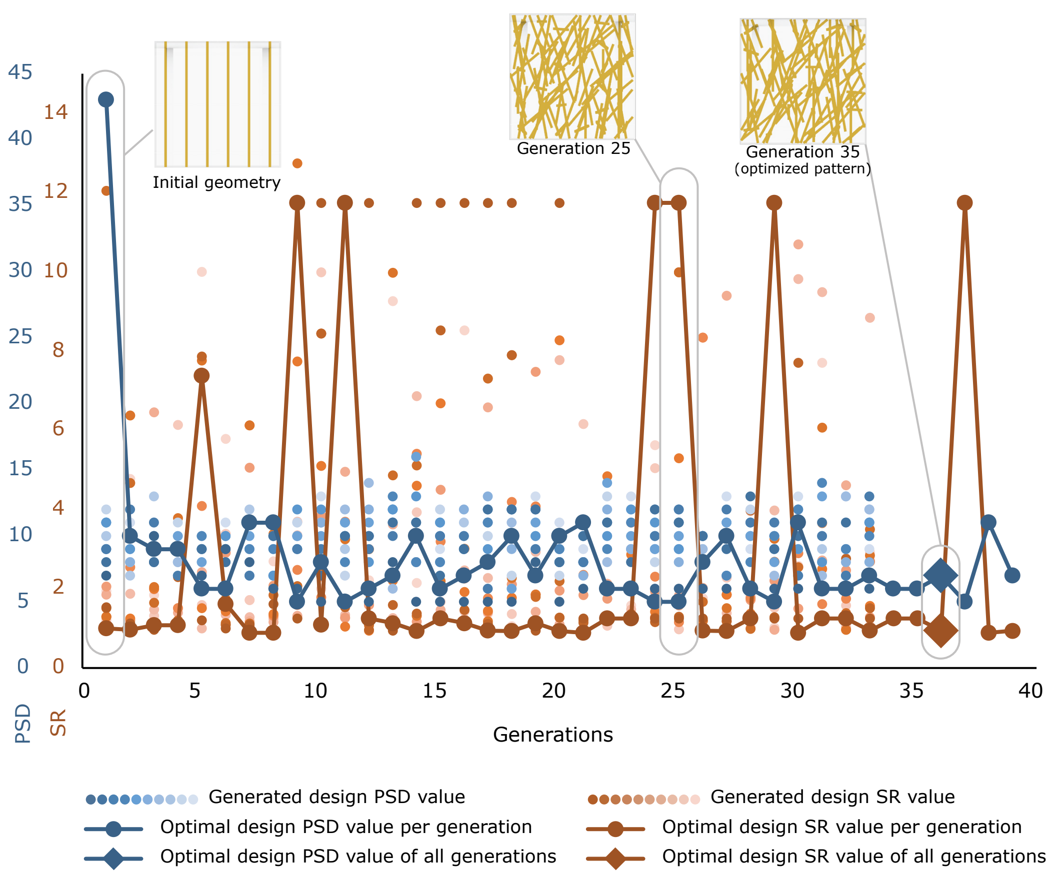

FIG. 9 Multi-objective optimisation experiment results graph

5 CONCLUSIONS AND FUTURE WORK

From the experiments presented here, it can be concluded that power spectrum analysis can be effectively employed to optimise parametrically generated façade geometry. This method, grounded in established digital signal processing techniques and computational design morphogenesis, facilitates the conception of artificial structures that are objectively similar to natural ones without copying them directly. This approach may present a novel way for natural form-finding in façade design and engineering, different from the traditional biomorphic approach, which counts on visual similarity in the spatial domain. The power spectrum density distance calculation can effectively be used to assess façade projections' spectral similarity to a selected natural image goal. Generative design through metaheuristic and model-based algorithms can make use of this computation to automatically optimise geometry and provide an extensive array of design solutions. This method can be combined with other structural analysis methods, such as the Finite Element Method, to create a multi-objective optimisation technique.

In the future development of this research, we aim to include other types of analysis in the multi-objective optimisation workflow. Daylighting analysis, view optimisation, and sun glare mitigation are all suitable objectives that could be combined with power spectrum analysis to pursue efficient, intelligent, comfortable, and aesthetically pleasing design solutions.

We will explore even more natural phenomena and expand our catalogue of natural images with power spectra suitable for optimisation goals. By expanding the natural image database, we can base the optimisation on more statistical data. Three-dimensional Fast Fourier transform may be utilised in the power spectrum analysis of spatial structures.

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