EXTRACTING ACTIONABLE INFORMATION FROM THE SITE CONTEXT USING A PHENOTYPE-BASED STRATEGY

BANLIANG LING[1] and BIGE TUNÇER[2]
[1]*Singapore University of Technology and Design*
[2]*Eindhoven University of Technology*
[1]*banliang_ling@mymail.sutd.edu.sg, 0000-0002-9855-2860*
[2]*b.tuncer@tue.nl, 0000-0002-1344-9160*

Abstract. As more computational design tools are developed, solution generation has been accelerated to provide real time feedback. However, a human designer is still required to translate generated data into actionable information. This is especially so for diverse design scenarios, where the data structure differs, and the computer is unable to draw conclusions across both scenarios. The site context is one key parameter that contributes towards the difference in scenarios. In short, how can an algorithm extract design-related information from diverse scenarios? To address this issue, a phenotype-based strategy is proposed as a representation method, and it re-parameterises diverse site conditions by focusing on their geometrical properties. Instead of parameterising the site context, street-view images are captured, and Gabor filters extract relevant geometrical properties, such that site conditions with different compositions, forms, and density can be organised. This method quantifies compositional and density-based properties of the surrounding building blocks, thereby enabling the computer to digest generated information and provide design suggestions. A new sample site is then used to demonstrate a query of the phenotype space, where suggestions about solar radiation performance is feedback to a human designer.

Keywords. Performance-based design, phenotype-based strategy, computer vision, site context representation, geometry-to-performance information

1. Introduction

Computational strategies accelerate repetitive actions, increasing the speed of performance calculations. With predictive methods, computational methods can even provide real time feedback (Duering et al, 2020). However, despite the large amounts of data generated, a human is still required to translate data into actionable information. This is because different data spaces are constructed using different structures. As a result, related design conclusions could exist in differently defined data spaces, but the computer is unable to discover them. For example, a previous data space might reveal that a building orientation leads to poor solar performance, yet a computer must

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rediscover this information using a new data structure. This contrasts human designers who can easily bridge information across data spaces. In other words, computers cannot repurpose information from past experiences and are only able to perform actions based on the current data structure. For example, Ampanavos and Malkawi (2022) trained a Variational Auto-Encoder (VAE) to generate high performing solutions using a context prompt. However, they mentioned that when prompts are outside of the training conditions, generated results become unpredictable. Compared to a computer, designers form flexible constraints that allow them to quickly ideate across various design spaces. A designer can therefore identify trends outside of the initial constraints, digest them into design actions and apply these to a new scenario. This also represents the gap between design and computational thinking.

This paper bridges this gap in knowledge using a deterministic method to extract design directions from the site geometry. It also addresses the larger research question: How can an algorithm extract design-related information from diverse scenarios? Looking at the site context, diversity refers to the various combinations of context buildings that affect the design performance. Focusing on the geometry, diversity looks at the composition, form, and the density of context blocks. By extracting geometry-related information from the site, computational design search can 1) avoid low performing solutions, and 2) provide early-stage performance-related suggestions based on past design scenarios. These are demonstrated using 19,683 different site contexts that describe a diverse range of possible scenarios.

With regards to the extraction of actionable information, Brown (2020) compared various computational strategies and concluded that an interactive method provides designers with the best tool for design exploration. On the other hand, a free exploration led to less quality outcomes. These results were based on the premise that design-related information involves an interplay between geometry and performance. Current methods differ upon this interplay with some prioritising geometry diversity, and others prioritising the design performance. Newton (2018) presents an open-ended search example that proceeds while designers interact and select intermediate solutions based on its looks. Through this human-computer interaction (HCI), a designer discovers the impact of façade folds on visual, thermal and condensation performance. While the above example is qualitative in nature, Brown (2020) presents an alternative that works off solution re-parameterisation. Using the re-calculated parameters, a computational analysis is conducted to extract design directions towards higher performance areas. The above represent different methods of extraction for design-related information.

While a computer can construct design spaces using the same parametric representation, a difference in data structure makes it difficult to computationally identify a design logic. This means that when different solutions are represented using different structures, it becomes impossible to compare. The site context has the same limitation as each site context is modelled to different levels of detail and to a different extent. This suggests that a purely parameter-based representation does not facilitate comparison across diverse cases. For algorithms to maximise its potential and tap on the increasing amounts of generated data, building representations should instead be geometry-based so that geometry-to-performance links can be discovered. This will also provide a different approach to the interplay between geometry and performance.

From the perspective of the site context, the mentioned research question poses two main challenges. Firstly, there is the extraction of design-related information. The basis of any extraction relies on the available data. This affects the type of design suggestions that a computer can provide. Secondly, there is the consideration of diverse scenarios. For a designer, it is easy to re-structure constraints and look at a design from a fresh perspective. However, the computer does not have this initiative. Both challenges will be looked at in detail and a phenotype-based strategy is proposed.

2. Phenotype-Based Strategy

In computational design, there are three ways to represent solutions (fig 1): 1) genotype — describes the actions that form a solution, 2) phenotype — describes the geometry, and 3) performance — describes the value of a solution. For the site context, genotypes describe the density and heights of neighbouring blocks as a list of numbers (Ling, 2019), while phenotypes describe the "look" of surrounding blocks using image pixel values (Ampanavos and Malkawi, 2022). Compared to genotypes, phenotypes are not described using their generating actions. This means that new site contexts, generated using different parametric models but are captured as images can be related to an existing pool of site context images. On the other hand, a genotype description necessitates one to keep to certain data structures (eg. number of surrounding buildings for density and heights). It also means that a phenotype-based strategy better allows the computer to appreciate geometrical properties.

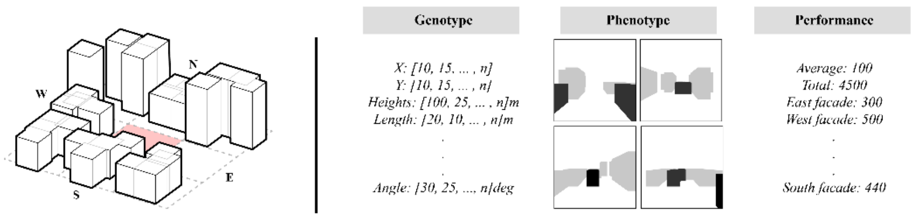

Figure 1. Genotype, phenotype, and performance representations for the site context

Shape composition is one geometrical property that is hard to quantify using a parametric approach. Yet it has an obvious impact on design performance. For example, a close composition of two squarish blocks might have a similar sun shading effect to one long slab block. If a genotype approach is used, this comparison is lost due to them having different data structures. Computer vision techniques offer an alternative to capture and extract desired geometrical properties from images. One technique is the use of Zernike polynomials to measure pixels radially, quantifying compositions in a circular direction and therefore acting as a measurement of shape similarity (Ling and Tunçer, 2022). The authors went on to demonstrate that a sketch could recall similar shapes, all constructed with different numbers of composite blocks. Gabor filters is another technique for capturing pixel compositions. Filters focus on different angles or colour intensity, and they generate a unique identifier for each unique pattern. Stuart-smith and Danahy (2022) used this method to quantify roof design patterns, contributing towards an overall aesthetic measure. Ling and Tunçer (2023) instead used Gabor filters to categorise daylight performance patterns. Given their simple floorplans, the filters covered the eight cardinal directions which was enough to differentiate amongst available patterns. Furthermore, they applied Principal Component Analysis (PCA) to identify dominant data patterns within these daylight images. Geometrical trends that relate to the look of daylight patterns are then extracted and used to influence computational design decisions.

2.1. GENERATING THE SITE CONTEXT DATABASE

The site context consists of context buildings that are built to different levels of detail and extent. Diversity in this sense refers to the block configurations, whereby distance and density result in different performance possibilities for the actual design. This paper will also adopt Gabor filters as the number of filters can be updated according to the level of detail and the defined filters focus on desired properties of the blocks. There are two parts to preparing the context images (fig 2). Firstly, a parametric model populates the land plots. Four square shapes per plot can move in the x- and y-directions, creating shape amalgamations that replicate real life contexts. They are each assigned a height (0, 50, 100m) to imitate an empty plot, medium height block, and a tall block respectively. Across all eight surrounding plots, a unique site condition is then created. Secondly, a camera in the middle of the site takes 1000x1000px pictures of the North, South, East, and West directions. Nearby buildings are coloured black (RGB 0,0,0) and faraway buildings are coloured grey (RGB 200,200,200). This creates a scale for nearby blocks (0) and faraway blocks (200) while differentiating from the background (256). Four images form the phenotype for one site condition. Compared to an overhead shot, a street-view capture was preferred as it does not limit the extent of modelling. For example, wind simulations require a large context and solar simulations work with a small context. The street-view allows a comparison of both types of site conditions, focusing on the impact of immediate contextual buildings.

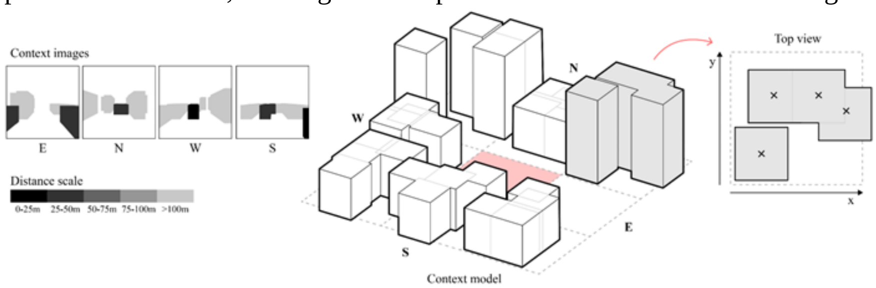

Figure 2. Example of context images (left) and context generation (right)

Two sets of parameters determined the difference in site context. The first relates to placement (x & y shifts) and the second relates to the building heights. Three sets of placements were created and the plots in these three sets were permutated with different heights (0, 50, 100m). Each set would therefore have 3^8= 6561 contexts and 3 sets provide 19,683 contexts. Placement set 1 and 2 have similar placements while set 3 is designed to be different. This relationship is also reflected in the PCA plot in figure 3.

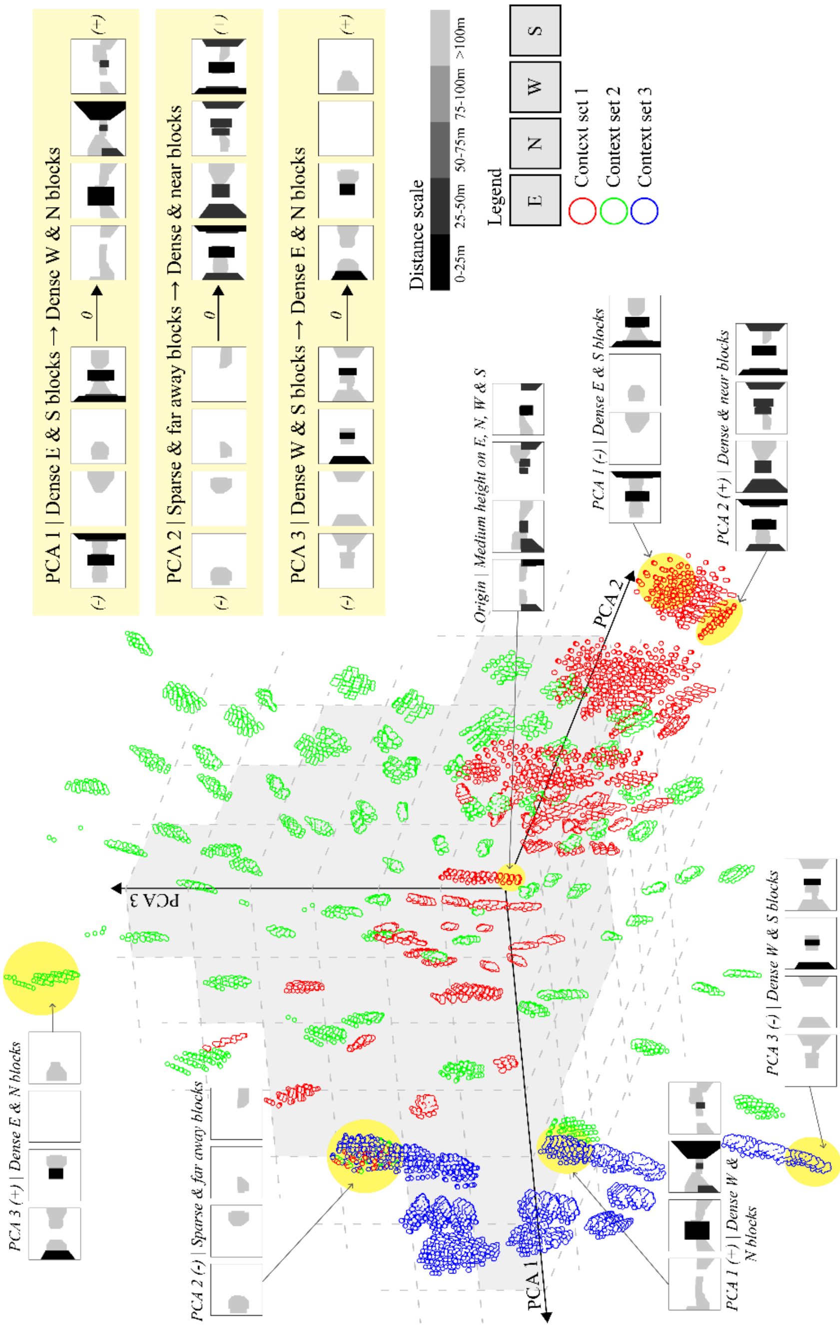

Figure 3. PCA plot of site context with each PCA axis demonstrating different geometrical trends. Similar looking site contexts nearby and different looking ones are further away.

2.2. PRESENTING GEOMETRICAL TRENDS

Geometrical trends should reflect the main types of site conditions within a database. This first layer of organisation must offer an understanding of geometrical information. This includes broad trends like density or compositional changes. A second layer would be the relative contributions of each geometrical trend. It is important to understand the ratio that each trend provides in the current database. Lastly, these trends should ideally be transferable and able to be re-applied into future analysis. PCA offers a solution for all three layers and is therefore presented in this paper. Figure 3 shows a plot of all the site context across PCA 1, 2, and 3. The phenotypes are derived using Gabor filters set at 0°, 90°, 180° and 270° with two variations of sigma (1 & 3) and frequency (0.05 & 0.25). These values account for macro- and micro-level geometrical properties, where a two-block composition has similar macro-level numbers to a slab block, yet they remain differentiated at the micro-level. PCA was conducted on the Gabor filters, and the first three axis accounted for 97.5% variance. Across PCA 1, the site context goes from having denser East and South conditions towards having denser West and North conditions. PCA 2 describes a shift from sparse and faraway blocks towards having densely packed site conditions. Lastly, PCA 3 goes from having densely packed conditions on the West and South, to having densely packed conditions on the East and North. Accordingly, this means that the origin consists of medium-sized blocks on all four directions. These results demonstrate that Gabor filters provide good descriptions of the geometrical properties of the context buildings, and PCA organises the phenotypes to reflect geometrical trends.

More importantly, PCA is deterministic, and results change according to available information. When there is a large diversity of site context, PCA might only extract generic geometrical trends. This is also described as overfitting, and it means that the PCA has not arrived at a conclusive trend which a designer can also arrive at by briefly interacting with the data. Conversely, if the diversity is minimal, the PCA might extract minute details of the site context that does not relate to new scenarios. Also described as an underfitting, the available data is not enough for the algorithm to make an appropriate geometrical conclusion. For the computer to overcome such challenges, the Gabor identities can be re-structured. One option is to cluster the identities such that an initial spread of data can be filtered into focused parts. Another option is to identify outliers that contribute towards overfitting. These are explored further in later sections.

3. Extracting Actionable Information

Building on fig 3, when a new context is under consideration, it can be placed onto the PCA plot. Since PCA is deterministic, the new site context holds a unique PCA position. If the PCA axis provides a good enough geometrical logic, then the new plot point will demonstrate to the designer, geometrical qualities that are similar to existing scenarios. This is in turn helpful for understanding possible constraints for the new site context. For example, if a similar site context had been used for running an optimisation for solar radiation, that scenario will have a substantial set of performance data. The PCA space would then enable the computer to cross reference based on site similarity and have a better understanding of the performance bounds. Using the old data as a basis, designers can now understand what the maximum and minimum solar radiation scores could possibly be. This offers a suggestion into the type of performance diversity that a designer can expect. To demonstrate, clusters are extracted using DBSCAN — density-based spatial clustering of applications with noise. This clustering algorithm was selected as it does not require one to preset the number of clusters and it detects outliers using a distance tree. By altering this distance parameter, hierarchical clusters can be identified. This means that similar looking site contexts that are located nearby in the PCA plot can be hierarchically categorised into representative groups. At the top of the tree would be site contexts that have broad similarities and at the bottom of the tree branch, site contexts still in the same cluster would be highly similar.

3.1. QUERYING A NEW SITE CONTEXT

A new site context (fig 4) based on a town in Tampines, Singapore is added to the PCA plot. The two closest Euclidean clusters were then determined, and the closest site context within each cluster were presented (fig 5). The queried Tampines model is deliberately modelled with a higher level of detail, and the extent has a long proportion compared to the squarish ones within the current database. However, the street view images still demonstrate a good ability to relate the new condition to the database. Furthermore, the images capture shape composition and describe building relationships better than a purely parametric approach. While the new site context has many surrounding buildings, the image focuses on a few significant nearby blocks (black). This is translated into the closest match in cluster 20, which has no blocks on the Southern and Eastern sides. The proportion and position of such nearby blocks (black) are also similar across both cases. Facing North, both sites have a looming presence to its left, and when facing West, both sides have a skewed imposing block to the right.

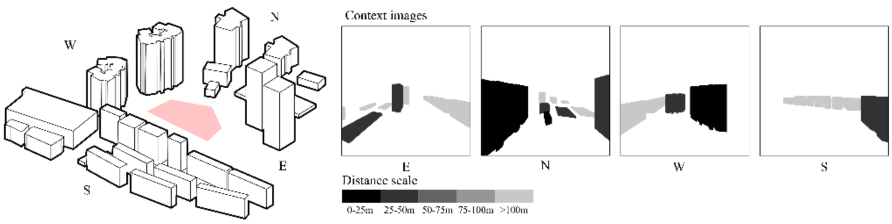

Figure 4. Model and phenotype of the new site context (Tampines, Singapore) added to the database

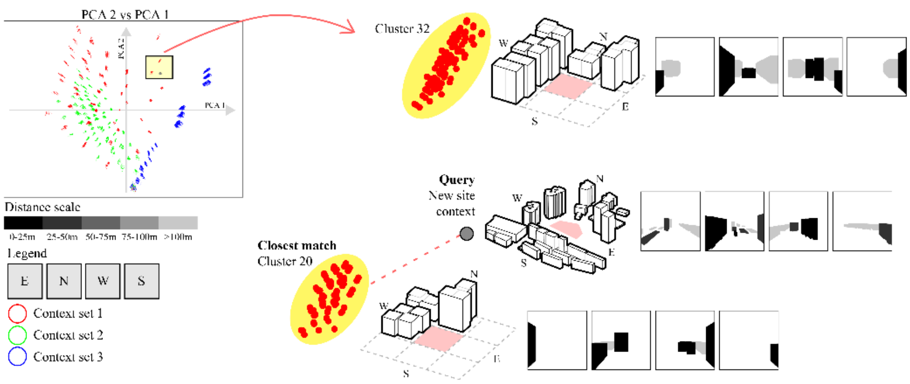

Figure 5. Most similar site contexts to the query option (fig 4) are denser on the N and W sides. This query allows the designer to understand performance ranges based on cluster 20 and 32.

This example demonstrates the computational actions that are enabled with the PCA space. While the street view images create a unified site data space, it also quantifies compositions of buildings and allow the computer to categorise models into clusters. Secondly, these clusters are arranged by geometrical properties that are discovered from the available data. In other words, this visualisation offers information about potential constraints, related to similar site contexts, that might have been unavailable had the design process begun from a clean slate.

Annual solar radiation based on the Singapore weather file is now added as performance data. The building block placed on site is a square block and the façades are captured as images. Using the query in fig 4 as a base, the three closest context clusters are extracted. Fig 6 shows the PCA 1 against PCA 2 plot (90% variance) of solar radiation patterns across all four façades. Since these were extracted from nearby context clusters, patterns are similar. However, PCA 1 still describes an increase in solar radiation on the East and South facing façades. PCA 2 focuses on the East façade, describing a decrease in solar radiation across its axis. Figure 7 is a comparison between the actual solar radiation performance between the query site and the closest matching site. Patterns are most similar on the West and South facing facades, while solar intensity differs on the East and North facades.

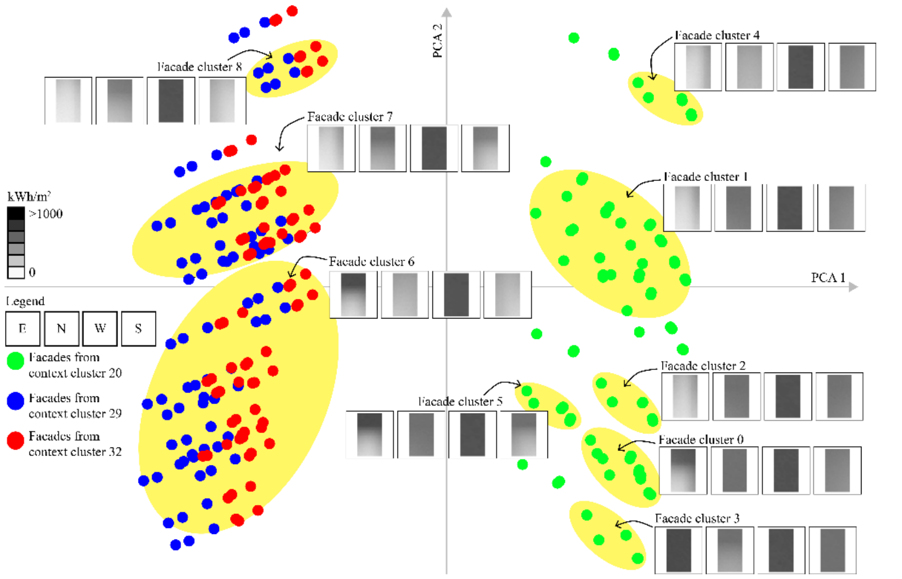

Figure 6. PCA plot of façade solar radiation patterns, demonstrate differences on the E and S facades (PCA 1) and a general decrease on the E façade (PCA 2)

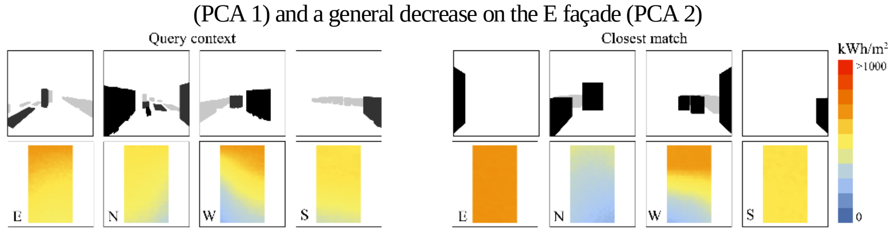

Figure 7. Comparing façade patterns from query site context and closest match

4. Discussion

Paper results aimed to address the research question: How can an algorithm extract design-related information from diverse scenarios? This was addressed from the perspective of site context representation, leading towards a phenotype-based strategy. This unified and consistent phenotype data space was visualised using the first three PCA axis. Being unified, it combines site contexts generated from different parametric processes and allows the addition of new contexts if a set of North, South, East, and West images can be furnished. This data space is also consistent because the Gabor filters always provide unique identities to unique site patterns. Extraction of geometrical trends is also consistent since PCA is deterministic. This is therefore a useful method for classifying site contexts and for relating performance bounds based on past search scenarios. In short, the proposed phenotype-based strategy bridges diverse design scenarios by focusing on the representation of geometrical properties.

4.1. ALTERNATIVE VISUALISATION

Figure 8 offers an alternative visualisation that describes the relationship between context clusters, façade clusters, and total solar radiation performance. The data is based on figure 6 and it uses a parallel categories plot to show links between each cluster type. For example, cluster 20 offers a different façade pattern compared to clusters 29 and 32. This is also evident in fig 6, where cluster 20 facades are all on the right side of the PCA plot. Branching from the façade clusters, there is no clear trend for total solar radiation. Across all categories of solar radiation, there is a good spread of contributors from all previous categories. This is attributed to the façade representation method, where solutions are coloured from white (0) to black (>1000). As a result, white-black patterns take precedence over performance intensity. This contrasts the perception of performance in figure 7, where the blue-yellow-red colour scale prioritises a different aspect of the façade pattern. Nevertheless, figure 8 is still helpful as it demonstrates to a designer, the various façade performance patterns that exist and the range of performance values that they contribute to.

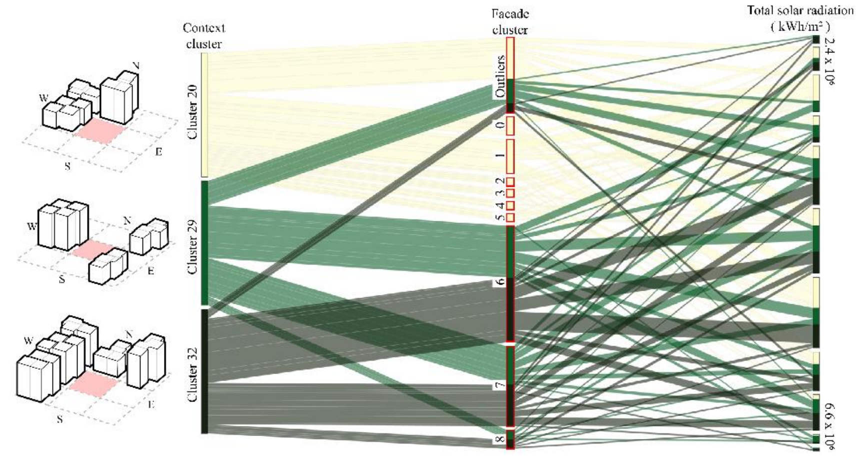

Figure 8. Parallel categories plot between context clusters, façade clusters, and total solar radiation provide a different understanding of the data space as each category is connected using bands

4.2. LIMITATIONS AND FUTURE WORK

While the presented method can relate diverse site conditions, it still depends on image related factors like the camera lens length and the image size. Beyond the preparation of images, the type of colour scale and the selection of computer vision techniques also impact any extraction of design-related information.

This paper has presented the main parts of a phenotype-based strategy, where an image-based representation method is first proposed before computational methods are used to extract design information. The presented camera capture method can be extended to represent design solutions, using images to capture key geometrical properties. On the other hand, phenotypes represent the "look" of any design artifact and a data structure that relates the site conditions, design solution, and performance-related patterns will contribute towards a more refined phenotype-based approach.

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