Han, Yoon J.; Kotnik, Toni

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Published in:
Architectural Research in Finland

DOI:
10.37457/arf.130438

Published: 29/05/2023

Document Version
Publisher's PDF, also known as Version of record

Please cite the original version:
Han, Y. J., & Kotnik, T. (2023). Computational analyses of dynamics of architectural space. *Architectural Research in Finland*, *6*(1), 78-96. https://doi.org/10.37457/arf.130438

Computational analyses of dynamics of architectural space

Han Yoon
Doctoral Researcher
yoon.han@aalto.fi

Abstract
Although space is the central element of architecture, questions of space are hardly addressed in computational research in architecture. On the other hand, current mainstream practice in computational design research in architecture tends to focus on efficiency of architectural procedures, entailing optimisation of form, structure, performance, data management or workflow, etc. Such focus utilises computation to handle quantitative data of tangible properties in architecture. However, architectural space is filled with abstract qualitative properties, one of which is its dynamics. Dynamic properties of architectural space have been discussed in diverse disciplines from diverse perspectives since the nineteenth century, but it is only in the past decades that some of the theories are revisited due to discoveries in neuroscience. Such reappraisal of past theories by new technologies anticipates further rediscovery of qualitative properties of architectural space, such as spatial dynamics, that have been investigated largely through speculative descriptive methods using phenomenological approaches. Hence, the research explores the idea of architectural space as dynamic field structures by reexamining theories since the nineteenth century in multiple disciplines, and develops a system of computational inquiries to investigate dynamics of architectural space. The computational procedures produce visual spatial data that are analysed and calibrated in comparison to the past studies of architectural space based on descriptive methods. The correlations observed between the two approaches substantiate potentials of the computational approach as ways to study abstract properties of architectural space further.

Keywords: architectural space, spatial dynamics, computational design research, dynamic field structures, qualitative properties of architectural space.

Introduction
Mainstream practice of computational design in architecture focuses on improving efficiency of architectural procedures, entailing optimisation of form, structure, performance, data management or workflow. Such focus stimulates development of computational research involving quantitative data of tangible material properties in architecture, such as data regarding computational geometry for optimisation of fabrication and construction procedures. (Pottmann, 2010) On the other hand, discourses of abstract and immaterial nature, such as questions of space, have not been addressed in relation to computation enough, despite its centrality in architectural creation. (Hillier and Hanson, 1984) Close alliance with the industry supporting its demands for practical problem solving is a valuable role of the academy. However, it is also imperative for scientific inquiries to address aspects which are overlooked and not prioritised by the industry, yet are fundamental and indispensable in the discipline. The

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fundamental purpose of scientific inquiries such as advancement of understanding through free inquiry independent of practical applications (Leatherbarrow, 2012) could produce new knowledge that may not necessarily be of ‘direct relevance to the needs of commerce and industry’, but can ‘lead to new or substantially improved insights’. (Rendell, 2004)

Needs for space-oriented inquiries in computational research in architecture is further supported by renewed interests in spatial qualities and spatial experiences in architecture influenced by neuroscientific findings since around the turn of the millennium. Discovery of the mirror neuron system supporting embodied simulation provoked architectural interests. (Mallgrave, 2009, 2013, 2018; Pallasmaa, Mallgrave and Arbib, 2013; Gallese, 2015; Robinson and Pallasmaa, 2015) This seems to corroborate notions such as embodied simulation that have been speculated in architecture since the nineteenth century. Scientific verification of some longstanding ideas in architecture encourages more investigation on many others that have been speculated but yet to be scientifically proven. One concept as such is dynamics of architectural space. The idea has been observed and described from diverse perspectives in diverse contexts; some of the theories which are revisited in the following section also indicate systematic interconnection between spatial dynamics and spatial structures. Such systematic nature of experiential space is also indicated by scientific discovery concerning mechanisms of space cells in the brain elucidating how systematically humans' allocentric spatial frame operates. (Hartley *et al.*, 2014; Jeffery, 2019)

Questions of space have been already investigated in computational research in architecture. One well established example is space syntax. (Teklenburg, Timmermans and Wagenberg, 1993; Key, Gross and Do, 2008) Space syntax analyses spatial qualities through systematic quantification and measuring. Space syntax is based on the idea that spatial configuration reflects sociocultural configuration. It considers space as an independent active subject of investigation, not a passive byproduct left by material elements in architecture. In a similar vein, spatial phenomena related to dynamics of architectural space can also be studied through computational methods, not only by descriptive ways that have been used in the past.[1] Systematising speculative studies of the past through computation can not only externalise and mobilise knowledge into the digital design procedure which is pervasive in the industry, but also facilitate future communication with relevant findings by other disciplines.

The research revisits a lineage of thoughts in regards to spatial dynamics to suggest hypotheses for a computational approach to systematic investigation of spatial dynamics from architectural perspectives. This includes to establish a computational framework that can map spatial data, to compare visual reading of the mapped spatial data to past theories of spatial dynamics, to organise spatial information based on comparative analyses of the data.

Theoretical framework

Discourses regarding spatial dynamics since the nineteenth century presuppose underlying spatial structures that are associated with the contemporaneous development in the notions of space.

Tracing back to dialogues about artistic experiences in nineteenth-century aesthetics, Hildebrand and Schmarsow considered the essence of artistic experiences lies in the idea of space rather than the idea of mass, at the outset of the discourses when the two ideas were competing with each other.

[1] Within the references included in the paper, Thiis-Evensen’s methods are what can be referred to as descriptive methods. As opposed to analytic methods used by space syntax that quantify qualitative measures, descriptive methods are primarily based on textual / literary descriptions of qualities.

(Hildebrand, 1907; Ven, 1987; Mallgrave and Ikonomou, 1994; Schmarsow, 1994; Mallgrave, 2018; Forty, 2020) For Hildebrand and Schmarsow, the idea of space is grounded in dynamic perceptual experiences of observers in artistic space. Spatial dynamics that they explicate are dynamic ways the human corporeality and proprioception are physiologically and psychologically engaged with spatial perception and spatial experiences. Hildebrand explores dynamics in relation to perceptual dynamics of a moving sensing body interacting with objects in space, through the ideas of visuomotor perception and kinetic vision. Schmarsow examines dynamics through spatial form perceived and constructed by moving bodies based on spatial relations of the bodily dimensions and the objects. He claims spatial form generates dynamics involving bodily sensations (raumgefühl), similar to corporeal experiences Wofflin theorised for architectural masses to induce (einfühlung). (Mallgrave, 2018; Forty, 2020)

In the discourses by Hildebrand and Schmarsow, the notion of spatial dynamics has little relation to dynamics of spatial structures, not unlike pervasive ideas of space in other fields of the time, such as the idea of absolute space in Newtonian physics. Dynamics of artistic space, in the theories of Hildebrand and Schmarsow, is internalised by the experiencing being. Space is merely a uniformly expansive container for intersubjective relations of objects in space and the observer in space, allowing the moving sensing body dynamically constructs spatial conception in relation to itself. The underlying conception of space refers to a spatial volume that is a homogeneous infinite extension of the body within which objects are contained without interacting with the spatial structure. Both ‘total space’ by Hildebrand (Hildebrand, 1907) and ‘intuited spatial form’ by Schmarsow (Schmarsow, 1994) denote extensive three dimensional homogeneous volume enveloping subjects. Space conceptualised here accommodates free bodily movements without being affected by them, and bodily measurements by axial systems based on the human body. Such properties resemble the ideas of space in Newtonian physics or Euclidean geometry, that presume an infinite homogeneous hollow container based on ‘man as measure of universe’, where objects can interact without influencing what encircles them. (Pérez-Gómez, 1983; Joachim, 2000; Leopold, 2002; Hensel, Menges and Hight, 2009; Emmer, 2010; Shelden and Witt, 2011; Üngür, 2011; Friedman, 2012)

In the meantime, the ideas of Newtonian and Euclidean spaces were challenged in mathematics and physics by the idea that space can be curved, differentiated. Accordingly, the notion of differential spatial structure was infused into the discourses of spatial conception and spatial experiences.

Mach’s idea of physiological spaces illustrates that spatial structures concerning dynamics of human sense experiences are non-Euclidean. (Mach, 1943) For instance, space of skin is experiential space structured according to intensities of tactile sense experiences, as Weber exhibited through mapping spatial relations of sense experiences (intensities of tactile experiences) constructing sensible space (space of skin). The resulting spatial structure possesses characters of unbounded finite surfaces, distinctive from Euclidean while similar to Riemannian geometry. According to Mach, such spatial characters are shared by sensible spaces constructed based on sense perceptions. He explicates that sensible space is “nothing like metric space”, although “the system of space-sensations is finite, continuous, three manifold, similar to Euclidean space”; the former consists of a system of graduated sense-impressions in scale (spatial gradients), hence anisotropic and nonhomogeneous – in other words, deformable – contrary to the latter. Spatial dynamics that was considered to involve dynamics of the human physiopsychology in relation to objects by Hildebrand and Schmarsow now shows its correlations with spatial structures that are non-Euclidean, heterogeneous, systematic, gradational, deformable.

Proxemics by Hall brings the correlations between spatial dynamics and spatial structures to the space of social dynamics. (Hall, 1963; Hall *et al.*, 1968) Proxemics is the study of how individuals structure space around oneself and organise spatial relations of entities (including humans, objects, structures, etc) based on the spatial structures. Hall's mapping of interpersonal spatial dynamics suggests that dynamics of spatial experiences in social settings is based on continuous negotiations among individuals' constructs of interpersonal spaces. Interpersonal space is the individual sensing body's spatial construct of structured spatial field (differentiated in gradients) around oneself. The structure of interpersonal space reflects one's idea of spatial relations, such as proximity, that are shaped by external factors, such as sensory, cultural or social environments. Therefore, changes in external factors can deform the structure of individual interpersonal space, which is followed by changes in the individual's spatial experiences and dynamics of social engagement. The space of social experiences shows similar traits as the space of sensorial experiences, that is heterogeneous, systematic, gradational, deformable.

The principles of proxemics are applied to interspaces of objects as well as interpersonal spaces. (Hall *et al.*, 1968; Arnheim, 1977) That is, humans experience similar comfort / discomfort and urges to balance interspatial relations when they observe non-sensing entities as well as when they interact with sensing bodies. This reflects that the human spatial experiences involve both frames of spatial reference that are established in psychology and neuroscience: egocentric and allocentric. (Mallgrave, 2018; Jeffery, 2019) Furthermore, similarities of bodily experiences of spatial interactions between sensing bodies and / or non-sensing bodies imply sensing bodies' spatial experiences through embodied simulation. (Pallasmaa, Mallgrave and Arbib, 2013; Gallese, 2015; Mallgrave, 2018) Arnheim's description translates experiencing through embodied simulation to experiencing dynamics of "invisible forces" in "perceptual fields". (Arnheim, 1977)

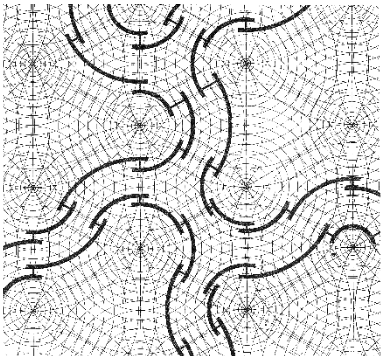


Figure 1. Perceptual field by Portoghesi (Arnheim, 1977)

The idea of perceptual fields was developed into architectural design methods by Portoghesi through his field theory ('Teoria dei Campi'). (Arnheim, 1977; Norberg-Schulz, 1988; Vanucci, 2020) Spatial dynamics of Hall's proxemics involving perceiving bodies in social space is transposed to that of Portoghesi's field theory involving non-sensing objects in architectural space. Influenced by the field concept in physics, Portoghesi's field theory presumes field and mass are only distinguished by quantitative differences of concentration of energy. (Arnheim, 1977) The structures of perceptual fields are composed of multiple fields of visual forces. Each field of visual forces propagates outwards from the centre, generating ripple-like patterns of a series of concentric circles that register decay of intensities of perceptual forces in gradients. (Figure 1) The structure of a field of perceptual forces is differentiated through modulated discretisation. When utilised in design methods, each field operates as a unit element of field composition. Multiple field units are manoeuvred to reach desired field compositions suited for the contexts of the project. The finalised field composition becomes templates for designers to define organisation of architectural objects and field structures generated by them. Portoghesi's field theory based on the notion of space as differentiated field emphasises the concept of space in architecture, that is distinctive from the preceding ideas of space in architecture as "a homogeneous structure" or "counterform to the mural envelope". (Arnheim, 1977) Portoghesi's design method using perceptual fields seemingly achieves to stress the continuous variability of the environments surrounding the architectural structures, but how multiple field units are assembled to the composite field structure lacks dynamic properties. The structure of a field of perceptual forces in Portoghesi's theory cannot deform according to the geometric properties of architectural structures that generate the field in the way Arnheim envasages. The field structures that Portoghesi suggests are heterogeneous, systematic, gradational, but not necessarily deformable.

On the other hand, Arnheim argues invisible forces generated by architectural objects deform perceptual fields and each configuration of perceptual fields is determined by geometric properties of the structures generating the forces.

Through studies conveying the idea of spatial dynamics of interspaces between architectural objects, he reassures that interspaces between architectural structures are part of the field structures and filled with spatial gradients differentiated by force field dynamics, in which perceptual forces can deform perceptual fields. Arnheim explains the phenomena using the idea of “dynamic displacement”, perceptual deformation of the spatial fields by the entities within the field boundaries. Deformation of the field structures can be registered through dynamic changes of the spatial gradients in the fields – dynamic topographic changes of density and pressure in the field structures. Arnheim also surmises that formal (correlative) relationships of geometric properties of perceived objects and spatial gradients of perceptual fields in the interspaces can be established. For example, relative sizes of objects could have correlations with the intensities of perceptual forces influencing pressure gradients of the field structures; while relative sizes of interspaces could have inverse correlations with density gradients of the perceptual fields. Based on correlations as such can be hypothesised and explored potential correlations of spatial dynamics and more complex geometric features, including curvature, concavity, convexity.

Force dynamics of the perceptual fields becomes fundamental media through which humans perceive and experience dynamics of architectural space in Arnheim’s theory. Differentiated field structures are filled with diverse gradients of density and intensity (pressure) that stimulate observers to experience perceptual compression and decompression. Experiences of perceptual compression and decompression are also processed through embodied simulation, similar to the cases of proxemics in-between non-sensing objects mentioned earlier. Such experiences through embodied simulation extends even further as observers could experience comfort or discomfort by balance or imbalance of the forces in the perceptual fields – while the experiences are continuously modulated as conditions or boundaries of the perceptual fields alter.

Based on the discussion thus far, dynamic field structures are the spatial structures that can facilitate dynamics of architectural space that have been studied and speculated from diverse perspectives for the past century. Dynamic field structures interact with objects following their intrinsic field dynamics. When dynamic field structures, with architectural objects, collectively constitute dynamic field conditions, the field dynamics unfolds. First, forces are generated by objects in the fields. The forces configured according to geometric characters of the objects deform the field structures. The resulting differentiated field structures steer organisation of density of the field structures and perceptual pressure in gradients. Characteristics of these field dynamics are determined by field properties regarding values of spatial data that the field structures carry. Values of the spatial data are those of intensive quantities, similar to temperature or speed. Intensive quantities are indivisible and not additive, distinctive from extensive quantities, such as volume, area, length, amount of energy or entropy. (DeLanda, 2005) Instead, intensive quantities, when differentiated in gradients, activate emergence of changes that tend to restore equilibrium of the system. The same happens in dynamic field conditions, when perceptual forces generated by objects in the fields activate deformation of the field structures. Deformation of the field structures is the process of intensive values of the field structures trying to reach the state of equilibrium, or the state of multiple local equilibria. The final states of each local equilibrium function as virtual attractors of the process, as it does in systems of nonlinear non-equilibrium thermodynamics. These attractors tend to be “steady-state, periodic and chaotic” resulting in the system’s dynamic equilibrium – that is, the state of equilibrium not as static inertia but as temporary stasis of the dynamics. (Arnheim, 1977; DeLanda, 2005)

Establishing architectural space as dynamic field structures enables quantification of qualitative values of the former. In the research, dynamics of architectural space that has been investigated and speculated through descriptive methods is quantified, computed, mapped visually through dynamics of field structures. Furthermore, having discussed above that dynamics of spatial experiences is interlinked with spatial dynamics and that spatial dynamics can be mapped through deformation of dynamic field structures, it can be assumed the mapping could reveal correlations of spatial experiences and geometric characters of spatial structures. Therefore, the research attempts to suggest computational analyses procedures of spatial dynamics, which include a computational framework to map deformation of dynamic field structures. Spatial data generated from mapping can be analysed compared to the texts based on descriptive methods. Through the comparative analyses, the data created by the system can be organised into valid spatial information. The system, then, is tested for potential application to built structures. Once the mapping system that can generate valid spatial information is established, it can be developed / integrated into design processes or be made to a metric.

Computational framework

As aforementioned, a computational framework to map deformation of dynamic field structures is required to construct computational analyses procedures for spatial dynamics.

What the computational framework needs to perform can be outlined as to compute the field dynamics and to generate spatial data through mapping what is computed. Computation of the field dynamics prerequires dynamic field conditions that are constituted by dynamic field structures and objects. The setup of dynamic field conditions activates the field dynamics initiating deformation processes as explicated in the previous section. Computation of the processes are resolved through dynamic relaxation algorithms[2]. As the algorithmic processes reach the state of dynamic equilibrium at multiple loci of the structures, the field structures are differentiated by gradients of diverse types of intensive quantities, including field density and perceptual pressure. Changes in intensive quantities from the neutral state to the deformed state of the field structures are measured to be mapped. Visual outputs mapping changes in different types of intensive quantities provide spatial data in colour gradients that can be analysed perceptually.

The computational framework is equipped with multiple system settings. The settings can be defined when the dynamic field conditions are established. Some settings are related to the field properties, such as the size of the field, the density of the data points in the field; some are related to data processing, as are neighbourhood size of the data points and weighting methods for data interpolation, while some are related to image production, for instance the size of the visual outputs.

Visual outputs for spatial data include density maps, pressure maps, vector maps. Density maps show topographic mapping of quantitative changes of field density from the neutral state to the deformed state of the field structures. Pressure maps show topographic mapping of quantitative changes of spatial expansion and contraction of the field structures that reflect perceptual decompression and compression, perceptual pressure by perceptual forces influencing the field structures. Vector maps show changes of vectors throughout iterations of the algorithmic processes. Each iteration during the deformation processes computes new vector data. Vector data recorded throughout the whole deformation processes can reveal details of the field dynamics' interactions with any particular geometric characteristics of the objects. Vector maps are constructed in two ways, one in monotone emphasising locations and magnitudes of the vectors throughout the deformation processes, the other in colour displaying collapsed versions of the former with ranges of vector magnitudes in colour gradients. In the latter, the sums of vector magnitudes are

[2] Dynamic relaxation algorithms are iterative processes frequently applied to form-finding approaches and structural optimisation in architectural computation.

interpolated and captured by data points – either a collection of vectors with higher intensities or that of greater number of vectors would result in larger sums.

Spatial data generated via mapping can be analysed comparatively against the texts describing qualities of architectural space. For this specific purpose, the preliminary test cases for the computational framework are organised based on “Archetypes in architecture” by Thiis-Evensen, in which the author depicts experiential qualities of architectural geometries based on phenomenological descriptive methods. (Thiis-Evensen, 1989) Among various archetypes he introduces, his categorisation of wall structures is selected to constitute the preliminary test cases, which encompasses geometric features such as curvature, concavity, convexity. The selection of extruded wall structures along a vertically straight axis allows for the mapping results to remain two-dimensional, which helps to keep computation and image production less complex for the early stage of the investigation.

Preliminary data analyses

Preliminary data analyses are conducted using Thiis-Evensen’s wall archetypes including straight and curved walls. The main objectives are to map systemic behaviours of the computational framework in relation to geometric features of the walls, to compare the visual mapping results to analyses by Thiis-Evensen – and other texts that are based on descriptive methods, to calibrate the framework to construct systemic spatial information.

The computational framework is composed of two layers. The data collecting layer constructed with data points (appearing as red points in Figure 2) capturing diverse data of the field structures, while the algorithm processing layer constructed with a grid structure computing deformation of the field structures through dynamic relaxation algorithms.

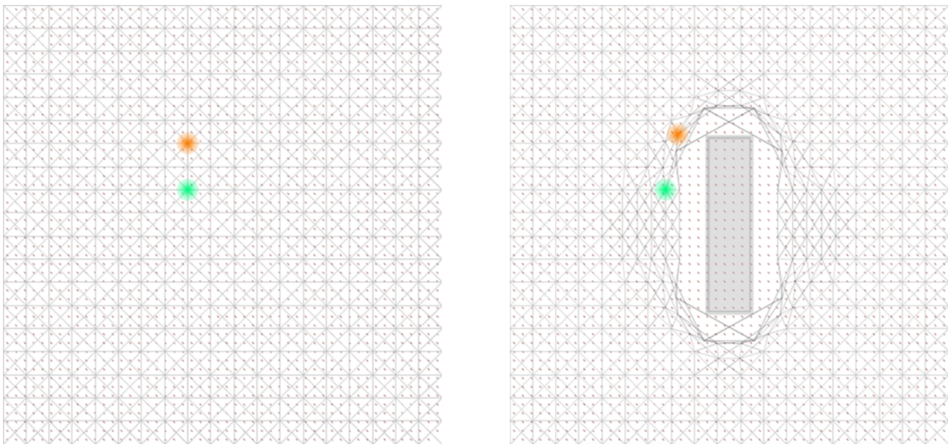


Figure 2 . The neutral state of the field structure (left) and the deformed state of the field structure (right). The two coloured points in the images indicate displacement in the field structures by deformation processes.

For all preliminary data analyses, settings for size of the field, density of the data points in the field, size of the visual outputs are constrained to 100x100 system units, 50%, 500x500 pixels respectively. Options for neighbourhood size of the data points and weighting methods for data interpolation are explored to produce diverse outputs for analyses; the results presented in the paper use 4 data point units for the former and the linear method for the latter.

The baseline set for the preliminary analyses consists of two cases: one with a single straight wall and the other with a single curved wall. (Figure 3) the computational framework generates four different mapping results for the two cases. (Figure 4)

Figure 3. The baseline set

In the results, one of the most discernible geometric features is symmetry. The single straight wall case exhibits reflectional symmetry with multiple axes – one with respect to the axis along its length and the other with respect to the axis across its length in the middle. The single curved wall case presents only the latter symmetry.

The symmetric nature of the flat wall is indicated in Thiis-Evensen's text as well. Thiis-Evensen describes the wall's extension as "the dynamic relationships between a central field and two peripheral fields." His description seems to explain the density map of the single straight wall case. Each side of the wall exhibits concentration of higher density around its centre, which gradates to lower density in the regions towards both of its corners – "a central field and two peripheral fields." Such organisation (of centre and peripheries towards both corners) results directionality to the wall, and can even evokes impulses to move along the wall to reach either end of the wall according to the author's illustration of the experiential phenomena of the wall. If the phenomena are compatible with topography of density and pressure in the field, the correlations can be presumed for directionality from higher to lower density and from compression to decompression. Such correlations, nonetheless, could only be formalised through sufficient data analyses and comprehension of complexity of the system. Symmetry is also understood as "an image of fundamental order" for dynamic balancing, dynamic equilibrium. (Thiis-Evensen, 1989) Through this understanding, Thiis-Evensen acknowledges the (perceptual) tautness of the flat wall by dynamics of forces and counterforces in balance. Yet the flat wall is described as an impassive, neutral background, merely for its state of equilibrium in symmetry does not convey information concerning inside-outside relationship. Despite its incoherence with other parts of the text, the description emphasises the flat wall's lack of ability to manoeuvre / generate spatial distinctions, which is also demonstrated by rather uniform patterns around the sides of the wall in the vector maps.

The curved wall, on the other hand, is referred to as what can "constitute the sum of counteracting forces in the life process". (Thiis-Evensen, 1989) The wall's capacity to address interior exterior relationship is enhanced when it is curved. (Norberg-Schulz, 1988) It is based on inherent characteristics of a curve as "an intensive line", "an intelligent better-informed line", "a complicated straight line", that can "negotiate differences" "through continuity". (Spuybroek, 2004) The curved wall organises perceptual forces largely in two different ways – through the convex side and through the concave side. Multiple texts link convex sides with outwardly projection and expansion, whereas concave sides with inwardly concentration and condensation (Norberg-Schulz, 1988; Thiis-Evensen, 1989) – accordingly, these counteracting forces achieve dynamic equilibrium in the curved wall case that comprises both convex and concave sides. The textual descriptions of convex and concave sides find their counterparts in the mapping results. For the density map and the pressure map, the convex side seems to distribute density and pressure along its length rather evenly, while the concave side seems to concentrate higher density and compression. The vector maps exhibit more intense interactions around the concave side compared to the convex side. Distribution of pressure and vector data around the convex side, in particular, can be interrelated to solidity conveyed by convexity. (Arnheim, 1977; Thiis-Evensen, 1989) Since equitable distribution of the values can be identified around the sides of the straight wall as well, its correlation to the quality of solidity is presumptive. Nonetheless, more differentiation and complexity around the convex side in the curved wall case induce different spatial phenomena to the straight wall case; for example, Thiis-Evensen explicates that the former yields impressions of movements around, while the latter evinces stasis. Meanwhile, the concave side is described to be "receptive and pliant" to the observers and the surrounding environments. Therefore, it can be presumed to be associated with concentration of higher density, compression and vector interactions in the mapping results.

The variations set is designed with pairs of straight walls or pairs of curved walls with varying interspace sizes and angles in-between. (Figure 5)

Symmetry is still observed in the mapping results of v01. (Figure 6~9) But addition of the straight wall to the field conditions changes the axis of symmetry along the wall's length from the centre of the wall to the interspace between the two walls; collective symmetry for a group of objects overrides individual symmetry of each

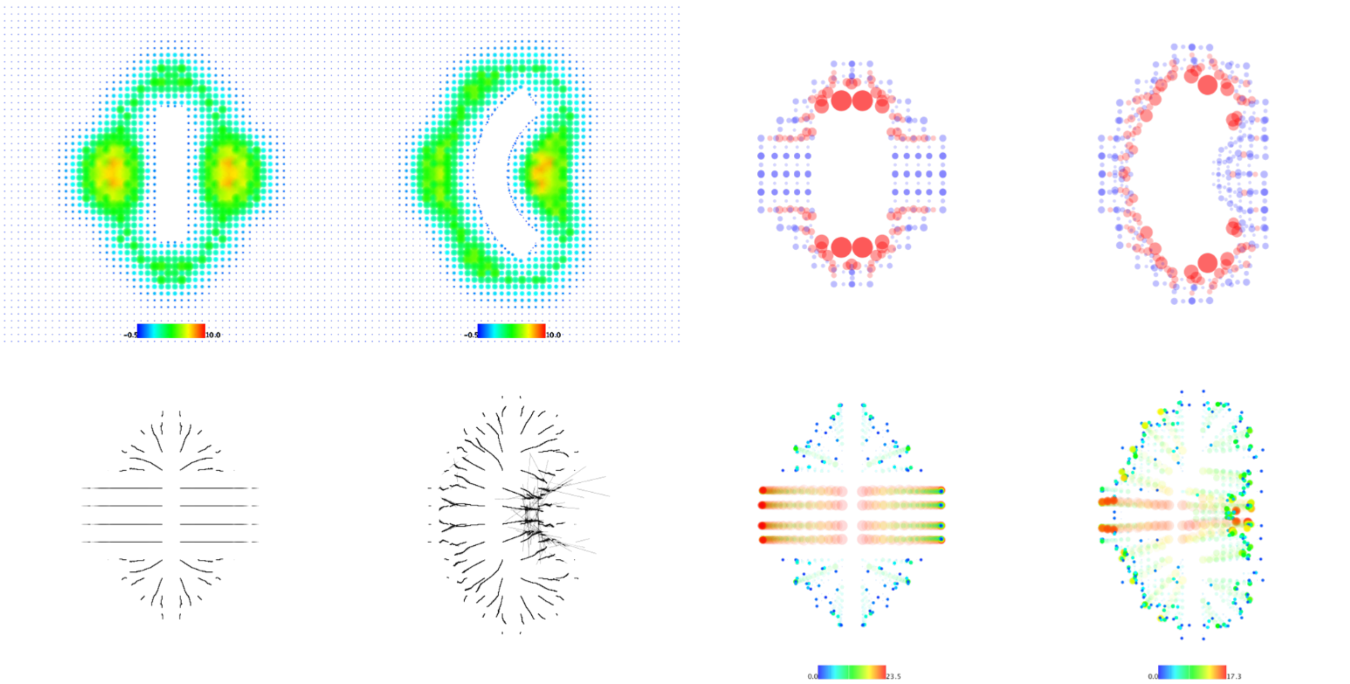


Figure 4. The mapping results of the baseline set. Density mapping (top left), pressure mapping (top right), vector mapping (bottom)

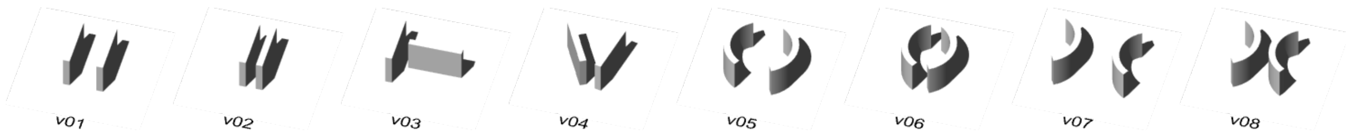


Figure 5. The variations set

object. This indicates symmetry of an object can be superseded by symmetry generated by organisation of multiple objects within the field. Furthermore, it implies spatial characters that are associated with symmetry can be manipulated by the manner of spatial organisation. For example, lack of spatial distinction capacity of the single straight wall observed in the baseline set analyses may be outmanoeuvred in v01 to convey spatial information such as inside-outside relationship. In the meantime, interactions between the objects present concentration of the values of density increase, pressure increase, vector dynamics increase in the middle of the interspace. With smaller interspace size as in v02, concentration of dynamics in the interspace intensifies for the mapped values except density topography which exhibits proliferation of higher density regions into multiple locations. (Figure 6)

Such proliferation behaviours are observed in other cases such as v04 and v08. (Figure 6) It can be presumed that proliferation in density topography happens where the interspace sizes decrease. v04, when compared to v02, shows more diversified proliferation, with more concentration in the interspace than other locations of proliferation. Such differentiation, with patterns of the other maps, indicates similarities to the patterns around the concave side of the baseline set – pressure dynamics and vector dynamics as well as density topography show more intense iterations of the patterns around the concave side with clear differences around where two walls almost meet at an acute angle. (Figure 7~9) If the link between the character descriptions of the concave wall and the patterns of the mapping results can be presumed as mentioned in the baseline set analyses, the characteristics of the concave wall – "receptive and pliant" – can also be applied to v04. This suggests that the straight walls can be manoeuvred and organised in ways that can mimic spatial dynamics of the curved wall, once again affirming the nature of a curve as "an intensive line"[3]. v08, on the other hand, exhibits particular behaviours in the interspace when compared to v02. Higher density regions in the interspace of v02 seem to change in v08 as if the central higher density region was split and pushed towards the two opposite ends of the interspace, leaving the centre of the interspace with negative values in density change – decrease in density. The behaviour repeats in the other maps, as observed through the intensified decompression in the middle of the interspace and the intensified vector dynamics from the centre to the ends of the interspace. The patterns of the mapping results reflect Thiis-Evensen's description of Casa Andreis (refer to case study of the paper) where space "presses forth between inwardly curves" opening itself towards another space. (Thiis-Evensen, 1989)

Returning to the issue of the parameters of the variations set, variation in interspace sizes can be analysed by comparing the pairs of v01 and v02, of v05 and v06 and of v07 and v08, while variation in angles by comparing v01, v03 and v04. (Figure 6~9) In general, addition of another object intensifies dynamics in the interspace as can be observed in v01, v05 and v07. However, decrease in the interspace size results more complex patterns as found in the case of v02 and v08, while it can simply result in more intensification of the dynamics than its counterpart with larger interspace as in v06. That is, the mapping results can provide information concerning more adequate spatial relations as well as geometric features of the objects for specific field conditions, depending on what spatial qualities the design intents are to convey. The same can be concluded for the angle variation. v01, v03 and v04 present that changes in spatial relations of the two walls by angles in-between induce differences in the mapped data which can be associated with differences in spatial qualities. It is evident that angles in the case of v03 and v04 intensify dynamics in the interspaces than the parallel configuration of the walls. The mapping results of v04, as analysed earlier, indicate potential manoeuvrability of straight and curved geometries. Whilst, the mapping results of v03 suggest ways dynamics of the straight wall can be diversified in terms of (reflectional) symmetry. By rotating one wall in 90 degrees from v01, the symmetry of the rotated wall partially restores its symmetric nature, showing traces of features of the single straight wall case mapping results. In contrast, symmetry of the unrotated wall remains destabilised with its dynamics concentrated towards the rotated wall. The vector maps present the peculiarities more prominently than other maps through patterns tracing from the unrotated wall to the sides of the rotated wall. (Figure 9)

[3] It would require further inquiries to confirm what is conveyed by the increase in the intensity of the mapped values in the mapping results of v04 in comparison to the concave side of the curved wall case, for example, its potential correlation with angles.

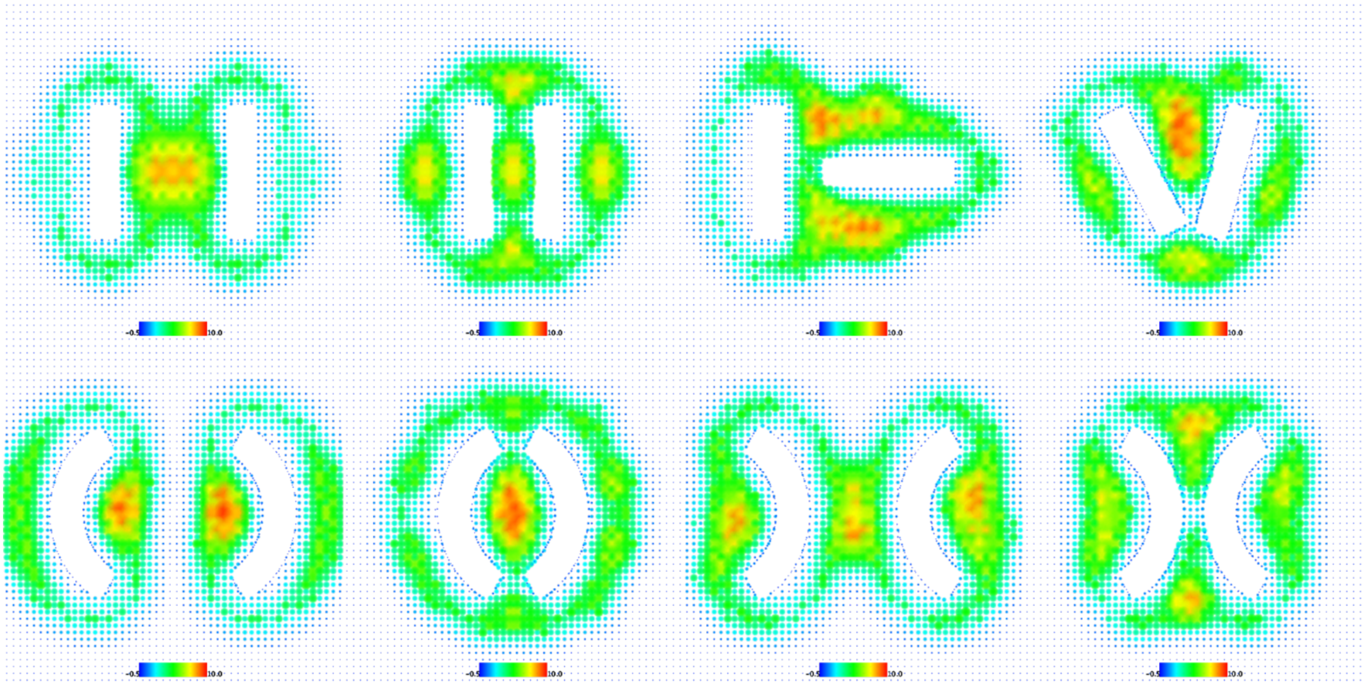


Figure 6. Density mapping of the variations set

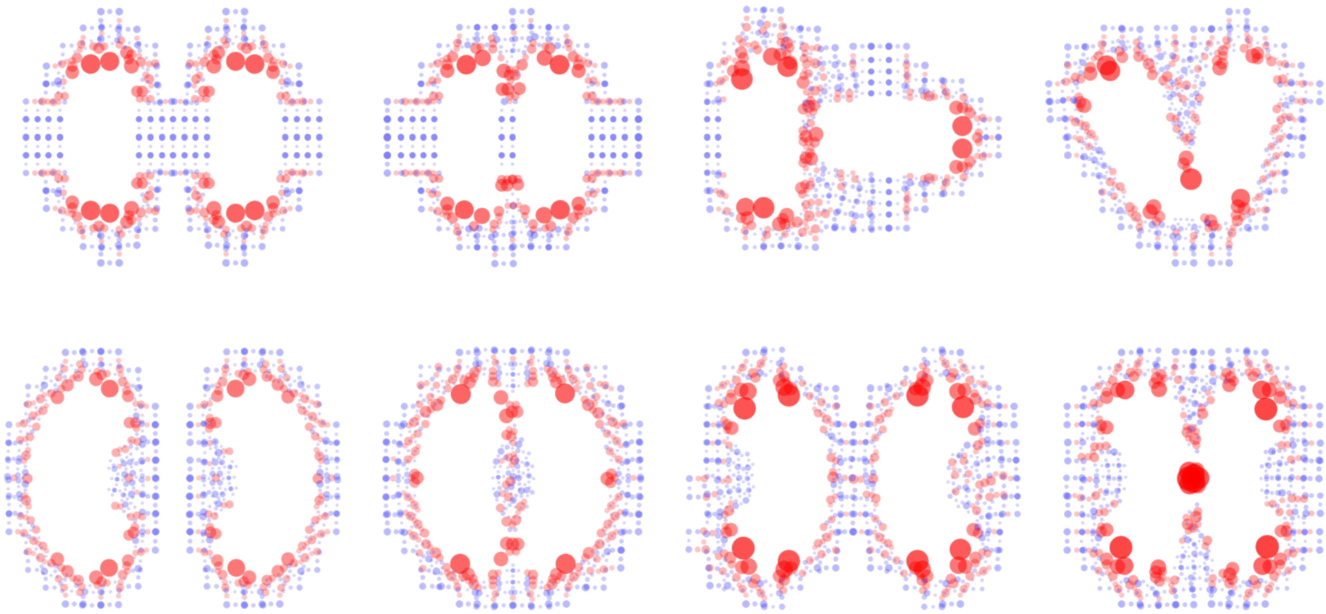


Figure 7. Pressure mapping of the variations set

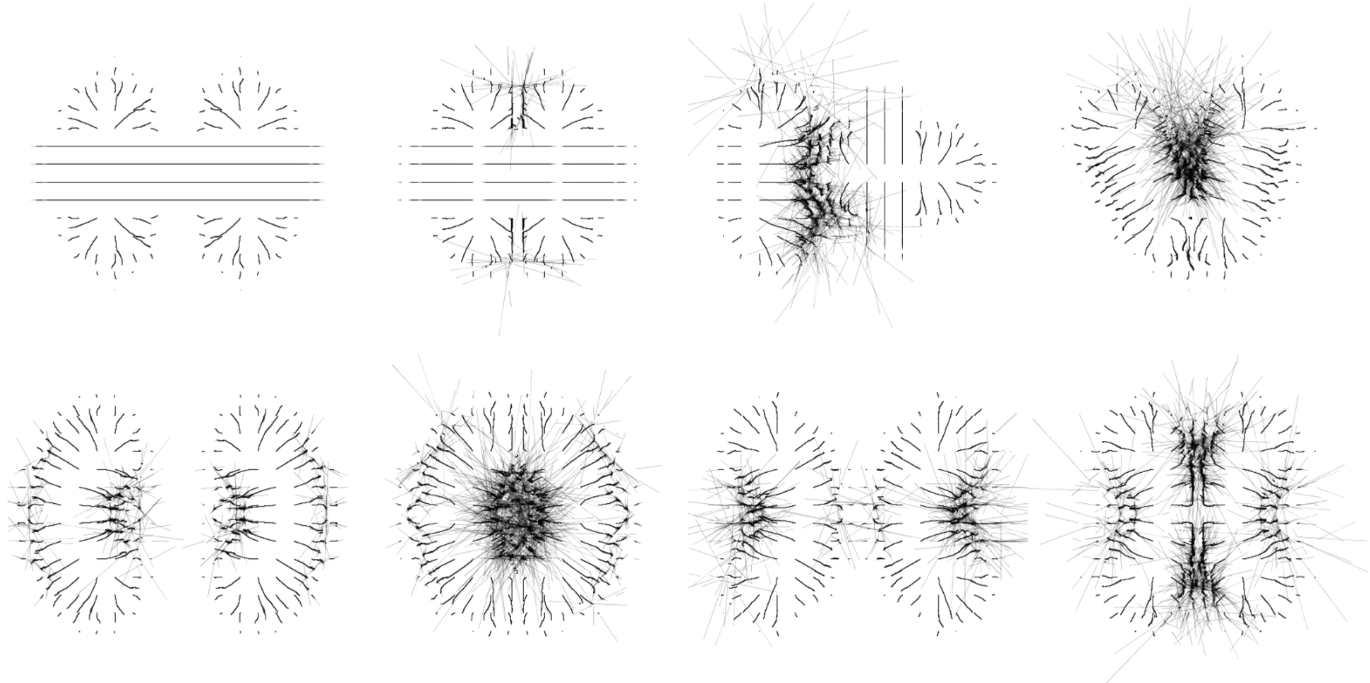


Figure 8. Vector mapping of the variations set

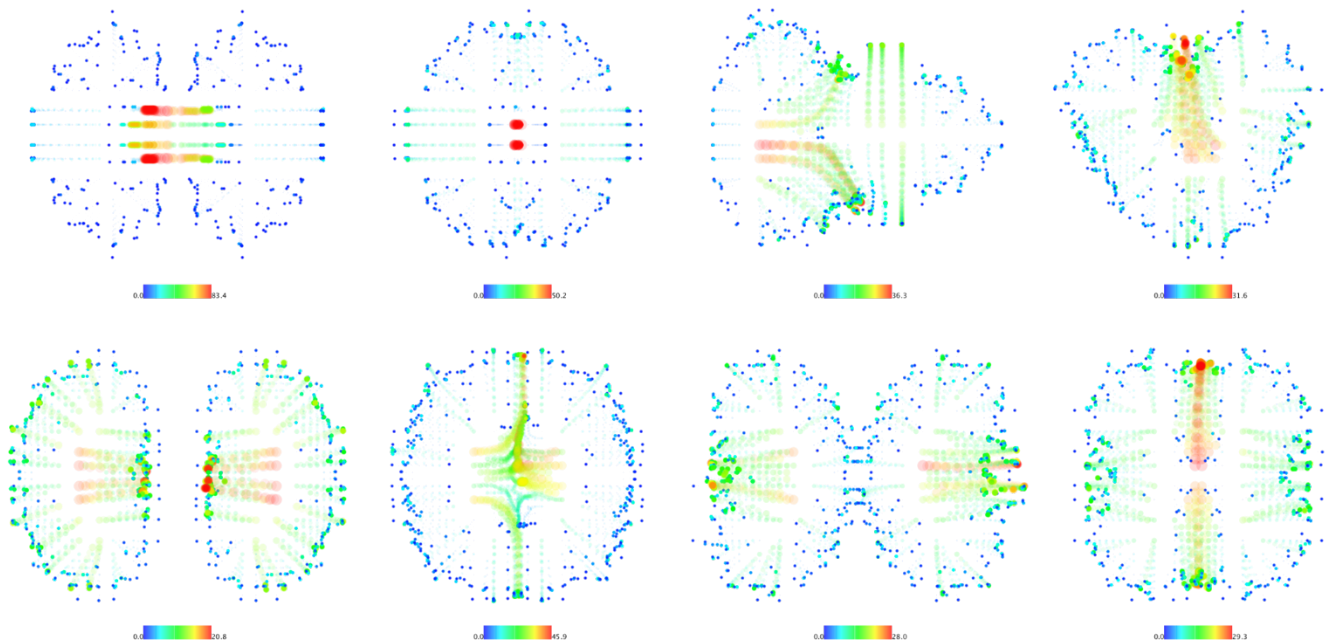


Figure 9. Vector mapping of the variations set

Case study

Casa Andreis is one of the built structures using the field theory method by Portoghesi. The ground floor of the two-storey residential building is computed and analysed by the computational framework. The ground floor is composed of the lounge area, the kitchen area, the dining area, bathrooms and bedrooms. (Figure 10) The design of the ground floor explicitly shows its design procedure based on the architect's field theory. It has five focal points, each of which propagates a group of concentric circles, collectively forming differentiated perceptual field structures. All five focal points are located outside the built structures constituting three triangles that guide the base configurations of the groups of concentric circles.

The plan of the ground floor alludes some underlying orders. First, most interior spaces are located where different groups of concentric circles overlap. Walls inside the three base triangles are primarily curved, while those outside the triangles are dominantly straight. Inside the three base triangles are where three groups of concentric circles overlap. The architect designated communal areas – such as the lounge area, the dining area and the entrance hall, and the corridor and the bathroom – within the three base triangles, while private areas, the bedrooms, outside. The communal areas are mainly environed by differentiated curved walls; the kitchen, the entrance hall and the bathroom are shaped between two concentric curves (by a concave and a convex side), while the lounge area, the dining area and the corridor are demarcated by convex sides of multiple curves (without concavity). (Figure 10)

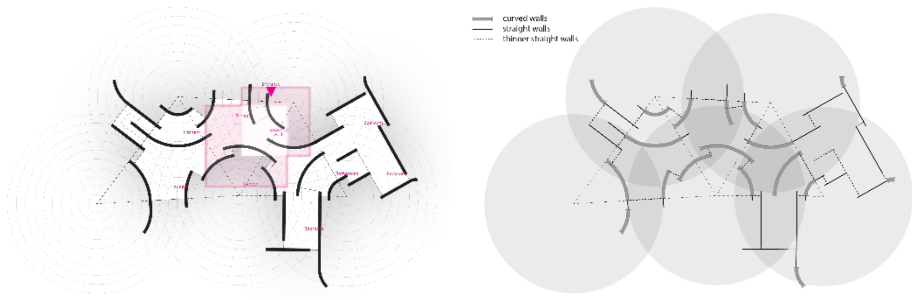


Figure 10. Ground floor of Casa Andreis

Figure 11. The selective wall configuration used for the study

For the purpose of showcasing the application of the computational framework without overloading computational processes, the selective wall configuration of the ground floor is used as the study case. (Figure 11)

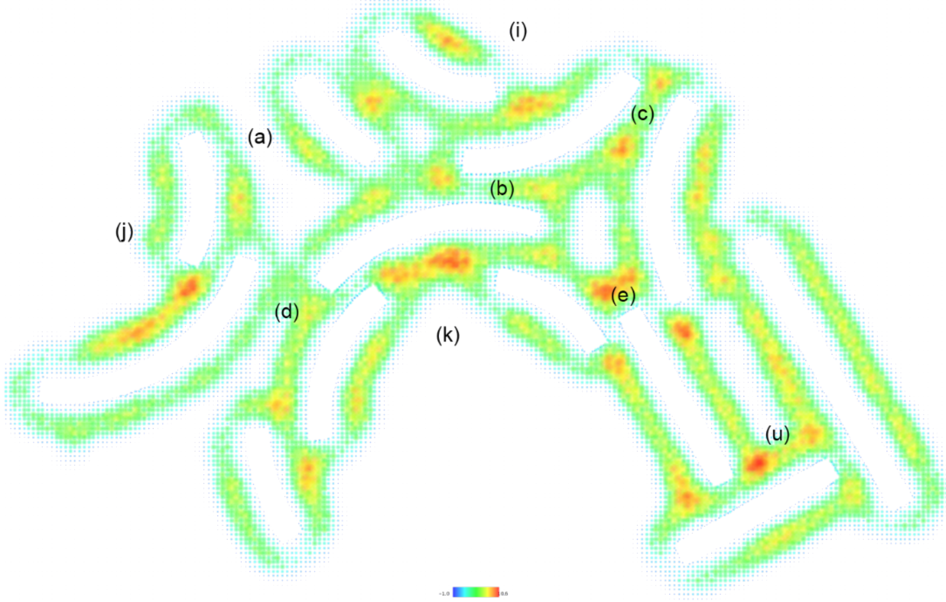
Primary components are curved walls. Since the centres of the arcs are located outside the building, all curves have concave sides facing exterior space and convex sides facing interior space. Thiis-Evensen's descriptions of concave form embracing the surrounding environments resonate with Norberg-Schulz's descriptions of exterior walls of Casa Andreis as "quiet zones" capturing surrounding spaces. (Norberg-Schulz, 1974; Thiis-Evensen, 1989) In the study case (Figure 12), locations (i), (j), (k) are found to match the geometric descriptions, enveloped by staggered layers of concentric arcs with concave sides exposed to the external environments. The descriptions as "embracing environments" or "capturing environments" seem to be reflected in the designer's decision to have a garden area in (k). The capacity of the geometric feature to interact with environments can be interlinked with the intense dynamics around the locations in the mapping results, while the description of these locations as "quiet zones" may not. In addition, the staggered layers of concentric arcs seem to intensify dynamics to different degrees for the three locations – the differences in their intensities can be caused by various factors such as different lengths of the arcs, different proportions of the overlapping lengths, different number of the walls interacting in the areas, etc. Another common description of the curves by the two authors concerns the interior space of the building. Both discuss that the arrangement of the curved walls inside the building achieves spatial continuity – as described as "divided waves" by Thiis-Evensen and "dynamic stream" articulated to afford "rest and movement" by Norberg-Schulz. Such descriptions can be probed further based on the mapping results as follows.

Some areas have wall configurations that can be identified with the cases of the preliminary data analyses in the previous section. Multiple occasions of spaces shaped by convex sides of the curved walls with varying interspace sizes can be identified as variations of v07 or v08. The three straight walls in the configuration constitute a more complex version of v03.

The situations with the former features are located in (a), (b), (c), (d), (e). (Figure 12) The five locations have different variables – such as the interspace sizes and the curvatures of the arcs – and induce slightly different patterns in the maps. (a) may be too large to have more substantial interactions in the current settings of computation; the size of the space may be required to accommodate communal spaces. (b) and (c) are narrow enough to subtly induce mapping patterns similar to v08, where two convex curves generate dynamics seemingly flowing from the centres of the interspaces towards both ends of the interspaces. If the aforementioned description of "interior which presses forth between inwardly curving sections opens itself towards the outside" can be transposed onto the conditions in (b) and (c), their conditions of spatial configuration are evaluated to be appropriate. Both locations are designed to be circulation spaces: (b) is between the communal areas and the private areas, while (c) is between private areas of the house. (d) and (e), where the sizes of the interspaces are similar to each other, show differences in density topography while similarities still stand in other mappings data. Differences between the two cannot only be explained by the interspace sizes since the dynamic field conditions of the two are slightly different not only from each other but also from those of v07 or v08. Possible reasons for the differences in density topography of (d) and (e) could only be speculated until they can be further investigated in the future development of the framework. They can be speculated to be the slight differential between sizes of the two interspaces, the spatial relations of the ends of the curved walls with each other, the interactions with the end of the third wall placed in each interspace, or the space where (e) is located has more closed wall configurations, while the space where (d) is located has one side of the space widely open.

Whilst, the situation with the latter features – the configuration with three straight walls, (u), can be interpreted either as two occasions of v03 interlinked with each other or as one occasion of v03 with one more wall added in perpendicular to one wall and in parallel to the other. Seen as the latter, addition of one more wall to the conditions of v03 changes characteristics of space, hence characteristics of dynamics. The most apparent change is that the addition can define interior and exterior sides of the walls. accordingly, (u) does not generate symmetry as v03 does, although patterns around the two junctions follow those of v03 quite closely. Instead, it prompts gradients and dynamics around the interior sides of the walls to be more intense than those around the exterior sides. The result extrapolates the analyses in the preliminary test cases in which configuration of multiple straight walls enables spatial distinctions, while the single straight wall cannot.

The case study of Casa Andreis showcases application of the computational framework by analysing the mapping results against the preliminary test case analyses and descriptive textual analyses by Thiis-Evensen and Norberg-Schulz. The mapping results of the case study affirm some of the previous analyses, while questioning or even competing with some others. With more complex dynamic field conditions provided by Casa Andreis, the mapping results seem to preserve features of some dynamics that are present in the preliminary test cases, while losing some others. For example, the differences of dynamics between around the convex side and around the concave side, in most cases, seem to persist in the complex field conditions of the case study. Such persistence may mean that the features distinguishing convex and concave geometry can be fundamental to spatial geometry and can explain why multiple theories compare the two. Some of the changes in the mapped patterns of dynamics can be explained by examining multiple test cases together, but some can only be speculated until further tests and analyses can be undertaken.


(i)
(a)
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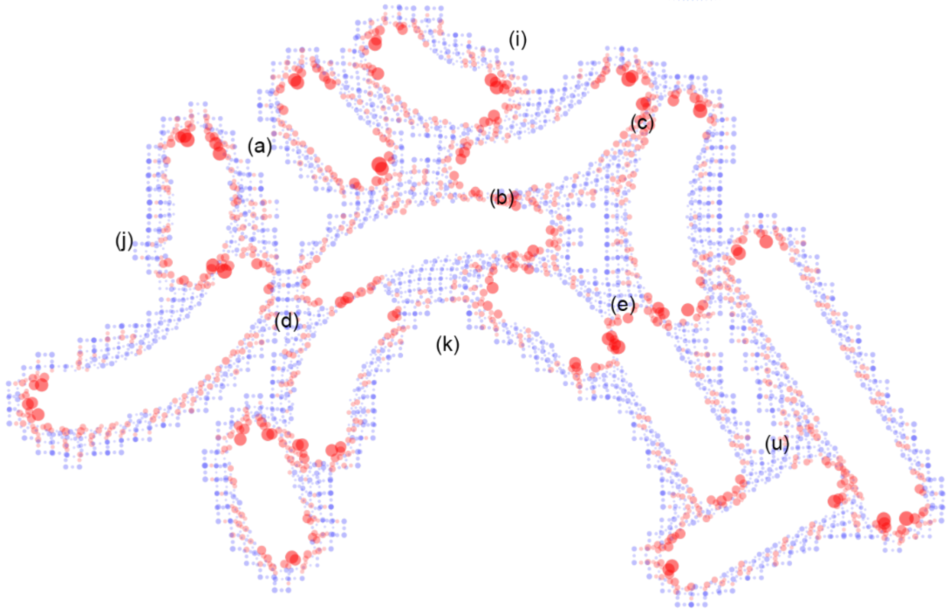
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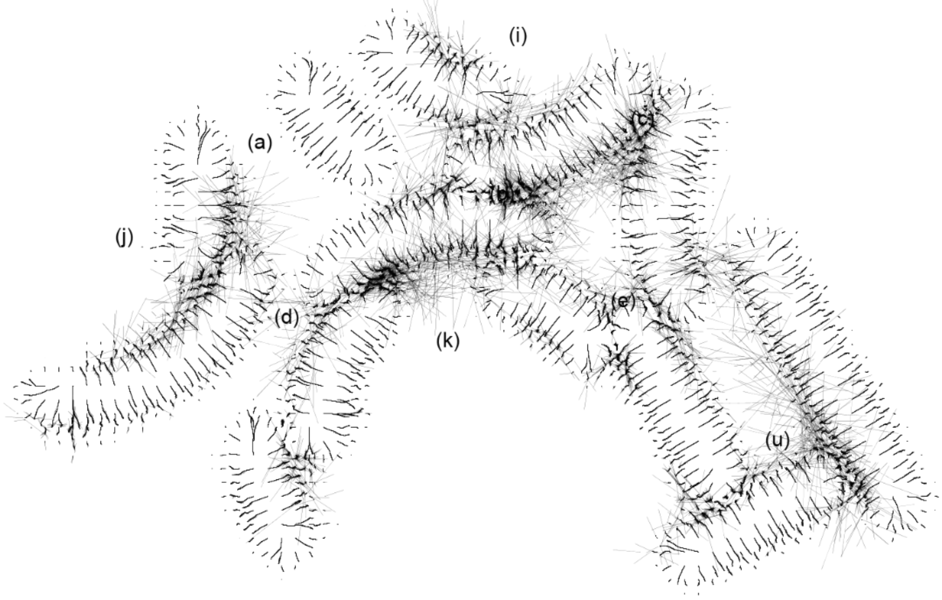

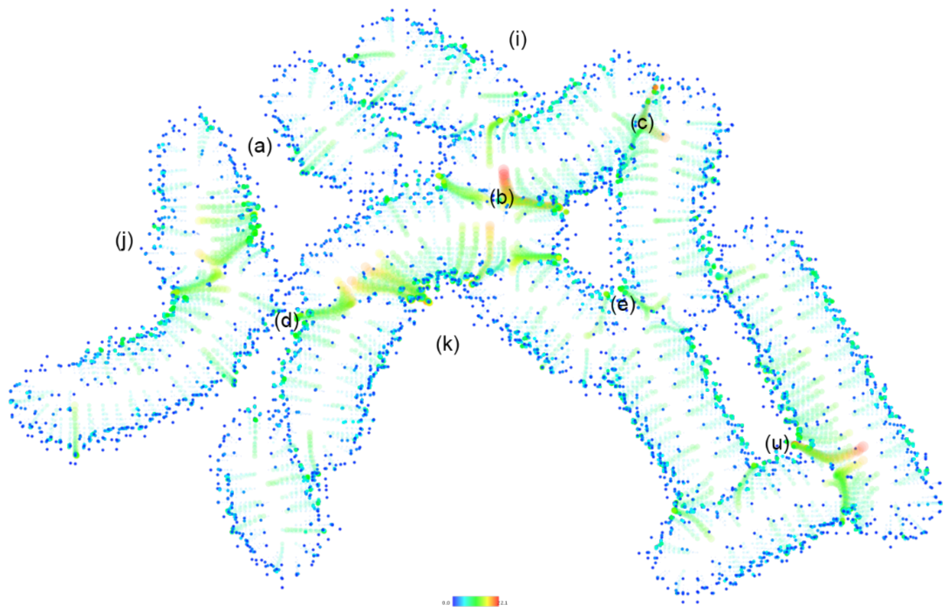

Figure 12. The mapping results of Casa Andreis (From the top: density mapping, pressure mapping, vector mappings)

Research summary

(Architectural) space is abstract, as well as intangible and immaterial, despite numerous attempts to grasp its qualities. The descriptive methods that are referred to in the paper have been serving as one of the most normative methods to communicate insights into those qualities. As the initial work presented in the paper exhibits, correlations can be observed between the computational approach and the phenomenolotigal approach. Such findings motivate development of more systematic approaches in the future to enable more collective effort for discourses of abstract qualities. Only after formalisation of systematic methods can follow development and communication of knowledge and expansion of spatial design potentials. Since computational environments can be sensitised for increasingly diverse types of computation, experiential qualities of architectural space that are described in the literature – especially since some are scientifically supported as well – can also be studied more systematically if assisted with computation. Therefore, the paper proposes systemic methods to investigate qualities of architectural space and to continuously augment new knowledge. Through establishing the theoretical framework and the computational framework, spatial data are generated in the form of visual mapping. The data are analysed in comparison to the existing texts describing spatial qualities, in order to calibrate visual patterns of the mapping by computation. Through comparative analyses the initial set of spatial information – in particular, correlations of architectural geometries and experiential dynamics – is constructed. The set of spatial information is further calibrated through a case study showcasing application of the computational methods to a built structure. The data from the case study is analysed in comparison to the studies on qualitative aspects of architectural space primarily through individual insights as well as the spatial information constructed in the preliminary analyses. What is presented in the paper is a step towards more communicable ways to analyse, to discuss, to construct knowledge concerning abstract properties of architectural space. Systematic externalisation of conceptual procedures and increased communicability can enhance collaboration and can catalyse more interaction with knowledge input from other disciplines or vice-versa. The approaches developed in the research are ultimately to facilitate design decisions to be better informed in ways that are more fundamental to how we operate in the world we live in. The further research will follow focusing on three dimensional assemblage of spatial information as well as continuing calibration through more number of case studies.

Acknowledgements

Authors may acknowledge contributions to the presented research or credit illustrations here. Also authors may provide information in this section on how the research is funded, for example through research foundation, university, authority, organization or spare time research.

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